A Status Report on Insecticide Resistance in Australia

With a focus on in-crop pests of the grains industry, although these pests also cross into horticultural, cotton or grazing industries

February 2016

A report by the **Grains Pest Advisory Committee** for industry stakeholders

GRDC Grains Research & Development Corporation
Your GRDC working with you

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Acronyms used in this report

APHC	Australian Plant Health Council
APVMA	Australian Pesticides and Veterinary Medicines Authority
AgVet collaborative Forum	Facilitates direct, formal discussion between the users of AgVet technologies and those companies which make decisions to invest in producing them
Bt	*Bacillus thuringiensis*, a naturally occurring soil bacterium; effective against Lepidoptera (caterpillars)
Bt (GM) cotton	Cotton genetically modified with inclusion of insecticide producing genes from Bt.
CropLife Australia	Peak industry organisation representing the agricultural chemical and biotechnology (plant science) sector in Australia
CPCs	Crop Protection Companies
CRDC	Cotton Research and Development Corporation
DBM	Diamondback Moth
GPA	Green Peach Aphid
GRDC	Grains Research and Development Corporation
GM/GMO	Genetically Modified (Organism)
IPM	Integrated Pest Management
IRMS (and RMS)	Insecticide Resistance Management Strategy
HIA	Horticulture Innovation Australia
MACE	Modified AcetylCholinEsterase
MOA / MoA	(Chemical) Mode of Action
OECD	the Organisation for Economic Co-operation and Development
OPs[¶]	Organophosphates
RDC	Research and Development Corporations
RIRDC	Rural Industries Research and Development Corporation
RLEM	Red Legged Earthmite
RNAi pesticides	RNA interference - new MoA, highly species-specific technology that destroys specific messenger RNA molecules
SPs[¶]	Synthetic Pyrethroids

[¶]See Appendix 5 for a list of Chemical Groups, common active ingredients, and abbreviations

Summary

Pesticide resistance is a major threat to the grains industry given the ongoing reliance on chemical control methods, the entrenched resistance in some key species and the recent emergence of resistance in high profile pests such as aphids and redlegged earth mites. Cross-industry collaboration will be critical to adequately address these issues given all grains pests with resistance cross into either pastures, horticultural and/or cotton crops.

At the annual day meeting of the National Insecticide Resistance Management (NIRM) Working Group of the Grains Pest Advisory Committee (GPAC) in April 2015, it was agreed that the complexity of issues underpinning the current and emerging cases of insecticide resistance justified a workshop of specialists and subsequent Status Report to benchmark our knowledge and to advise all stakeholders of emerging concerns and how these might be tackled.

This Status Report is presented in five sections: a) global experiences with pesticide resistance; b) lessons from previous Australian experiences with resistance management; c) summaries of the current state of knowledge relating to pesticide resistance in pests that attack in-field grain crops; d) predictions of future resistances; and e) assessments of future risks and opportunities to better manage these risks.

Recent international trends in the Americas and the EU are compelling considerations for resistance mitigation planning in Australia. Some key examples include the palpable incursion of resistant alleles across quarantine lines, community concern about sub-lethal chemical impacts on non-target species such as bees spilling over to chemical bans, new technologies for precision pest control and monitoring resistance acquisition, retailers acting on demands by consumers for much greater chemical-use transparency or prohibition, as is evidenced now (2016) with Aldi (European) supermarkets, and ultimately, the legislative requirement for IPM in EU cropping.

In Australia, we must take heed from decades of failures and successful experiences in managing insecticide resistance. Some stark examples include four pests that range across the grains, cotton, vegetable and grazing industries.

> Chemical battles with the cotton bollworm provide an invaluable legacy of contrasts: a pest that almost destroyed an entire industry is now being successfully managed in Australia, literally, by world's best practice, based on a combination of gene technologies, IPM including soft options, ongoing monitoring, and industry collaboration. These practices do not extend to the grains industry, which leads to potential selection of new resistance in critical chemical groups in this pest.
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> The diamondback moth is internationally renown for its resistance to most groups of insecticides but has been managed successfully in brassica vegetables because of a significant industry-government extension effort involving grower champions, the use of IPM including soft options and the ability to access and rotate five MoAs. Lack of cross-industry coordination around this pest may have a much larger impact on the vegetable industry than on grains because of low tolerance thresholds and ongoing cropping throughout the year.
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> The green peach aphid is a global pest of horticultural and grain crops. In Australia, it attacks cruciferous vegetables, canola and numerous pulse crops. Resistance is widespread to OPs, SPs and carbamates, and appears to be evolving to neonicotinoids. Selection for resistance is most intense in vegetable crops, although that industry has more MoAs than are available for grain growers. In a recent national survey, three genetic clones (or 'biotypes') were found to make up about 80% of all aphids screened; all three have OP, SP and carbamate resistance. There is some evidence to suggest resistance alleles may have been introduced from overseas populations through biosecurity incursions in recent years.
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> The redlegged earth mite resistance experience is currently playing out in Western Australia: repeated applications of the same group of insecticides within and between seasons has led to the relatively rapid development and spread of resistance which now includes the two main MoAs (SPs and OPs) routinely applied against this pest in both the grains and grazing industries.

In looking to the future, new instances of resistances WILL occur. There are approaches and frameworks being developed to help predict insecticide resistance (which chemicals, which species, time to resistance to new MoAs, etc.) and the utility of these is still being assessed. But we do have the beginnings of a species list for grains that should be used to help focus resistance monitoring. We can also predict with some confidence what will happen with current resistance problems (including their spread) under different scenarios. Unless there is a considerable shift in pest management approaches (particularly around the use of chemicals), the total area affected by insecticide resistance will increase dramatically in all major grain growing regions of Australia; there are substantial economic savings in the medium-long term if growers adopt Resistance Management and Integrated Pest Management principles to reduce selection pressures for resistance.

Pesticide manufacturers have a massive investment in the newer chemistries, and have a strong commitment to their enduring stewardship. As an example of the cross-industry challenges in the northern region, at the grains-cotton interface, resistance in common cotton and grain pests is likely to be acerbated by management practices in grains. Overuse of OPs and SPs is common and there are few selective options. A resistance management strategy that has a multi-pest, multi-crop focus based on new selective options is needed, and must be underpinned by IPM practices in both industries.

Workshop participants considered future risks and opportunities under four themes: Current industry practices; Institutional and policy issues; Leadership and stewardship; and Education. An array of issues was examined under each theme by reflecting on the current state, the desired state and a suggested Action Plan for successful transition (Appendix 3). Recommendations were drawn from these actions through a prioritisation process, and separately submitted to GRDC.

Introduction

The emergence of pesticide resistance, as with resistance to herbicides, fungicides and of course antibiotics, is a societal issue as it impacts on economic, environmental and social issues across the food chain. In some ways, it's a 'wicked' problem because available information is incomplete, resistance is interconnected with other problems and the number of people, opinions, interests and perspectives involved make resolution particularly difficult.

Risk factors for insecticide resistance development represent a combination of interacting factors that include the nature of the target pest (and its evolutionary background) including its mode of reproduction and generation time, the pest's distribution and abundance, the crop type attacked, extraneous factors including climate (change), pest control practices (calendar, IPM focus etc.), the type of chemistry involved in the pesticide (limited & older MOA's), and the amount of chemical applied. Many of these factors contribute to the selection pressures for resistance acting on pests.

