Science behind the Resistance Management Strategy for *Helicoverpa armigera* in Australian grains

Developed by the grains National Insecticide Resistance Management (NIRM) working group of the Grains Pest Advisory Committee (GPAC)

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Helicoverpa armigera is a major pest of grain crops and represents a significant challenge for the grains industry given the ongoing reliance on chemical control methods. *H. armigera* reduces yield of pulses, oilseeds, coarse grains and occasionally winter cereals. Economic losses result from larvae feeding directly on the reproductive structures of crops (seeds and grain). Grain quality may also be downgraded through unacceptable levels of damage. Although widely distributed and recorded in all states and territories within Australia, *H. armigera* is more common in the northern and coastal regions of eastern states, particularly in warmer areas.

Helicoverpa armigera has evolved some level of resistance to the three chemical groups with broad spectrum activity (organophosphates, carbamates and pyrethroids) which represent the majority of the 200 chemicals registered for this pest in Australia. Historically, it is this resistance that caused devastation in the cotton industry prior to the introduction of GM cotton. The use of chemicals to target *H. armigera* in grain crops continues to grow in Australia, placing strong selection pressure for the development of resistance in some of the more selective products.

Growers should understand how to minimise the development of further resistance. Chemicals within a specific chemical group usually share a common target site within the pest, and thus share a common mode of action (MoA). A key aim of *H. armigera* resistance management is to minimise the selection pressure for resistance to the same chemical group across consecutive generations.

This document forms the scientific basis upon which *H. armigera* resistance management strategy was developed. The strategy is primarily focused on product use windows for chlorantraniliprole and indoxacarb in spring and summer pulses. It is particularly relevant for chickpea and mungbean crops where insecticide use is likely to have the greatest impact on the management of resistance in *H. armigera*.

1.0 Background information on *Helicoverpa armigera*

Attribute	**What is known for pest?**	**References**	**Knowledge gaps**
Economic importance to grains	• Direct feeding by *Helicoverpa* spp. reduces yield of pulses, oilseeds, coarse grains and, to a lesser extent, winter cereals. • Ranked as the second most important invertebrate grains pest based on estimated losses from grains crops and the third most costly pest to control with pesticides.	Brier *et al.* 2008; Murray *et al.* 2013	Prevalence and impact in southern and western regions of Australia remains unclear.
Mode of reproduction	• Sexual reproduction, nocturnal. • Males respond to sex pheromones released by receptive females. • Sex pheromone commercially available routinely used in monitoring species composition and insecticide resistance. • High fecundity, 90% of eggs laid in dark cycle.	Rothschild 1978 Baker *et al.* 2013; Bird *et al.* 2017 Singh and Rembold 1989	
Life cycle (incl. # generations)	• Australian tropical and sub-tropical climates (central QLD and areas further north) support *H. armigera* populations year-round. • In temperate and cool climate zones (southern QLD and areas further south) the majority of *H. armigera* undergo a facultative pupal diapause from mid-March onwards. • Emergence from diapause in late September onwards initiates the first of 3-5 generations per season in central and southern regions. • The lifecycle (egg to adult) is typically 42 days at 25ºC. In summer, it takes 5-6 weeks to complete a single generation and over 8 weeks in spring and autumn. • Discrete *H. armigera* populations occur in spring, peaking in late summer by which time there can be overlapping cohorts and multiple life-stages in host crops.	Sequeira and Playford 2001 Fitt and Daly 1990; Murray and Zalucki 1994; Lloyd *et al.* 2008. Room 1983 Room 1983 Baker *et al.* 2011	
Crop hosts	• Polyphagous, including broadleaf and grass-related species. • Commodity crops include cotton, pulses, oilseeds, Solanaceous vegetables, coarse grains and winter cereals. • Most significant grains crops are chickpea, soybean, mung bean adzuki bean, faba bean, maize, sorghum, canola, lupins, linseed,	Zalucki *et al.* 1986	

