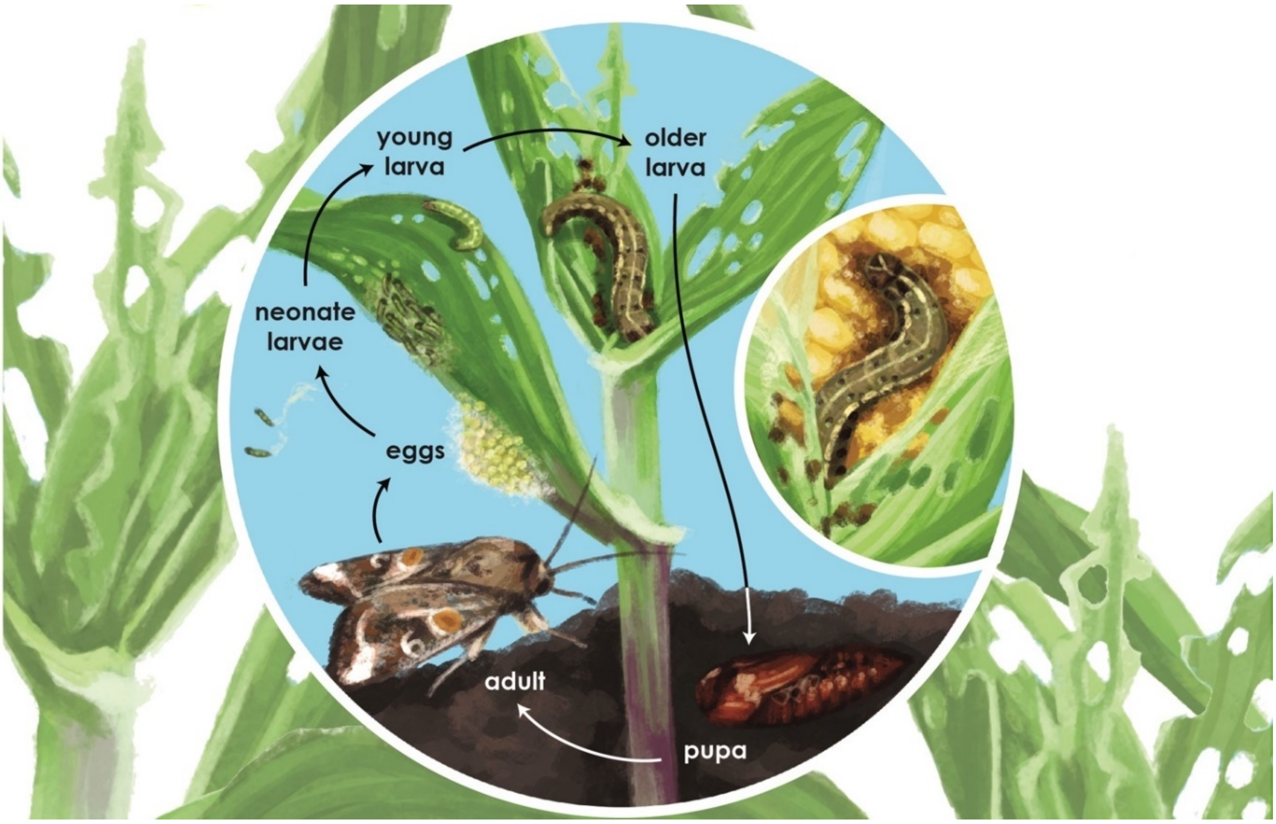
FALL ARMYWORM CONTINUITY PLAN

for the Australian grains industry

Version 1, November 2020



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Project partners

Queensland Government

cesar

GRDC Grains Research & Development Corporation

Plant Health Australia

CABI

This is a Grains Research Development Corporation investment initiative led by **cesar** with project partners Plant Health Australia, Centre for Agriculture and Bioscience International, and the Queensland Department of Primary Industries. Contract code: CES2004-003RTX.

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CONTENTS

Acknowledgements 1

Scope 2

Intended readership 2

Quick guide -Fall armyworm 3

- Key points 3
- Assessing your regional risk 4
- Knowing when and how to look for signs of FAW 5
- Positively identify FAW by consulting with an industry specialist 7
- Insect pest and damage thresholds 10
- Make informed decisions and act decisively 12
- Reporting 13
- Useful resources 14

Introduction 16

FAW Biology and Behaviour 17

- Biology and life history 17
- FAW strains 19
- Geographic distribution within Australia 19
- Hosts 19
- Signs and symptoms 20
  - Emerging seedling 20
  - Leaf and stem development 21
  - Flowering, grain development and maturation 22

Spread, Impact and Seasonal dynamics 24

- Potential impacts 26
  - Maize and sorghum in Australia 26
  - Economic impacts associated with FAW infestation 27
  - Applicability of yield loss data to Australian grains industry 29
  - Quality loss or downgrading 29
  - FAW chemical management costs 29
  - FAW economic injury levels, economic thresholds and action thresholds to inform management 31

Identification and Scouting **35**
Identification 35
Morphological identification of FAW 35
Molecular identification of FAW 40
FAW monitoring and crop surveillance 41
Monitoring for FAW 41
Crop surveillance for FAW 44
Management considerations **47**
Management tools 47
Integrated pest management 47
Cultural controls 47
Chemical control (chemical insecticides) 48
Biological controls (predators and parasitoids) 53
Microbial biopesticides 54
Semiochemicals 56
Future options 58
Genetic-based control of FAW 58
GM traits such as Bt 58
Resistance to *Bt* Crops 59
Resistance management **60**
Resistance to chemical pesticides 60
Resistance risks and management 62
Resistance mechanisms in FAW 63
FAW extension **65**
Evolution of messages after a new pest is found 65
Key questions raised about FAW at the outset of the incursion 66
Considerations when undertaking extension 66
References **68**

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SCOPE

This continuity plan for fall armyworm (FAW; *Spodoptera frugiperda*) has been developed for use by professionals, specialists, and consultants in preparing more localised and industry specific communication and extension material. The plan focuses on the grain industry and provides relevant background information on the current knowledge and status of FAW in Australia, key considerations in developing localised management strategies, and future research and development for the Australian grain industry. The intended purpose of the plan is to provide a reference point and a basis for industry to build upon in designing resistance management strategies, area wide management plans and crop specific management manuals together with other extension materials such as audio and visual products for the management of FAW within the Australian broadacre farming systems.

INTENDED READERSHIP

This Fall Armyworm Continuity Plan is national in scope and will evolve quickly as our knowledge on FAW grows. Updated versions of this plan will be published as new findings come to light.

It is intended as a reference document for professionals, specialists, and consultants in preparing more localised and industry specific communication and extension material. This Continuity Plan compiles information from international literature and expertise and provides a solid background of knowledge on the pest, which will support the development of effective management strategies, plans and information sharing networks.

QUICK GUIDE - FALL ARMYWORM

Fall armyworm (FAW, *Spodoptera frugiperda*) was first reported in Australia in February 2020 and quickly established across parts of Northern Australia's tropical and sub-tropical regions, including northern Queensland, Northern Territory, and northern parts of Western Australia.

This Quick Guide synthesises essential baseline information on the biology and behaviour of FAW together with symptoms of plant injury and management strategies that will be useful in developing effective local and crop specific management strategies, plans and other requirements to address FAW in Australia.

Key points

- FAW is a highly migratory, invasive pest and as of October 2020 is present in parts of Queensland, the Northern Territory, New South Wales and Western Australia.
- FAW is able to travel long distances into more temperate or arid regions that are unfavourable for permanent populations. Annual population movements of over 2000 km with overnight migration distances of 400 km have been observed.
- FAW completes its lifecycle in around 30 days at optimal temperatures and will be able to complete multiple generations each year in Australia's subtropical and tropical climatic regions.
- Plants within the grass family (Poaceae) including maize, sweetcorn, sorghum and C4 pastures are favoured hosts of FAW.
- While two strains of FAW have been reported internationally, based primarily on their host plant preference, they can mate and form hybrids. In Australia, FAW populations have been detected on several crops including maize/sweet corn, sorghum, chickpea, soybean, melon, green beans and pastures (Rhodes grass).
- The rate of FAW population growth will increase during warmer months and decrease during the colder months.
- Migrations into southern regions are predicted to generally commence from spring with populations subsequently building up into summer.
- Maize, sorghum and other crops can tolerate some level of damage to leaves without yield impacts.
- It is difficult to distinguish the eggs and early instar larvae of FAW from other *Spodoptera* spp. found on grains crops; older larvae have distinct markings that enable them to be more readily identified from other similar pests.
- Monitoring for FAW eggs and larvae should involve visual inspection of the crop or host plant.
- In maize/corn, young leaf tissue is more suitable for larval growth and survival than mature leaves. In mature plants, larvae tend to settle and feed in the ear zone.
- Fortunately, many of the products registered for *Helicoverpa* control will also be effective against FAW, and there will, at certain stages of crop development, be incidental control.
- Getting the crop off to a good start with good agronomy and crop nutrition will ensure plants are more resilient.
- Managing volunteers in fallows and other sources of green bridge will reduce pressure, thereby reducing local populations of FAW.
- Avoiding sequential plantings of preferred crops such as maize and sorghum, will help reduce local populations of FAW.

Assess	Find	Identify	Thresholds	Enact
Assess your inherent FAW regional risk.	Use trigger points to know when to commence active monitoring of crops. Having appropriate traps and lures ready and share trapping results with neighbours.	Accurately identify pests by consulting with your local agronomist or crop protection specialist.	Develop, use and fine tune FAW specific economic thresholds, where available	Make informed selection of appropriate IPM approaches including use of beneficials and the application of good resistance management principles. Do not spray unnecessarily, only spray when economic thresholds are reached.

1. ASSESS

Assessing your regional risk

1. Check the risk zones below to determine whether you are in a zone where there is FAW risk all of the time, most of the time or some of the time. FAW is predicted to be present all year round in zone 1, present in all seasons apart from winter in zone 2 and present in some years from mid spring through summer and into autumn in zone 3 (Figure 1).

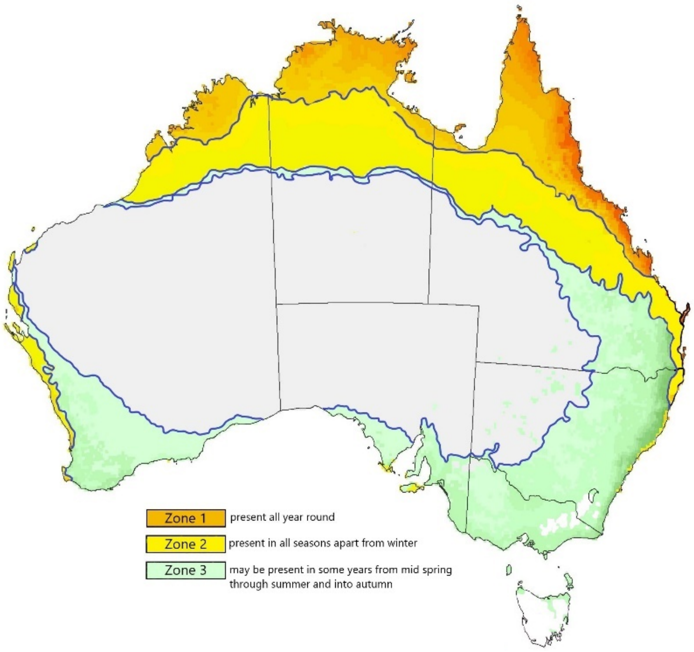

Figure 1. FAW risk prediction map showing zones where there is FAW risk all of the time, most of the time or some of the time

2. Know whether your crops are preferred FAW hosts maize/sweet corn, sorghum, and determine when crops are at risk and their susceptible stages.

3. The host range of FAW includes more than 140 species of reported cultivated and wild plants within the Poaceae (grasses) family and non-grass hosts. While Australian research is ongoing, recent international research indicates that FAW tends to favour summer crops in this general order.

    1. Maize
    2. Sweet corn
    3. Sorghum
    4. C4 pasture grasses
    5. Sugarcane
    6. Rice

    More preferred

    Less preferred

4. FAW can be particularly difficult to control with chemicals in maize due to the plant's whorl and characteristic ears and protective husks – plant structures that assist the pest's ability to seek shelter and avoid insecticide exposure.

5. When larvae are very numerous**,** they defoliate the preferred plants, acquire an 'army' habit and disperse in large numbers, consuming nearly all vegetation in their path. Many host records reflect such periods of abundance and are not truly indicative of oviposition and feeding behaviour under normal conditions.

6. Actively monitor the presence, population, and movement of FAW in your risk region. Be aware of the population status by checking for local updates and alerts on moth migration provided by relevant networks such as the Beat Sheet trapping network.

7. Share trapping and scouting data with neighbours to ensure high levels of communication and cooperation between growers, consultants, and research/extension personnel in order to better manage pests at a regional level.

2. FIND

Knowing when and how to look for signs of FAW

1. Early detection is critical to ensure effective timing of control measures.
2. The first indicators of FAW arrival in your area is the presence of migrating moths in Zones 2 and 3 and the emergence of adult moths from pupation in Zone 1 and 2.
3. Use pheromone-baited traps, suspended at canopy level, to detect early moth arrival and activity in the region in accordance with APVMA permit requirements.
4. There are a number of commercially available bucket or pheromone traps (Figure 2) that attract male adult FAW. These can be sourced together with lures and insecticide cubes online *via* retailers. Not an exhaustive list, but some examples include Bugs for Bugs, **www.bugsforbugs.com.au/product/bucket-trap** and Grochem Australia, **www.au.grochem.com**
5. Place a dry cellulose sponge in the bottom of the trap to absorb rainwater that may enter the trap, keeping the moths reasonably dry.
6. Consider establishing a trapping and reporting network with neighbours to detect and record the spread of FAW into new regions. Sharing information between growers and agronomists can provide an early-warning of fall armyworm activity and trigger crop monitoring.
7. Traps are best suited to signalling the arrival of significant peaks or influxes in moths over broad areas. They are unreliable indicators of level of egg-laying intensity or infestation of nearby crops. Scouting is required to determine egg-laying intensity (percent infested plants).

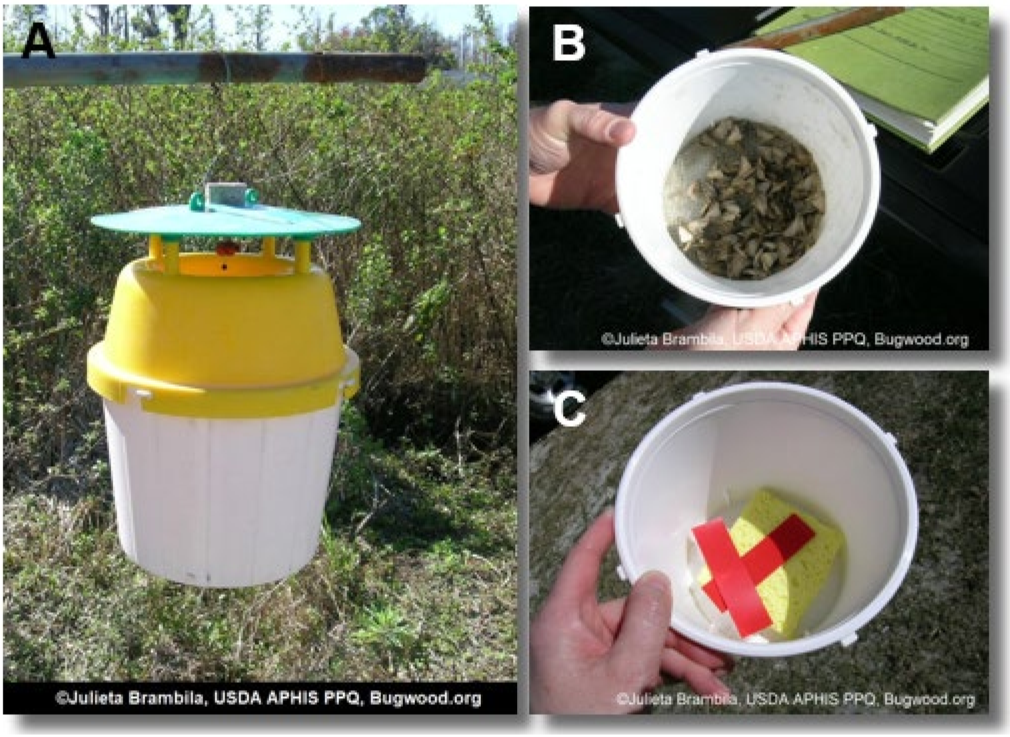

Figure 2. A) Bucket or pheromone trap; B) FAW adult male captures; C) Insecticide strips to kill adult moths

8. Conduct crop scouting regularly when pest migration is imminent. At least fortnightly at vegetative stage and increase to weekly if larvae are detected.
9. Early detection of FAW larvae before they become entrenched in the crop (e.g. whorl of maize, sweet corn or grain sorghum) or before they become later instars is essential for effective management.
10. Using a repeatable pattern, scout entire crops for FAW eggs and larvae as during early infestation (or directly after egg hatch) they are often unevenly distributed and can be confined to small patches within the crop (Figure 3).

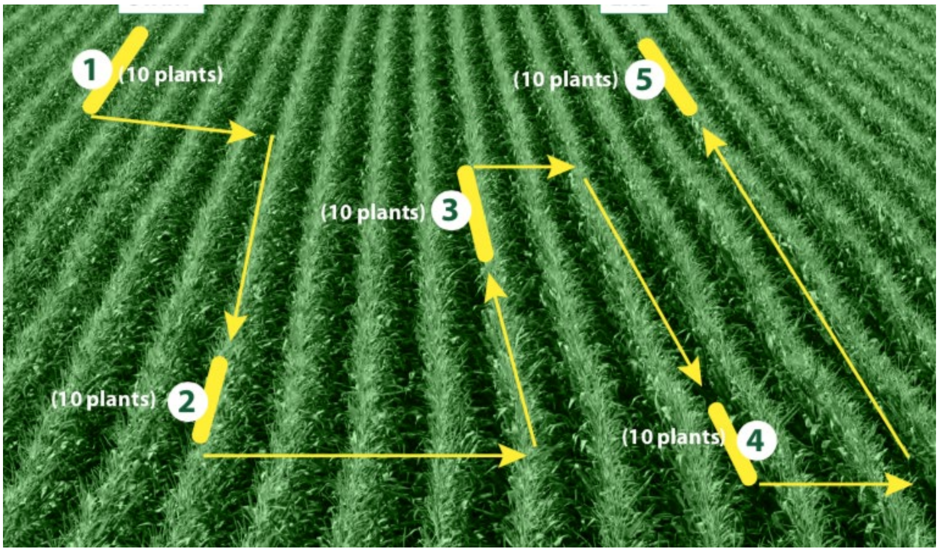

Figure 3 Example 'along the row' scouting pattern may be used for FAW in row crops

11. In row crop situations check 10 consecutive plants in a row (Figure 3) and count the number of larvae per plant. Ensure careful inspection of the plant structure (e.g. open the whorl of maize, sweet corn or grain sorghum). Repeat this at a minimum 5 sites in the crop at 100-200 meters apart to ensure the whole crop is represented. For large fields increase the number of sites from 5 to 10.
12. For solid planted crops use a 'W' shaped search pattern across the crop (Figure 4).

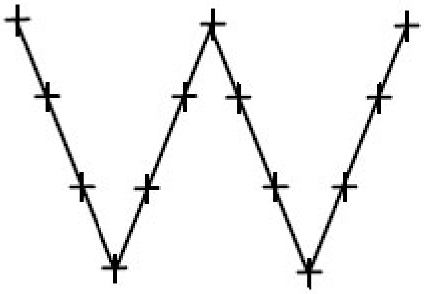

Figure 4 Example 'W' scouting pattern to be used for FAW monitoring in solid planted crops

13. Record the number and size of larvae observed.
14. The first signs of infestation are most often feeding marks by first instars. They typically only feed superficially on one side of the leaf, and create damage that looks like pin holes, shot holes and 'window panes', or windowing (Figure 5a). Young FAW larvae use 'ballooning' (spreading by wind on a thread of silk) to spread to new host plants (Figure 5b). The small airborne larvae have no control on what plants or crops they land on.

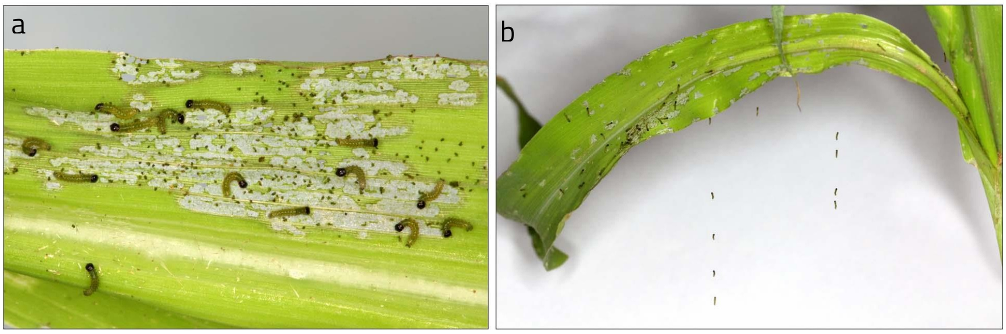

Figure 5. (a) FAW first instar feeding damage (b) 'ballooning' behaviour

3. IDENTIFY

Positively identify FAW by consulting with an industry specialist

1. Familiarise yourself with the key markings and characteristics of FAW through its various growth stages (Figures 6, 7, 8 and 9).

