Final Report

Identifying potential parasitoids of the fall armyworm, *Spodoptera frugiperda*, and the risk to Australian horticulture

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Project:

Identifying potential parasitoids of the fall armyworm, *Spodoptera frugiperda*, and the risk to Australian horticulture (MT19015)

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Public summary

Fall armyworm (FAW) was first detected in January 2020 in far-north Queensland. It quickly spread and established in several locations in Queensland, Western Australia, the Northern Territory, New South Wales and Victoria. Establishment of FAW in production areas has caused major concerns for the sweet corn and vegetable industries. Within a short period from the initial detection of FAW, high levels of crop damage (up to 80%) were recorded in organic and conventional sweet corn crops and to some extent in other vegetable crops such as capsicums. The rapid rise in FAW numbers and the high use of pesticides to manage the pest are a major threat to existing Integrated Pest Management practices adopted by the vegetable industry for other pests.

Hort Innovation funded a multi-industry project to examine the potential use of endemic parasitoids to manage FAW in Australia. The aims of this project were to conduct field surveys of FAW host plants and its endemic parasitoids, a comprehensive literature review of FAW parasitoids, and an economic risk analysis for horticultural crops in Australia. The project team from the QLD Department of Agriculture and Fisheries (DAF), the WA Department of Primary Industries and Regional Development (DPIRD), and the NT Department of Industry, Tourism and Trade (DITT) conducted regular field surveys and crop samplings to study the host crops and endemic parasitoid fauna associated with FAW.

Field surveys were conducted in the QLD, WA, NT and NSW locations targeting sweet corn, capsicum, and melons. More than 6400 FAW larvae and 750 egg masses were sampled across 65 locations between March 2021 and May 2022 and reared to recover parasitoid species. The number of parasitised FAW larvae varied between 1.3 and 47% of larvae collected at different sites, with a total of 961 parasitised larvae recovered from across all locations.

The team discovered 18 endemic parasitoid species that attack egg and larval stages of FAW. The species were taxonomically identified using molecular techniques and morphological characters. Among the list, three species are unique to Australia and have not been previously reported as attacking FAW larvae. Better understanding of the parasitoid and predatory fauna will allow growers and consultants to make better decisions about spray timing and pesticide selection, including using 'softer' insecticides to preserve beneficial populations.

The project staff completed a literature review of FAW parasitoids from countries where the FAW pest is well-established. The literature review provides detailed information on the parasitoids associated with FAW overseas and parasitoids of closely associated noctuids already present in relevant Australian horticultural crops. From this dataset, a list of 87 parasitoid species that are known to attack FAW were identified, and also 15 known species found as parasitoids of FAW that are already present in Australia. The next step is to investigate the potential of these species for controlling FAW in Australia.

The project has documented a FAW host plant list. Knowing the host plant range will enable growers to manage cultivated crops and surrounding non-crops to reduce FAW populations.

The project economist has calculated the risk that horticultural crops in Northern Australia face from FAW populations. In the first-year, losses total $409 million or 23% of total losses. However, once industry adjustment occurs, losses are dramatically reduced with an estimated annualised loss of $59 million across Northern Australia.

Technical summary

In Australia, sweet corn and maize are reported as a highly preferred host crops of fall armyworm *(Spodoptera frugiperda*; FAW). Within the short period from the detection of FAW, significant crop damage (anecdotally up to 90%) was observed in sweet corn and maize crops in QLD, NSW and WA. Whilst damage to other horticultural crops has been limited, there is concern that, as populations increase, and FAW adapts to Australian conditions it will move onto other crops. Recent infestations of FAW include brassicas, capsicum, melons, cucumber, heliconia and okra. This report describes the scientific literature review of FAW parasitoids, economic risk analysis for horticulture crops, results of the field survey and sampling of endemic parasitoids, and update on FAW host plant status.

Parasitoid surveys in several locations of QLD, WA, NSW and NT by followed a sampling protocol, under appropriate COVID-19 and farm biosecurity measures. Fall armyworm collections and damage surveys have included sweetcorn, capsicum, cucurbits, tomato and cover crops. More than 6400 FAW larvae and another 750 egg masses were collected across 65 locations in QLD, WA, NT and NSW during March 2021 to May 2022. FAW larvae and eggs were reared under laboratory condition to recover parasitoid species. A total of 961 parasitised larvae were recovered with parasitism at the various locations ranging between 1.3 and 47 %.