The threat of resistance is a major challenge for the grains industry given the ongoing reliance on chemical control methods, the entrenched resistance in some key species and the recent and predictable emergence of resistance to pesticides in aphids and redlegged earth mites given current usage patterns.

The stakeholders for successful stewardship of resistance management include growers (following label, rotating chemicals), chemical manufacturers/ companies (stewardship of chemicals), RDCs (investing in IPM and IRMS), advisors/agronomists/consultants including resellers (giving advice on label use and good stewardship), as well as researchers, applicators, communication extension people, government agencies, APVMA, bulk handlers, and representative bodies such as CropLife Australia and the National Farmers Federation AgVet Chemicals Taskforce.

At the annual face to face meeting of the National Insecticide Resistance Management (NIRM) Working Group of GPAC in April 2015, it was agreed that the complexity of issues underpinning the current and emerging cases of insecticide resistance justifies a workshop to benchmark our knowledge and advise all stakeholders of emerging concerns and how these might be tackled. The Workshop used a three stage process aimed at a) drawing out lessons from both past global and Australian experiences (case studies of pest resistance management); b) predictions of existing and new resistances; and c) assessing future risks and opportunities to better manage these risks.

This report summarises the current state of knowledge relating to pesticide resistance in pests that attack in-field grain crops and in many cases, cross into pastures, horticultural crops and/or cotton and to identify and recommend strategies towards improved stewardship.

Global perspectives on resistance management

Why are global perspectives critical to resistance management in Australia?[1]

- The number of pesticide options is declining globally: How long can we expect new insecticides to last before resistance appears? How do we manage this?
- Gene incursion. Global trade is increasing, especially from developing countries to developed countries. How do we manage the increased incursion risk of resistance alleles? Most resistance issues in Europe are thought to be from immigration. "If you select for it, it will come". Resistance alleles are already out there and there are currently no strategies to limit their importation.
- Sub-lethal doses. Honey bee colony collapse disorder in the US and Europe has been, and continues to be a game changer in terms of public perception of (sub-lethal) pesticide effects on beneficials. While chemical residues are not entirely responsible, it has significantly raised the public's concerns about pesticides. This gives pro-active retailers a market edge. Testing of sub-lethal effects is now required for all OECD countries.

1 Contribution from Dr Owain Edwards

Effects of O_2 and temperature synergism with sub-lethal doses of phosphine in grain storage chemical illustrate the importance of understanding sub-lethal doses.

- Where do we look globally for best practice in resistance management? Nobody has done it better than our Australian cotton industry.
- Techologies: Advances in genomics knowledge and technologies, is improving resistance monitoring – and will also help us to predict what species are likely to develop resistance to new chemistries. Technologies for precision pest control are being broadly discussed overseas and have the potential to markedly reduce selection pressures for resistance. New chemical formulations can also assist in this process.
- RNAi pesticides are on the horizon (Monsanto BioDirect). How is this going to change pest management and resistance? How will resistance to these products develop?
- Genome editing: There are global discussions of applications of genome editing in resistance management. For example do we deploy gene drive to help us manage resistance, such as driving susceptible alleles back into resistant populations, or making beneficials resistant to pesticides? There are examples of natural resistance in beneficial species such as in some parasitic wasps and mites, but has not been locally explored. The principle is good in theory – hard to deliver in practice.

European Union (EU) and United States[2]

Selection for pesticide resistance in the EU is being reduced for some classes of chemicals because IPM approaches have been legislated and are being widely implemented. Conversely, fewer chemicals available in the EU can also increase selection pressures for the remaining actives. There is general agreement that IPM amounts to best practice and underpins the stewardship of the highly valued chemistries. The legislation has defined IPM, with key principles paraphrased below:

  - Prevention and / or suppression by… crop rotation, adequate cultivation, host plant resistance, hygiene, protection and enhancement of important beneficial organisms
  - Monitoring is central
  - As a result of monitoring, decision support for taking appropriate pest control action…
  - Preference for non-chemical control methods …if they provide satisfactory pest control
  - Pesticide applied shall be as specific as possible for the target…
  - Using only as much pesticide as necessary…
  - Resistance management strategies must be applied
  - Pesticide user must check the success of the applied plant protection measure

- The three drivers of IPM in the EU are Government policy, market access issues and resistance.
- Retailers are re-orienting; they see themselves as agents of both consumers and of product producers. Consumers are driving significant change and demanding much greater transparency of chemical use. For example, as of 1 January 2016, Aldi Süd (Germany) is the first big retailer in Europe to ban eight pesticides from domestic fruits and vegetables produced for their markets; the pesticide range included OPs, SPs, fipronil, several neonicotinoids and sulfloxaflor. The Aldi supermarkets share is growing in Australia – will they adhere to German transparency factors?
- Chemicals banned in other OECD countries are still used in Australia.
- In the US, initiatives such as the Pesticide Risk Mitigation Engine (PR'ME) (Oregon) are deigned to help food producers to evaluate pesticide risk.

What have we learnt from the past?

Three case studies reveal the extent of pesticide resistance in key Australian pests, but also the lessons learnt towards living with and managing resistance in individual pest species. The complete Workshop of the Case studies is provided in Appendix 2, which comprehensively describes the lessons that we have, or should have, learnt.

2 Contribution from Dr Nancy Schellhorn

a) Cotton Bollworm (*Helicoverpa armigera*)[3]

- Bollworm has been the predominant resistance issue in cotton for 30 years (SP's, OP's and carbamates). Now there are useful selective alternatives.
- Cotton is a highly invested industry – grower driven; ownership of issues is high.
- The cotton IRMS (Insecticide Resistance Management Strategy) is adaptive and absolutely underpinned by monitoring.
- The IRMS has an annual review – involving strong communication and participation with considerable extension.
- The IRMS and IPM are inexorably linked – the IRMS maintains chemical efficacy while IPM reduces selection by reducing pest pressures through the careful management of beneficials, cultural practices and monitoring. Knowledge of pest and beneficial ecology is critical.
- IPM is achieved in close partnership with industry; it has strong backing by CRDC, and relies on best practice science and "best bets". It entails a huge extension effort.
- The IRMS operates across multiple pests (which could extend to multiple crops).
- Bollworm is now appearing more often in southern systems (south WA, SA, Vic, south NSW) in the traditional native budworm areas (there is a paucity of good historical information).