Adult females lay 100-200 eggs on the lower leaves. They change from green to light brown before hatching.

Eggs are covered in protective scales rubbed off from the moths abdomen.

After hatching, the young caterpillars begin feeding on the leaves.

As they grow, caterpillars change from light green to brown.

Fall armyworms have four dark spots forming a square on the second-to-last body segment.

Fall armyworms have a dark head with a pale, up-side-down Y-shape on the front.

They are at their most damaging when they are 3-4 cm long.

The pupa is shiny brown and usually found 2-8 cm into the soil.

Adult moths (top: female, bottom: male). The females are slightly bigger than the males.

Figure 6. Key identification characteristics of FAW. CABI, 2019

2. Use a hand lens (10x) or hand magnifier to identify key characteristics of captured moth and larval samples.

3. Confirm pest identity by consulting with your local agronomist or crop protection specialist. Diagnostic labs with taxonomic capability, such as your state department of agriculture are also able to provide accurate identification.

Figure 7. FAW armyworm male and female adult moths

4. Fall armyworm moths are nocturnal, i.e. active during the evening and rest during the day. They are sometimes found hiding between maize leaves or in whorls. Male moths find females by following pheromones released by the females. Mating takes place and eggs are laid in masses, two or three days later.

5. Eggs are laid in masses on leaves, mostly on the underside, but also on the upper side and on stems (Figure 8). Females can deposit eggs in more than one layer before they are covered by hairs from the abdomen of the female moth. Egg masses without hair covers may also be encountered. Eggs may be cream-coloured, green or brown, but the whitish colour of the hair covers is easily observed on the green leaves. The presence of egg masses plays an important role in the scouting process.

Figure 8. FAW egg masses

6. Larger caterpillars have characteristic marks and spots (Figure 9). Marks that are often used for identification include the upside Y mark on the head region and the four larger spots on the second last segment. The most common distinguishing characteristics (lines and spots) are indicated below. Note: variations from the illustrations above may be encountered, and other non-related caterpillars may show similar marks and spots, although usually not as vividly as in FAW.

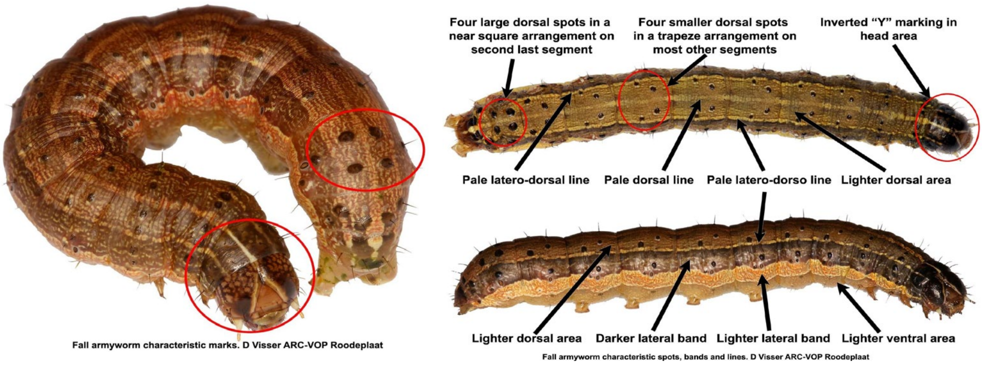

Figure 9. FAW characteristic marks

7. If the crop is not inspected regularly, FAW infestations, may only be noted at later larval stages, when feeding damage is observed. In maize, large holes accompanied by larval droppings (frass), are noticed in the whorls or on surrounding leaves. When dry, the excrement takes on a characteristic appearance of sawdust. Larger larvae usually hide deep in the whorl while the excrement they produce serves as a protective barrier or plug which also helps to camouflage them from predators.

Figure 10. FAW damage to young maize plants

4. THRESHOLDS

Insect pest and damage thresholds

1. Having positively identified FAW, determine your economic threshold in terms of pest pressure and damage threshold. Threshold values from the USA are recommended to guide FAW management decisions in Australia until local thresholds are available (Table 1).
2. Aggressive action to kill FAW larvae should only be taken after numbers reach these thresholds
3. For maize, the threshold for control is reached when 3 or more larvae are found per plant, or 20% of whorl stage plants have 1 or more larvae. When making this assessment, it is essential that a positive identification of FAW larvae is established.
4. For sorghum, control is warranted when damage results in more than 30% defoliation, or there are 1–2 (or more) larvae per whorl. If the infestation occurs during the grain fill stage, use the online *Helicoverpa* economic threshold calculator available at **thebeatsheet.com.au**

Table 1. Best evidence thresholds for a range of crops based on USA data

CROP	THRESHOLD
Maize **vegetative**	>3 larvae per plant and/or 50% of plants show signs of fresh feeding
Maize **whorl stage**	>20% of plants at whorl stage with one or more larvae and/or more than 75% of plants showing signs of feeding damage
Sweet corn **Tassel emergence**	>15% of plants infested at tassel emergence
Sorghum **vegetative**	>30% defoliation, or there are more than 2 larvae per whorl
Sorghum **grain fill**	Economic thresholds (ET) can be calculated using the following formula: ET = (C × R) ÷ (V × N × 2.4), where C is cost of control ($/ha), R is row spacing (cm), V is value of crop ($/t), N is number of heads/m row, 2.4 is damage (g/larva)
Cotton	No established threshold
Soybeans **vegetative**	>33% defoliation
Soybean **budding-podding**	3 larvae /m^2
Pasture **(hay production only)**	18-27 larvae / m^2 There are currently no permits available for FAW control in pastures.

5. When scouting for FAW, examine plants for characteristic leaf damage. The Davis scale has been developed to rate the extent of leaf damage. The rates are from 1 = no foliar damage to 9 = severe foliar damage. Larger larvae consume significantly greater leaf material than younger larvae and are best controlled when young. Plant damage caused by FAW does not necessarily result in yield loss.
6. Visual rating scales for leaf damage assessment.

Scale	Description
0	No visible leaf damage
1	Only pinhole damage on leaves
2	Pinhole and shot hole damage to leaf
3	Small elongated lesions (5–10 mm) on 1–3 leaves
4	Midsized lesions (10–30 mm) on 4–7 leaves
5	Large elongated lesions (>30 mm) or small portions eaten on 3–5 leaves
6	Elongated lesions (>30 mm) and large portions eaten on 3–5 leaves
7	Elongated lesions (>30 cm) and 50% of leaf eaten
8	Elongated lesions (30 cm) and large portions eaten on 70% of leaves
9	Most leaves with long lesions and complete defoliation observed

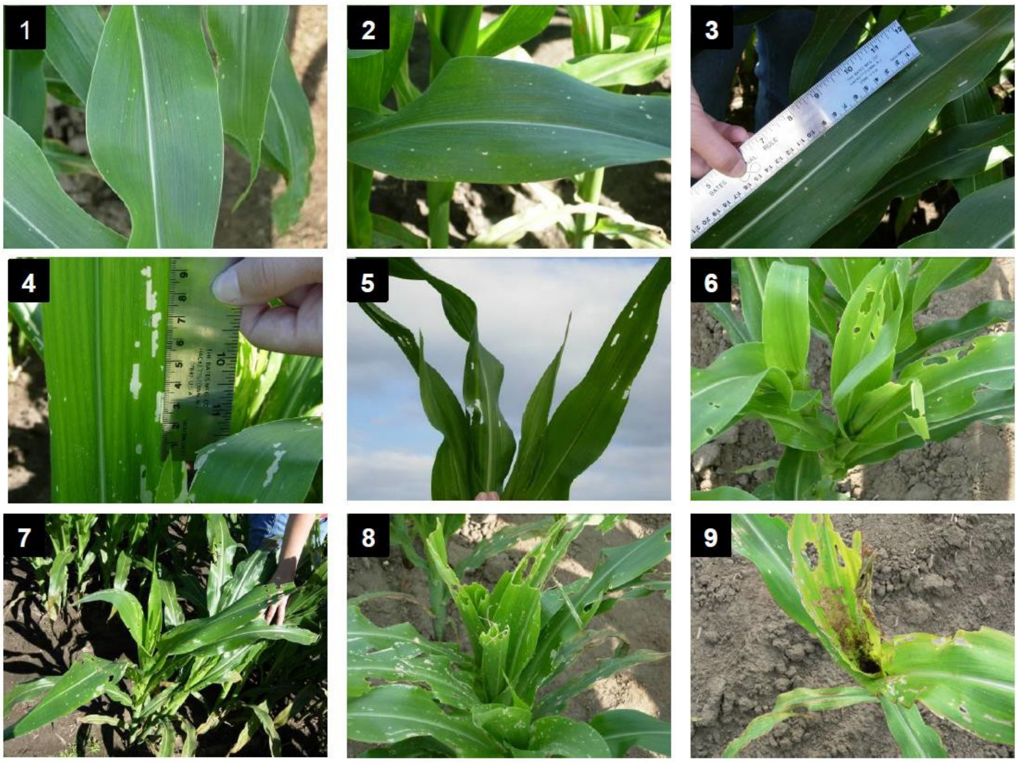

Figure 11. Visual guide of Davis Scale (Source: DuPont Pioneer, Brazil)

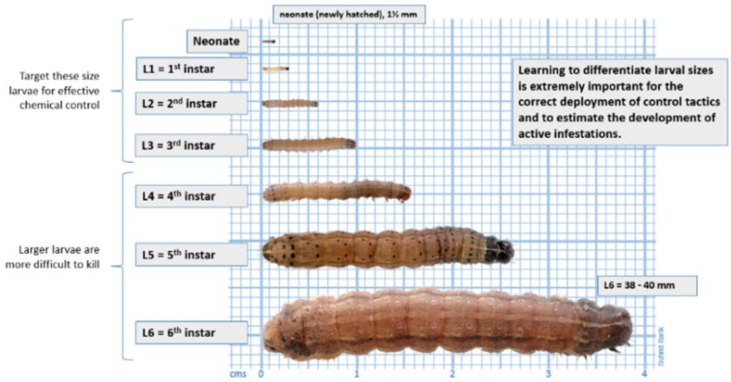

Figure 12. Relative size differences of FAW larval instars and the timing of control tactics

5. ENACT

Make informed decisions and act decisively

1. Do not spray unnecessarily, only spray when economic thresholds are reached.
2. As there may be multiple infestations within a season, multiple treatments may be required.
3. Consider spraying when larvae are actively feeding (e.g. out of the leaf whorls), for instance early morning or at dusk to maximise effectiveness. This is also when honeybees and other pollinators have returned to their hives. During these times be aware of surface temperature inversion conditions as these are unsafe for spraying as the potential for spray drift is high.
4. Select insecticides that have minimal impact on natural FAW enemies, beneficial insects and honeybees.
5. Where possible, avoid the use of broad spectrum foliar applied insecticides in the production system for both larvae and moth control. If broad-spectrum insecticides are to be used, apply at timings when preservation of beneficial species is less likely to be important – i.e. at end of growing season
6. Always follow label and permit directions for individual insecticides.
7. Practice IPM and follow resistance management strategies **croplife.org.au/resources/programs/resistance-management/various-fall-armyworm-spodoptera-frugiperda**
8. Spray smart. Timing and coverage are both critical to achieving good control of FAW. Inappropriate timing risks crop loss and the costs of retreating and increases the likelihood of insecticide resistance.
9. Once thresholds are reached, do not delay; manage the crop early and accurately. Target early instar stages (hatching larvae) of the pest before they become entrenched in the crop (e.g. lower whorl of maize, sweet corn or grain sorghum).
10. When spraying an insecticide: a) use enough water to ensure thorough coverage of the crop; b) use a well calibrated, functioning boom spray with appropriate water rate for the target crop to ensure optimum spray coverage; c) use the full insecticide rates as stipulated on the relevant permit or label; d) use an adjuvant if stipulated on the relevant permit or label.
11. Inspect the performance of application 3 to 4 days after treatment.
12. Always document the effectiveness of each insecticide application and never re-spray a failure with an insecticide with the same Mode of Action (MoA).
13. Do not treat successive generations of FAW with products of the same MoA
14. Rotate insecticides from different MoA groups, especially for crops that currently only have one or two chemicals permitted or registered within a MoA group.
15. Plan future insecticide decisions considering permit and label instructions, such as the maximum number of applications per crop per season, minimum reapplication interval and minimum withholding periods if considering using the crop for feed.
16. Where possible, an Area Wide Management strategy should be adopted where the same MoA insecticides are used by all growers in the same time period.
17. Keep abreast of the evolving FAW status in your area through local newsletters and grower networks.

Reporting

Each jurisdiction has differing reporting requirements for pests of biosecurity concern. For FAW, the reporting requirements within each state or territory are outlined below.

New South Wales

Fall armyworm (*Spodoptera frugiperda*) is a notifiable plant pest in NSW. All notifiable plant pests and diseases must be reported within one working day. You can report notifiable plant pests and diseases by one of the following methods:

Call the Exotic Plant Pest Hotline 1800 084 881.

Email **biosecurity@dpi.nsw.gov.au** with a clear photo and your contact details.

Complete an **online form** at **dpi.nsw.gov.au/biosecurity/report-a-pest-or-disease**

Queensland

Early detection and reporting are key elements in controlling fall armyworm.

If you suspect fall armyworm, report immediately to the Department of Agriculture and Fisheries on 13 25 23.

Victoria

Report any unusual plant pest or disease immediately to the national Exotic Plant Pest Hotline on 1800 084 881.

Early reporting increases the chance of effective control and eradication. Alternatively, you can make a report via our online form via **forms.bio.vic.gov.au/public-reporting** together with a photo (where possible).

South Australia

Report any unusual sightings of caterpillars, reports or identification requests via the **PestFacts Map online report form**.

Insect identification services in South Australia are free to subscribers of PestFacts SA and is open to confirming species identification of caterpillars.

Western Australia

Early detection and reporting of fall armyworm will help protect the State's plant industries and the environment. If you suspect fall armyworm in your crops, home garden or urban area, make a report using:

MyPestGuide™ Reporter (app or **online** tool), or Pest and Disease Information Service (PaDIS) by calling 08 9368 3080 or emailing **padis@dpird.wa.gov.au**

Northern Territory

For more information on control measures contact the Department of Primary Industry and Resources, Entomology unit on 08 8999 2258 or via email **insectinfo@nt.gov.au**

Useful resources

Department of Primary Industries and Regional Development, Western Australia
agric.wa.gov.au/plant-biosecurity/fall-armyworm-western-australia

The Department of Primary Industries and Regions South Australia
pir.sa.gov.au/biosecurity/plant_health/emergency_and_significant_plant_pests/fall

Agriculture Victoria
agriculture.vic.gov.au/biosecurity/pest-insects-and-mites/priority-pest-insects-and-mites/fall-armyworm

New South Wales Department of Primary Industries
dpi.nsw.gov.au/biosecurity/plant/insect-pests-and-plant-diseases/fall-armyworm
lls.nsw.gov.au/news-and-events/news/nc-news/2020/newsletters/winter-2020/fall-armyworm-update

Grains Research and Development Corporation
grdc.com.au/resources-and-publications/resources/fall-armyworm

Department of Agriculture and Fisheries Queensland
business.qld.gov.au/industries/farms-fishing-forestry/agriculture/crop-growing/priority-pest-disease/fall-armyworm
business.qld.gov.au/industries/farms-fishing-forestry/agriculture/crop-growing/fall-armyworm
publications.qld.gov.au/dataset/queensland-fall-armyworm-resources

Sugar Research
sugarresearch.com.au/pest/fall-armyworm

Northern Territory Government
nt.gov.au/industry/agriculture/food-crops-plants-and-quarantine/fall-armyworm

The Beat Sheet
thebeatsheet.com.au/key-pests/fall-armyworm
thebeatsheet.com.au/fall-armyworm-should-you-be-concerned

CottonInfo
cottoninfo.com.au/publications/insect-id-guide-endemics-exotics

Department of Agriculture Water and the Environment, Australian Government
agriculture.gov.au/pests-diseases-weeds/plant/exotic-armyworm

Fall Armyworm Management – **Quick Guide**

Assess

Assess your inherent regional risk.

Check the risk zones to determine whether you are in a zone where FAW risk is all of the time, most of the time or some of the time.

FAW is predicted to be present all year in Zone 1, present in all seasons apart from winter in Zone 2 and present in summer and autumn in Zone 3 (Figure 1).

Find

Early detection is critical to ensure effective timing of control measures.

The first indicators of FAW arrival in your area is likely to be the presence of migrating moths in Zone 2 and 3 and/or emerging moths from Zone 1 and 2.

Use pheromone-baited traps to detect early moth arrival and activity in the region.

There are a number of commercially available bucket or pheromone traps that attract male adult FAW. These can be sourced online via retailers such as Bugs for Bugs, **bugsforbugs.com.au/product/bucket-trap**
and Grochem Australia, **www.au.grochem.com**

Identify

Accurately identify pests by consulting with your local agronomist or crop protection specialist.

Larger caterpillars contain characteristic marks and spots. Marks used for identification include the

1. upside Y mark on the head region,
2. four larger spots on the second last segment and
3. three white stripes on first segment behind the head.

Thresholds

Aggressive action to kill FAW larvae should only be taken after numbers reach economic thresholds.

For maize, a guidance threshold for control is reached when 3 or more larvae are found per plant, or 20% of whorl stage plants have 1 or more larvae. When making this assessment, it is essential that a positive identification of FAW larvae is established.

For sorghum, control is warranted when damage results in more than 30% defoliation, or there are 1–2 (or more) larvae per whorl. If the infestation occurs during the grain fill stage, use the online *Helicoverpa* economic threshold calculator available at **The Beatsheet**.

Enact

Do not spray unnecessarily, only spray when economic thresholds are reached.

Focus spraying when larvae are actively feeding (e.g. in maize, out of the leaf whorls) during early morning or at dusk to maximize effectiveness.

Always follow label or permit directions for individual insecticides.

Spray smart. Timing and coverage are both critical to achieving good control of FAW. Inappropriate timing risks crop loss and the costs of retreating and increases the likelihood of insecticide resistance.

INTRODUCTION

Fall armyworm (FAW, *Spodoptera frugiperda*) is a noctuid moth native to the Americas. It was first reported in Africa in January 2016[1], where it is now established. It was subsequently reported in the Middle East and Asia in 2018. In Australia, it was reported in January 2020 in the Torres Strait and subsequently discovered in Queensland in February 2020. By March 2020, FAW was reported in the Northern Territory and Western Australia.

FAW undergoes a complete lifecycle (egg, larva, pupa and adult) in approximately 30 days (during summer) and does not diapause. The larva is the only destructive stage of this pest. It is likely that it will complete multiple generations in a year, more in the tropical and sub-tropical climatic regions of Australia. FAW is highly polyphagous, reported to impact upon more than 350 plant species[2].

Preliminary evidence suggests that it is unlikely that FAW will be limited by the distribution of potential host plant species in Australia. Its preference for members of the Poaceae family makes it important to understand the influence non-crop Australian vegetation has on the population dynamics of FAW. In Australia, FAW has been detected on several crops including maize/sweet corn, sorghum, chickpea, soybean, melon, green beans and pastures (Rhodes grass). Plant damage has been characterised by grain, ear, kernel or fruit damage, altering plant architecture.

In Australia, NSWDPI have identified resistance alleles in several FAW populations, to both carbamates and organophosphates, but not to synthetic pyrethroids[3]. This combination of i) a wide host plant range, ii) feeding behaviour, iii) multiple generations per year, iv) ability to develop tolerance/resistance to insecticides, insecticidal proteins and transgenic crops, v) migratory capability and vi) the ability to persist in temperate through to tropical climates are key characteristics that make FAW such a successful invasive pest. Predictions of FAW abundance suggest that the pest is likely to be observed through many of the grain-growing regions of Australia with year-round populations in northern parts of QLD, NT and WA, and periodic activity in more southerly regions.

While FAW has been declared ineradicable in Australia, its establishment is predicted to have economic, and ecological impacts.

The production area and volume of maize and sorghum, the most susceptible crops to FAW-related losses, in Australia is relatively small compared to other grain crops such as wheat, barley and canola. Maize is a multipurpose, summer, cereal, grain and silage crop that serves as a good rotation crop with legumes and cotton. Maize has a low capital investment, low growing risk and generally a longer window of harvest than other crops. The high value production regions of maize and sorghum in Australia are mainly throughout southern Queensland and northern and southern New South Wales. Pest management costs and surveillance activities are likely to increase due to control of FAW. A number of insecticide permits have been issued for FAW control in Australia. Over time the associated costs to control FAW will be integrated into establishing FAW's overall economic impact.

Amidst other existing lepidopteran pests within the Australian farming system, the long-term management of FAW will require an integrated pest management approach, with a key consideration around resistance management. It is envisaged that region-specific IPM approaches and a resistance management strategy for FAW will be developed under Australian conditions. Overall, a regional approach to manage FAW is emphasised, which requires a high-level of communication, engagement, and coordination amongst stakeholders.