	and sunflowers.		
Non-crop hosts	• Common weed hosts include Pattersons curse, *Verbenaceae* spp., *Malvaceae* spp., and the scrophulariaceous weed host, *Verbascum virgatum*. • Cultivated pigeon pea as a refuge crop for Bt cotton.	Zalucki *et al.* 1986 Baker and Tann 2014	
Distribution	• Introduced species with origins in the Old World. • Closely associated with agricultural areas which supply a sequence of suitable hosts across a wide area. • Most prevalent across all northern grain growing regions of eastern Australia with usually lower abundance in the south. • Rarely reported in inland Australia. • Reports of populations in some southern mainland districts. • Immigrants occasionally reported in northern TAS but not known to establish beyond one or two generations.	Zalucki *et al.* 1986 Fitt *et al.* 1995 Gregg *et al.* 1989; Zalucki *et al.* 1994 N. Meyers, R. Fox (Pers. Comm.) L. Hill (Pers. Comm.)	Do pest populations arise due to increased abundance of local cohorts because of a change in carrying capacity, or does it expand its range by migration into agricultural areas driven by ephemeral nature of host crops?
Dispersal/movement	• Facultative migrant. • Known to be capable of long-range, wind assisted migration. • Local dispersal is more typical of *H. armigera* and is strongly influenced by local cropping and climatic conditions.	Daly and Gregg 1985; Fitt 1989 Feng *et al.* 2005; Weeks *et al.* 2010 Fitt *et al.* 1989	What is the relative amount of immigration and local emergence and how does this contribute to population dynamics and gene flow?
Feeding behaviour	• Chewing pest; larvae can feed and survive on leaves but are most damaging when feeding directly on growing terminals, and reproductive plant parts (buds or squares, flowers, pods, seed and/or fruit). • Economic thresholds are well established in cotton. • Economic thresholds in grains are largely nominal, best guesses. Northern region has empirically derived, dynamic thresholds for chickpeas, mungbean, soybean, sorghum.	Fitt 1989 Williams 2016 Brier *et al.* 2008 GPAC/NIPI/Miles threshold review 2014-16	
Chemical controls	• Chemical insecticides remain the key to control within grains and as well as other industries. • There are over 200 insecticide products registered in Australia.	Murray *et al.* 2013 APVMA	

	• The majority are from 3 chemical groups with broad spectrum activity (organophosphates, carbamates and pyrethroids) and to which *H. armigera* has evolved some level of resistance. • There are an additional 3 insecticides with unique MOA which are selective for *Helicoverpa* spp. (indoxacarb, avermectin and diamides) and to which there is low or no resistance. • Spinetoram is also registered for *Helicoverpa* spp. in cotton, chickpeas, summer pulses and fruit/vegetable crops.	McCaffery 1998 Wing *et al.* 2004; Cordova *et al.* 2006; Ishaaya *et al.* 2002 Bird 2015; Bird *et al.* 2017	
Biological control options	• There are many effective natural enemies of *H. armigera*. These include: predatory beetles such as red and blue beetles, and the larvae of various species of lady beetles; predatory bugs such as damsel bug, big eyed bug, assassin bug, and various species of shield bugs; lacewing larvae; spiders; hoverfly larvae; larval parasitoids including various species of ichnumonid and braconid wasps, and tachinid flies; the egg parasitoids including trichogramma and telenomis wasps. • Pathogens available commercially as biopesticides include formulated products of Nuclear Polyhedrosis Virus (NPV) and the bacterial toxins from *Bacillus thuringiensis* (Bt). • Plant extract from *C. ternatea* is commercially available as Sero-X. • Entomopathogenic fungi are also being investigated for future commercialization.	Williams 2016	

2.0 Products with label claims for *Helicoverpa armigera* (and *Helicoverpa* spp. generally) in Australia

IRAC MoA Group	**Insecticide category**	**Active ingredient**	**Example trade name**	**Registered crops for *Helicoverpa armigera* (Helicoverpa spp.)**
1A	Carbamates	methomyl	Lannate, Marlin, Nudrin, Electra	Maize, sorghum, canola, summer and winter pulses (incl. mung beans [seed production only], chickpeas, adzuki beans, soybeans), lupins, lentils, linseed, sunflowers, winter cereals (wheat, oats, barley), apples, citrus, blueberries, capsicum, cotton, ginger, lettuce, poppies, peanuts, sesame, strawberries, stone fruit, sweet corn, tobacco, tomatoes, brassica and legume vegetables.
1A	Carbamates	thiodicarb	Larvin, Showdown, Confront	Maize, summer and winter pulses (incl. mung beans, chickpeas, soybeans, navy beans), cotton, tomatoes, potatoes, sweetcorn, tobacco.
1B	Organophosphates	chlorpyrifos	Chlorban, Chlorpos, Lorsban, Chlorpyrifos (various products)	tomatoes, brassica vegetables
3A	Pyrethroids	alpha-cypermethrin	Alpha-Scud, Astound, Dominex Duo	Maize, sorghum, canola, field peas, chickpeas, faba beans, mung beans, navy beans, soybeans, lupins, linseed, sunflowers, cotton, vegetable crops (incl. lettuce, sweetcorn, tomatoes)
3A	Pyrethroids	beta-cypermethrin	Chix, Banshee	Maize, sorghum, canola, field peas, mung beans, navy beans, lupins, linseed, sunflowers, cotton, vegetable crops (incl. tomatoes, brassicas)
3A	Pyrethroids	cypermethrin	Cyrux 250, Cyper Plus	Maize, sorghum, field peas, faba beans, mung beans, navy beans, soybeans, lupins, linseed, sunflowers, cotton, tobacco, vegetable crops (incl. tomatoes, sweetcorn)
3A	Pyrethroids	deltamethrin	Decis Options, Ballistic Elite, Deltashield	Maize, sorghum, canola, cereals, field peas, chick peas, faba beans, mung beans, navy beans, soybeans, lupins, lentils, linseed, sunflowers, safflower, cotton, tobacco, vegetable crops (incl. tomatoes, sweetcorn, berries)
3A	Pyrethroids	gamma-cyhalothrin	Trojan	Sorghum, canola, field peas, chickpeas, faba beans, mung beans, navy beans, soybeans, lupins, sunflower, cotton, tomatoes
3A	Pyrethroids	lambda-cyhalothrin	Karate, Cyhella, Matador	Sorghum, canola, field peas, chickpeas, faba beans, mung beans,