Lessons

- GM (Bt) cotton has been the cornerstone to successfully managing the pest, but IPM including the careful management of beneficials, is a crucial partner strategy.
- IPM is challenging when there are only a few or no selective chemistry options.
- Pests also develop resistance to soft products.
- Cross industry issues provide an excellent platform for cross-industry collaboration, particularly around Group 28s and indoxacarb, which are used widely across all 3 industries.
- Have to be prepared to be unpopular.

b) Diamondback moth (DBM) (*Plutella xylostella*)[4]

- The 'New' chemistry era from 1998-2015 provided 17 years without product field failure.
- The lessons for grains from the vegetable DMB IRM story include a) motivated to act was driven by crisis (30-40% production losses despite 50-60 sprays pa.); b) the key IRMS response hinged on a rotation strategy based on 5 new chemistries each with novel MOA's, similar efficacies and cost ha-1, and c) the design and implementation required strong leadership (IRMS technical champion – Rick Roush), chemical company 'buy-in' was critical as were effective partnerships (chemical companies, resellers, growers, extension specialists, researchers and Industry investment (HRDC-HIA).
- Cross industry: DBM gene-flow between industries and crops including vegetables (horticulture), canola (grains) and forage brassicas (grazing industries), although there is a great disparity in available group chemistries for rotation between crops (7, 3 and 1 respectively). Gene flow between crops and weeds is also a critical factor.
- Despite crop system differences, cross-industry management of DBM IRM presents many opportunities for further improvement in IRM outcomes for each sector. But this will require co-investment, broad industry 'buy-in', adaptive management techniques, and on-going reinforcement of the IRM and IPM messages.

Cross industry lessons

- Funding economies (resistance monitoring, mechanisms and diagnostics, extension specialists across cropping systems; improved spray application systems; novel tactics e.g. mating disruption in vegies; Magnet™ in canola).

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3 Contributions from Dr Lewis Wilson

4 Contribution from Greg Baker

- Improved IRM Rotation Strategies, including real-time adaptive management such as annually modifying a window strategy to reflect resistance risk based on regional screening data as per Hawaii system, and segregate MOA actives between 2 cropping systems.
- Lessons for vegetables is to manage spring influx from canola and weeds as an asset (susceptible source) rather than a liability and integrate Bt use, releases of parasitic wasps (*Diadegma* spp.) and mating disruption. Need to rework the non-adapted old two-window strategy. Clean seedlings, monitor and use economic thresholds (ET), use Bt early, soft insecticides preferences, avoid DBM spray mixtures, adhere to label rates.
- Lessons for canola – manage green bridge, 'go soft early', monitor, don't spray until economic thresholds have been met
- Expect some industry "fatigue" – IRMs and their promotion require ongoing engagement and new, refreshed strategies.

c) Green peach aphid (GPA) (*Myzus persicae*)[5]

- The green peach aphid is a serious pest throughout the world, attacking a broad range of horticultural and grain crops across >40 plant families. In Australia, cruciferous vegetables, canola and numerous pulse crops are particularly susceptible.
- Other vegetables including capsicums, eggplant and tomatoes are also known to sustain severe damage; GPA can also be a pest of citrus, pome/stone fruits, broad leaf pastures and in the cut flower industry.
- GPA is present all year (>10 generations) and can be found Australia wide.
- Transmits many important viruses to grains crops, including Beet Western Yellows Virus (2014 outbreak resulted in yield losses >150,000 tonnes).
- Resistance is now confirmed to OPs, SPs and carbamates, and appears to be evolving to neonicotinoids.
- Enzyme-based resistance to OPs (Group 1B) widespread in Australia; knockdown resistance to SPs (Group 3A) present in Australia.
- In 2010, the first documented case of MACE resistance to carbamates (Group 1A) in WA.
- GPA are largely asexual in Australia and populations can build up quickly. In a recent survey of populations nationally (2014-2015), 3 genetic clones (or 'biotypes') were found to make up about 80% of all aphids screened. These super-clones have resistance to OPs, SPs and carbamates.

Lessons

- GPA moves freely between horticultural and grains crops. Selection for resistance is most intense in horticultural crops, although there are several more MoAs in many horticultural crops than currently available for grain growers.
- Resistant aphids can move large distances and resistance can rapidly spread across regions and States. Ongoing resistance monitoring is needed to regularly update Resistance Management Strategies.
- In the grains industry, GPA populations are often suppressed below thresholds by the action of beneficial organisms and without chemical intervention, underscoring the importance of beneficials in resistance management.
- There is some evidence to suggest resistance alleles may have been introduced from overseas populations through biosecurity incursions in recent years.
- Management for insecticide resistance in GPA would be better served through cross-industry collaboration (particularly between grains and horticulture).

d) Redlegged earth mite (RLEM) (*Halotydeus destructor*)[6]

- Resistance in RLEM to synthetic pyrethroids (SP) first detected in 2006 in Esperance and is restricted to WA. RLEM has low natural capacity to disperse, therefore spread is likely to be to human transport.
- There are only two chemical groups of foliar insecticides (SPs and OPs) registered.

[5] Contribution from Dr Paul Umina
[6] Contribution from Svetlana Micic and Dr Paul Umina

- Control of resistant RLEM is increasingly relying on weed management and the use of organophosphate insecticides. Seed treatments (Neonicotinoids) do reduce in-crop sprays.
- With the recent detection of OP resistance in RLEM, chemical control failures and crop losses will become more common.
- Less than 35% of broadacre farms in WA have livestock. Hence, the only option for weed control is herbicide applications.

Lessons

- Repeated applications of the same group of insecticides within and between seasons has led to resistance developing in the higher rainfall areas of WA.
- Resistance has emerged in environments where mites were exposed to repeated targeted and non-targeted broad-spectrum sprays. Some questions over the quality of pest management advise being given to farmers in WA, particularly in the higher rainfall areas.
- Urgent need for new MoAs, particularly softer options.
- Need more selective insecticides against beetles (& other crop establishment pests) that are not SP's.

The Status of insecticide resistance in 2015

Currently insecticide resistance in Australia is established in corn earworm (*Helicoverpa armigera*), diamondback moth (*Plutella xylostella*), redlegged earth mites (*Halotydeus destructor*), green peach aphid (*Myzus persicae*), silverleaf whitefly (*Bemisia tabaci*) and western flower thrips (*Frankliniella occidentalis*), all significant pests of grains crops and mostly also of horticultural, cotton or grazing industries (Table 1). These exclude the grain storage pests some of which have notable resistance issues. Other resistant pests that are occasional pests of grains but are more significant in other industries are the two spotted mite (*Tetranychus urticae*), onion thrips (*Thrips tabaci*) and cluster caterpillar (*Spodoptera litura*). Notable resistance issues in the grazing industries include sheep blowfly (*Lucilia caprina)* and various species of lice.

The specific crop hosts for these key grains pests are listed in Appendix 1. Some pests, particularly cotton bollworm, green peach aphid and redlegged earth mite, range across most crops while others such as diamondback moth are restricted to the grains and vegetable brassicas. The resistance management strategy for cotton bollworm, in part dependent on new generation Group6, 22a and 28 insecticides, comes under greater pressure now that these more selective compounds have registrations in various other crops (see Appendix 1) that do not have an integrated rotational strategy.