The emerged parasitoid specimens were taxonomically identified using molecular techniques and morphological characters. Eleven hymenopteran and five dipteran species of larval parasitoids, and two egg parasitoids were identified (details in Table 1 and 2). Hymenopteran parasitoid species that emerged from fall armyworm larvae were *Cotesia ruficrus*, *Cotesia icipe*, two *Chelonus* spp., and two *Coccygidium* spp., *Eriborus sp, Microplitis abrs, Temelucha* sp, an unidentified Eulophid, and an unidentified Ichneumonid. Dipteran larval parasitoid included two tachinids (*Exorista xanthaspis and Drino sp),* two unidentified tachinids and one phorid (*Megaselia scalaris*). Two egg parasitoids were collected, *Trichogramma pretiosum* and *Telenomus sp.*

A literature search was undertaken using the GoogleScholar, Web of Science, and CABI databases and library holdings. The list of parasitoids was compiled from the references in a database along with associate information about taxonomy, host range, presence in Australia, and geographic range. This search yielded 124 full length peer-reviewed articles and 2 technical reports. For each of the 113 parasitoids meeting the criteria we cross-checked the nomenclature to avoid duplication, and gathered additional information regarding the host range, climate, and distribution. From this source dataset, a list of 87 parasitoid species that are known to attack fall armyworm was identified. A second list was compiled of fifteen known parasitoids species found as either endoparasitoids or ectoparasitoids of fall armyworm that are already present in Australia parasitising key lepidopteran horticultural pests.

Establishment of fall armyworm in the production areas has caused major concerns for the sweetcorn and vegetable industries. Results indicate economic losses from fall armyworm to be between $1.3 and $1.7 billion across Northern Australia with 79 per cent of the losses originating in Queensland. The majority of losses occur in the first 5 years after infestation whilst producers shift to the next best commodity, that is either non-susceptible or less susceptible to Fall Armyworm. In the first year, losses total $409 million or 23 per cent of total losses. However, once industry adjustment occurs losses are dramatically reduced with an estimated annualised loss of $59 million across Northern Australia.

The project findings including key parasitoid species with identification characters and their potentials were delivered to the horticulture industry at Hort Connection conference in Jun 2021, webinars, AUSVEG industry meetings and local field days.

Keywords

Fall armyworm (FAW); *Spodoptera frugiperda;* field survey; sweetcorn; parasitism; parasitoid; *Costesia*; *Chelonus; Telenomus*; *Trichogramma*, Tachinids.

Introduction

Fall armyworm was detected throughout northern, western, and southern regions of Australia after initially being found in the Torres Strait Islands and Bamaga in Cape York. It was first detected in March 2020 in the Bowen, Burdekin, and Mareeba production regions. Subsequent detections were reported in Kununurra, Darwin, Katherine, Broome, Carnarvon, Bundaberg, Southern QLD, Northern NSW, Gippsland (VIC) and recently in TAS.

Year-long establishment of FAW in the production areas in QLD, WA, NT, NSW and seasonal establishment in Vic has caused major impacts for the sweet corn and vegetable producers in those areas. In Australia, sweet corn and maize are reported as a highly preferred host crops of FAW. Within the short period from the detection of FAW, significant crop damage (anecdotally up to 90%) was observed in sweet corn and maize crops in QLD, NT and WA, and NSW,. Whilst damage to other horticultural crops has been limited, there is concern that, as populations increase, adapt to Australian conditions, and the favoured host plants (maize/sweetcorn) vary in availability, the pest will move onto other crops. Recent infestations have been recorded on some other horticulture crops such as brassicas, capsicum, melons, cucumber, heliconia and okra. FAW has also become a significant pest for the production of fodder for the grains and livestock industry, mainly maize and sorghum.

The rapid rise in FAW numbers has become a major threat to the IPM practices currently used by the vegetable industry. The increased use of insecticides to control FAW in various crops is highly disruptive to natural enemies and biological control programs. There is also a concern that pesticide failure will occur due to current and emerging genetic resistance. FAW populations from the production regions of NT, NSW, QLD and WA were confirmed to already have gene alleles associated with organophosphate and carbamate resistance (Nguyen *et al.* 2021) and exhibited reduced sensitivities to pyrethroid insecticides (Bird *et al*. 2022). Therefore, the use of insecticides cannot be considered as a stand-alone technique to manage fall armyworm infestations and their continued used may impose additional selection pressure to develop further resistance. The development of integrated pest management (IPM) strategies will necessitate the use of natural enemies and developing biological control is a priority for sustainable management of fall armyworm in Australia.

Field surveys in other countries have documented various parasitoid species attacking fall armyworm larvae in the U.S. (Pair *et al*. 1986) and South America (Murúa *et al*. 2009). As FAW has arrived recently, there is no information on parasitoids attacking fall armyworm in Australia. Identification of naturally occurring parasitoids that can parasitise fall armyworm may yield another tool for fall armyworm management in Australian horticulture.

Hort Innovation has funded this project (MT19015) to conduct a comprehensive literature review on FAW parasitoids, survey fields to collect endemic parasitoids associated with FAW, and undertake an economic risk analysis for relevant horticultural crops in Northern Australia. This project directly contributes to Strategic Investment Plan (SIP) of vegetable industry Outcomes 3 ‘increasing farm productivity and decreased production costs through reduced impact of pests’ by identifying possible biocontrol agents that will protect the vegetable industry from both endemic and exotic pests. This project also aligns to SIP’s of Onion (outcome 3), Melon (outcome 2), Sweetpotato (outcome 2) Nursery (outcome 3) and Turf (outcome 3).