				navy beans, soybeans, lupins, lentils, sunflowers, cotton, tomatoes
3A	Pyrethroids	esfenvalerate	Sumi-Alpha Flex	Maize, sorghum, canola, cereals, field peas, chick peas, pigeon peas, faba beans, mung beans, navy beans, soybeans, lupins, lentils, linseed, sunflowers, safflower, cotton, tobacco, brassica and legume vegetables, sweetcorn, tomatoes
3A	Pyrethroids	permethrin	Ambush, Pounce, Axe	Field peas, linseed (TAS and WA only), legume vegetables (incl. green beans and peas), sweetcorn, tomatoes, tobacco, nursery plants and ornamentals
3A	Pyrethroids	bifenthrin	Talstar, Compel, Astral	Navy beans, cotton, tomatoes, cucurbit vegetables
3A	Pyrethroids	tau-fluvalinate	Klartan, Mavrik	Cauliflowers, tomatoes, ornamentals, cotton (Mavrik concentrate restricted to use on cotton only)
Synergists		piperonyl butoxide	PBO 800, Puppet Synergy	Cotton Also for use on cucurbits and tomatoes
5	Spinosyns	spinetoram	Success Neo	Cotton Chickpeas Pulses (all summer and winter) Canola & forage brassicas Vegetable crops: Brassica, cucurbit (incl. cucumbers, melons, squash zucchinis), leafy (incl. lettuce, endive, spinach, silverbeet), fruiting (incl. capsicums/peppers, eggplants, okra, tomatoes), legume (incl. beans and peas; snow and sugar snap), root/tuber, stalk/stem, berry fruit. Fruit trees: Citrus (incl. grapefruits, mandarins, lemons, limes, oranges).
6	Avermectins	Emamectin benzoate	Affirm Warlock Proclaim	Canola, summer and winter pulses (incl. chickpeas, faba beans, adzuki beans, mung beans, soybeans), cotton Cotton, capsicums, lettuce, tomatoes, sweetcorn Capsicums, lettuce, tomatoes, sweetcorn
6	Avermectins	Abamectin	Agrimec, Stealth, Abachem	Cotton
11C	*Bacillus thuringiensis*	B.t. subsp. kurstaki	DiPel, Delfin, Costar	Cereal grains, oilseeds, cotton, vegetables, fruits, nuts, vines,

				herbs, tobacco, ornamentals
11C	*Bacillus thuringiensis*	B.t. subsp. kurstaki	Bollgard II & III	Cotton
11C	*Bacillus thuringiensis*	B.t. subsp. aizawai	Bacchus	Cereal grains, oilseeds, cotton, vegetables, fruits, nuts, vines, herbs, tobacco, ornamentals
22A	Oxadiazines	Indoxacarb	Steward, King doxa, Commissioner Avatar	Summer and winter pulses but limited to chickpeas, faba beans, adzuki beans, mung beans, soybeans, cotton Vegetable crops: Brassica, leafy (incl. cress, kale, lettuce, spinach, silverbeet, Chinese veg), fruiting (incl. capsicums/peppers, eggplants, tomatoes) Fruit trees: pome fruit (incl. apples, pears, Nashi pears), stone fruit (incl. apricots, nectarines, peaches, plums)
28	Diamides	Chlorantraniliprole	Altacor Coragen	Chickpeas, mung beans, soybeans, sunflower (permit only), cotton Vegetable crops: Brassica, stalk/stem, leafy, legume, tuberous, cucurbit (cucumber, melons, pumpkins, squash, zucchinis) and fruiting (capsicums/peppers, eggplants, tomatoes, sweetcorn)
28	Diamides	Cyantraniliprole	Benevia Exirel	Vegetables crops: Cucurbit (cucumber, melons, pumpkins, squash, zucchinis) and fruiting (capsicums/peppers, eggplants, tomatoes) Cotton
28	Diamides in combination with other insecticides	Chlorantraniliprole + thiamethoxam (4A) Chlorantraniliprole + abamectin (6)	Voliam Flexi Voliam Targo	Cotton Pome fruit
No Group	Attract and Kill Formulations	(Eucalyptol, D-Limonene, Phenylacetaldehyde, Anisyl Alcohol, Butyl Salicylate, Alpha-Pinene) + mixing partner (Group 1A or	Magnet	Cotton, green beans, sweetcorn