Table 1: Resistance attributes for key grain pests in Australia

Species with resistance	Chemical group and IRAC level[§]	Geographic range	Industries impacted	Key contact
diamondback moth (*Plutella xylostella*)	1A, 1B, 3A, 4A, 6, 28	Qld, NSW, Tas, SA, Vic, WA	hort, grains, forage	Greg Baker
redlegged earth mite (*Halotydeus destructor)*	1B, 3A	WA	grains, grazing, hort	Paul Umina
green peach aphid (*Myzus persicae*)	1A, 1B, 3A, 4A	Qld, NSW, Tas, SA, Vic, WA	hort, grains, forage	Paul Umina/ Owain Edwards
cotton bollworm (*Helicoverpa armigera*)	1A, 1B, 3A, 5	WA, NSW	cotton, grains, hort	Lisa Bird
western flower thrips (*Frankliniella occidentalis*)	1A, 1B, 3A, 5, 4A	Qld, NSW, SA, WA	cotton, hort	Grant Herron
silverleaf whitefly (*Bemisia tabaci*)	1A, 1B, 3A, 4A, 7C, 16, 19	Qld, NSW, NT, WA	cotton, grains, hort	Jamie Hopkinson

§ For details on each chemical group in the IRAC classification see Appendix 5

Predicting insecticide resistance[7]

In looking to the future, we know that new resistances will occur. There are frameworks being developed to help predict insecticide resistance (which chemicals, which species, time to resistance to new MoAs, etc.) and the accuracy of these is still being assessed. But we do have the beginnings of a species list for grains. However, we can predict with some confidence what will happen with current resistances (e.g. spread, other chemical classes).

These modelling approaches could also be used to:

- pinpoint sampling/monitoring to avoid having to monitor everywhere;
- discover the drivers that will slow resistance down or speed it up;
- highlight the need to monitor base level resistance;
- determine the relative contribution of the ecology of the organism (eg host and landscape range) vs in-crop management practices;
- develop sensitivity data for species 'at risk', so that there is something to compare it to;
- undertake sensitivity analysis on predictors – critical model elements/criteria where data is needed. Certain key elements – gene dominance, temperature, stress; and
- model the potential of using co-formulated insecticides as has been done in weeds/modeling.

a) The expansion and spread of existing resistances

Modeling is a relatively cheap means of assessing resistance evolution and risk and to compare the effectiveness of different management scenarios.

A model is being developed for RLEM in order to help define:

- optimal strategies that maximise time to evolution of resistance given local climate and land usage
- effective methods to eliminate resistance from a paddock
- climatic (or other spatial) signatures in the spread of resistance
- identification of outbreak regions with high likelihood of resistance development for priority monitoring

A coarse-grained, process based model has been developed, accounting for carrying capacity (as influenced by land usage or crop type), selection pressure and chemical application rates, lifecycle biology and generation times (age structure – selective mortality & temperature effects, microclimate and macroclimate effects), resistance biology, dispersal capacity, and various pesticide scenarios (Figures 1 & 2). The RLEM model can be modified to deal with resistance in other pests.

b) Predicting resistance in other pest species

Over 500 invertebrate species worldwide have developed resistance to pesticides. Given selection pressure on pests will almost certainly remain high through the ongoing reliance of chemicals for crop protection, it is reasonable to assume that over the coming years Australia will be faced with new species developing resistance to insecticides. If resistance could be reliably predicted, it would allow us to devise approaches to minimise this risk.

It should be possible to predict the next tranche of pests that may evolve resistances to pesticides currently used in broadacre systems. In a first attempt to do this, a framework has been developed by P. Umina *et al.* based on a series of techniques aimed at identifying pest species with the highest risk of developing insecticide resistance.

In phase 1, a strong phylogenetic signal to resistance was identified, whereby resistance evolution can be linked to the relatedness of evolutionary lineages. This was explored by tabulating cases of resistance where complete lists of arthropods were available (from Italian and northern American datasets). From this it was seen that some orders and families are more likely to develop resistance across both Italian & northern American datasets.

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[7] Contributions from Drs Paul Umina**,** Ary Hoffmann, Siobhan de Little & James Maino

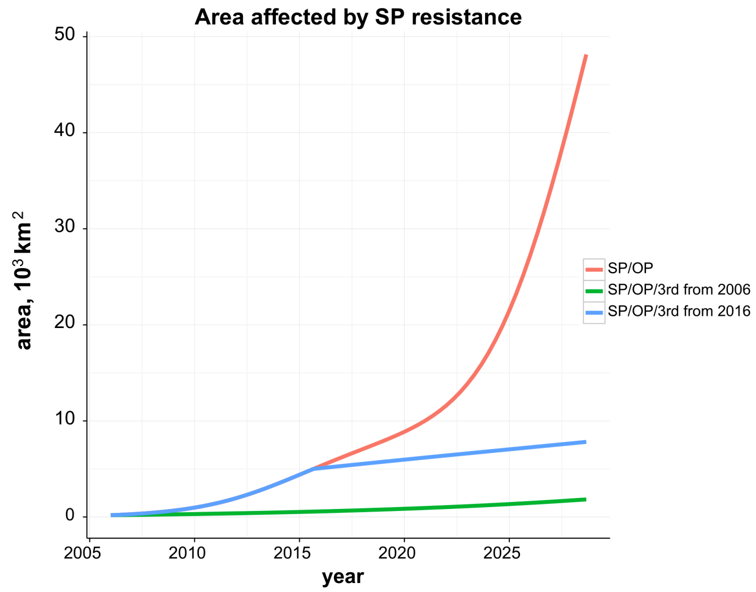

Fig 1: Area of RLEM habitat affected and expected to be affected by synthetic pyrethroid resistance under three pesticide strategies involving Synthetic pyrethroids (SP), Organophosphate (OP) and a 3rd Group insecticide (3rd). The first scenario (SP/OP) represents "business-as-usual" at current OP and SP application rates (red line). The second scenario (SP/OP/3rd from 2006) (blue line) represents the hypothetical situation where a third group pesticide was introduced and spray frequencies reduced by 1/3 from 2006 (the first detection of SP resistance). The third scenario represents "business-as-usual" until 2016 (green line) where strategy 2 is implemented.

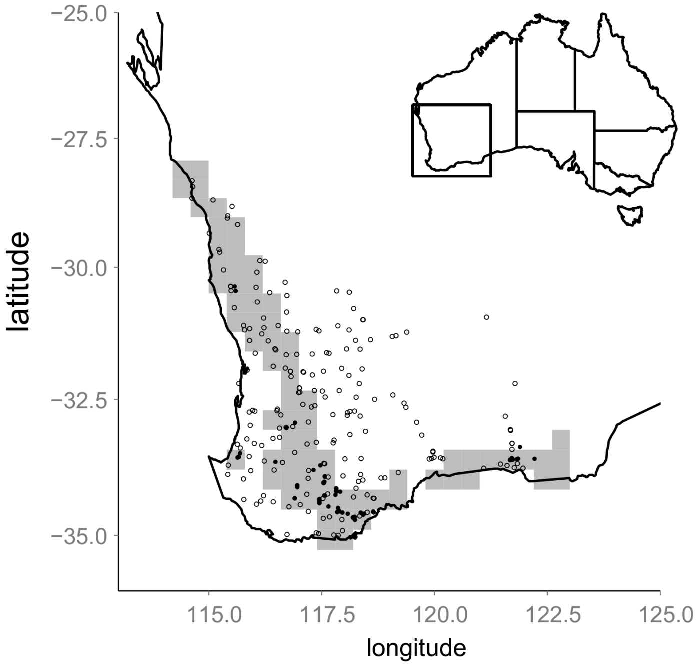

Fig 2. Using climatic data and land usage data to infer chemical usage and selection pressure, a distribution of high-risk areas for the development of resistance is calculated. The predicted high-risk areas (grey region) captures the present distribution of resistant RLEM populations (filled circles). The western distribution of RLEM (resistant and susceptible populations) is represented by occurrence data (open circles) from Hill (2013).