FAW BIOLOGY AND BEHAVIOUR

Common name	Fall armyworm (FAW)
International common names	Alfalfa worm; fall armyworm; buckworm; budworm; corn budworm; corn leafworm; cotton leaf worm; daggy's corn worm; grass caterpillar; grass worm; maize budworm; overflow worm; rice caterpillar; southern armyworm; southern grassworm; wheat cutworm; whorlworm
Scientific name	*Spodoptera frugiperda* (J.E. Smith)
Synonyms	*Caradrina frugiperda*; *Laphygma frugiperda*; *Laphygma inepta*; *Laphygma macra*; *Noctua frugiperda*; *Phalaena frugiperda*; *Prodenia autumnalis*; *Prodenia plagiata*; *Prodenia signifera*; *Trigonophora frugiperda*
Taxonomic position	Class: Insecta Order: Lepidoptera Family: Noctuidae Genus: Spodoptera Species: *Spodoptera frugiperda*

Biology and life history

Spodoptera frugiperda (JE Smith) is a noctuid moth and member of the Order Lepidoptera. It undergoes complete metamorphosis (egg, larva, pupa and adult) (Figure 13, page 18) and completes its lifecycle in approximately 30 days at optimal temperatures. During cooler temperatures experienced in spring and autumn the lifecycle can be as long as 60 days, and up to 80-90 days during winter[4]. The minimum temperature threshold for egg to adult development is 12.57°C[5]. FAW is unable to survive extended periods of low temperatures and does not enter a diapause during any stage[6]. It is highly adaptable to a wide range of ecological conditions. In Australia FAW will be able to complete multiple generations per year in the subtropical and tropical climatic regions of northern Australia, reducing in number further south as temperatures decrease. The life stages are described below:

Eggs

Adult females lay eggs in clusters of 100-200 (two to four layers deep) on the foliage of plants and occasionally on very young crops[7,8]. Up to 1000 eggs may be laid by each female in a lifetime. Eggs hatch after 2-4 days when mean temperatures are between 21 and 27°C[7].

Larvae

As larvae hatch, they consume the protective egg layer before initiating feeding on the host plant. There are generally six larval instars[7] with the last three larval stages the most destructive[9]. The larval period lasts for 14 days on average, though ranges between 5 and 19 days. During cool weather, the larval period can take up to 30 days. Neonate larvae can colonise adjacent plants by 'ballooning', a process in which the larva lowers itself on a strand of silk and is carried by the wind. Many noctuids practice this larval dispersal strategy, however FAW is known to disperse further on average than other related species. This behaviour decreases as larvae age due to their increased weight[10].

Pupae

Pupation occurs in the soil at a depth of 2.5 cm to 7.5 cm depending on soil texture, moisture and temperature[10]. Pupation may also occur on the plant's reproductive parts or webbed together leaf debris forming a cocoon (20 to 30 mm in length)[12]. Pupal development varies from 7-37 days, depending on soil temperatures ranging from 15-29°C[11].

Adult

The adult emerges from the pupal case and climbs onto a plant or object where they inflate and dry their wings. This behaviour is observed from 2-3 hours after sunset until about midnight. Their wingspan ranges from 3.7 to 3.8 cm and the adult body is 1.6 to 1.7 cm in length. Adult FAW are nocturnal flying moths. At dusk, they begin movement near host plants suitable for feeding, oviposition, and mating. In maize, movement within adjacent plants has been observed to occur with the wind at about 1 m above the ground up to 10 m above the canopy. At dark, or soon after, this is followed by movement against, and across the wind and includes slower flight or hovering[7].

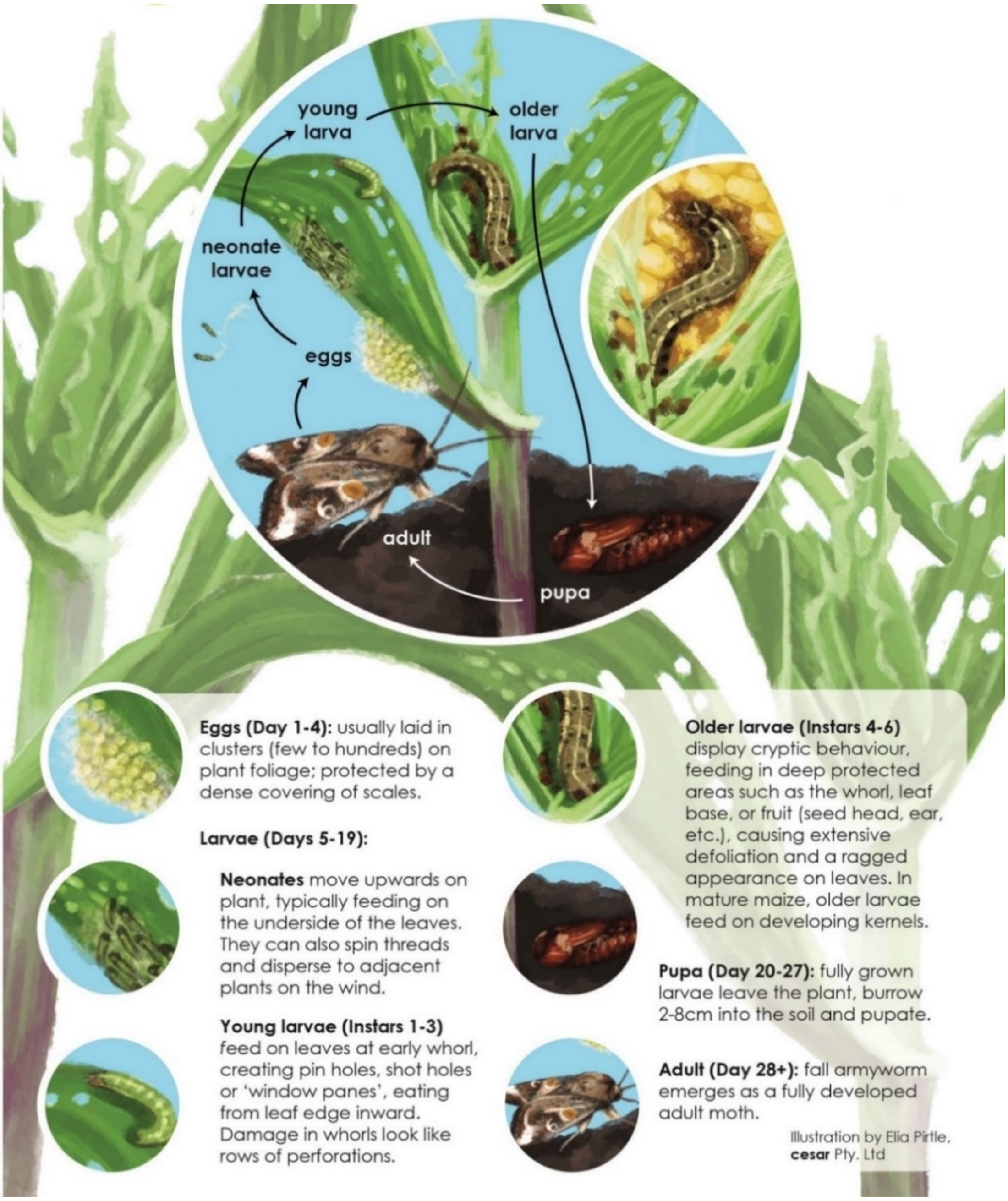

Figure 13. Life cycle and damage of FAW larvae Credit: Elia Pirtle, cesar Pty. Ltd

FAW strains

FAW comprises two morphologically indistinguishable strains, the 'corn strain' and the 'rice strain,[12] as well as 'hybrids' of the two strains. The two strains reportedly differ in host-plant preferences[12], female sex pheromones[13], and time of mating[14]. Mating between the two strains results in viable offspring. Hybrids have been detected in Australia and makes the biology and management less straightforward.

Geographic distribution within Australia

FAW is a subtropical to tropical pest, with a geographic distribution closely associated with climatic conditions. The geographic distribution of the pest in Australia is expected to be closely linked to its host plants and pest genetics.

Hosts

Since FAW arrived in Australia, it has predominantly been observed in maize crops, but also sorghum, chickpea, soybeans, sweet corn, melons, green beans and pasture seed crops, with some reports of larvae on Rhodes grass in Western Australia. Formal inspections or surveys for FAW are yet to be conducted on native vegetation or introduced grasses and broadleaf weeds throughout the pastoral zone of Australia.

While much of the international focus on FAW is in relation to maize, sorghum, sweetcorn, rice, cotton, pearl millet, the pest has a broad host range. FAW reportedly attacks over 350 commercial and non-commercial hosts across 76 plant families[15]. This includes widely grown and important food, fibre, feed and fodder crops, especially those from the favoured Poaceae family, including maize and sweet corn (*Zea mays* L.), sorghum (*Sorghum* spp.), rice (*Oryza sativa* L.) and various pastures and grasses. Broadleaf crops such as cotton (*Gossypium* spp.) (Malvales: Malvaceae) have also been considered a host.

While the reported host list is large, it is unclear if the reported range are true hosts that could support the development of larvae and contribute to the number of reproducing adults in the population[16]. Out of the 26 leviable grain crops grown in Australia, vetch, mung beans, lentils and canary seed are not reported as FAW hosts.

Given FAW*'s* preference for plants of the Poaceae family, non-crop vegetation may play an important role in the regional population dynamics of FAW in Australia. For example, the vast areas of native vegetation and introduced pasture species within Australia's pastoral zone could significantly alter population dynamics. At this stage, these non-crop hosts, and their contribution to FAW populations remain unknown.

Confirmed crop and non-crop host plants have been cross-referenced against Australian occurrence records at the same genus level using the Australian Living Atlas (ALA) database (Figure 14, page 20). The wide range of host plants suitable for FAW coupled with this preliminary evidence, suggests that FAW is unlikely to be limited by the distribution of host species in Australia.

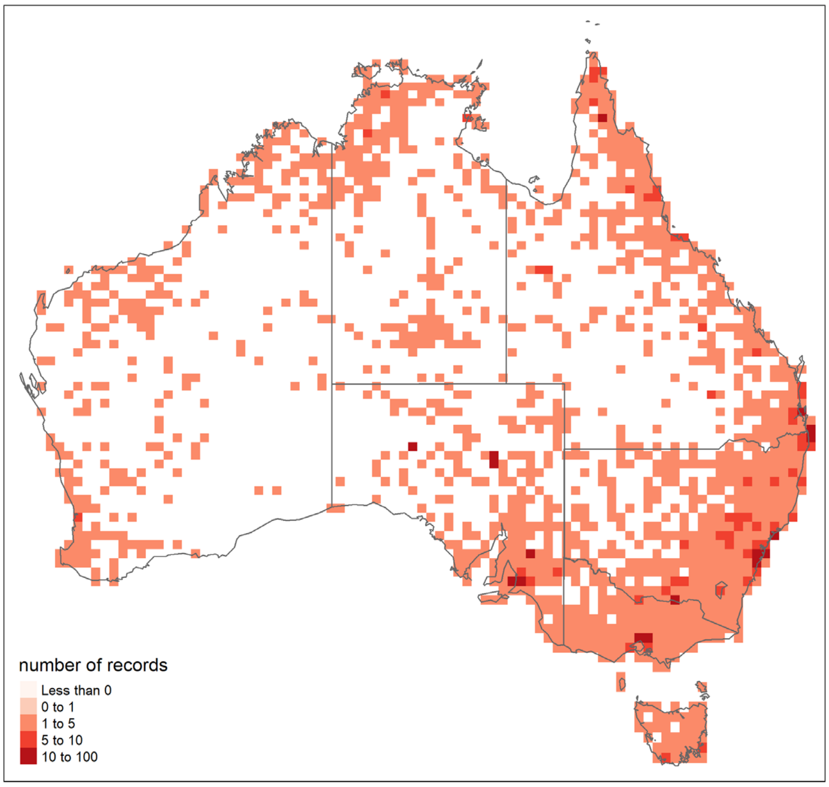

Figure 14. Crop and non-crop host plants at the genus level identified in Montezano et al. (2018) are cross-referenced with Australian occurrence records at the same genus level using the Australian Living Atlas (ALA) database. The host representation on this map is dependent on host records from particular areas as obtained from the ALA database. This causes a bias towards records in areas more densely populated by people, with fewer records in the arid interior.

Signs and symptoms

FAW can feed on a wide range of plants and inflicts damage in several ways at all growth stages on above-ground plant structures. FAW can defoliate plants, feed on fruits or developing grains and reduce plant stands[9]. A plants response to this injury is influenced by the type of injury, the growth stage, plant parts injured, the extent or intensity of the injury, and environmental conditions including crop nutrition. It is important to understand the movement of early instar larvae within the host plants as this largely determines the establishment of feeding sites[17]. The type and extent of damage inflicted by the larvae at various plant growth stages is described below.

Emerging seedling

During seedling emergence in maize, young mid-stage FAW larvae (instars 1-3) can infest seedlings and feed on young leaf whorls resulting in substantial defoliation and damage, leading to plant death and occasional total yield loss[18]. Mature larvae can behave like cutworms by completely severing off the stem of maize seedlings[1]. The extent of the damage depends on geographical region, planting season, cultivar planted and cultural practises in the field[19].

In sorghum, damage affects plant development by delaying plant maturity, reducing plant height and increasing the number of tillers and panicles per plant[20]. Sorghum seedlings can recover more from FAW damage compared to later growth stages[12]. In wheat and barley, young FAW larvae have been found to hide in seedling plants and feed on the centre of the developing leaf whorl forming windowing[21,22].

Leaf and stem development

FAW is primarily a defoliating pest, impacting crop establishment, growth, and yield through reduction in functional leaf area. Early instar larvae feeding on grasses, initially feed on the underside of leaves creating characteristic windowing and pin holes. As the larvae grow, feeding results in larger holes. Once established in the whorl, larval feeding results in large, jagged holes in the expanding leaves. When whorl-feeding results in complete 'perforation' across the leaf blade, distal sections of the leaf can detach, increasing the leaf area loss significantly[23] (Figure 15).

The mature larvae produce a moist sawdust-like faecal matter in the form of lumps (frass) accumulated within the whorl (Figure 15). In sweet corn, the early whorl stage is the least sensitive to FAW injury, mid whorl stage is intermediate, and the late whorl stage is most sensitive[24.] This defoliation pattern in sorghum is comparable to maize where young larvae feed on expanded leaves and mature larvae eventually feed on the whorl[12] (Figure 16, page 22).

In wheat, mature larvae feed on leaves during the heading to grain filling stage destroying the aerial part of the crop[25].

Figure 15. FAW larvae damage on maize (Zea mays). a) Foliage damage on developing corn plant with distinctive row of perforations; b) Mid-instar larvae feeding on leaf of corn resulting in shot holes. Image credit: John C. French Sr., Retired, Universitie s: Auburn, Georgia, Clemson and University of Missouri, Bugwood.org

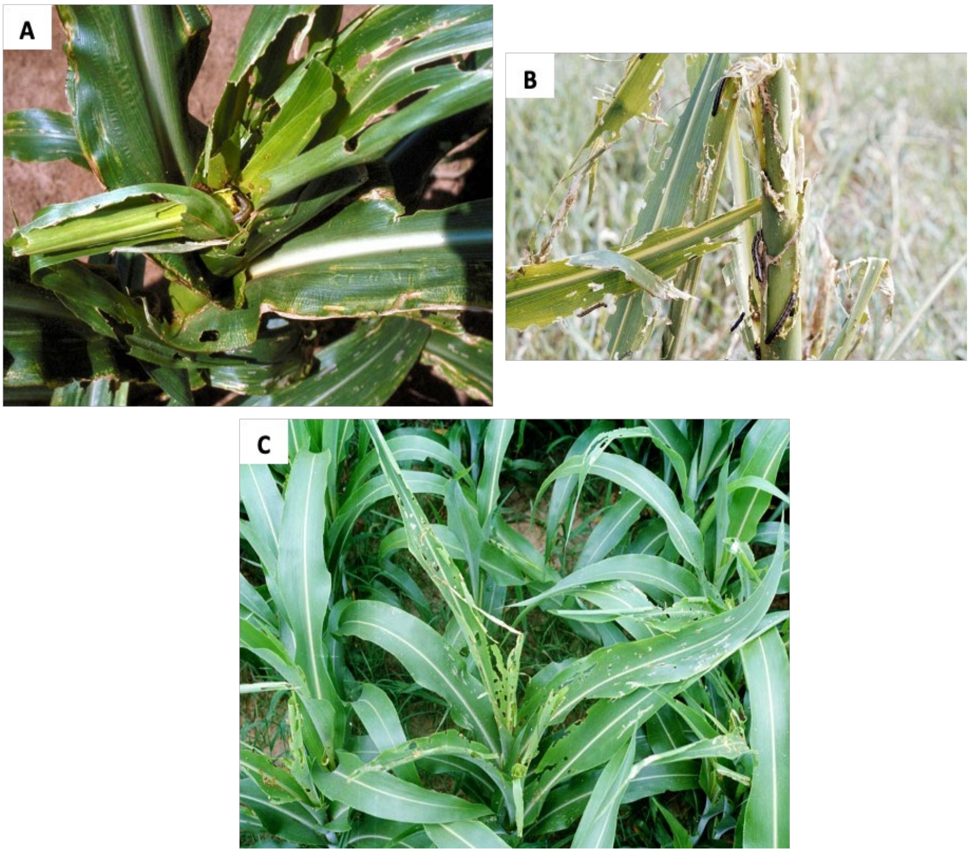

Figure 16. Young and mature FAW larvae damage on maize (*Zea mays*) and sorghum (*Sorghum bicolor*). a) Larval damage with sawdust-like faeces accumulated in whorl of corn plant; b) Larval damage resulting in extensive defoliation and torn/ragged appearance; c) Larval damage on sorghum leaf whorl. Image credits: a) University of Georgia, Bugwood.org; b) John C. French Sr., Retired, Universities: Auburn, Georgia, Clemson and University of Missouri, Bugwood.org; and c) Clemson University - USDA Cooperative Extension Slide Series, Bugwood.org.

Flowering, grain development and maturation

During the late whorl stage in maize, mature larvae may cause extensive injury to tassel development[12]. While young (vegetative stage) leaf tissue is suitable for FAW larvae growth and survival, mature leaves are less suitable, and the larvae tend to settle and feed in the ear zone[25]. Larvae will also damage developing silks restricting pollination and reduce kernel number per ear[26]. Direct injury occurs when mature larvae burrow into the side of the ear and feed through husks[27] resulting in yield reduction, exposure to secondary infestation and loss of grain quality[22].

In sorghum, FAW larvae feed on leaves and directly on seeds in the panicle during the reproductive stages of plant development, similar to *H. armigera* [28](Figure 17, page 23). It shows a preference for grain prior to physiological maturity[29] and can reduce yield in sorghum through whorl defoliation during mid to late whorl stages[24].

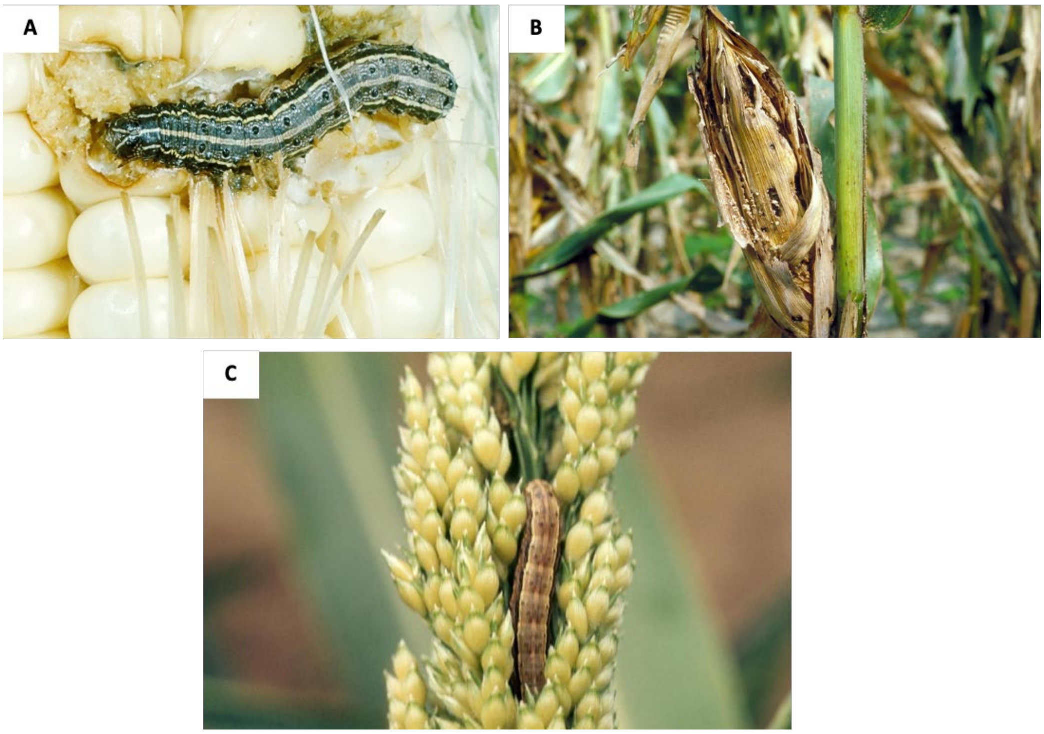

Figure 17. Mature FAW larval feeding damage on a) Corn kernel (Zea mays); b) mature corn husk; C) sorghum (Sorghum bicolor) panicle. Image credits: a) Phil Sloderbeck/Kansas State University, Bugwood.org; b) Billy R. Wiseman, USDA Agricultural Research Service, Bugwood.org; and c) John C. French Sr., Retired, Universities: Auburn, Georgia, Clemson and University of Missouri, Bugwood.org

Key biology and ecology points to consider for the Australian grains industry

FAW is a migratory noctuid moth present in parts of northern Queensland, the Northern Territory and Western Australia (August 2020).