		5)		
No Group	Nuclear polyhedrosis virus	Nuclear polyhedrosis virus	Gemstar, Vivus Max/Gold, Heliocide, Helicovex, Armigen	Cereal grains, oilseeds, pulses, sorghum, cotton Vegetable crops: Brassica, stalk/stem, leafy, legume, tuberous, cucurbit (cucumber, melons, pumpkins, squash, zucchinis) and fruiting (capsicums/peppers, eggplants, tomatoes, sweetcorn) Fruit crops: berry fruit, pome fruit
No Group	Diatomaceous earth	Amorphous silica	Abrade	Cotton Brassica vegetables
No Group	Paraffinic spray oils	Paraffinic oil	Canopy Bioclear, Biopest	Pulse and oilseed crops Cotton Fruit and vegetable crops (numerous)

Source: APVMA-Public Chemical Registration Information System Search (PubCRIS), Australian Pesticides & Veterinary Medicines Authority; accessed March 2017.

Note: crops in red are grain crops.

Industry chemical use and secondary exposure:

Crop	**Target pest**	**Active(s)**
Canola	diamondback moth	spinetoram, emamectin benzoate
Summer pulses	loopers	Bt, indoxacarb, emamectin benzoate, chlorantraniliprole
Summer pulses	podsucking bugs	SP
Mungbean, soybean	beanpodborer	chlorantraniliprole
Mungbean, soybean	mirids	indoxacarb, dimethoate
Sorghum	sorghum midge	SP
Sorghum	Rutherglen bug	SP, OP
Winter cereals	armyworm	SP, OP
Sunflower	Rutherglen bug	SP, OP
Sunflower	loopers	Bt, SP, OP
Chickpea	*H. punctigera*	SP
Linseed (permit to 2021)	Helicoverpa	chlorantraniliprole
Sunflower (permit to Oct. 31st 2018)	Helicoverpa	chlorantraniliprole

3.0 Current status of *Helicoverpa armigera* resistance in Australia

Insecticide	Attribute	What is known for *Helicoverpa armigera?*	References
1A **Organophosphates**	Mode of Action	ACHE inhibition	McCaffery 1998
	Resistance status	Low (<1%) to chlorpyrifos	Rossiter *et al.* 2008; Appendix 1
		Moderate (10%) to profenofos and methyl parathion	Gunning 2002
		No cross-resistance between chlopyrifos and profenofos/methyl parathion	Gunning *et al.* 1998
	Mechanism of resistance	Target site (insensitive ACHE)	Gunning *et al.* 1998
		Metabolic (sequestration by carboxylesterase)	Teese *et al.* 2010; Farnsworth *et al.* 2010
	Fitness costs	Slower larval growth of resistant genotypes	Gunning *et al.* 1998
	Genetic basis for resistance	Not evaluated in Australian populations	
1B **Carbamates**	Mode of Action	ACHE inhibition	McCaffery 1998
	Resistance status	Moderate – high (30-50%)	Rossiter *et al.* 2008; Bird 2018; Appendix 1
		Cross resistance between methomyl and thiodicarb	Gunning *et al.* 1996a
		No cross resistance between carbamates and OPs	Farnsworth *et al.* 2010
	Mechanism of resistance	Target site (insensitive ACHE - different to OPs)	Gunning *et al.* 1996a
		Metabolic (P450/esterase)	Gunning *et al.* 1992
	Fitness costs	Not evaluated in Australian populations	
	Genetic basis for resistance	Incompletely dominant	Gunning *et al.* 1996a
3A **Pyrethroids**	Mode of Action	Voltage-gated Na channel	McCaffery 1998
	Resistance status	Metabolic resistance is high (50-100%)	Rossiter *et al.* 2008; Bird 2018; Appendix 1
		Target site resistance is low (<5%)	Gunning *et al.* 1996b; L.J.B Unpublished
		Broad cross-resistance to all SPs	Forrester *et al.* 1993
	Mechanism of resistance	Primarily metabolic (P450 [*CYP337B3*] /esterase)	Joußen *et al.* 2012; Teese *et al.* 2013
		Target site (*kdr* and *super-kdr*) present under some circumstances and in some locations	Gunning *et al.* 1991; 1996b
	Fitness costs	Reduced survival in resistance genotypes after diapause	Daly and Fisk 1995
	Genetic basis for resistance	Metabolic resistance inherited as a completely dominant trait	Daly and Fisk 1992
		Target site resistance inherited as an incompletely	*Ru *et al.* 1998