In the second phase a database was built to encapsulate traits likely to influence the development of resistance. Information included 34 factors for 77 species. Twenty-one traits were identified through literature searches and expert elicitation, having allowed for highly correlated variables. A regression approach was used to investigate which traits contributed most to predicting resistance in Australian broadacre pests, followed by a leave-one-out cross-validation approach to validate the models.

From this process, it became evident that each of the following species may be a resistance candidate:

Thrips imagins (common thrips)
Pieris rapae (cabbage white butterfly)
*Aphis craccivora (*cowpea aphid) and
Sminthurus viridis (lucerne flea).
Agrotis infusa (cutworm)

A strong knowledge of the species' biology and ecology is needed to ensure the robustness of the model. For example, the species with extensive migratory capacity from arid rangelands and hosts that are never exposed to pesticides would diminish the resistance risk of species like *Agrotis infusa*.

The framework allowed an assessment of the relative importance of various traits in predicting the likelihood of resistance evolution in a given system, as well as flagging species at risk. This information should be used to prioritise monitoring /education efforts for the target species, and devise management strategies centred on minimising selection pressures (targeting specific traits known to have a large impact on resistance evolution). Ideally this framework would be combined with existing risk assessment methods that focus on the chemical agents, and incorporate future changes in agronomic practices where this information can be reliably gathered.

Preparing for the future

a) Industry perspectives

Crop Protection Companies[8]

Crop Protection Companies (CPCs), having developed new chemistries following enormous investment, have a major stake in preventing resistance to these products and thus stewardship programs.

- CPCs consider growers/producers & consumers are the first priority.
- Growers strive to maximise produce quality and yield whilst fulfilling a "clean, green image" with acceptable MRLs as this gives them a marketing edge on the local and global food market. They prefer not to be on the pesticide treadmill.
- Regulators are demanding higher standards on new active ingredient characteristics e.g. human health safety (toxicology) and environmental impacts (run-off, aquatic systems, persistence, non-target organisms).
- CPCs listen to the demands of community, industry and markets. But there is a lag time to delivery. $100+ millions are invested to commercialise each new proprietary active ingredient (from discovery to first sales). To be more viable, processes are being put in place to shorten registration timelines.
- CPCs are a commercial business and are mostly exposed to shareholder's demands, so this investment must be protected. Hence most CPCs have strong stewardship programs in place so as to maintain the longevity of their investment including detailed resistance management strategies.
- Current practices for managing insecticide resistance-
    - Through CropLife Australia and support from IRAC, industry focus on responsible IRM principles including product labels and annual updates of each IRMS
    - Collaborate with Government Departments and industry specialists for effective insecticide resistance monitoring which includes baseline studies pre-registration of new active ingredients
    - Develop insecticides (both synthetic and biological) that fit into IPM programs including commercial release of beneficial insects by UAVs (drones).
    - Conduct positioning trials pre-commercialisation to understand where best to position the product in relation to other registered insect control options with unique MOAs (synthetic or GMO).
- Standard/current bioassays do not work for new chemistries. Need to develop methods that can cope with a much longer response time. Longer/sub-lethal assay methodology gives a trade-off between efficacy and cost.

[8] Contribution from Geoff Cornwell, CropLife Australia representative

Northern consultants perspective[9]

In northern cropping, at the grains cotton interface, resistance issues may drive cross-industry collaboration. Resistance in pests common to grains and cotton is being maintained in grain crops. Overuse of OPs and SPs is common and there are few selective options. A resistance management strategy that has a multi-pest, multi-crop focus based on new selective options is needed, and must be underpinned by IPM practices.

- The "nightmare" of resistance in cotton bollworm drove IPM and cross-industry IRMS-linked strategies that continue to work today.
- Silverleaf white fly (SLWF) is now also a resistance issue for grains (summer pulses and oilseeds).
- There are few selective control options in grains for the majority of pests, creating a potential issue for the future.
- There is an urgent need to review risks of insecticide resistance evolving in grain pests. The risks are growing: Rutherglen Bugs, mirids and thrips, all with multiple generations per year, are being selected across many crop species. Cereal aphids, wireworm and other soil pests are being targeted with prophylactic seed treatment while GPAs are present, enhancing the rate of resistance in GPA to neonicotinoids.
- The chemistry use patterns are a concern. Many in the industry have an enduring commitment to SP's and OP's which are generally over used, and used ahead of soft options. They are used prophylactically for aphids, mites and mirids. There is an increasing use of neonicotinoids for soil pests, aphids and thrips. The continued use of SPs for other pests maintains Bollworm and SLWF resistance. Two-spotted mite is a common pest, and is continuously exposed to non-target sprays. Stink bugs are increasing is eastern areas.
- There are opportunities for effective resistance management at the cotton grains interface:
    - The cotton industry is now a sink for Bollworm susceptibles.
    - IPM can underpin an IRMS provided more softer options become available.
    - There are a lot of common pests in cotton and grains but thresholds in grains are quite unclear and there are less product choices.
- There is an urgent need for a multi-pest, multi-crop RMS in grains, backed up by IPM.

b) Assessing risk of resistance selection and identifying opportunities

Workshop participants considered risks and opportunities under four themes: industry practices; Institutional and policy issues; Leadership and stewardship; and Education. An array of issues was examined under each theme by reflecting on the current state, the desired state and a suggested Action Plan for the transition. The issues under each theme are listed below:

Industry practices that encourage resistance selection include product co-formulations, commoditised seed treatments, bare earth and prophylactic applications, tank-mix pesticide practices, poor rotation of chemical groups and patchy adoption of IPM practices.

Institutional / policy barriers to addressing resistance include an inadequate range of registered chemical group options, perceived conflict between community/grower benefit vs reseller benefit, movement of resistant pests between industries with different use patterns, the cost-benefit imbalance of developing/registering new chemicals in Australian grains, and international incursions of new alleles and genotypes not considered by APHC (within species biosecurity).

Leadership and stewardship principles needed include integrated leadership and stewardship from the agrichemical industry, a coordinated program of chemical use monitoring (per pest, crop, region, etc.), cross industry agreements and cooperation around resistance management, and APVMA assistance with minor use options, etc.).

Extension and education programs need to address the drivers for uptake of individual RMS and IPM options, and be based on grower understanding of the cost of resistance development.

[9] Contribution from Iain MacPherson

The suggested action plans for each issue are listed in Appendix 3.

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The report was prepared by Garry McDonald (The University of Melbourne) on behalf of the Grains Pest Advisory Committee.

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Appendix 1: Crop type by pest incidence of resistance in Australia

Crop hosts for key insecticide resistant pests.