At optimum conditions FAW completes its life cycle in approximately 30 days. In the subtropical and tropical regions of Australia FAW will complete several generations a year.

Plants belonging to the grass family Poaceae are preferred hosts of FAW. These include maize, sweet corn and sorghum.

As with many other lepidopteran pests, larvae emerging from egg masses laid on a plant (typically 100-200 eggs per egg mass) are able to colonise nearby plants through 'ballooning'. The dispersal capacity of FAW larvae (on average) is known to be much higher than other related moth pests.

SPREAD, IMPACT AND SEASONAL DYNAMICS

FAW has been declared ineradicable in Australia and is established in the northern parts of the country. Even so it may be necessary to consider pathways for additional arrivals of exotic strains/hybrids of FAW that could carry new traits such as insecticide resistance. To predict the level of impact that FAW may have on Australian crops, it is important to recognise the establishment potential, and spread though migratory patterns and seasonal dynamics.

FAW is predicted to establish in some parts of Australia, with permanent year-round populations likely to occur in the northern tropical regions. The population growth rate (number of individuals per individual per day) is estimated to increase as temperatures increase (Figure 18).

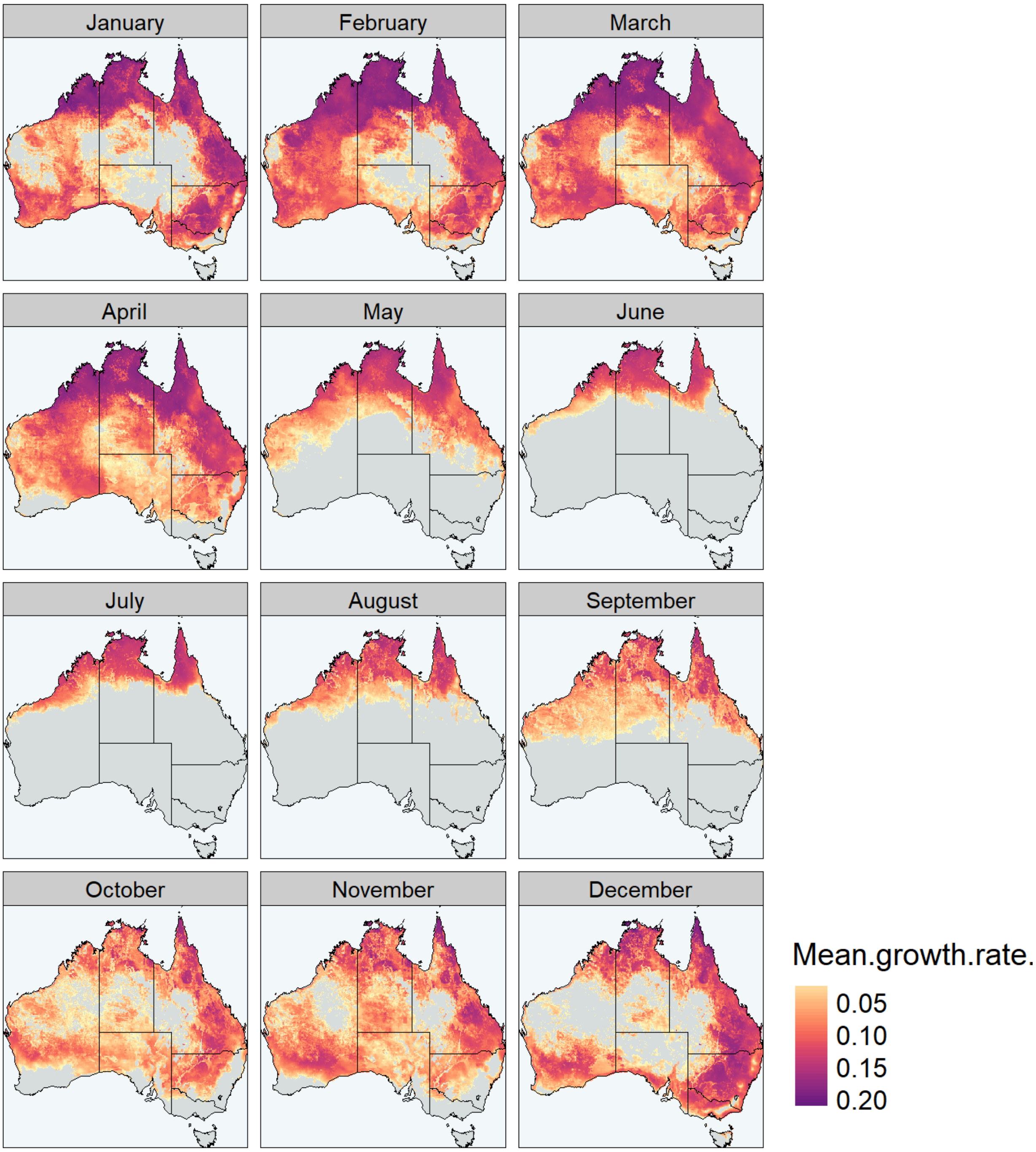

Figure 18. The monthly estimated population growth rate for FAW in Australia (growth rate per day; number of individuals per individual per day) shown throughout the year (based on 2018 climatic data). Suitability is lowest during the coldest months and generally increases with temperature.

For example, given a population of 100 individuals, and a mean growth rate of 0.1 per day, it would be expected that an additional 10 individuals would be added on day 1, 11 individuals on day 2 and so forth.

FAW's highly migratory nature will allow it to exploit favourable conditions for population growth. Understanding migration processes will provide a better understanding of FAW's ability to exploit transient host resources, such as broadacre grain crops. The biological and environmental processes involved in FAW dispersal can provide insights for the monitoring and management of FAW populations.[30]

Long-distance migration

Adult FAW can disperse over large distances, with migration occurring at early adult stages and, prior to the reproductive stage (in females). Males exhibit a more varied migration and reproduction pattern[31]. Long-distance migration is a behavioural adaptation by FAW to extend to new areas. Annual population movements of over 2000 km from FAW's permanent range have been observed, with overnight migration distances of 400 km also detected[32].

Short-distance spread

FAW larvae can disperse short distances (at least 80 cm away) to surrounding plants within a crop[33] through ballooning (see Section: Biology and Life History). In comparison to other related lepidoptera, FAW neonate larvae are more successful at spreading to adjacent maize plants, with approximately 50% of the larvae exhibiting the ballooning behaviour[34].

FAW outbreaks

Based on overseas observations, the likelihood of a general FAW invasion depends on prevailing winter conditions. In the USA, FAW thrives with the arrival of spring weather characterised by warmer temperatures and abundant rainfall, which leads to abundance of green material and grasses, and less natural enemies. Further, if humid conditions prevail, considerable crop damage may occur[12]. In Australia, other grass-feeding noctuids (particularly armyworms), are strongly adapted to breeding in native grasses, within and beyond the cropping zone[35]. Given FAW's wide host range, the pest is likely to exploit such niches.

Seasonal dynamics

Population dynamics of FAW are more influenced by the prevailing climatic conditions rather than the abundance of commercial hosts available (such as maize fields) [36]. It is estimated that FAW will likely disperse throughout many of the key Australian grain-growing regions, persisting for longer periods in the northern regions. Regions such as the Ord (WA) or the Burdekin (QLD) will likely see year-round populations while, more southern regions, such as central WA or the Mallee region in SA and Vic or Victoria's high rainfall region, will see migratory populations occurring from around October with population build up into summer and autumn. The cold climate of Tasmania's grain growing areas will result in a low likelihood of large populations.

Potential impacts

FAW's establishment in Australia will have economic, management and ecological impacts across different crop commodities and non-crop hosts:

- economic-related impacts (such as yield losses, downgrading and surveillance and control costs)
- management-related impacts (such as potential issues with insecticide resistance)
- ecological impacts on the dynamics of native pest and natural enemy populations

Maize and sorghum in Australia

While the production area and volume of maize in Australia is relatively small compared to other grain crops such as wheat, barley, canola and sorghum it is one of the key crops susceptible to FAW-related losses. It is a multipurpose, summer, cereal, grain and silage crop that serves as a good rotation crop with legumes and cotton. Maize has a low capital investment, low growing risk and generally a longer window of harvest than other crops. Production is largely concentrated in southern Queensland, northern NSW and the irrigation areas of southern New South Wales and northern Victoria.

The maize industry is valued at AU$25–35 million annually, depending on prices, area planted and yields. In Australia maize is a minor summer crop with an annual production of 350,000–450,000 tonnes (t), historically most of which is consumed domestically. However, with the help of the Maize Association of Australia, the peak body representing Australian maize growers and the industry at large, a new export market has been opened up to farmers and traders. Maize produced in Australia is approximately 50% rainfed or dryland and 50% grown with the assistance of irrigation. All Australian maize is non-genetically modified (non-GM).

Grain sorghum is the main summer grain crop in the northern grains region and plays a key role in providing feed grains to the beef, dairy, pig and poultry industries. It is a good rotation crop, tolerating heat and moisture stress, and performing better than maize on soils with marginal potassium (K) levels. Grain sorghum is a major component of the dryland cropping system of north-eastern Australia. Approximately 60% of the Australian crop is grown in Queensland and the remainder in northern NSW. Grain sorghum is predominantly a summer season crop, with an extended season in higher latitudes including Central Queensland and further north. The area of sorghum planted for grain in northern NSW is on average 160,000 ha and Queensland 470,000 ha annually. The main zones for sorghum production are the area east of the Newell Highway and the Liverpool Plains in NSW; and the Darling Downs in Queensland. Average farm yields vary around 2 t/ha and reflect the severity of constraints, as water stress during grain filling is the common production environment.

As sorghum is the main summer grain crop in the northern region of Australia, it could be favoured during the warmer FAW seasonal risk period.

Economic impacts associated with FAW infestation

The key economic impacts likely to arise from FAW infestations include yield loss, management costs (including pesticides and application costs), loss in quality or downgrading[37] and impacts on trade/export through restrictions or biosecurity measures[38]. The economic impacts of FAW in its native range is estimated to be between US$300 to 500 million per annum[39], while yield losses of up to US$6.3 billion per annum are estimated in FAW's introduced regions of sub-Saharan Africa[40].

Damage from FAW infestation

Damage refers to the measurable injury to the plant and grain produced. Direct yield loss resulting from this damage is attributed to larval feeding on the developing or mature part of the plant that is harvested (e.g. invasion of ears and feeding on cob for maize or feeding directly on grain for sorghum)[41]. Indirect yield loss occurs through FAW-induced defoliation, which subsequently reduces grain yield[40] and/or destruction of seedlings.

To estimate the intensity of foliar damage due to FAW infestations, the Davis scale has been developed to rate the extent of leaf damage. The rates are from 1 = no foliar damage (highly resistant) to 9 = severe foliar damage (totally susceptible)[41] (Table 2, Figure 19). It is noteworthy that plant damage due to FAW infestation does not necessarily result in yield loss; pest injury can be inflicted to a certain degree without resulting in measurable plant damage[12]. In addition, plant damage incurred at some growth stages does not translate to yield loss. Quantifying yield losses attributed to FAW infestations is crucial in estimating economic thresholds and injury levels.

Table 2. Visual rating scales for leaf damage assessment

Scale	Description
0	No visible leaf damage
1	Only pinhole damage on leaves
2	Pinhole and shot hole damage to leaf
3	Small elongated lesions (5–10 mm) on 1–3 leaves
4	Midsized lesions (10–30 mm) on 4–7 leaves
5	Large elongated lesions (>30 mm) or small portions eaten on 3–5 leaves
6	Elongated lesions (>30 mm) and large portions eaten on 3–5 leaves
7	Elongated lesions (>30 cm) and 50% of leaf eaten
8	Elongated lesions (30 cm) and large portions eaten on 70% of leaves
9	Most leaves with long lesions and complete defoliation observed

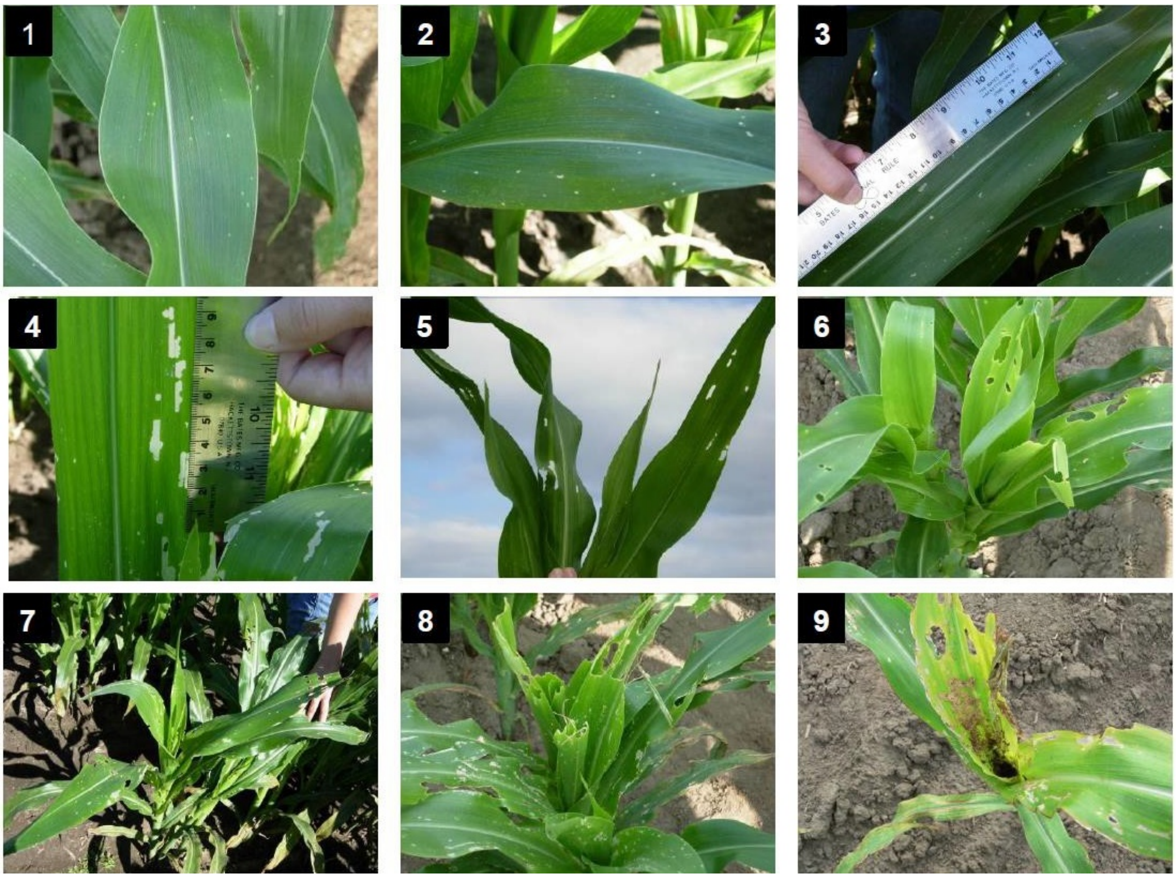

Figure 19. Visual guide of Davis Scale (Source: DuPont Pioneer, Brazil)

While the relationship between the level of infestation, damage and yield loss across major crops has not been validated in Australia, there are international sources that provide examples to estimate how the grains industry (and others) may be impacted in Australia.

In non-GM maize, differing levels of yield loss have been observed in managed (pesticides) and unmanaged crops across a range of geographical locations. Based on experimental trials and grower surveys (that report higher yield impacts), average losses of approximately 28% were reported in unmanaged maize, although there are some reports of almost total crop loss. In managed maize, crops losses were lower at an average of 19%; however this figure is likely overinflated as it included testing both efficacious and inefficacious pesticides. For sorghum, yield losses vary across variety, pest infestation density and plant growth stage, with reported average yield losses of 14% in managed crops compared with average losses of 24% in unmanaged crops.

There is minimal quantification of losses in rice, sweet corn and pearl millet. However, there is a clear relationship between yield losses and FAW density in rice. In sweet corn, significant yield losses (43 to 77%) can occur when unmanaged, with reduced plant height, leaf area and stalk diameter attributed to FAW infestation during the early and mid-whorl stages[42]. In unmanaged pearl millet, a potential emerging industry in Australia[43], a yield reduction of 14% due to FAW infestation was reported in Africa[44].

Typically, yield losses in unmanaged Bermudagrass pastures internationally are associated with higher FAW densities, early-mid instar larval stages and earlier plant growth stages. Yield losses reported on Bermudagrass ranged from 0 to 50%. Complete defoliation of pastures and hayfields due to FAW infestation has been observed[45].

Wheat is not commonly attacked by FAW with international research classifying wheat as a low-risk crop for FAW in Africa[46]. In the USA, wheat seedlings are at greatest risk although loss of stand and head lopping in maturing plants can occur[47].

Applicability of yield loss data to Australian grains industry

The impact of FAW on crop commodities in Australia is currently unknown. However, we can use average yield losses from international reports and studies to derive potential yield losses for grain crops in Australia, but this should be met with caution and is considered a 'best guess' based on currently available data. For non-Bt maize (based on international experimentally derived yield losses), a mean yield loss of 19%, could result in an approximate loss of 1.3 t/ha based on the estimated 2019-2020 Australian production of 6.9 t/ha. Similarly, for sorghum (managed with pesticides), a mean yield loss (derived from international data) of 14% could result in an estimated loss of 0.3 t/ha, based on the 2019-2020 production of 2.0 t/ha. In other GRDC-leviable grain crops even small patchy and/or sporadic yield losses may translate to significant cumulative economic impacts.

FAW is not expected to have a large impact on cereal yield where defoliation of young plants occurs (i.e. early planting of wheat). Risk is highest where crops are planted early and/or conditions are suitable for FAW to persist on crops for longer because temperatures do not constrain the population and limit defoliation to vegetative stages. This is supported by previous defoliation impact experiment on wheat (Miles *et al)* and modelling of FAW defoliation impacts at low, moderate and high infestation levels (Hagan and Miles **thebeatsheet.com.au/key-pests/fall-armyworm**).

While it has been reported overseas that FAW can cause head lopping in maturing crops, the relative attractiveness of maturing wheat crops compared to new young spring foliage in pastures, maize or sorghum in Australia is expected to be low.

Quality loss or downgrading

Reduction in grain quality is also an important economic impact caused by FAW. Based on literature, direct feeding on maize grain or ears and kernels results in risk of pre-harvest losses[48], direct weight loss due to seeds being partly or completely eaten and unacceptable levels of chewed grain[49]. Delays in maturity due to FAW impacts on quality, biomass of harvested crop and extends the window for additional pest problems. These delays in maturity also shorten the development cycle for subsequent plantings or extends their maturity past the optimal date[50]. Diseases may be introduced into maize cobs by FAW damage reducing kernel quality. There is potential for introduced saprotrophs and pathogens to result in mycotoxin contamination under certain conditions[51]. In sorghum, direct injury to sorghum seed results in fewer seeds per head[52].

FAW chemical management costs

Pest management costs include costs of pesticides, labour and equipment. In Australia, the cost of permitted insecticides for FAW control across a range of commercial crops range from $1.68/ha through to $122/ha (see Table 4, page 30). In addition, the operational cost of an insecticide application varies depending on whether aerial or ground-rig application is used. If an average operational cost of $13/ha[37] is used costs would be approximately $14.68/ha through to $135/ha per application (for product and operation). Total cost per year for FAW management will vary due to the number of sprays applied per season, associated costs with increased surveillance, and insecticide products used will likely vary between growing regions, seasonal differences, and experience with FAW. By monitoring management costs annually, it will be possible to integrate these associated costs into establishing FAW's overall annual control cost into specific crop budgets as well as the overall on farm crop protection budget.