		recessive trait	
5 **Spinosyns**	Mode of Action	Nicotinic ACH receptor	Orr *et al.* 2009
	Resistance status	Low to moderate before transgenics (10-15%) Very low following introduction of Bollgard (<2%) Low or no cross-resistance to products from other MoA groups	Gunning 2002 Rossiter *et al.* 2008 Sparks *et al.* 2012
	Mechanism of resistance	*Metabolic (P450)*	*Wang *et al.* 2009
	Fitness costs	*Reduced survival, reduced larval and pupa weights, slower larval development*	*Wang *et al.* 2010
	Genetic basis for resistance	Unknown in *H. armigera*	
6 **Avermectins**	Mode of Action	Glutamate-gated chloride channel	Ishaaya *et al.* 2002
	Resistance status	Low or no resistance detected	Rossiter *et al.* 2008; Bird *et al.* 2017; Appendix 2
		Cross-resistance status unknown in *H. armigera*	
		Cross resistance between emamectin benzoate and abamectin in Spodoptera exigua	*Che *et al.* 2015
	Mechanism of resistance	Unknown in *H. armigera*	
	Fitness costs	Unknown in *H. armigera*	
	Genetic basis for resistance	Unknown in *H. armigera* *Incompletely dominant in Spodoptera spp.*	 *Shad *et al.* 2010; *Che *et al.* 2015
11C ***Bacillus thuringiensis***	Mode of Action	Midgut receptor	Van Rie *et al.* 1990
	Resistance status	Low (<5%)	Mahon *et al.* 2007a
	Mechanism of resistance	Target site resistance Metabolic resistance	Akhurst *et al.* 2003 Gunning *et al.* 2005
	Fitness costs	Recessive fitness cost - delayed development in homozygous resistant genotypes	Bird and Akhurst 2004; **Cao et al.* 2014
	Genetic basis for resistance	Target site resistance inherited as a completely or incompletely recessive trait	Bird and Akhurst 2004; Mahon *et al.* 2007b
22A **Indoxacarb**	Mode of Action	Voltage-gated Na channel (different receptor for SPs)	Wing *et al.* 2004
	Resistance status	Low (<5%) But increased frequencies observed in CQ in 2016-17	Bird *et al.* 2017; Appendix 2 L.J.B. Unpublished

	Mechanism of resistance	Metabolic	Bird 2016
	Fitness costs	No evidence of fitness cost associated with larval survival or development under lab conditions.	L.J.B. Unpublished
	Genetic basis for resistance	Partially dominant (*D*LC = 0.8)	Bird 2016
28 **Diamides**	Mode of Action	Ryanodine receptor	Cordova *et al.* 2006
	Resistance status	Very low (<1%). Strains with enhanced survival are unstable under laboratory conditions	Bird *et al.* 2017; Appendix 2
	Mechanism of resistance	Unknown in *H. armigera*	
	Fitness costs	Unknown in *H. armigera*	
	Genetic basis for resistance	Unknown in *H. armigera*	

* Indicates studies were performed on Chinese strains of *H. armigera*

4.0 Resistance management & minimisation strategy

General rationale for the design of the strategy

The aim of the strategy is to minimise the selection pressure for resistance to the same chemical groups across consecutive generations of *H. armigera*. Chickpeas and mung beans are currently, and for the foreseeable future, the most valuable grains crops influenced by the RMS. Therefore, the RMS is primarily focused on insecticide MoA rotation in these systems and is built around product windows for chlorantraniliprole (e.g. Altacor®) and indoxacarb (e.g. Steward®) because:

1. Chlorantraniliprole is at risk from dangerously high levels of over-reliance in pulses, but resistance frequencies are currently low.
2. Indoxcarb is at risk due to genetic predisposition (high level genetic dominance and metabolic mechanism) and pre-existing levels of resistance in NSW and QLD (with elevated levels in CQ during 2016-17). In addition, the use of indoxacarb in pulses is expected to increase.