	Pests with established resistance					
Grain crops	**diamondback moth**	**redlegged earth mite**	**green peach aphid**	**cotton bollworm**	**western flower thrips**	**silverleaf whitefly**
Canola	y	y	y		y	
Sunflower				y		y
Other oilseeds			y			
Wheat		y		y		
Sorghum				y		
Barley		y				
other cereals		y				
Chickpeas		y	y	y		
Lupins		y	y	y	y	
Mung beans				y	y	y
Soybean and other Legumes		y	y	y	y	y
Cotton				y	y	y
Vegetables	y	y	y	y	y	y

Appendix 2: Lessons learnt from Australian case studies

	What have we learnt about what works?	What could we have done better in hindsight?	What are the gaps if we were to do it better?
i. Bollworm	• Grower & Industry ownership of the issue • IPM & RMS together • Adaptive RMS with monitoring, flexibility • Resistance disappears without spraying • Cannot rely on prophylactic sprays • Crisis driven and Industry wide response • Monitoring resistance is critical "if we don't know what you've got you cant manage it" • Sound resistance strategy with strong industry adherence to the strategy • a set planting time for cotton makes it easier • IPM, beneficials, pupae busting importance • Restricting application to a set window single generation (eg SPs) • GM management and stewardship. Mandatory resistance management • Big investment in ecology/basic biology – not just pest species (identifying thresholds) • Group 28s good example of cross industry collaboration	• Using soft options earlier rather than broad spectrum • Being more pro-active in the early stages • Non-cotton grower using SPs etc at any time could have had better co-ordination • Outside of cotton, mung bean etc growers managing separately • Cross industry collaboration could have started earlier in the piece	• Linking IPM with economic analysis earlier • Imperative for cross-industry collaboration (see Greg Bakers last couple of slides capture this well) • monitoring of some species is lacking/poor; monitoring for chemistries is difficult • Are there opportunities in the farming system approach to reduce pest population build-up (IPM)
ii. DBM	• Rotating MoAs has delayed resistance • 5 new chemistries that had the same costs = options to rotate insecticides • Significant extension is very important (particularly in veg) • Grower Champions shaping the research • Chemical company investment is important, research for new chemicals and stewardship • Options for chemical rotations (5 new chemistries)	• Monitoring - adaptive RMS • Potentially area wide management • Better cross industry understanding. Eg. Gene flow from canola -> vegies & vice versa • Cross industry collaboration – not sure this happened at all with DBM. Potential was recognized and attempted but never reached beyond discussions. Why not? Problem is out of sync across industries eg. Acute problem in veg but DBM still being	• Ecology/Movement/Migration • Area wide management, canola, veg • More investment into resistance management • Investing more in extension • Improve spray application • imperative for cross industry collaboration (see GBs last slides) • monitoring of some species is lacking/poor; monitoring for chemistries is difficult • Are there opportunities in the farming

	• Monitoring resistance is critical "if we don't know what you've got you cant manage it" • IPM & RMS together	controlled in canola •	system approach to minimize population build-up (IPM)
iii. RLEM	• Detected resistance • Weed Control • Seed Treatment • Increased seeding crop rotations • Time Rite • Grazing • Good IPM practices will reduce selection • East coast v West coast spray practices	• "RLEM not the most important pest" • Need a system view: • other pests • agronomy • weed control • No options to SPs for beetle pests • No targeted spray options • Better appreciation of non-target sprays for resistance development	• Mechanisms of evolutions of resistance • Need soft options for beetle • Better cultural controls for pests • More and broader extension • New MoAs (particularly softer options) • Very basic RMS at best • Industry needs more selective products to control problematic pests (e.g., beetles) to reduce non-target broad-spectrum sprays of RLEM
iv. General Learnings	• Industry leadership • Excellent communication across industry / growers / stakeholders	• Exposure to sprays against other pests • Broad spectrum insecticides are the catalyst for spray problems • No single stakeholder will solve the problem	• Compliance is hard • Different lessons for farmers, industry, researchers • Multi-layered approach with all stake holders on board including chemical companies, retailers, agronomists, researchers (basic science) • No single stakeholder will solve the problem • Industry leadership

Appendix 3: Preparing for the future - assessing risk & identifying opportunities

Risks that may affect current, emerging and future resistances and opportunities to address them

a. Industry practices

	Current state	Desired state	Suggested actions and plan for change
1.1 Co-formulations	• Promote prophylactic treatment • Reduce flexibility in ability to rotate • Less selective • Increased introductions of these products by chemical companies • Pyrinix Super – chlorpyrifos bifenthrin • Cobalt – chlorpyrifos + lambda cyhalothrin • Cruiser Opti – thiamethoxam + lambda cyhalothrin • Cotton – Voliam flexi (chlorantraniliprole + thiamethoxam)	• Only used when absolutely necessary • Only combine chemicals that fulfill strict criteria eg. Persistence, level of efficacy • No prophylactic treatments as required • Co-formulation increase efficacy of hard to kill mites	• Strongly evaluate need for co-formulations • More regulations for co-formulations • Chemical companies consult with resistance experts to determine suitability of co-formulation • Systems in place to predict pest so as to determine if need treatment or not eg. Balaustium model, better monitoring required
1.2 Commoditised seed treatments	• Lack of availability of untreated seed in some industries • Lack of choice • Increases resistance risk • Insecticide ST becoming far more prevalent • As above for Cruiser Opti + imidacloprid options • Cosmos (fipronil)	• Growers have a choice • More seed treatment actives • Ability to rotate • Grower awareness that actives in ST will select for resistance – thus they are carefully considered in rotations • More seed treatment options made by seed companies	• Apply pressure to have more options • Seed treatments need to be rotated – this needs to be legislated • Education on resistance risks with reference to use of seed treatments • As above, 1.1, even longer term predictive mode for population development
1.3 Bare earth applications	• Declining trend of BE applications (particularly insecticide – only BE). (still some tank mixing)	• It is not done	• Education • Cultural control options that fit into a farming system
1.4 Tank-mix pesticide practices	• Happening in some areas but becoming less common in some parts • Reasonably common practice with insecticide added to fungicide and nutrient applications	• Only done on threshold basis • Tank mix with herbicide/fungicide with insecticide only if needed • Use insecticide as required based on monitoring. Do not use	• Better targeted spray applications • De-registrations of cheap options • Education & stewardship from chemical companies – need to demand it

		prophylactically	• As above for 1.1, monitoring, extension, upskill resellers
1.5 Rotation of chemical groups	• Limited by lack of alternatives • Limited by lack of cost-effective alternatives • Minimal • Limited options available to rotate	• More choice of MoAs to rotate including Magnet® • New registrations • More selective options • Comparable pricing for rotation options • More use patterns for existing chemistries • Rotate chemicals effectively	• Education investment • IRM strategy • Stewardship • Have good chemistries to rotate to • Established RMS available
1.6 IPM adoption (thresholds etc)	• Thresholds in place for spring pests • Limited for establishment pests • Limited focus on beneficials • Partial adoption of IPM but patchy uptake within regions and between regions	• Establishment pest thresholds required • Softer options for establishment pests • Widespread option of IPM/IRMS strategies	• Coordinated program to improve the uptake of IPM and IRMS • Legislate it or deregulate old broad spectrum chemistries to get more options • Retailer driven practices
1.8 Spray rates	• Some instances/regions in which low label rates being employed	• Use recommended effective rate	• More trials to know by how much spray rates can be decreased • Labels updated to reflect current field efficacy • Education and awareness of rate cutting • Deeper understanding of effect of rate cutting on different pests • Better understanding (advisors and growers)
1.9 Spray timing	• Prophylactic – in some areas/situations • Over-spraying/unnecessary application	• Improved understanding of thresholds • Increased accuracy of models • Increased monitoring	• Threshold-based • Monitor-based • Predictive models
Which current industry practices have a positive influence on resistance mitigation?		• Interaction with other industries • Area wide management • Plant breeding	