Table 4. Approximate costs of insecticides for FAW control, for which permits have been issued by the APVMA

INSECTICIDE	MOA†	CROP	COST (AUD$/L OR KG)[1*]	PRODUCT VOLUME (L/HA)	COST (AUD$) PER HECTARE AT MAXIMUM FIELD RATE
Methomyl	1A	Maize, sorghum, sweetcorn, soybean, peanut and millet	10	2	20
Alpha-cypermethrin	3A	Winter cereals	7	0.24	1.68
Alpha-cypermethrin	3A	Millet	7	0.28	1.96
Alpha-cypermethrin	3A	Pulse crops	7	0.3	2.10
Alpha-cypermethrin	3A	Maize, sorghum and sweetcorn	7	0.4	2.80
Gamma-cyhalothrin	3A	Lupins	108[1]	0.02	2.16
Gamma-cyhalothrin	3A	Canola, field peas, chickpeas, faba beans, lentils, vetch	108[1]	0.03	3.24
Gamma-cyhalothrin	3A	Barley, wheat	108[1]	0.035	3.78
Gamma-cyhalothrin	3A	Navy beans, mung beans, sorghum, soybeans	108[1]	0.06	6.48
Gamma-cyhalothrin	3A	Sunflower	108[1]	0.07	7.56
Spinetoram	5	Canola	409.30[1]	0.15	61.40
Spinetoram	5	Chickpeas	409.30[1]	0.2	81.86
Spinetoram	5	Soybeans, maize cereals, sorghum grain and millet	409.30[1]	0.3	122.79
Emamectin benzoate	6	Wheat, maize	80	0.9	72
Emamectin benzoate	6	Canola, pulse	80	0.7	56
Indoxacarb	22A	Soybean	60	0.4	3.20
Indoxacarb	22A	Maize cereals	60	0.5	4.00
Chlorantraniliprole	28	Winter and summer pulse crops	440	0.07	30.80
Chlorantraniliprole	28	Maize cereals	440	0.09	39.60

†MoA: Mode of action

[1]J. Khurana, pers. comm. August 2020

*Prices provided are approximate at the time of publication and may change or differ between areas.

FAW Economic thresholds to inform management

The extent of damage leading to yield loss or quality downgrade depends on a combination of factors, including plant growth stage, FAW life cycle stage, and the degree of FAW infestation. Economic thresholds help to rationalise the use of pesticides and are one of the keys to profitable pest management.

The relationship between pest numbers over time and calculation of the economic threshold is shown in Figure 20[53].

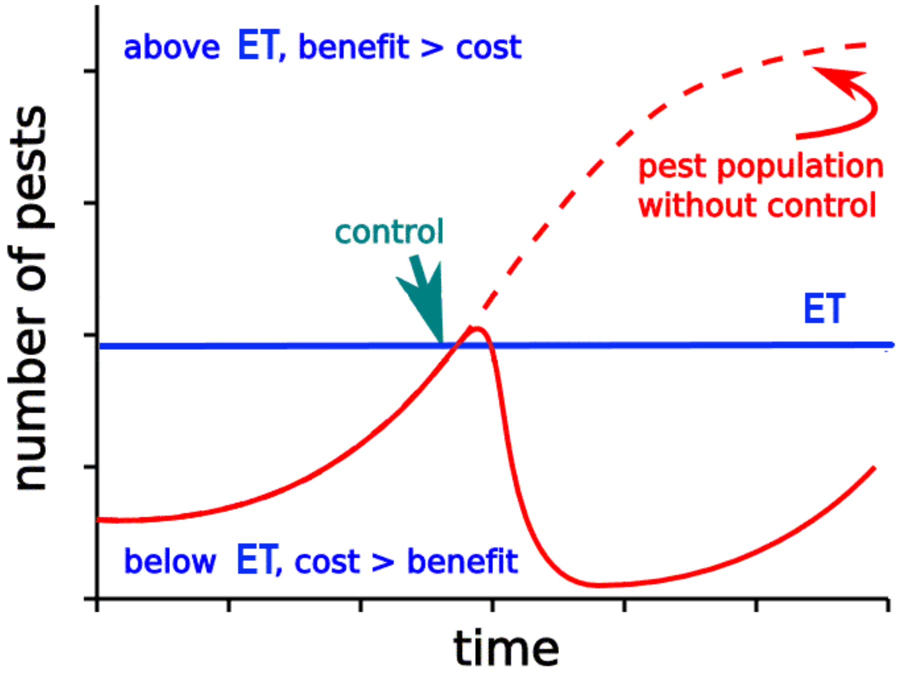

Figure 20. The Economic Threshold (ET) is the pest abundance (or level of damage) at which the dollar cost of crop yield loss to the pest begins to exceed the dollar cost of controlling the pest if left unmanaged. The ET is considered to be the point at which action against the pest is economically justified. The ET is sometimes called an Action Threshold (AT). Figure Credit: Ed Zaborski, University of Illinois[55].

FAW thresholds have been established for some crops in other countries:

Maize

ETs vary depending on cost of control, value and growth stage of the crop. For example, lower ETs are established for maize priced at higher value and higher ETs established for higher costs of controls. In South America, ETs between 15% and 50% infestation at 2 to 6 weeks following germination were reported. In Arkansas, USA ETs of 3 to 6 larvae per whorl are reported[51]. Also in Arkansas, the ETs for *Bt* and non-*Bt* maize varieties were set at 2.6 and 1.9 larvae per 10 plants in two growing cycles of a susceptible maize variety, and 2.8 larvae per 10 plants in the first cycle for a *Bt* maize variety[54].

Sorghum

There is variability in thresholds between growth stages of sorghum. In the USA, some growers utilise an ETof one larva per plant at growth stage 2 (five leaves)[55]; an additional threshold of one or two FAW larvae per leaf whorl and two per head of sorghum[56]. In Arkansas, one larva (0.5 inches or greater) per head elicits a chemical control response[48]. Simulations in Mississippi predicted ETs of 2.5 and 3.9 larva per plant for eight and 10 leaves (growth stage 3) respectively[57]. In Georgia, the ETs for FAW were determined based on three justifications. These were: i) sorghum seedlings with at least 10% of plants with egg masses, (ii) sorghum whorl/shoot stages with 1 larva per plant, and (iii) 2 larvae per plant at the head growth stage[33].

Wheat

Wheat seedlings are of greatest risk to FAW damage. In Arkansas, USA, an ET of 50–60 larvae per square meter justifies treatment in wheat[58]. In Kansas, USA, wheat growers are advised to monitor for windowing injury that is caused by early instars chewing on the seedling leaves. Larvae, which are typically very small and can be difficult to see, are typically observed hiding in or around the base of seedlings. Within a few days, larvae become large enough to destroy entire leaves. When windowing injury is observed in 25 to 30% of plants, the crop should be re-examined daily and treated immediately if stand establishment appears threatened. As later instars do more damage due to their increased food requirements and are simultaneously less susceptible to insecticides, treatment should ideally be performed at earlier lifecycle stages to avoid later stages potentially destroying entire stands[59].

Peanuts, soybean, and rice

In Arkansas, USA, treatment is recommended when numbers of FAW exceed 4 per meter of crop row and foliage loss is greater than 15% in peanuts[51]. ETs for treatment in soybean are when defoliation at pre-bloom exceeds 50%, and 25% post-bloom[51]. For rice, the ET for FAW is under refinement[51].

Due to Australia's different production systems, management costs, and unique environmental conditions, economic thresholds from different countries although useful are not directly applicable to Australia. The overseas values can only be utilized as a foundation to determine thresholds relevant in an Australian grains context. The Queensland government has developed action thresholds based on international data and is presented in Table 5, page 33.

The Western Australian government has developed recommendations to apply control measures for FAW in maize and sweet corn at different growth stages. These are listed below and can be found at the WA government website[60].

- At the seedling stage, if more than 5% of plants are cut.
- At the early whorl stage (knee high), if more than 20% of plants are infested.
- At the late whorl stage (shoulder high), if more than 40% of plants are damaged and live larvae are present.
- At the tasselling/early silking stage, in sweet corn, if more than 5% of plants are infested and in maize, if more than 20% of plants are infested.

The ET for pasture and/or lucerne is 20 larvae per square meter[61].

Table 5. Action thresholds for FAW management interventions based on overseas data (thebeatsheet.com.au/key-pests/fall-armyworm/#dis)

CROP	THRESHOLD	NOTES
Maize vegetative **Maize** whorl stage	3 or more larvae per plant *50% of plants with fresh feeding *20% of plants with one or more larvae *>75% of plants with feeding	Based on USA recommendations: *Purdue University Need to consider economics of control i.e. $/ha to treat vs potential yield loss ($/ha).
Sweet corn Tassel emergence	15% of infested plants	USA recommendations: If necessary, control at tassel emergence is more effective than applications in the vegetative stages.
Sorghum vegetative **Sorghum** grain fill	30% defoliation, or >2 larvae per whorl Use Helicoverpa threshold calculator	Based on USA recommendations. Damage at grain fill equivalent to Helicoverpa.
Soybeans vegetative **Soybean** budding-podding	33% defoliation $3/m^2$	Based on *S. litura* (DAF)

Key spread, impact and seasonal dynamics points to consider

- There remains an ongoing need to review and manage pathways for new incursions of FAW into Australia, due to the possibility of invasive populations introducing additional biotypes and associated novel traits.
- The population growth potential of FAW in Australia is estimated to increase during the warmer months and decrease during the colder months. It is expected that more northerly parts of Australia, particularly regions closer to the coast, can support permanent year-round populations.
- FAW uses long-distance migration to extend into more temperate regions that cannot support permanent populations. Movements of over 2000 km from FAWs permanent range can occur, with overnight migration distances of 400 km observed.
- Australia has a unique climate and host plant profile, distinct from other countries and regions in which FAW currently occurs.
- FAW will likely be observed in a wide range of key Australian grain-growing regions, with the Ord in WA and the Burdekin in QLD likely to have permanent populations. In the southern regions, FAW populations will build up from October and into summer and autumn.

Potential impact

- Maize, and other commercial grain crops can tolerate some level of damage without impacting yield.
- The extent of damage depends on a combination of plant growth stage, pest growth stage and the degree of FAW infestation.
- Best evidence thresholds for a range of crops based on data from the USA have been developed for use until scientifically robust thresholds for Australian conditions and costs are developed.

IDENTIFICATION AND SCOUTING

Identification

Since the arrival of FAW in Australia, growers and agronomists monitoring maize, sweet corn and sorghum crops in the north of Australia have found it challenging to: i) detect egg masses; ii) distinguish FAW from cluster caterpillar, *Spodoptera litura* (Fabricius) (Lepidoptera: Noctuidae) larvae as neonates through to second instar; and iii) identify later instar FAW larvae when present in mixed populations with *Helicoverpa* spp. (Hardwick) (Lepidoptera: Noctuidae), *Leucania* spp. (Ochsenheimer) (Lepidoptera: Noctuidae), and *Mythimna* spp. (Ochsenheimer) (Lepidoptera: Noctuidae).

It is likely that FAW will continue to be confused with other noctuids (Lepidoptera: Noctuidae) in Australian agroecosystems, particularly at the egg, early larval instar and pupal stages. Although keys are available for separating some *Spodoptera* species, none is devised to separate the noctuid larvae and adults that may be found in Australian grains systems. The GRDC and other website shows some useful distinguishing characteristics between several species. Currently there is not a side-by side graphic illustration differentiating related species, including a field guide of the egg, larval and adult stages of the noctuids found in Australian grains (and other crops) systems. Cottoninfo have developed a brochure distinguishing the cluster caterpillar, northern armyworm and FAW (**cottoninfo.com.au/sites/default/files/documents/ID_guide_sc2.pdf**).

Plant damage symptoms by lepidopterous stem-borers (foliar and ear damage) and *Helicoverpa armigera* (Hübner) (Lepidoptera: Noctuidae) (ear damage) can be easily mistaken for those caused by FAW. Molecular identification to confirm pest identity and strain may be required.

Morphological identification of FAW

Egg, larval and pupal morphology

FAW can be confused with other noctuids in agroecosystems, particularly at the egg, early larval instar, and pupal stages when they are almost impossible to distinguish morphologically (Table 6, page 36).

Egg morphology

The eggs are 0.4 mm in diameter and 0.3 mm in height, dome-shaped, pale yellow or creamish in colour at the time of oviposition, becoming light brown prior to hatching. The egg mass is typically covered with a protective, felt-like layer of grey-pink scales (setae) from the female abdomen (Figure 21).

Figure 21. FAW egg mass. Image credit: John C. French Sr., Retired, Universities: Auburn, Georgia, Clemson and University of Missouri, via Bugwood.org

Table 6. Lepidopteran species (Noctuidae) that can be confused with FAW (egg, early larval and pupae stages) and the common crop types where they may be found

COMMON NAME	SPECIES NAME	CROPS COMMONLY FOUND ON (NOT EXHAUSTIVE)
Cluster caterpillar, Tobacco cutworm	*Spodoptera litura* (Fabricius)	Cotton, maize, sorghum, summer pulses, pastures, hay
Beet armyworm	*Spodoptera exigua* (Hübner)	Beets, asparagus, beans, peas, cabbage, pepper, tomato, lettuce, celery, strawberry, eggplant, sugar beet, alfalfa, cole crops, potato, cotton, cereals, oilseeds, tobacco, flowers and weed species
African armyworm	*Spodoptera exempta* (Walker)	Cereals, maize, rice, sorghum, sugarcane, and pasture grasses, especially Cynodon and Pennisetum species
Native budworm	*Helicoverpa punctigera* (Wallengren)	Cotton, chickpea, canola, mung bean, navy bean, peanut, pulses, safflower, sunflower, flax, pasture legumes, fruit and vegetable crops
Corn earworm, Cotton bollworm	*Helicoverpa armigera* (Hübner)	Major hosts: maize, tomato, cotton, pigeon pea, chickpea, rice, sorghum, and cowpea. Other hosts include: groundnut, okra, peas, field beans, soybeans, lucerne, Phaseolus spp., other Leguminosae, tobacco, potatoes and flax
Lesser budworm	*Heliothis punctifera* (Walker)	Cereals, sorghum and lucerne
Northern armyworm	*Mythimna separata* (Walker)	Rice, maize, sorghum, wheat, sugarcane and wild grasses
Common armyworm	*Mythimna convecta* (Walker)	Poaceae (inc. cereals and grasses), pineapple, sweet potato and lucerne
Sugarcane armyworm	*Mythimna loreyimima* (Lower)	Sugarcane, Poaceae (inc. cereals and grasses)
Southern armyworm	*Persectania ewingii* (Westwood)	Poaceae (inc. cereals and grasses), peas and flax
Inland armyworm	*Persectania dyscrita* (Common)	Poaceae (inc. cereals and grasses)
Black cutworm	*Agrotis ipsilon* (Hufnagel)	Maize, crops and weeds
Sugarcane armyworm	*Leucania stenographa* (Lower)	Pasture grass, sugarcane
Lawn armyworm	*Spodoptera mauritia* (Boisduval)	Rice, maize, sorghum, wheat, and various grasses
Brown cutworm	*Agrostis munda* (Walker)	Attacks all field crops. Crops are at most risk during seedling and early vegetative stages.
Bogong moth	*Agrostis infusa* (Boisduval)	Attacks all field crops. Crops are at most risk during seedling and early vegetative stages.
Black cutworm	*Agrostis ipsilon* (Hufnagel)	Attacks all field crops. Crops are at most risk during seedling and early vegetative stages.
Variable cutworm	*Agrostis prophyricollis* (Guénée)	Attacks all field crops. Crops are at most risk during seedling and early vegetative stages.

Table adapted from **agric.wa.gov.au/plant-biosecurity/fall-armyworm-western-australia?page=0%2C3** ; accessed 20 May 2020.

Larval morphology

There are usually six larval instars, occasionally five. For instars 1-6, head capsule widths are approximately 0.35, 0.45, 0.75, 1.3, 2.0, and 2.6 mm, respectively, and larval length is typically 1.7, 3.5, 6.4, 10.0, 17.2, and 34.2 mm, respectively[62]. Larvae can, however, grow up to 50mm in length. Larvae have eight prolegs and a pair of prolegs on the last abdominal segment. They are variable in colour, from light green to dark brown, with longitudinal white lines down the body, and a darker lateral band. First and second instar larvae have pinkish-coloured markings down the side, with developing white lines down the body.

The head of larger larvae has a reticulate pattern of mottled appearance and a thoracic shield of similar colour to the head. The head of mature larvae is also characterised by an inverted Y-shape in yellow. Large larvae also have black dorsal (back) pinaculae (spots) with long primary hairlike setae (two each side of each segment within the pale dorsal zone) and the hairlike setae on the second and third thorax segment and on the ninth abdominal segment, which is implanted on a pinaculum (spot) with a ring-shaped dark sclerotization. The skin appears granulose but is smooth to touch. The body has enlarged black dorsal pinaculae (spots) in a trapezoid shape on the abdominal segments (including abdominal segment 9), and a square shape on abdominal segment 8[63,64]. It is the enlarged pinaculae and granulose skin combination that distinguishes this pest from other *Spodoptera* species. A full description of the larvae is given in several sources[65,66]. Diagnostic features are shown in Figure 22.

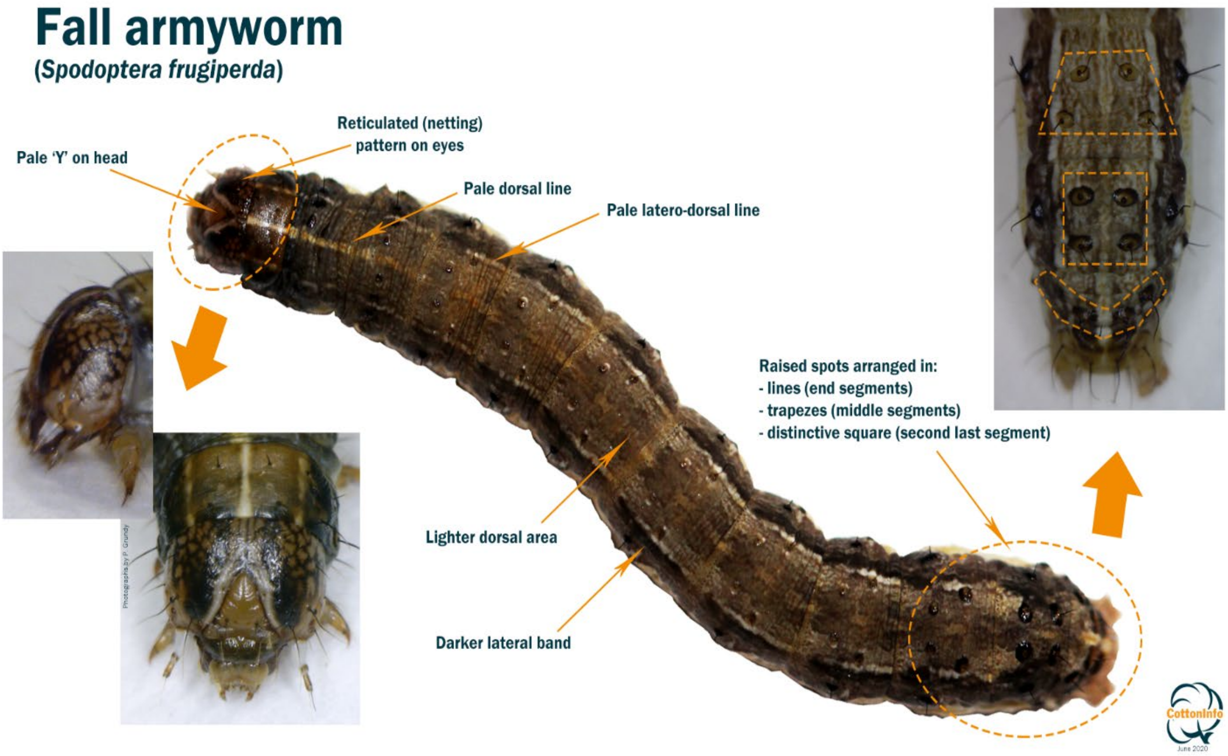

Figure 22. Larval morphology of FAW. Image credit: Paul Grundy

Pupal morphology

Pupae are shorter than mature larvae, approximately 1.3-1.5 cm in males and 1.6-1.7 cm in females, and about 4.5 mm in width and are a shiny reddish-brown colour[11] (Figure 23).

Figure 23. FAW pupae. Image credit: Scott Bauer, United States Department of Agriculture (USDA), via Wikimedia Commons

Adult morphology

Adult FAW, in good condition, can be differentiated morphologically from other noctuids. However, trapped moths often loose some of their morphological identification characteristics during the trapping process, and only the males can be identified through genital dissection. *Leucania loreyi* has commonly been found as bycatch in FAW pheromone traps in Australia and can be differentiated from FAW as it is a larger moth with large fluffy tail (coremata), differing wing patterns and distinguishing male genitalia.

Adult male morphology

The male body length is 1.6 cm and wingspan 3.7 cm[11]. The forewing is a light greyish brown, straw to rust brown colour and mottled (light brown, grey, straw) with pale/white triangular markings at the tip and near the centre of the wing[11,67] (Figure 24). There are darker hourglass shaped markings on the outer edge. The hindwing is creamy white with a narrow dark brown outer margin[64]. The male genitalia, which are diagnostic, have been described[64,67].

Adult female morphology

The female body length is 1.7 cm and wingspan 3.8 cm[11] (Figure 25). The forewings of females are less distinctly marked, ranging from a uniform greyish brown to a fine mottling of grey and brown and lack the pale markings near the tip of the wing. The hindwings are of the same colouration and appearance as the male[64].

Figure 24. Adult male FAW. Image credit: Lyle Buss, University of Florida, via Bugwood.org

Figure 25. Adult female FAW. Image credit: Lyle Buss, University of Florida, via Bugwood.org

Molecular identification of FAW

In-field molecular diagnostics can complement morphological or taxonomic identification to differentiate between related noctuid species found in Australian grains systems, particularly for eggs and early instar larvae. The development of rapid in-field molecular diagnostic tools may be considered. There are some significant advances occurring with in-field molecular identification of FAW. This includes a FAW specific loop-mediated isothermal amplification assay (LAMP) molecular diagnostic being reported in the literature overseas[68] and the development of a LAMP diagnostic protocol in Australia. If adopted, this will provide an in-field molecular diagnostic option.