There are two RMS regions:

1. Northern Region: Belyando, Central Highlands, Dawson & Callide (Table 1)
2. Central Region: Balonne, Bourke, Burnett, Darling Downs, Gwydir, Lachlan, Macintyre, Macquarie & Namoi (Table 2)
    - The RMS provides windows-based recommendations common to Southern QLD, Central & Northern NSW because *H. armigera* moths are highly mobile and have the capacity to move between these regions, potentially increasing the risk of further exposing cohorts of insects previously selected for resistance.
    - We have limited knowledge of the likely risk of *H. armigera* occurrence in winter crops in the Southern and Western Grains regions (Victoria, Tasmania, South Australia and Western Australia) because there has been little formal monitoring for this species in these regions. However, there is some historical data, and anecdotal records of *H. armigera* outbreaks in the Southern Grains region, which suggests that in some years and regions there is a risk of control failure and/or selection of resistance in the Helicoverpa population because of the presence of *H. armigera*.
    - No RMS is currently proposed for these regions. Biological indicators are that the risk of *H. armigera* occurring in winter crops, at densities where control failures may occur, is presently considered low. Helicoverpa control in summer crops in these regions to use the Central region RMS.

Use of broad-spectrum insecticides

The early use of SPs in winter pulses (August – early September) is a strategy adopted where the assumption is made that early infestations of Helicoverpa will be predominantly *H. punctigera* which are susceptible to SPs. If adopting this strategy, be aware of the following risks:

- Recent monitoring with pheromone traps has shown *H. armigera* to be present in all parts of the Northern Grains region from early August.
- Reduced efficacy of SPs when *H. armigera* is present can be masked when treating very low population densities (< 2/m^2).
- If *H. armigera* are present, even at low levels in a population treated with SPs, the treatment will select for further resistance.

Does the RMS impact on recommendations for insecticide use in cotton?

The RMS is not intended to compromise the ability of the cotton industry to utilise any products registered for *Helicoverpa* spp. in Bollgard. This is because selection for insecticide resistance is considered low due to the high likelihood that survivors of conventional sprays used in Bollgard would be killed by Bt toxins expressed in plants. For further information go to: http://www.cottoninfo.com.au/publications/cotton-pest-management-guide.

Integrated pest management is a central feature of resistance management

The use of integrated pest management (IPM) tactics for *H. armigera* management is integral to achieving a reduction in insecticide use and consequently helping to minimise resistance selection pressures. Examples of IPM tactics for *Helicoverpa* management include minimising the risk of pest build-up on in-crop weeds, pupae-busting stubbles where pupae are overwintering (especially corn/maize, late sorghum, summer mungbeans), spraying only when pest populations exceed economic threshold, and using the softest insecticides available to preserve beneficial insects in the crop.

When using insecticide, monitoring is the key to better targeted spraying and effective management. The use of pheromone traps (which attract male moths) can provide an early warning of moth immigration into an area or their emergence from local winter diapause. Traps should be set up in late winter/early spring (July–August). The beat-sheet is the most commonly used sampling tool in the northern region. Obtain an estimate of pest and beneficial insect numbers in a crop by taking at least 5 to 10 beatsheet samples from across the field.

Sweep netting is a quick and easy method to sample some crops but is more subjective. Take a minimum of 5 sets of 10 sweeps and calculate the average number of larvae per 10 sweeps.

Table 1. Grains resistance management strategy for *Helicoverpa armigera* across Australia

Best practice product windows and use restrictions to manage insecticide resistance in *H. armigera*

Northern Region: Belyando, Central Highlands, Dawson & Callide

Increasing ↑ SELECTIVITY ↓ Decreasing

Insecticide	June				July				Aug				Sept				Oct				Nov				Dec				Jan				Feb				Mar				April				May			
	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
Bacillus thuringiensis	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
Helicoverpa viruses	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
Paraffinic oil [Note 1]	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
Chlorantraniliprole [Note 2,3]	⬜	⬜	⬜	⬜	⬜	⬜	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	⬜	⬜	⬜	⬜
Indoxacarb [Note 4]	🟧	🟧	🟧	🟧	🟧	🟧	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	🟧	🟧	🟧	🟧	🟧	🟧	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	🟧	🟧	🟧	🟧	🟧	🟧	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜
Spinetoram [Note 2,4,5]	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
Emamectin benzoate [Note 2,4,5]	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
Carbamates [Note 2,4,6]	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧
Pyrethroids [Note 2,4,7]	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧

🟩 **No restrictions**	⬜ **DO NOT USE during this period**	🟧 **No more than one application per crop per season**	🟦 **No more than two applications per crop per season**

ADDITIONAL INFORMATION

Note 1: Some nC27 paraffinic spray oils can be used to suppress Helicoverpa populations and are best used as part of an IPM program.

Note 2 : Observe withholding periods. Products in this group have WHP 14 days or longer.

Note 3 : Maximum one spray of chlorantraniliprole alone or in mixtures per crop per season.