b. Policy / institutional

	Current state	Desired state	Suggested actions and plan for change
2.1 Registered chemical group options	• Lack of range of selective /mode of action options in some crops (only SPs Ops) • Not many, absent to limited target specific options • Minor hort crops have access to restricted chem; rely on permits not registrations	• Availability of range of options – selectivity • More than one, so can rotate • Value & use • More targeted product options	• Grains need to put this up through AgVet forum • Minor crop registration • Minor use registration • Research to establish value & use proposition DTE • Prioritised options for pests that do not have soft options available • Collaboration with chemical companies, industry, RDCs to develop better soft chemical options
2.2 International incursions of new alleles not considered by APHC (within species biosecurity)	• No policy • Not being considered	• Lobby for change with effected industry bodies • Establish monitoring protocol • New tier of quarantine required especially in light of free trade agreements where a product is not allowed to be excluded due to pests eg cut flowers	• Policy changed to include intra specific differences (eg insecticide resistance strains) • Better quarantine practices in light of Free Trade Agreement
2.3 Conflict between community benefit vs reseller benefit	• Regional/cultural issue • In some cases reseller is also advisor so not independent • Focus is on private benefit – growers, resellers, chemical manufacturers • Generic, cheap	• Best choice based on need • Win – wins • Resellers to stop flogging old chemicals and to promote best practice	• Improved extension (education of growers for better decisions and processes) • Invest in independent extension specialists
2.4 Movement between industries with different use patterns	• Crop specific solutions (no AWM) • Little conversation between industries and a lot of “finger pointing”	• Move to greater co-ordination System Approach • Area Wide Management (AWM) • RMS need to encompass all crop uses	• Co-operation • Multi-crop form • Seek to understand the problem • GRDC, HIA, RIRDC, GRDC, AWI • More collaboration, communication

			between industry, RDCs
2.5 GM pest resistance	• Well-managed but only cotton • Very good institutional framework in Australia to evaluate and delay resistance	• Maintained – supports other industry • Would need to reconsider if another GM Crop	• GM for everyone • Insects & plants • Better competition • Stronger and varied (eg. Glufosinate Ammonium tolerance) GM traits in crops other than cotton with incentives to expand to other crops (remove barriers) (public perception)
2.6 Cost-benefit of new chemicals (no regulatory incentives)	• Time lag for registration globally versus Australia (scale) • Cost of producing a chemical relies on the benefit to the company; incentives are being applied for through AgVet	• Australia gets access same time as other countries • Government incentives for targeted soft products	• Push for global joint reviews -> submission for data goes in at the same time
2.7 Other	• Market access due to residues relating to trade tolerances	• Barriers to market access need to be realistic eg off label use	
Which current policies have a positive influence on resistance mitigation?			

c. Leadership and Stewardship

	Current state	Desired state	Suggested actions and plan for change
Who are the key stakeholders and what is the responsibility of each?	• Growers especially Champions, RDCs, retailers, consultants inc resellers, manufacturers, researchers, applicators, communication extension people, government, chemical companies (stewardship of chemicals), advisors/agronomists (giving advice on label use and good stewardship), farmers (following label, profitable Q&A product, rotating chemicals), APVMA, bulk handlers • Brand Australia – reputation of Australian produce being "clean and green" -> market access and reputation – price and product		
3.1 Chemical use monitoring (per pest, crop, region, etc.)	• Poor understanding of pesticide usage in Australia • Monitoring is non-existent	• Can we acquire data on chemical use patterns, nationally and regionally? Do such data translate into selection pressures and how else might these be measured? • Grains industry has access to seasonal pesticide usage data	• Records of recommendations made by consultants across season (learn from cotton industry) • Chemical industry agree to devise a plan that results in R&D access to grower Chemical Use data • Get growers (ditto everyone on supply

		• Spray diaries mandatory • Regional and crop type data collection and analysis -> recommendations and practices	chain) on board – outline benefits re market access, decreased chemical use
3.2 Integrated leadership and stewardship from agrichem industry	• Currently in place "Crop Life" • What stewardship/leadership is CropLife doing? • CropLife Australia involving most agrichemical companies who produce basic RMS for some pests	• Collaboration with other relevant stakeholders (as listed above) • Increase grower involvement	• Hear from ag resellers/champions • Insisting for commitment on best practice • Legislate these requirements • Increase grower involvement and other stakeholders
3.3 Cross industry agreements	• Very few cross-industry agreements • CropLife brings industry ownership • Silo approach persists • Rural R&D for Profit could help • Lack of research co-ordination across industries	• Grains, Cotton, Horticulture, RIRDC etc -> agreement -> research activity, extension activity, policy activity, minor use permits • For relevant pests and issues all industries involved to pull their weight in investment/ communication	• Directed by DAWR; generate report to RDCs on what issues/topics of commonality are and what the value proposition of joining forces is • DAWR – facilitate meetings between chemical industry and RDCs • Discuss and coordinate investment
3.4 APVMA options (minor use etc.)	• Slow process • Bureaucratic • Red tape reducing for soft options	• See above at 3.3 • More minor use permits on labels - with consideration given to resistance risks	• Terms of Reference (TOR) for APVMA increased to account for resistance
3.5 Australian Dept of Agric (DAWR)	Rural R&D for pesticides is strong but there is a: • Lack of experience in resistance and pest management • Lack of extension staff • High turnover of staff • Lack of funds for pests Unknown status of resistance strategy in DAWR	• Coordinated research centre across industries and with interactions across weed and disease space • DAWR has a full appreciation of resistance issues and directs RDCs, APVMA accordingly (priority area)	• Ensure residues appropriate as per US, EU • Local testing on beneficial impacts mandatory • define relationships between DAWR/States/APVMA/chemical industry (where is line of influence?)
3.6 Other Retailers & Consumers eg grain corp	• no tracking • gate keeper for what growers do pre and post harvest	• tracking of producer/region throughout supply chain and to consumer	• Implement consumer pull – demonstrate need • engagement throughout supply chain • get champions to push for it • growers lobby direct and via industry regulatory bodies