Key identification points to consider

- Eggs and early stage FAW larvae are practically impossible to distinguish from other *Spodoptera* species in the field. Distinguishing early FAW instars from those of other larvae that may also occur in crops is challenging. Tools, information and education for growers and agronomists will be essential to ensure appropriate management is implemented.
- The older FAW larvae have distinct markings that enable them to be distinguished from other similar pests. Delaying control until such time can allow significant damage to occur and, reduce the effectiveness of chemical control.
- Eggs, larvae and pupae can be distinguished using molecular tests (in collaboration with research institutions). An in-field diagnostic is currently unavailable for field use. LAMP technology is being investigated but has some limitations for immediate field deployment.

FAW monitoring and crop surveillance

Monitoring and surveillance is important to generate information on the distribution and abundance of a particular pest within a defined area. The information collected can be used for a range of purposes including predicting when the pest will likely be present in an adjoining area, and then assessing the severity of the infestation.

It will be valuable for FAW management in Australia if a proportion of this monitoring is coordinated nationally with information and data sharing across and within each state and territory. This will inform the timely implementation of management practices and minimise the number of unnecessary interventions required to effectively and economically guard against yield loss.

Surveillance methodologies will vary for FAW depending on the purpose of the surveillance. For example, a grower inspecting a specific crop to determine timely implementation of management practices will undertake different surveillance approaches than FAW monitoring at a regional scale to actively track the presence, population, and movement of FAW to and within a specified region.

This section highlights the different FAW monitoring and surveillance approaches to be used as the basis for an integrated monitoring network in Australia.

Monitoring for FAW

National monitoring

Activities to monitor the spread of FAW within Australia are currently in place within WA, NT, Queensland and NSW. It is important that these activities continue and that they are extended into areas that are only affected by seasonal immigration, to know when the moths have arrived in a locality.

FAW is beginning to be incorporated into some of the existing pest trap networks such as the pheromone trap networks operating in Queensland. Information generated from these trap networks are captured and made available through services such as Beatsheet, PestFacts and PestFax.

Maintaining an emphasis on FAW within border surveillance program such as the Northern Australia Quarantine Strategy (NAQS) will also be important for the detection of new FAW immigration from outside Australia, which is potentially important if there are different biotypes of FAW that have not yet arrived in the country. Such immigrants might also be a source of novel traits such as insecticide resistance.

Regional and local monitoring using pheromone traps

There are two commercially available FAW pheromone lures that are permitted for use in pheromone-baited traps in Australia for monitoring male FAW populations (Table 7, page 42).

Table 7. FAW pheromone lures and their permitted use in Australia

PRODUCT NAME	COMPANY	ACTIVES	AUSTRALIAN PERMIT
Trécé Pherocon Fall Armyworm Pheromone Lure	Trécé	(Z)-9-Dodecenyl Acetate, (Z)-9-Tetradecenyl Acetate, (Z)-11-Hexadeccenyl Acetate And (Z)-7-Dodecenyl Acetate	PER89169
ChemTica lure (3C) *Spodoptera Frugiperda* Lure Bio Spodoptera	ChemTica Internacional	(Z)-11-Hexadecenyl Acetate, (Z)-11-Tetradecenyl Acetate And (Z)-7-Dodecenyl Acetate	PER89169

The value of the information that can be derived from what is attracted to and caught in these traps is essentially an early indicator or trigger to prompt growers within the area to start actively monitoring for eggs and larvae in their fields. Trap captures indicate the presence of FAW in the area but it is important to note that they do not indicate the level of infestation or in-crop egg-laying.

Moth counts can remain low (less than one moth per trap per day) even during an outbreak. There may be no moths in the traps within crops even though a significant percentage of plants are infested with FAW. This is highlighted in the plotting of FAO monitoring and crop scouting data (Figure 26). While there is a general positive relationship, there are many situations where prevalence in the crop is low while trap catch is high, and vice versa. Crop inspection is required to determine the intensity of egg-laying by measuring the percentage of infested plants.

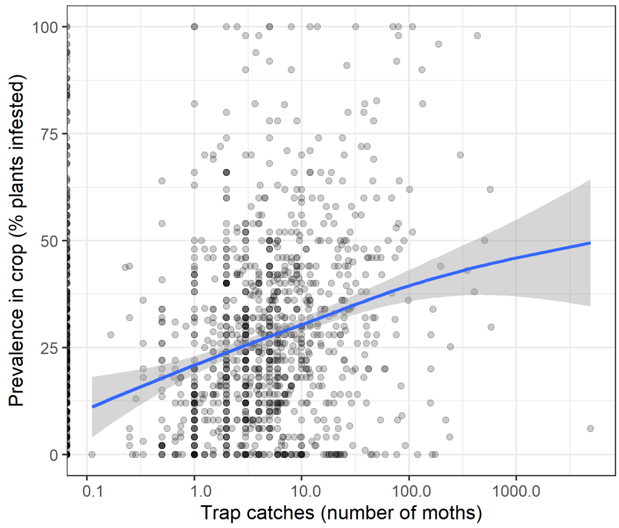

Figure 26. FAO's FAMEWS platform provides an international crop monitoring tool comprising FAW trap catches and field scouting data, which we have used to explore the relationship between monthly trap catches and corresponding observed field infestations. The majority of data consists of observations on maize. Countries represented in the dataset include Bangladesh, Benin, Botswana, Burkina Faso, Burundi, Cape Verde, Central African Republic, East Timor, Egypt, Eswatini, Ethiopia, Ghana, Guinea, Guinea-Bissau, India, Iran (Islamic Republic of), Italy, Ivory Coast, Kenya, Liberia, Madagascar, Malawi, Mali, Mozambique, Myanmar, Nigeria, Russia, Rwanda, Senegal, Somalia, South Africa, South Sudan, Sudan, Thailand, Togo, Uganda, United Arab Emirates, United Republic of Tanzania, Yemen, Zambia, and Zimbabwe. Data was kindly provided by FAO's Fabio Lana. The FAMEWS platform is available at **fao.org/fall-armyworm/monitoring-tools/famews-global-platform/en**

Trapping in Australia has shown that the ChemTica lure (3C) *Spodoptera frugiperda* Lure Bio Spodoptera can attract a large amount of bycatch. It is expected that this will change over time as the FAW population and component of trap catches increases, but between March-May in Queensland, False Armyworm comprised around 90% of the trap catches[24]. *Helicoverpa punctigera* and *Mythimna loreyimima* have also been trapped[69]. Further research is required on the relative efficacy of lures to fully enable the use of traps to support decision making in ongoing surveillance and/or monitoring of local populations.

While instructions on the use of traps will vary by manufacturer the following trapping guidance is suggested:

- Talk to neighbouring growers about establishing a community trapping network
- Select one of the currently registered pheromone trapping systems
- Traps should be suspended in the field just after planting with trap inspection commencing after emergence of the seedlings to detect the first arrival of FAW moths.
- Select a site or trap location inside or on the edge of a crop, or in an adjacent open area.
- Suspend the trap from a pole or branch about 1.5 m above the ground. More than one trap may be required for large crops.
- When traps are hanging, they should be oriented in the most vertical, straight up-and-down orientation possible, to prevent water from getting in from the side.
- Check and empty the trap every week. Replace the lure every month and replace dichlorvos block every 3 months in accordance with the permit.
- There may be a number of moths other than the FAW in the trap. Sort and count the FAW moths.
- Consider sharing catch data with neighbouring growers.
- Be aware of FAW alerts and updates in your area.
- As the crop grows, move the trap up the pole so that the bottom of the trap is always about 30 cm above the plants, This may not be feasible in tall crops such as maize.

For more detailed information on trapping guidance refer to the following online resources:

- Fall Armyworm Surveillance Trapping Manual developed by DPIRD **agric.wa.gov.au/sites/gateway/files/DPIRD%20Fall%20armyworm%20surveillance-trapping%20training%20manual_1.pdf**
- Food and Agriculture Organisation (FAO) has developed guidance on pheromone-baited trap use **www.fao.org/fileadmin/templates/fcc/Fall_Armyworm/web_guidance-note-3.pdf**

Advancing technologies and novel approaches to monitoring FAW

There are a number of existing systems for automatic counting of catches in insect traps. In Australia some of these technologies are currently being used for monitoring fruit flies (see, for example, **snaptrap.com.au** and **rapidaim.io**). Trials are currently underway overseas assessing the potential for monitoring FAW (eg. **trapview.com/v2/en**) so the possibility of deploying it for FAW monitoring in Australia could be considered in coming years.

Radar has also been used to study FAW migration in the USA, and China[70,71] and there is some indication that South Korea and Japan may have also commenced some work in this area. Radar entomology is a well-established approach for monitoring flying moth populations, and much work has been undertaken in Australia for locusts and a variety of noctuid moths[72]. Given the cost of radar equipment, such techniques are more commonly used for research purposes rather than operational monitoring.

Surveillance systems for adult FAW using radar techniques may be an option in Australia, however development of systems for the real-time detection of FAW will need to be explored. Some initial work in this area is under investigation in the United Kingdom.

Crop surveillance for FAW

On farm surveillance

Early detection of FAW infestations requires timely and regular crop inspections following the detection of adult moths. The timing of these inspections may be guided by the presence of adult moths in the pheromone traps set up in the crops before crop emergence and monitored throughout the growing season. Feeding this crop inspecting data into regional networks can provide powerful information about the dynamics of pest infestation in an area.

On-farm decision-making based on crop inspection, trap catches and other information affecting population build-up is a key purpose of surveillance, and usually requires predetermined action thresholds (see Section: FAW Economic injury levels, economic thresholds and action thresholds to inform management). On-farm decisions may also be supported through data-driven forecasting models such as DARABUG2 (see for example **cabi.org/projects/prise-a-pest-risk-information-service**).

Inspecting crops for FAW

The key to managing FAW is early detection, before they become entrenched in the crop (e.g. whorl of maize, sweet corn or grain sorghum), or before they mature and develop into later instars and cause significant defoliation.

Whilst formally recognised crop specific FAW surveillance protocols are yet to be developed there are some general guidelines that can be used when scouting for FAW in Australia.

It is important to consider the growth stage of the crop when planning crop inspections. Inspections are relatively quick and easy in young maize crops for example compared to crops in the post-tassel stage. While the yield impacts are highest when the maize crop is infested in the early vegetative stages compared to during its reproductive-stage, damage to developing and maturing cobs can affect grain quality and so assessments of FAW presence and damage throughout all growth stages is warranted.

In high risk areas where FAW populations persist for most of the year general scouting should begin early, at the seedling stage[48,72]. FAW completes its life cycle in 30–40 days at optimal temperatures and the first generation (coming out of winter in colder areas) of FAW larvae generally attacks the seedlings. Crops should be inspected weekly at the seedling and early whorl stages.

Efficient and effective methods for detecting larvae at different stages of development are necessary and will include a range of visual inspection tactics such as visual observation and beatsheeting.

Visually, there are a number of characteristic signs to look out for. The presence of egg masses is one of the early signs of FAW presence. Eggs are laid in masses usually on the underside of leaves but can be found on the upper side and on the stem. The eggs are usually found in more than one layer and are covered by whiteish, abdomen hairs from the female moths.

The first sign of FAW infestations however, is usually the detection of feeding marks by first instar larvae. They typically only feed on the outside of one side of the leaf, creating damage that looks like 'window panes' or 'windowing'. As the larvae grow, feeding results in larger holes right through the leaf and once established in the whorl, larval feeding results in large, 'jagged' holes in the expanding leaves. Continued whorl feeding results in more 'jagged holes' creating complete perforation across the leaf blade and significantly reducing the leaf area.

Beatsheeting is a useful technique to assess FAW infestations. A beat sheet is an easy to use tool to sample row crops for pests including FAW and beneficial insects.

A standard beat sheet is made from yellow or white tarpaulin material with heavy dowel attached to each end. Beat sheets are generally between 1.3-1.5 m wide by 1.5-2.0 m deep, and the beat stick a 1m length of dowel. The width catches insects thrown out sideways when sampling and the sheet´s depth allows it to be draped over the adjacent plant row to prevent insects being flung or escaping in that direction. Using smaller beat sheets, such as small fertiliser bags will reduce sampling efficiency by as much as 50%.

Beatsheeting can be useful for detecting exposed larvae, but may not always be useful in maize, sweet corn, sorghum or crops where FAW larvae can become entrenched in the host and cannot be easily dislodged e.g. corn whorl.

Based on currently available information in Australia, the following guidance on crop inspection for FAW is provided:

- Inspecting the crop should commence from the seedling stage.
- Enter the crop and look for the presence of FAW eggs, larvae, frass, and feeding signs. This relies on the ability to correctly identify FAW, understand its biology, behaviour and plant symptoms of early feeding.
- Crops should be inspected frequently, moving to once a week when conditions favour infestations. For example, in the vegetative stage, an increase in male moth trapping, presence of egg masses etc.
- Inspect the underside of the leaves for egg masses and newly hatched larvae. Young larvae cause windowing damage, and larger larvae are often found in the whorls or in the cob, as well as on the tassels, in the case of sweet corn or maize.
- Larvae feeding in whorls cause 'shot holes' in the unfurling leaves. The leaves of plants attacked by larger larvae will have a ragged appearance.
- Large larvae feeding in the whorl are often covered with a 'plug' of yellow-brown frass (larval droppings). If damage is evident, but larvae are not visible, check the whorl for frass and confirm identification as *Helicoverpa armigera* can cause similar damage in sweet corn or maize crops.
- Check whorls for larvae a few days before tasselling.
- With the emergence of winter crops in Zone 2 and 3, scouting should start early and include inspecting crop edges as larvae may move out of recently harvested summer crops into the emerging fresh feed source.
- It is important to confirm identification of FAW as there are a number of other pests that can cause similar damage.
- Consider sharing observations and inspection records with neighbouring growers.

Unmanned Aerial Vehicles (UAVs) and remote sensing

Unmanned aerial vehicles (UAVs) have been used for the application of pesticide for FAW management internationally[73]. Their use in monitoring pest damage is being investigated using artificial intelligence (AI) to analyse crop images and to detect holes in the leaves caused by larval feeding. Early results indicate that the UAV must be no more than 10m above the crop[74] to achieve sufficient accuracy. Remote sensing, from satellites or aircraft, can detect unhealthy crops including those damaged by pests and diseases, due to the increased reflectance in the red part of the spectrum. This approach is being tested internationally[75] on maize and may have broad application in Australia given our larger farm sizes.

Key monitoring and surveillance points to consider

- Surveillance for FAW eggs and larvae should involve visual inspection of the crop or host plant.
- To manage the pest, early detection provides best results, before they become entrenched in the sweet corn or maize whorls, or before they become later instars that can cause significant defoliation. Regular monitoring will allow assessments to be made as to whether thresholds have been reached.
- Early instar stage damage is characterised by pin holes, shot holes, or windowing on plant leaves, while that of older instars is characterised by significant leaf damage including larger, jagged holes.
- There are no locally developed scouting guidelines for Australia, so grain growers (particularly maize, sorghum) should inspect their crop for any invertebrate pest damage (commencing from the seedling stage), at least every week.
- Beatsheeting, is currently used for other Lepidopteran pest species, and may be useful in maize, sweet corn, sorghum or other crops except where FAW larvae are entrenched in the host and cannot be easily dislodged (such as the corn whorl).
- More automated tools for effective and efficient detection of larvae at different stages of crop development (such as Unmanned Aerial Vehicles) will become more accessible in coming years.
- Surveillance of adults is best performed using FAW pheromone-baited Uni-traps or bucket traps. Pheromone traps will assist growers and agronomists determine the timing and frequency of crop monitoring, particularly in seasons and/or regions where FAW incidence is likely to be sporadic.
- Pheromone trap surveillance is not a substitute for in-crop monitoring. Consistent with *Helicoverpa* spp experiences, there is no correlation between the number of moths trapped adjacent to a host crop and the intensity of FAW infestations in the crop.
- Monitoring of FAW moth activity and use of larval development models (e.g. DARABUG2) will assist growers and agronomists to target their crop monitoring efforts.

MANAGEMENT CONSIDERATIONS

Currently growers manage a range of pests affecting winter and summer crops. It must be recognised that no one specific management program will be effective against FAW across all the varied regions within Australia.

Management tools

The following management considerations have been guided by a review of the international literature in consultation with industry experts in Australia. Management considerations outlined in this plan have been based on overseas information as FAW behaviour under specific Australian conditions is yet to be documented. More detailed information will emerge as Australian researchers, agronomist and extension specialists learn more about this pest, its behaviour and impacts under local cropping systems. It is important to consider that the management of FAW in Australia may differ to those in other parts of the world and that our farming systems will be a significant foundation in the successful management of FAW. This section outlines the current knowledge on management of FAW from overseas experience and provides key points to consider for the management of FAW within Australian farming systems.

Integrated pest management

An Integrated Pest Management (IPM) approach should be adopted in the production system to help manage this pest, with focus on cultural methods and the preservation of beneficials. This includes regular crop monitoring (at least once a week) to determine FAW incidence, crop damage and the impact of beneficials. Consideration should also be given to the impact of prevailing weather conditions on the rate of pest development in the field.

Like other lepidopteran species, such as *Helicoverpa,* a whole-farm or regional approach rather than each grower making control actions in isolation will need to be considered. This requires high levels of communication and cooperation between growers, consultants, and research/extension personnel.

Cultural controls

Early planting, use of early maturing varieties, presence of extensive crop residue and early harvest are cultural practices employed in FAW IPM strategies in the USA. As FAW densities in northern Australia crops are expected to increase as the dry season progresses as a result of the browning off of other host plants. Early harvest may reduce the impact that may be experienced later in the season[76]. Crop rotation has also been recommended for FAW control in rice[77]. In environments where there is year-round continuous cropping or no seasonal breaks due to unsuitable climate or crop availability, crop rotation with non-favoured hosts is recommended to limit population build-up of FAW especially in regions where it is persistent year-round[78]. Good crop nutrition and the promotion of beneficial species at a range of spatial scales (field to landscape) through the provision of non-crop habitat are some of the agroecological tactics employed to control FAW. Practices, which promote conservation biological control (see Biological control below), can be readily integrated into existing management practices[79].

Key cultural control points to consider

- A number of cultural controls are employed overseas, with the principles of early planting and crop sequencing likely to have application in certain Australian situations.

Chemical control (chemical insecticides)

Insecticides will be one of the main tactics used by growers to manage FAW and so the impact on other pests in the system and associated natural enemies must be considered for successful FAW management programs. It is important that landholders do not spray unnecessarily; only spray when economic thresholds are reached. The following section includes information on insecticides used overseas for the control of FAW and current insecticide registrations and permits for control of FAW in Australia.

Actives used overseas

Chemical insecticides used for the control of FAW overseas include organophosphates (e.g. chlorpyrifos), carbamates (e.g. methomyl, carbaryl), diamides (e.g. chlorantraniliprole, cyantraniliprole, and flubendiamide), spinosyns (e.g. spinetoram), oxadiazines (e.g. indoxacarb), pyrethroids (e.g. lambda-cyhalothrin); diacylhydrazines (e.g. methoxyfenozide), and benzoylureas (e.g. novaluron)[80]. Chemical control through foliar application is the most common application however seed treatment has also been applied. Seed treatments currently registered overseas include dual active products containing cyantraniliprole and thiamethoxam.

Efficacy of active ingredients on FAW

The effectiveness of insecticides against FAW depends upon a range of factors including the application technique, rate and formulation. Once the larvae are in the whorl, the insecticides must reach them there. Targeted spraying in to the whorl at this stage would be effective.

The timing of insecticide application is also a key factor in determining its efficacy. Both the life cycle and the time of day are important. Spraying when larvae are deeply embedded inside the whorls and ears of maize is ineffective; and spraying during the day is more likely to be ineffective because larvae typically feed on plants at night, dawn or dusk.

Efficacy of seed treatments are not dependent on threshold levels or timing however there has been varied reported effectiveness of seed treatments. While seed treated with thiamethoxam did not prevent FAW infestation eight days following plant emergence in maize[81], seed treated with chlorantraniliprole and cyantraniliprole reduced the need for foliar sprays against FAW in soybeans[82]. The absorption and redistribution capacity of chlorantraniliprole and cyantraniliprole throughout the plant has been shown to confer a prolonged residual action with satisfactory control of FAW in maize[83] indicating seed treatment with these compounds as a potential management option.

Current registrations and permits

Some insecticides may be registered for the control of other armyworm, *Helicoverpa* species and other Lepidoptera and thus may provide incidental control of FAW. In these use patterns, a permit may not have been applied for, as a use pattern was already available. However, efficacy against FAW in situations not addressed by the permits below have not been considered by the APVMA and may prove to be ineffective. For further information contact the product manufacturer or your local agronomic advisor.

Industry groups and R&D Corporations have already successfully sought permits across a range of active ingredients for use in the control of FAW. The grains industry has been proactive in seeking permits for FAW.

Current details of Minor Use Permits issued by the Australian Pesticides and Veterinary Medicines Authority (APVMA) for FAW control in Australia as of September 2020 are provided in Table 8. The actual permits, plus new ones as they are issued, can be found using the APVMAs web portal PubCRIS **portal.apvma.gov.au/permits**. It is important that all instructions on the permit, including the rates and application methods specified are strictly followed.