Note 4 : Refer to label for warning of insecticide risk to bee populations.

Note 5 : Maximum two consecutive sprays alone or in mixtures per crop per season.

Note 6 : MODERATE RESISTANCE IS PRESENT IN *H. ARMIGERA* POPULATIONS – FIELD FAILURES LIKELY.

Note 7 : HIGH RESISTANCE IS PRESENT IN *H. ARMIGERA* POPULATIONS – FIELD FAILURES EXPECTED!

Table 2. Grains resistance management strategy for *Helicoverpa armigera* across Australia

Best practice product windows and use restrictions to manage insecticide resistance in *H. armigera*

Southern QLD, Central & Northern NSW Regions: Balonne, Bourke, Burnett, Darling Downs, Gwydir, Lachlan, Macintyre, Macquarie & Namoi

Increasing

SELECTIVITY

Decreasing

Insecticide	June				July				Aug				Sept				Oct				Nov				Dec				Jan				Feb				Mar				April				May			
	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
Bacillus thuringiensis	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
Helicoverpa viruses	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
Paraffinic oil Note 1	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
Chlorantraniliprole Note 2,3	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜
Indoxacarb Note 4	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	🟧	🟧	🟧	🟧	🟧	🟧	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	🟧	🟧	🟧	🟧	🟧	🟧	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜	⬜
Spinetoram Note 2,4,5	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
Emamectin benzoate Note 2,4,5	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
Carbamates Note 2,4,6	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧
Pyrethroids Note 2,4,7	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧

🟩	No restrictions
⬜	DO NOT USE during this period
🟧	No more than one application per crop per season
🟦	No more than two applications per crop per season

ADDITIONAL INFORMATION

Note 1: Some nC27 paraffinic spray oils can be used to suppress Helicoverpa populations and are best used as part of an IPM program.

Note 2 : Observe withholding periods (WHP). Products in this group have WHP 14 days or longer.

Note 3 : Maximum one spray of chlorantraniliprole alone or in mixtures per crop per season.

Note 4 : Refer to label for warning of insecticide risk to bee populations.

Note 5 : Maximum two consecutive sprays alone or in mixtures per crop per season.

Note 6 : MODERATE RESISTANCE IS PRESENT IN *H. ARMIGERA* POPULATIONS – FIELD FAILURES LIKELY.

Note 7 : HIGH RESISTANCE IS PRESENT IN *H. ARMIGERA* POPULATIONS – FIELD FAILURES EXPECTED!

Table 3. Explanatory notes for product windows in all regions

Insecticide	Number of insecticide windows	Duration of insecticide windows	Maximum number of applications/crop/season
Chlorantraniliprole (Altacor®)	2	10 weeks	1
• 10 week windows restrict selection to a maximum of 2 consecutive generations of *H. armigera* (includes 2-3 weeks residual beyond the end of each window i.e. 12-13 weeks total exposure). • Start date of first window correlates well with historical data relating to average daily temperatures that result in early pod-set. • Exposure of 2 consecutive generations is off-set by long non-use periods (8 weeks in southern/central region and 18 weeks in northern region). • Use is not recommended in spring mung beans as there is less likelihood of both *H. armigera* and bean pod borer being present.			
Indoxacarb (e.g. Steward®)	Northern - 3 Central - 2	6 weeks	1
• 6 week windows restrict selection to a single generation of *H. armigera*. • Each window is followed by a non-use period of a minimum of 6 weeks. • Indoxacarb is an important early season rotation option for chickpeas and faba beans, and provides a robust selective alternative to Altacor® when Helicoverpa pressure is high.			
Bacillus thuringiensis	1	Season long	No restrictions
Helicoverpa viruses			No restrictions
Spinetoram (e.g. Success Neo®)*			2
• Low resistance risk and not widely used.			
Emamectin benzoate (e.g. Affirm®)*	1	Season long	2
• Very low resistance frequency and not used widely. • However, emamectin benzoate is a good option for rotation to spread resistance risk away from Altacor®. • BUT industry needs to become more confident with using this product for it to be of value in resistance management.			
Carbamates	1	Season long	1
Synthetic pyrethroids			
• *H. armigera* resistance is present at moderate to high levels, but one strategic application per season in regions where *H. punctigera* predominates in early spring may be effective. • Carbamates are a rotation tool for indoxacarb and Altacor® either early season in chickpeas or late season in mungbean.			

*Resistance monitoring for selective products is a key component of the RMS and changes in resistance frequencies will result in the introduction of product windows for those insecticides not currently windowed.