d. Education

	Current state	Desired state	Suggested actions and plan for change
4.1 Grower understanding of the cost of resistance development	• Very low understanding • Denial can occur • False optimism of continuous effective chemistry options • Disconnect between current state and the future in terms of cost of resistance	• Better understanding leading to better level of interest • Cost of resistance: Need a cost-benefit analysis and then communicate to growers and agronomists • Communication and engagement with all stakeholders on cost of resistance • R&D in terms of economics	• Company/retailer/grower champions and extension education
4.2 Drivers for RMS/IPM uptake	• Crisis required/ driven • Avoidance of pesticide treadmill (economics, lifestyle, environmental) • Social and market pressures • More profitable/sustainable production	• Pre-emptive • Proactive, not reactive • IPM is the primary management system • RMS and IPM are standard practice and information and tools	• Better economic analysis • Obvious economic incentive • Need to explore options: carrots – preferential pricing for soft option insecticides • More R&D before extension. Need bottom up engagement for adoption to occur • Three carrot: linked with who is supplying you; 'have' to buy soft with hard; preferential price grain that uses IPM principles • Stick – legislate for IPM
4.3 Extension options	• Uneven and uncoordinated between industry • Inconsistent message • Farmers are being bombarded with extensions, rely on agronomists to disseminate options • How do we get someone to own a problem? Identify other examples where it has happened	• More coordination • Farmers need to take ownership, bottom up drivers of change • Peer to peer learning • Case studies with economics analysis • Education as per "desired state" and funding to support this • Farmer friendly communications, recognising different modes of	• Co-ordinated annual activities calendar • RDCs to facilitate coordination • More grower champions • Model successful WeedSmart® program that gives farmer ownership • Urban pest control example – can only buy chemical if you have trained with product owner (and follow up/ stewardship). Require agronomist to do training in product use/IPM before

		learning and engagement	providing advice • Certified training for agronomists every 2yrs in crop protection. Need this certification to practice as agronomist. Chemical use withdrawn if follow-up detects usage problems • Bottom up engagement to direct R&D -> communication not other way around
4.4 Education about target markets	• A lot of myths about GM that clouds the debate • Are agronomy courses relevant to needs? • Link between application technologies and legislation (drift retardant technologies)	• Best option for high value and profitable markets (GM)	• Consumer education on GM crops especially to give growers more tools to decrease spray use
4.5 Education across research grps (fungicide/ herbicide) and industry		• Researchers invited to grower group meeting as a guest speaker	
4.6 Regulator education	• none	• better connect with RMS and regulators and state governments	
4.7 Improved understanding of IRAC classes and understanding of relevance to resistance management	• none • Not great understanding (particularly insecticides, fungicides) among growers		• Incorporate training into chemical accreditation training/courses • NIRM to consider how to incorporate into RMS communications

Appendix 4: Prioritising suggested actions

Workshop participants were asked to prioritise Actions from the "Suggested Actions and Plans" (Appendix 3) and assemble each in an appropriate location on a chart with axes labeled "Feasibility or Practicality" and "Likely impact".

a. Industry practices

	Low Impact		High impact
High feasibility	Experts combine to clarify benefits of BMP (particularly around spray rates) and this is distilled and communicated to industry	IPM for key insect pests and generic principles communicated and translation of labeling system; Voluntary industry code Predictive models developed to predict outbreaks and improve monitoring	GRDC to consider GPAC IPM adoption report for on-ground IRMS/IPM practice change (1.6) More economic thresholds and clarity around spray timing are needed for key pests
		Champion farmers to focus on IPM adoption for management of pests that includes focus on resistance (1.6)	Educate growers and advisers around resistance management strategies
Low feasibility			

b. Policy and institutional

	Low Impact		High impact
High feasibility			Flag priorities at AgVet forum; looking for soft options that are IPM compatible (2.1) Collaborate with chemical companies industry, RDCs to develop soft options
			Collaboration between industries on a regional basis to ensure consistency in approach to IRMS
		Advocate for global joint product reviews (global registration) Make the case for greater transparency of chemical use	Regulate out old chemistries to reduce barriers to new chemistries (regulated by APVMA) (2.1)

Low feasibility		through the food chain (2.3) Remove barriers to introducing more GM products including incentives, education and public perception and cost	Policy change to improve legislation and quarantine (incorporate free trade agreements. Push from industry

c. Leadership and Stewardship

	Low Impact		High impact
High feasibility		DAWR take active role in coordinating and funding resistance issues across industries and pests (inc adoption)	GRDC to source databases that are presently capturing chemical use data (Farm management software eg Back Paddock®) and analysing seasonally. Even better would be to improve chemical use data captured (3.1)
		All chemical companies part of CropLife so that smaller companies do adhere to stewardship and take more proactive approach to RMS development	Lobby industry representative bodies and researchers for a coordinated resistance research and extension centre
Low feasibility		Review APVMA registration model; focus on proposed RMS, residues, toxicology; do not conduct data review and thereby streamline registration process (DAWR) Education of kids and whole supply chain of IPM	

d. Education

	Low Impact		High impact
High feasibility		National registration of industry Certification Programs for agronomists (such as existing Ag Technologists Association) that mandates courses in integrated crop protection strategies	Invest in a project that develops and communicates to industry case studies that expose the true cost of resistance (4.1) RDCs to facilitate grower champions for the

			uptake of IRMS and IPM in broadacre farming (4.2) Piggyback on successful programs such as WeedSmart®; look for integrated messages.
		Certification training (compulsory) for agronomists every 2 years on pesticides and their usage. Industry to sell soft and hard pesticides together so farmers can't ignore more expensive soft chemical options	Grains industry creates preferential pricing for IPM/soft chem (4.2)
Low feasibility		Mandatory training provided by technology owners for buyers/users of technology. If failure, loose buying rights. (4.3)	RDCs to lobby government to legislate IPM as per EU model

Appendix 5: Insecticide groups from IRAC MoA Classification

http://www.irac-online.org/documents/moa-classification/?ext=pdf

IRAC chemical modes of action classification group		E.g. Active ingredients	E.g. Registered Products
Group 1A	Carbonates	methomyl, pirimicarb, thiodicarb	Pirimor®, Aphidex
Group 1B	Organophosphates (OPs)	omethoate, dimethoate, chlorpyrifos	Lemat®, Lorsban®
Group 2B	Phenylpyrazoles	fiprinil	Cosmos®
Group 3A	Synthetic pyrethroids (SPs)	alphacypermethrin, bifenthrin, gamma cyhalothrin	Astound®, Dominex®, Fastac®, Trojan®, Emerge®, Hombre®,
Group 4A	Neonicotinoids	Imidacloprid, thiamethoxam	Gaucho®; Confidor®; Poncho Plus®
Group 4C	Sulfoximines	sulfoxaflor	Transform®
Group 5	Spinosyns	spinetoram, spinosad	Success Neo®
Group 6	Mectins	emamectin benzoate	Affirm®; Proclaim ®
Group 7C	Juvenile hormone mimics (IGR)	pyriproxyfen	
Group 11A	Microbial disruptors of insect midgut	Bacillus thuringiensis (Bt)	Dipel®
Group 16	Inhibitors of chitin biosynthesis (IGR)	buprofezin	Buprofezin
Group 19	Octopamine nerve receptor agonists	amitraz	
Group 22A	Voltage-dep sodium channel blockers	indoxacarb	Steward®
Group 28	Ryanodine receptor modulators (diamides)	chlorantraniliprole, flubendiamide	Altacor®, Coragen®, Exirel®
		NPV	Vivus Max

Appendix 6: Attendees of the GPAC workshop

GPAC/NIRM members	Affiliation	Guests	Affiliation
Greg Baker greg.baker@sa.gov.au	South Australian Research and Development Institute, SA	Sally Ceeney sally@ceenag.com.au	Ceeney Agricultural Consulting Pty Ltd; Cotton Info
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