Table 8. Summary of permits for fall armyworm control as of September 2020. The original permit must be consulted, and the approved use pattern followed

PERMIT NO.	ACTIVE CONSTITUENT	PRODUCT	MOA*	CROPS
PER89279	Alpha-cypermethrin	ACCENSI ALPHA-CYPERMETHRIN 100 INSECTICIDE	3A	Maize, sorghum and sweetcorn
PER85447	Alpha-cypermethrin	TITAN ALPHA-CYPERMETHRIN 250 SC INSECTICIDE FASTAC DUO INSECTICIDE	3A	Maize, sweet corn chickpeas, faba beans, field peas, mung beans, navy beans, soybeans, sorghum, millet, winter cereals
PER89279	Alpha-cypermethrin	ACCENSI ALPHA-CYPERMETHRIN 100 INSECTICIDE	3A	Millet
PER89279	Alpha-cypermethrin	ACCENSI ALPHA-CYPERMETHRIN 100 INSECTICIDE	3A	Pulse crops listed on the product label (including chickpea, fava bean, field pea, lupin, soybean, mung bean, and navy bean)
PER89279	Alpha-cypermethrin	ACCENSI ALPHA-CYPERMETHRIN 100 INSECTICIDE	3A	Winter cereals (including triticale and wheat)
PER89425	Alpha-cypermethrin	ALPHANEX 100 EC INSECTICIDE	3A	Rice
PER89425	Carbaryl	KENDON CARBARYL 500 SC INSECTICIDE	1A	Rice
PER89290	Chlorantraniliprole	ACELEPRYN TURF INSECTICIDE	28	Turf
PER89366	Chlorantraniliprole	ALTACOR INSECTICIDE	28	Maize cereals
PER89281	Chlorantraniliprole	CORAGEN INSECTICIDE, ALTACOR HORT INSECTICIDE	28	Blueberry and Avocado

PERMIT NO.	ACTIVE CONSTITUENT	PRODUCT	MOA*	CROPS
PER89353	Chlorantraniliprole	CORAGEN INSECTICIDE, ALTACOR HORT INSECTICIDE	*28*	*Rubus* spp., tree nuts (except almonds), strawberries, parsley, root and tuber vegetables (except potatoes).
PER89384	Chlorantraniliprole	CORAGEN INSECTICIDE, ALTACOR INSECTICIDE	28	Sugarcane
PER89259	Chlorantraniliprole	CORAGEN INSECTICIDE, ALTACOR INSECTICIDE, ALTACOR HORT INSECTICIDE	28	Brassica vegetables, brassica leafy vegetables, stalk and stem vegetables, leafy vegetables, fruiting vegetables (including cucurbits), legume vegetables, potatoes, sweet corn, lettuce, corn, almonds, pome fruit, grapes, stone fruit
PER89354	Chlorantraniliprole	CORAGEN INSECTICIDE, ALTACOR INSECTICIDE, ALTACOR HORT INSECTICIDE	28	Citrus fruit
PER89280	Chlorantraniliprole and Thiamethoxam	DURIVO INSECTICIDE	28, 1A	Brassicas including broccoli, brussels sprouts, cabbage, cauliflower, brassica leafy vegetables, leafy vegetables including lettuce, endive, silverbeet, spinach, fruiting vegetables(excluding cucurbits) including tomatoes, capsicum, eggplant
PER89285	Emamectin	PROCLAIM OPTI INSECTICIDE	6	Various leafy vegetables, celery, blueberry
PER89263	Emamectin	PROCLAIM OPTI INSECTICIDE	6	Brassica vegetables, root and tuber vegetables (except potato), leafy vegetables, brassica leafy vegetables , sweet corn, strawberries, lettuce cucurbits, legume vegetables, fruiting vegetables (field grown and protected cropping), grapes (except grapes grown for dried fruit production)
PER89300	Emamectin	AFFIRM INSECTICIDE	6	Canola, pulse
PER89344	Emamectin	AFFIRM INSECTICIDE	6	Cotton
PER89358	Gamma-cyhalothrin	TROJAN INSECTICIDE	3A	Canola, field peas, chickpeas, faba beans, lentils, vetch, barley, wheat, lupins, navy beans, mung beans, sorghum, sunflower, soybeans

PERMIT NO.	ACTIVE CONSTITUENT	PRODUCT	MOA*	CROPS
PER89306	Indoxacarb	STEWARD EC INSECTICIDE	22A	Cotton
PER89279	Indoxacarb	LYMO 225 INSECTICIDE	22A	Soybean
PER89278	Indoxacarb	AVATAR INSECTICIDE	22A	Broccoli, brussels sprouts, cabbage (closed head varieties only), cauliflower, celery, capsicum, eggplant, peppers, tomato (field or trellis), leafy vegetables, Chinese leafy vegetables, apples, nashi pear, pears, apricot, nectarine, peaches plums, grapes, cherries, blueberries and *Rubus* species, strawberries, macadamia nuts
PER89311	Indoxacarb	STEWARD EC INSECTICIDE	22A	Pigeon Pea
PER89530	Indoxacarb	STEWARD EC INSECTICIDE	22A	Maize cereals (including maize, popcorn and teosinte)
PER89286	Indoxacarb	PROVAUNT TURF INSECTICIDE	22A	Turf
PER89279	Methomyl	LYMO 225 INSECTICIDE	1A	Maize, Sorghum, sweetcorn, soybean and peanut
PER89293	Methomyl	LANNATE-L INSECTICIDE EUROCHEM SENECA ULTRA 400 SP INSECTICIDE	1A	Apples, pears, blueberries, strawberries, citrus, stone fruit, cherries, non-bearing ornamentals, mangoes, persimmons, grapes, brassica vegetables, capsicums, sweet corn, beans, peas, potatoes, macadamia, turf, tomatoes, shallots, spring onions, fruiting vegetables, legume vegetables, sweet potato, radish, swede, turnip, lettuce, root and tuber vegetables, celeriac, silverbeet, myoga, ginger, rakkyo, parsley, spinach, fennel brassica leafy vegetables, bulb onion, fennel bulb, leeks, avocado, celery.
PER89400	Methomyl	NUDRIN 225 INSECTICIDE	1A	Millet
PER89241	Spinetoram	SUCCESS NEO INSECTICIDE, DELEGATE INSECTICIDE	5	Sweet corn, brassica vegetables, leafy vegetables, cotton, cucurbits, fruiting vegetables, legume vegetables, stalk and stem vegetables, culinary herbs, root and tuber vegetables, citrus fruits, soybean, pulses, chickpeas, bananas, ornamentals tropical and sub-tropical fruits (inedible peel, including avocado, mango and kiwifruit), macadamias, berryfruit, coffee, pistachios, forage brassicas, canola, grapes, pome fruit, stone fruit
PER89331	Spinetoram	SUCCESS NEO INSECTICIDE	5	Onion
PER89327	Spinetoram	SUCCESS NEO INSECTICIDE	5	Olives
PER89284	Spinetoram	SUCCESS NEO INSECTICIDE	5	Various tubers and bulbs
PER89390	Spinetoram	SUCCESS NEO INSECTICIDE	5	Maize, popcorn, teosinte, sorghum grain, millet, hungry rice, job’s tears, teff or tef
PER89295	Permethrin	AMBUSH AND AXE	3A	Sugarcane

PERMIT NO.	ACTIVE CONSTITUENT	PRODUCT	MOA*	CROPS
PER89330	Acephate	Various products	1A	Nursery stock (non-food)
PER89371	Emamectin	AFFIRM INSECTICIDE	6	Various cereals
PER89705	Indoxacarb	AVATAR INSECTICIDE	22A	Sweet Corn
PER89870	Spinosad	ENTRUST ORGANIC INSECTICED	5	Various vegetable and sweet corn

*Mode of action

Key chemical control points to consider

- The emergency permits currently available in maize should enable growers to rotate modes of action as part of managing insecticide resistance risks. The range of options in other crops is currently more restricted, which may limit rotation options.
- Fortunately, many of the products registered for *Helicoverpa* control will also be effective against FAW, and there will, at certain stages of crop development, be incidental control.
- The use of more selective products that minimise adverse impacts of applications to beneficial predators and parasitoids is desirable. If the frequency of spraying increases as a result of FAW infestations, growers may elect to minimise costs by using cheaper broad-spectrum products that will adversely impact the contribution of natural enemies to control.

Biological controls (predators and parasitoids)

Biological control and hence natural enemies are an important pillar in IPM. Management interventions that incorporate or promote natural enemies (including selecting targeted pesticides where available) may be able to keep FAW populations or infestations below economic thresholds. Conservation, augmentative and classical biological control may provide options to manage FAW sustainably and are described briefly below:

a) Conservation biological control is a cheap and effective technique that aims to preserve natural enemy populations. It involves identifying and encouraging the use of native or endemic parasitoids in managing pests. An example is habitat management where FAW parasitism is related to more plant-diverse habitats and may comprise flowering strips that provide floral resources for parasitoids[84]; trap crops that attract insects in order to protect target crops from pest attack[85]; push-pull strategy which involves the behavioural manipulation of insect pests and their natural enemies via the integration of stimuli that act to make the protected resource unattractive or unsuitable to the pests (push) while luring them toward an attractive source (pull)[86] and; intercropping which involves growing crops amongst other crops of a different kind and are used to reduce pest infestation, for example by reducing FAW larval movement between crop plants. Habitat management strategies are effective against FAW internationally, however require research in Australian agroecosystems. Promoting diverse habitats on farm, including shelterbelts, riparian zones, and crop types can reduce pest pressure.

b) Augmentative biological control involves the mass rearing and release of natural enemies for the control of a target pest. The parasitoid *Telenomus remus* has been recorded as a successful augmentative biological control agent[87]. It was introduced into Western Australia for the control of other lepidopterans however, its persistence and current distribution are unknown. *Trichogramma pretiosum* is used in augmentative programs to manage FAW in Latin America[88]. In Australia it is commercially produced and released predominantly for the control of *H. armigera* in sweet corn and strawberries as part of an IPM program. Further, innovative use of drone-releases in Australia has made it more feasible to conduct releases on broadacre crops. In the last couple of years, two parasitoids, *Eretmocerus hayati* Zolnerowich and *Eretmocerus debachi* Rose have been released by drone into cotton crops in northern NSW for silverleaf whitefly, *Bemisia tabaci*. *Trichogramma pretiosum* may provide some level of FAW control, when being used to manage *H. armigera*, however the effectiveness of this parasitoid against FAW has not been established in Australia.

c) Classical biological control refers to the introduction of a natural enemy of exotic origin to control a pest, usually also exotic, in order to achieve permanent control of the pest. The parasitoids *T. remus, Co. marginiventris* (USA) and the ichneumonid, *Eiphosoma laphygmae* (CAB International) are classic examples. *T. remus* has been introduced in several countries for the control of *Spodoptera* spp. and other Lepidopteran pests. Bringing biological control agents into Australia would involve a rigorous and lengthy scientific and regulatory process and should only be considered after conservation and augmentative biological controls options are exhausted.

Key points to consider for biological control options

There are a range of biological control options available for FAW that provide an important avenue for mitigating potential impacts in crops.

- Conservation biological control or promoting non-crop habitat on farm will provide resources for natural enemies and include shelterbelts and floral resources.
- Augmentative biological control could be used to boost native, as well as introduced natural enemies, and should initially focus on those agents already being reared in Australia (e.g. *Trichogramma pretiosum*) that may be useful in controlling FAW.
- Classical biological control should only be considered after all options for conservation biological control have been fully explored. Bringing biological control agents into Australia would involve a rigorous and lengthy scientific and regulatory process.
- It will be important to select chemical pesticides that have minimal impact on natural enemies as part of IPM programs.

Microbial biopesticides

Viruses, fungi, bacteria (microbials) and nematodes (macrobials) biopesticides derived from these have been developed for FAW. These are often more specific than synthetic pesticides and also often slower to take effect, although infected insects may also have a reduced feeding rate prior to death. Information on the registration status of biopesticides for a range of lepidopteran pests in Australia is provided in Table 9.

Bacteria

Bacillus thuringiensis (Bt) is widely used as an insecticide. *Bt* produces toxic proteins that kill insects on ingestion, and particular *Bt* strains are more effective on particular groups of insects. *B. thuringiensis subsp. aizawi* and *B. thuringiensis subsp. kurstaki* infect lepidopteran larvae including FAW[89] and may be effective against FAW populations in Australia. *Bt* is formulated as either dry flowable granules, emulsifiable suspension or a wettable powder. Other bacteria *B. subtilis* and *Chromobacterium subtsugae* are also used as biopesticides. The management of potential resistance of FAW to bacterial biopesticides needs to be considered (see Section: Resistance management).

Viruses

FAW is susceptible to a specific nucleopolyhedrovirus (SfMNPV)[90]. The suitability of products derived from SfMNPV strains are dependent on the virulence and speed of action. The product marketed as Fawligen® is produced by an Australian company, AgBiTech, using an American SfMNPV strain. Import and registration in Australia would possibly require a lengthy review process, however an import application is under consideration by the commonwealth government.

Fungi

Entomopathogenic fungus (EPF), *Metarhizium* kills FAW eggs and neonates[91]. *Metarhizium* (*Nomuraea*) *rileyi* causes moderate mortality when tested against FAW[92]. A product derived from *M. rileyi* is being registered for FAW control in South Africa. FAW is also susceptible to *Beauveria bassiana* but requires relatively high concentrations of conidia for effective control. Commercial strains of *B. bassiana* and *M. anisopliae* have been found to cause high mortality on FAW[93]. Field trials and registrations for these are underway in East Africa[94].

Nematodes:

Entomopathogenic nematodes (EPNs) *Steinernema carpocapsae* and *S. feltiae* Filipjev have been found to kill FAW in the field[95]. It is noteworthy that EPNs are susceptible to desiccation and to UV light therefore foliar application is generally less successful. A patent for Steinernema sp exists in USA for suppression of *H. zea* and FAW[96]. Trials of commercially- and locally isolated EPNs (*S. carpocapsae* and a Heterorhabditis sp) against FAW are in progress in Rwanda.

Table 9. Registration status of microbial biopesticides in Australia for a range of Lepidopteran pests

ACTIVE INGREDIENT	REGISTRATION/AVAILABILITY IN AUSTRALIA
Bacteria	
Bacillus thuringiensis	Many products registered containing various strains including *Bt* subsp. aizawi and *Bt* subsp. kurstaki
Chromo-bacterium subtsugae	No approvals or registrations
Viruses	
Anagrapha falcifera NPV	No approvals or registrations
Beet armyworm NPV	No approvals or registrations
Helicoverpa zea NPV	Several products registered
Spodoptera exigua NPV	No approvals or registrations
Spodoptera frugiperda NPV	No approvals or registrations
Spodoptera littoralis NPV	No approvals or registrations
Fungi	
Isaria fumosorosea	No approvals or registrations
Metarhizium spp.	Several *M. anisopliae* products registered for orthoptera and scarab beetles
Nematodes	
Steinernema spp.	Products available for lawn armyworm, *S. mauritia*.

Key microbial biopesticides control points to consider

- Some biopesticides offer an alternative to synthetic pesticides. Several products registered in Australia for other pests may be effective against FAW, but no permits for their use on FAW have been issued yet.
- Many grain growers in Australia already use virus-based biopesticides for *Helicoverpa* control. Similar products exist for FAW but are not yet available in Australia.

Semiochemicals

Semiochemicals are volatile signalling compounds produced by plants as a response to feeding damage[97]. Several of these, together with a number of natural products have been trialled against FAW overseas and may offer potential control options for FAW under Australian conditions.

Attract and kill
This strategy combines an attractant, such as an odour and/or visual cue, and a killing agent, such as a pathogen or insecticide, and is known to be highly effective to control isolated and low-density populations of pests. It also has the potential to add value to long-term pest management[98]. A product derived from this strategy, Magnet®, has been developed for *Helicoverpa* spp. management[99] and is permitted for use against FAW in Australia. The product attracts both male and female *Helicoverpa* spp. moths, with international studies indicating it is also attractive to FAW. Efficacy trials of this system against FAW in maize are ongoing in the Ord region of Western Australia, with a use pattern yet to be established. Further refinement of this product could further increase its attractiveness to FAW.

Herbivore induced plant volatiles (HIPVs)
These compounds attract natural enemies from surrounding habitats into crops. Parasitoids or predators of the attacking herbivore use these HIPVs to orient to their host or prey. Lepidopteran larval feeding in maize has seen the release of a blend of volatiles attractive to various parasitoids. This knowledge could contribute to breeding maize varieties highly attractive to parasitoids in the future.

Attract and reward
This strategy combines the use of HIPVs to improve immigration of beneficial taxa into crops, and nectar-rich flowering plants to maintain their populations. In Australia, sweetcorn sprayed with synthetic HIPVs, and intercropped with buckwheat grown to support natural enemies has shown significantly fewer *H. armigera* larvae in HIPV-sprayed plots than unsprayed plots[100]. Consequently, a successful HIPV-based product (Eco-Organic Eco Oil, Organic Crop Protectants) was commercialised, although it has not been trialled against FAW.

Mating disruption
This technique has proved difficult to control FAW, likely due to the pests polyphagous nature, its tendency to mate more than once and its highly migratory ability, whereby females mated elsewhere can move into new areas[99]. A single study in the USA in the early 1980's, showed that mating disruption of FAW through the aerial application of (Z)-9- tetradecen-l-01 acetate formulated in hollow fibres, reduced mating and egg deposition (86% & 84% respectively) in maize[101]. However, a reduction in trap catches or damage was not demonstrated. In several studies with *Spodoptera* spp., economically prohibitive amounts of pheromone are often used, and while occasionally mating disruption has been reported, it did not result in egg or larvae reduction[102], which is a common phenomenon in mobile noctuid moths such as *Helicoverpa armigera*[103]. Mating disruption has also historically been very expensive. Recently, a cost-effective and novel method to mass produce FAW pheromone has been developed and trials are being conducted in Kenya by CAB International in collaboration with a biotechnology company (**provivi.com**). In Australia we see mating disruption used for smaller lepidopteran species (e.g. Light brown apple moth), that generally don't move as far as FAW, tend to mate only once and occur in high value crops, such as apple and pears, where this technology is considered economically feasible.

Mass trapping

Unpublished data suggests that mass-trapping of FAW using 4-5 pheromone-baited traps per ha has routinely lowered the requirement of *Bt* sprays used to maintain FAW larval numbers below economically damaging thresholds by 30 to 70%[102]. In Australia, the high density of traps required on an area-wide basis, the high labour requirement including servicing, and maintenance costs of a large deployment of traps makes this an impractical FAW management approach.

Key semiochemical points to consider

Using an attractant that lures both female and male moths is a promising semiochemical option for FAW in Australia. A product called Magnet®, which uses plant volatiles for his purpose and is mixed with a chemical insecticide to kill the insects, is registered in Australia for *Helicoverpa* spp., and is known to be attractive to FAW. There is a permit for its use in a range of crops against FAW and efficacy trials are currently being conducted in the Ord region with results pending.

Attract and reward may be useful in promoting natural enemies of FAW, thereby enhancing the effectiveness of conservation biological strategies. There are several successful HIPV-based products in the market. Despite this, their role in attracting FAW parasitoids has not been determined.

Mating disruption using the FAW pheromone has proved difficult and is possibly due to its polyphagous character, its tendency to mate more than once and its migratory capacity, whereby females mated elsewhere can move into new areas. The company Provivi® is undertaking trials using mating disruption, having developed a novel method for producing the FAW pheromone at a much lower cost, which could make mating disruption cost-effective. However, while it may be possible to disrupt mating, this does not always translate into reductions in eggs and larvae.

Mass trapping is unlikely to be a practical tool in Australia due to the high density of traps required on an area-wide basis, as well as the high labour and other associated costs involved in servicing and maintaining a large deployment of traps.

Future options

Genetic-based control of FAW

Self-limiting FAW

This approach involves the mass release of male insects (Friendly™) carrying a self-limiting gene, which when they mate with wild females results in the death of the female's offspring. Death occurs when the FAW larvae are young, prior to crop damage. Over time the ongoing release of Friendly™ males leads to a decrease in the number of wild females hence a reduction in the population. This approach has received regulatory approvals for trials in Brazil to address pesticides and *Bt* resistance[104].

While a related approach, the Sterile Insect Technique (SIT), is used in Australia to manage the Queensland fruit fly (*Bactrocera tryoni*) and Mediterranean fruit fly (*Ceratitis capitata*), the release of self-limiting insects has not been deployed. A first stage trial of the approach was conducted for *C. capitata* in Western Australia several years ago (**agric.wa.gov.au/fruit-fly-trial-western-australia**), but the work has not been advanced since then.

Key genetic-based control of FAW points to consider

Self-limiting FAW is still under development and testing. In addition, the regulatory process for this technology is unclear.

GM traits such as Bt

Genetically modified (GM) crops complement other approaches in the control and management of several agricultural invertebrate pests. Host-plant resistance, in the form of GM crops, is compatible with and can be incorporated as part of effective integrated pest management (IPM) strategies[105]. The use of genes from the naturally occurring soil bacterium *Bacillus thuringiensis* (*Bt*) has seen the development of GM crops (known as *Bt* crops) resistant to several invertebrate pest species[106]. These *Bt* crops with insect resistant traits can target several lepidopteran pests when expressed in a number of crop types[107]. However, the current availability of insect-resistant *Bt*-crops targeting FAW in the Americas, Africa and Asia are limited to *Bt* maize and *Bt* cotton.