General principles to avoid or minimise resistance development:

- Avoid repeated use of insecticides from the same chemical group against *H. armigera* or other pests, as this will increase selection pressure for resistance development, not only in *H. armigera,* but, also in other species;
- Comply with all directions for use on product labels including applying the recommended label rate. **DO NOT cut rates and DO NOT exceed the maximum number of allowable applications per crop per season**;
- Do not re-spray a crop in the same season where a known spray failure has occurred using the same product or another product from the same chemical group, or if a spray failure has occurred where the cause has not been identified;
- Where possible, avoid use of SPs and organophosphates (OPs) for control of other crop pests, and instead use target-specific “soft chemicals” such as pirimicarb for aphids and Bt or virus for caterpillars;
- Ensure the target pest is identified correctly to ensure the most effective insecticide and rate is used. Misidentification and incorrect insecticide selection results in poor control and contributes to selection for resistance;
- Assess *H. armigera* and beneficial populations by regular monitoring to determine if chemical control is warranted;
- Consider the impact on target and non-target pests and beneficial insects when applying insecticide sprays;
- Ensure spray rigs (both ground and aerial) are calibrated properly and sprays achieve good coverage, particularly in crops with a bulky canopy;
- Monitor post-treatment pest populations for evidence of loss of field efficacy and report field failures.

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6.0 Appendices

Appendix 1. Frequency of resistance in *Helicoverpa armigera* to broad-spectrum insecticides pyrethroid, carbamate and organophosphate in populations sampled from NSW and QLD.

Insecticide	Year	Number tested	Frequency of R	Binomial CI	%R
Fenvalerate	2008-09	253	0.704	0.6446-0.7564	70.4
	2009-10	194	0.680	0.6065-0.7372	68.0
	2010-11	243	0.617	0.5548-0.6761	61.7
	2011-12	902	0.905	0.8837-0.9221	90.5
	2012-13	2446	0.906	0.8933-0.9156	90.6
	2013-14	542	0.906	0.8784-0.9277	90.6
	2014-15	1053	0.933	0.9158-0.9462	93.3
Bifenthrin	2008-09	456	0	0.0000-0.0084	0.0
	2009-10	276	0.065	0.0416-0.1007	6.5
	2010-11	402	0.075	0.0528-0.1045	7.5
	2011-12	1197	0.396	0.3687-0.4240	39.6
	2012-13	2215	0.389	0.3691-0.4096	38.9
	2013-14	596	0.438	0.3986-0.4780	43.8
	2014-15	1047	0.553	0.5228-0.5829	55.3
Methomyl	2008-09	666	0.333	0.2957-0.3669	33.3
	2009-10	229	0.266	0.2133-0.3271	26.6
	2010-11	598	0.171	0.1425-0.2028	17.1
	2011-12	1049	0.340	0.3123-0.3695	34.0
	2012-13	1965	0.231	0.2124-0.2497	23.1
	2013-14	559	0.283	0.2469-0.3214	28.3
	2014-15	951	0.493	0.4615-0.5249	49.3
Chlorpyrifos	2008-09	645	0.002	0.0000-0.0087	0.2
	2009-10	158	0.000	0.0000-0.0237	0.0
	2010-11	659	0.005	0.0015-0.0133	0.5
	2011-12	1051	0.010	0.0059-0.0186	1.0
	2012-13	2037	0.013	0.0087-0.0186	1.3
	2013-14	562	0.018	0.0097-0.0324	1.8
	2014-15	979	0.019	0.0125-0.0301	1.9

This monitoring program was conducted by NSW Department of Primary Industries with support from the Cotton Research and Development Corporation (CRDC) and the Grains Research and Development Corporation (GRDC).

Appendix 2. Frequency of resistance in *Helicoverpa armigera* to selective insecticides indoxacarb, chlorantraniliprole and emamectin benzoate in populations sampled from NSW and QLD.

Insecticide	Year	Total tests	Total alleles	Total positives	Frequency of R	%R
Indoxacarb	2013-14	548	1096	9	0.016	1.6
	2014-15	665	1330	25	0.038	3.8
	2015-16	650	1300	16	0.025	2.5
	2016-17	1026	2052	62	0.060	6.0
Chlorantraniliprole	2013-14	525	1050	0	0.000	0.0
	2014-15	656	1312	1	0.002	0.2
	2015-16	636	1272	4	0.006	0.6
	2016-17	988	1976	4	0.004	0.4
Emamectin Benzoate	2013-14	500	1000	0	0.000	0
	2014-15	652	1304	0	0.000	0
	2015-16	628	1256	0	0.000	0
	2016-17	932	1864	0	0.000	0

This monitoring program was conducted by NSW Department of Primary Industries with support from the Cotton Research and Development Corporation (CRDC) and the Grains Research and Development Corporation (GRDC).