Genetically modified maize: GM maize expressing *Bt* insecticidal proteins has shown efficacy in FAW control in the Americas, Asia and Africa[108,109]. These crops carry either a single (one cry) *Bt* gene or dual (two cry or a cry+vip) *Bt* genes that express insecticidal toxins[110]. The cry and vip genes encode the crystalline (cry) protein and vegetative insecticidal protein (vip), respectively. These two forms of toxins bear no sequence similarity to one another and have different modes of action hence complement each other in the development of *Bt* crops for insect resistance management[111,112,113]. The *Bt* maize events or varieties used to control FAW overseas include MON810, TELA™, MON89034, VT Double Pro (with its hybrid DEKALB), *BT*11, MIR162.

Genetically modified cotton: GM cotton expressing Bt toxins has shown efficacy against FAW larvae in the Americas and Asia. Transgenic cotton (Bollgard™) carrying *Bt*-derived gene(s) revealed tolerance to FAW infestation[114]. Bollgard®II cotton (now withdrawn in Australia in the interest of resistance management for *H. armigera*) contain two forms of cry genes (cry1Ac and cry2Ab2)[115], while Bollgard III® contains cry1Ac, cry2Ab2 and vip3Aa[116]. Several commercial *Bt* cotton varieties are approved for use in Australia. These target lepidopteran pests *H. punctigera* and *H. armigera*, with widespread adoption by Australian cotton growers documented more than a decade ago[117,118].

Resistance to *Bt* Crops

Bt crops such as Bt corn expressing Cry1Ab, Cry1F, Cry2Ab2, Cry1A.105 and Vip3Aa20 can be used for the control of FAW[119]. However, due to the widespread and continuous cultivation of *Bt* crops in South America, FAW has gradually developed field-evolved resistance to various *Bt* proteins (Table 10) which puts further emphasis on the use of synthetic insecticide sprays to manage this pest[120].

In Australia, the availability of GM broadacre crops with insecticidal traits is limited to cotton, increasing the reliance on insecticide applications in other crops[121].

Table 10. FAW resistance to Bt toxin

COUNTRY/REGION	BT TOXIN	REFERENCE
America	Cry1A.105, Cry1F	Huang *et al.* (2016); Li *et al.* (2016)
Puerto Rico	Cry1F, Cry1Ac, Cry1Ab	Blanco *et al.* (2010); Storer *et al.* (2010)
Brazil	Cry1F, Cry1Aa, Cry1Ab, Cry1Ac, Cry1A.105, Cry2Ab2	Monnerat *et al.* (2015); Fatoretto *et al.* (2017)
Argentina	Cry1F, Cry1A.105, Cry2Ab2	Chandrasena *et al.* (2018); Signorini *et al.* (2018)

Table adapted from Wu *et al.* (2019)

Key GM trait points to consider

- Genes from *Bacillus thuringiensis* (*Bt*) express toxins with insecticidal activity against FAW. The presence of Bollgard III™ cotton (Bollgard II™ cotton has been withdrawn in the interest of resistance management) and the potential for resistance development in FAW populations is of particular importance for Australia. *Bt* cotton has delivered considerable gains in terms of pest management, especially IPM, and there are mandatory requirements for growers to help manage potential resistance through growing refuges, pupae busting etc.
- Any future introduction of new *Bt* crops, such as *Bt* maize, would need careful consideration and cross-industry consultation and planning to manage resistance. For example, it would be important to avoid accelerating selection pressure on *H. armigera*, which, as well as being a pest of cotton also damages other crops including maize, sweet corn, sorghum, millet, pulses, oilseeds and other grass crops and pasture species. For example, in the USA, the selection pressure on *H. zea* in *Bt* corn and subsequent resistance development has contributed to the pest status and management impacts on *Bt* cotton[122].
- Aside from regulatory costs, concerns over market acceptance (domestic and export) for GM crops destined for human consumption (or stock feed) has been a major consideration for such crops in Australia. Benefits will need to be weighed up against a traditional IPM approach in the Australian context.

RESISTANCE MANAGEMENT

International studies have shown that populations of FAW have evolved resistance to multiple insecticides and *Bt* toxins in many parts of the world.

Resistance to chemical insecticides

Although synthetic insecticides are rapid and effective in controlling and managing pests, long-term use and dependence generally results in FAW developing resistance to certain chemical controls[117,123]. The repeated use of insecticides from one chemical grouping or mode of action (MoA) groups will increase selection pressure and therefore increase the risk of rapid build-up of resistance to that chemical group. Rotating the use of different chemical groups with different MoAs will slow down the process of selection for resistance. Current permit applications for FAW have in most cases products from at least two MoA groups per crop (Table 11, page 61). It is important to note that targeting mature FAW larvae, which typically feed on plant tissues and are concealed, with insecticides has limited effect and can be misdiagnosed as resistance[117].

Across the Americas FAW has developed varying levels of resistance to at least 29 insecticidal active ingredients (mainly belonging to organophosphates (OP) and pyrethroids) in six mode-of-action groups[120].

Insecticide resistance of the invasive populations that have recently established in countries such as Africa and India are not widely reported or understood. In contrast, two FAW populations collected from Yunnan Province in China showed potential for resistance risk to pyrethroids and organophosphate pesticides[124].

Pesticide resistance genes have been detected in Western Australia's FAW populations following recent initial screening by NSW DPI. The research coordinated by DPIRD revealed that all of the larvae in the samples that were tested carried at least one of three mutations that confer resistance to Group 1 pesticides, including organophosphates and carbamates[125].

While further testing of samples from other states will be necessary, these findings highlight the need for careful management of Group 1 pesticides, to slow the rate at which these genes become dominant in the state's FAW population.

Within large-scale broadacre cropping systems in Australia, chemical insecticides continue to be applied intensively, placing high selection pressure on target pests[126]. This leads to Australian growers progressively grappling with insecticide resistance issues that threaten the effective control of pests using chemicals[123].

Table 11. Current permits across chemical Mode of Action groups for some grain crops in Australia

CROP	IRAC CLASSIFICATION (CHEMICAL GROUP)					
	1A	3A	5	6	22A	28
Barley		■				
Canola	■	■	■	■		
Chickpeas		■	■	■		■
Faba beans		■	■	■		■
Field peas		■	■	■		■
Lentils		■	■	■		■
Lupins		■	■	■		■
Maize	■	■	■	■	■	■
Popcorn			■	■	■	■
Teosinte			■	■	■	■
Millet	■	■	■			
Mung beans		■	■	■		■
Peanut	■					
Pulses		■	■	■		■
Rice	■	■				
Rye					■	
Sorghum	■	■	■			
Soybean	■	■	■	■	■	■
Sunflower		■				
Triticale					■	
Vetch		■				■
Wheat		■			■	

Resistance risks and management

Field-evolved resistance of invertebrate pests, now including FAW, is a continuous threat and one of the most challenging issues in the sustainability of Australian agriculture.

There are a number of invertebrate pests that impact the Australian grains industry that have developed resistance[123,127,128]. Pests such as the Cotton Bollworm, *H. armigera*, Diamondback Moth, *Plutella xylostella* (Linnaeus) (Lepidoptera: Plutellidae), and Green Peach Aphid, *Myzus persicae* (Sulzer) (Hemiptera: Aphididae) are known to have developed resistance to a range of insecticides both overseas and in Australia[129,130,131,132]. Given the ongoing reliance on insecticides in the Australian grain industry, selection pressures are expected to remain high[123]. Overall, it is expected that the pest status of some species is likely to increase due to changes in Australian farming practises, insecticide usage patterns and climate[123].

Existing Insecticide resistance management strategies (IRMs) in Australia aim to prevent or delay insecticidal evolutionary resistance; and to help regain susceptibility in pest populations that have already developed resistance[123]. Species-specific IRMs have been developed recently for some pests of concern to the Australian grains industry[123,133]. Each species-specific IRM emphasises the underlying principles relating to minimising the development of insecticide resistance: i) apply insecticides when pest infestations reach economic thresholds; ii) avoid application of broad-spectrum formulations where possible; and iii) avoid applying sequential applications of the same MoA across consecutive generations of the target pest[123]. However, similar to overseas, there are key challenges and barriers in the wide-scale adoption of IRMs in Australia.

It will be important for industry to develop an RMS for FAW under Australian conditions, however additional information on the behaviour and ecology of the pest in Australia is required before this could commence. Similar to other strategies, this RMS should cover IPM strategies and careful timing and the time period permitted (windowing) for chemical options so that growers can effectively and economically manage FAW but at the same time minimise the selection pressure for further resistance evolution.

The addition of other chemical controls within broader grain farming systems may also have the potential to interfere with existing Resistance Management Strategies (RMS) in Australia for major pests such as *Helicoverpa*. This will particularly be the case in the north eastern regions of Australia where *H. armigera* are commonly found in summer grain, pulse and oilseed crops. Any application of insecticides for fall armyworm control will need to be considered against existing *Helicoverpa* Resistance Management Strategies. The majority of active ingredients used for the control of *H. punctigera* are from 3 chemical sub-groups with broad-spectrum activity: carbamates (Group 1A); organophosphates (Group 1B); and synthetic pyrethroids (Group 3A). Organophosphates are not registered for use against *H. armigera* in Australian grain crops, and *H. armigera* is effectively resistant to Groups 1A and 3A. Insecticides from Group 6 (emamectin benzoate), Group 22A (indoxacarb) and Group 28 (chlorantraniliprole) have become more widely used against *H. armigera* in pulses because of their high efficacy and low impact on beneficial insects. These actives also have permits in various grain crops for use against FAW. Insecticides such as emamectin, benzoate and spinetoram, are currently not considered to be at high risk of resistance development based on low frequencies of resistance in field populations of *H. armigera*. However, if usage patterns of these insecticides increase then selection for resistance is also likely to increase. A RMS for FAW will need to focus on the rotation of MoAs and the management of FAW and *H. armigera* together across crops and across farming systems. The application of pesticide mixtures containing two or more products with different decay times may increase the risk of resistance development against many insecticides.

Resistance mechanisms in FAW

The diversity of pesticidal resistances possessed by FAW represents a considerable threat to its successful management in Australian agricultural systems.
Awareness of the underlying genetics of resistance provides other benefits in addition to monitoring. Typically, management strategies involving insecticide rotations and (or) mixtures and refuges assume that resistance is monogenic (a single gene) and related to target-site mechanisms[134, 135, 136, 137]. Collectively, determining genetic properties of resistance provides important parameters for evaluating options for management. A brief overview of the current evidence of resistance mechanisms in FAW for the IRAC classifications that are currently permitted for use in Australia is compiled in Table 12. Most of the well reported genetic mechanisms occur in the Americas and few studies have documented the frequency of resistance mutations in the greater (invasive) cosmopolitan distribution of FAW.

Table 12. Current evidence and knowledge gaps on genetic mechanisms for insecticide resistance, relevant to Australian invasive FAW

CHEMICAL GROUP	MOST LIKELY GENETIC MECHANISM	EVIDENCE
1	*ace1*: target-site	Target-site resistance conferred by *ace1* mutations provide good *a priori* expectations of resistance. Correlation between allele frequencies, the mean phenotype, and possible costs is unknown[138, 139, 140, 141, 142, 143].
3A	*para*: target-site	Target-site resistance conferred by *para* mutations provide good *a priori* expectations of resistance. Correlation between allele frequencies, the mean phenotype, and possible costs is unknown[136, 144, 145, 146, 140].
5	Unknown	Small number of studies suggest possible oligogenic resistance. Group 5 resistance is relatively uncommon globally. Potential for resistance to evolve in Australia is unknown[147, 148, 149, 150].
6	Unknown	Virtually nothing is known. Group 6 resistance is relatively uncommon globally. Potential for resistance to evolve in Australia is unknown[151].
11	*ABCC2*: target-site Other?	*ABCC2* the most well characterised target-site mutation to Bt toxins. However, it is rare or absent outside Puerto Rico. It is currently unknown whether invasive Australian populations possess *Bt* resistance[152, 153, 154, 155, 156, 157, 158, 140].
15	Unknown	Little data exists. Single study suggests cuticular proteins and detoxification enzymes might be putative candidates of resistance. Resistance to Group 15 is however globally rare. The target for Group 15 chemicals is *chs1*[159, 160].
22A	Unknown	Virtually nothing is known. Group 22A resistance does not appear to be a problem in FAW. Potential adaptability of populations to this chemical is unknown[161, 162, 163, 164, 165, 166].
28	*RyR*: target-site Other?	*RyR* mutation has been associated with rare field-derived resistance. It remains unclear if this is the most common way diamide adaptation will evolve in the field under strong selection[167, 140].

The diversity of pesticide resistance observed overseas across FAW strains/hybrids represents a considerable threat to its successful management in Australian agricultural systems. Bioassays will undoubtedly be important in evaluating the presence and magnitude of resistances that might exist in the current invasive population. Genetic approaches are also likely to provide utility in resistance monitoring and the development of action plans.

When the genes and associated alleles of resistance traits are known, fast and efficient molecular assays can be used to estimate the relative frequency of resistance in a field population[168, 137]. Molecular assays negate the maintenance of live cultures and breeding large numbers of individuals for bioassays and genetic screens (e.g. F1 or F2 screens). They cannot replace standard bioassays but provide an alternative tool for management strategies when the genetic basis of resistance is understood.

Understanding the underlying genetics of resistance provides other benefits in addition to monitoring. Typically, management strategies involving pesticide rotations, use of multiple actives in a single application and refuges assume that resistance is monogenic (a single gene) and related to target-site mechanisms[134,131,133]. Target-site resistances generally entail a loss of function mutation that reduces a pesticides ability to affect its target gene (protein), and therefore, reduces its toxicity. Under this scenario, mutations conferring resistance have a large effect on the phenotype and are expected to have considerable costs in the absence of selection[169]. Hence, management strategies that vary selection pressures (the modes of action used and their application rates) within agroecosystems decrease the duration that a resistance allele is favourable, maintaining it at a lower frequency[131]. It is also assumed that resistance conferring mutations are recessive, such that individuals must contain two copies of an allele to express resistance, which is unlikely if the frequency of the mutation is low[131].

Key resistance management points to consider

- A medium- to long-term challenge for the Australian grains industry will be minimising risk of resistance development in FAW to Group 5 (spinosyns), 6 (avermectins), 22A (oxadiazine) and 28 (diamides). Resistance to these groups is not common globally and thus little is known about how field populations might adapt to these chemicals over time. These four chemical groups are important newer modes of action that are displacing chemical groups, such as Group 1 (carbamates and organophosphates) and 3A (pyrethroids).
- Groups 5, 6, 22A, and 28 are important in control of other Lepidopterans in grain crops, so there is considerable potential for multi-species selection for resistance in the field.
- FAW could pose a threat to *Helicoverpa* resistance management if there is an increase in the frequency of spraying in broadacre crops where FAW and *Helicoverpa* occur together, for example in maize and sorghum. It will therefore be important that a resistance management strategy for FAW consider *Helicoverpa* resistance management.

FALL ARMYWORM EXTENSION

Australia is in the early stages of a FAW incursion and the development of practical and strategic solutions for crop advisor/consultant/grower decision making needs in the short, medium, and long term is of upmost importance. It will be essential to utilise existing accumulated scientific information on FAW in the development of extension resources.

The following section provides guidance on the expected evolution of messaging needs that will occur in relation to FAW over the short and medium term, and the key points that advisors and industry representatives should consider when developing training materials and delivering communication on FAW.

Evolution of messages after a new pest is found

Messaging needs will evolve as the industry learns to manage this new invasive pest. It must also be recognised that the industry's understanding of the pest and local conditions will grow more sophisticated over time according to industry needs and available research findings. Experiences with Russian wheat aphid is a good example of this. Russian wheat aphid communication has evolved since it incurred in 2016, in line with the changing situation and industry understanding. The expected evolution of messaging needs for FAW over the short to medium term are estimated in Table 13, although fine tuning at a local level will be necessary.

Table 13. Expected message evolution over the short to long term

	• AFFECTED REGIONS	• UNAFFECTED REGIONS
Short-term (<6 months)	• Damage symptoms • How to confirm a detection • Identification • Lifecycle information • Monitoring • Immediate management considerations • Confirmed host range and host susceptibility • Threshold guidance • Status of permits • Highlight resistance risk • (High focus on these regions)	• Identification • How to confirm and report an identification • Why reporting is necessary if eradication is not possible • Distribution • Confirmed host range and host susceptibility • Preparedness for management – what you need to know
Medium-term (6-24 months)	• Research findings (e.g. threshold validation) • Updates to management advice	
Long -term (>24 months)	• Updates to management advice • Chemical registration approvals	

Key questions raised about FAW at the outset of the incursion

An appreciation of key concerns, knowledge gaps and needs, is an important step when developing a national knowledge base for FAW. Feedback from stakeholders should be addressed at the regional, or even farm level and is likely to include questions which relate to monitoring, seasonal risk, impact and control. These are highlighted in Table 14.

Table 14. Key questions to support development of extension resources and extension activities

TOPIC	KEY QUESTIONS
Monitoring	What lures should be placed out, how and when? What are the signs of infestation? At what time of year would this occur? How do infestation signs differ by crop and crop growth stage? How does FAW differ in how it looks compared to other caterpillars found in the area? Would they be found in the same crop, or in the region at the same time?
Seasonal risk	Where will FAW be found throughout the year? If FAW is expected to migrate, when will it appear? If FAW is expected to remain in the region, what will it survive on throughout the year? How can green bridge risk be reduced?
Impact	When are crops most susceptible? What crops and varieties are most susceptible? When is the highest 'risk' window across crops?
Control	What thresholds are available? What permits are available? How effective are these chemicals? When and how should they be applied? Are there non-chemical options to help control FAW? What beneficials will impact on FAW? Is it resistant to any chemicals? How can resistance be managed?

Considerations when undertaking extension

FAW has been regularly described as having a wide host range, and its effects will span many leviable crops in Australia. It will be important to maintain a coordinated knowledge base across plant industry sectors to avoid duplication and fragmentation in the development of research findings or extension resources. Only four months after the first detection there is a plethora of resources that have been developed across industries at a regional, state, and national scale. It is important to recognise that development of more resources may hinder attempts to extend clear guidelines for identification and control of FAW, and some measure of rationalisation, within and across industries should be considered before the number of available resources become too abundant and distracting. In the months and years following the first FAW detection growers and advisors may suffer from information overload and confusion if advice varies.

A summary of considerations when developing communications or training materials for FAW are provided in Table 15 (page 67).

Table 15. Summary of considerations when developing communications or training materials for FAW

CONSIDERATION	DESCRIPTION
Priority Extension in Affected regions	Priority needs may be identified quickly by organizing a local grower advisory group in each affected region to provide feedback on extension needs, which may then inform short-term, local extension activities throughout the season. In current and future FAW affected regions there is an immediate need to build confidence in FAW identification and knowledge of management considerations, particularly as management advice is refined over time. An iterative extension approach delivered over several seasons would place an emphasis on re-engaging a core group of industry participants in multiple activities, resulting in the building of capability at the local level among a nucleus of informed individuals who may transfer knowledge to counterparts.
Leverage existing extension networks	Regional grain grower groups and agronomy business have the potential to form a strong communication network, particularly in the social media space, for distributing key messages about FAW. Regional grower group communication networks can be leveraged to extend messaging about FAW and reach industry members who do not follow GRDC communication channels.
Linking with educational initiatives	Linking with educational initiatives undertaken by sympatric or similar crop industries Based on feedback from industry in affected regions it is also worth considering methods for strengthening the ties between researchers and advisors / growers, such as inviting researchers to affected regions for guest presentations (or virtual presentations).
Peer to peer learning	There are many communication, extension and training needs that will need to be met on the topic of FAW, and formal or informal peer to peer learning channels may be used to increase extension effectiveness. Peer to peer learning activities have the potential to play a significant role in increasing FAW management knowledge in affected regions, as well as to pre-emptively increase grower and advisor confidence in unaffected regions. One risk with this approach is the potential for incorrect advice to be transferred from peer to peer. Therefore, there will need to be some level of review involved when publishing interviews or inviting growers / advisors as speakers at meetings.
Drawing on overseas information	Basic topics that may draw on information available from overseas include: FAW lifecycle, available information on hosts, feeding damage symptoms, lures and traps. Another topic that may be an early focus is available chemistry and integrated pest management (IPM basics). It is important to consider that messaging across different countries differs and country and regional differences will need to be acknowledged. International outputs should be reviewed by Australian entomologists before use as extension resources for Australian growers to ensure that information is pertinent to the Australian context.
Regional messaging	Regionally tailored management recommendations will be important according to how FAW behaves in the region, crops grown, knowledge levels, and communication network strength.
Linking with on the ground regional contacts	Consulting with grower groups has the benefit of creating time efficiencies and would aim to leverage the collective knowledge of grower group staff and board members who maintain extensive professional networks.
Non alarmist messaging	Non alarmist messaging is vital, sensationalising the situation can cause unnecessary stress for growers
Gain feedback	Gaining feedback on what needs to be known at a regional level

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