Methodology

1. Field surveys and parasitoid taxonomic study

A sampling protocol outlines the methodology and specifies detailed steps to survey for fall armyworm (*Spodoptera frugiperda*) predators, parasitoids and entomopathogens was developed. This protocol was used as a guide for field surveys and samplings by the project staff and collaborating agronomists (see Appendix 1). Field surveys for FAW parasitoids were in the FAW established production regions in QLD, WA, NT ,and NSW as regularly as possible during the production seasons and within the constraints of the COVID-19 pandemic (Table 1 and 2). FAW eggs and larval samples were collected from commercially grown organic and conventional sweetcorn, maize, sorghum and other vegetable crops.

In Western Australia a total of 11 sites were selected for the survey (4 in Kununurra, 4 in Carnarvon and 3 Broome). In Queensland, the parasitoid surveys were conducted in 21 sites North QLD (Bowen, Gumlu and Burdekin) and 9 sites at far North QLD (Mareeba, Atherton and Innisfail). The survey in the Northern Territory was conducted in in Darwin and Katherine regions across 10 sites. Surveys in some areas were not conducted during spring and summer in 2021 due to COVID-19 lockdown and travel restrictions. NSW (Bonshaw and Glen Innes) and SE QLD (Lockyer and Fassifern valleys) surveys were conducted in 7 sites in collaboration with local agronomists from Mulgowie farming and Kalfresh Pty Ltd during March to May 2022.

Field collected eggs and larval were reared in the laboratory with artificial diet or host plant foliage. The emerged egg and larval parasitoids were sent to Dr. Erinn Fagan-Jeffries at the University of Adelaide for morphological and molecular identification. Details information on sampling locations, survey periods, host crops, sample size and rearing methods are given in Appendix 1, 2 and 3.

2. **A comprehensive literature review of FAW parasitoids**

A literature search was undertaken using the GoogleScholar, Web of Science, and CABI databases and searching library holdings using the following search terms: "Natural enemies of fall armyworm", "parasitoids of fall armyworm", "parasitoids of *Spodoptera* species", "parasitoids of *Helicoverpa* species", "distribution of lepidopteran parasitoids", and "parasitoids of Australian horticultural noctuids".

It is anticipated that parasitoids, adapted to *Spodoptera litura* may be able to readily expand the host range to *S. frugiperda* (FAW). Likewise, two other noctuids *Helicoverpa armigera*, and *H. punctigera* were also selected as they have an overlapping host range with *S. frugiperda*. *Helicoverpa punctigera* is also a native insect and therefore may have a host of native parasitoids that could shift to attack *S. frugiperda*. The list of parasitoids was compiled from the references in a database along with associated information about taxonomy, host range, presence in Australia, and geographic range. Full details of this review are found in Appendix 5).

3. Economic Impacts of Fall Armyworm on vegetable crops in Australia

A *Benefit Cost Analysis (BCA)* framework is used to estimate the potential economic losses of incursion of Fall Armyworm. In this method, the time preference of money (opportunity cost) is accounted for by discounting future benefits and costs to present values or compounding past benefits and costs to present values. A base year of 2021 is used. All dollar costs and benefits are expressed in constant dollar terms and discounted or compounded to that year. Economic losses at the State and National level are measured using the investment criteria of Net Present Value (NPV). The NPV is the difference between the Present Value (PV) of benefits and the PV of costs (more details in Appendix 6).

Results and discussion

1. Field surveys and parasitoid taxonomic study

Western Australia field survey: One egg and six larval parasitoids have been found to attack fall armyworm in Western Australia (Table 1). A total of 171 larval parasitoids were collected from the 1222 FAW larvae sampled yielding an overall parasitism rate of 14%. Parasitoid species that emerged from fall armyworm larvae were *Cotesia ruficrus* Haliday (Hymenoptera: Braconidae) (strain B), one unidentified eulophid wasp species (Hymenoptera: Eulophidae), two unidentified tachinid spp. (Diptera: Tachinidae), *Coccygidium* spp. (Hymenoptera: Braconidae), and *Megaselia scalaris* Loew (Diptera: Phoridae). *Trichogramma pretiosum* Riley (Hymenoptera: Trichogrammatidae) was recovered from fall armyworm eggs but only at the Kununurra research station where the sentinel eggs were set out. Overall, nine out of 144 released egg masses (6.25%) were parasitised by *T. pretiosum* (see detailed report in Appendix 2)

Queensland and NSW parasitoid survey: In Bowen and Burdekin regions, one egg and 13 larval parasitoids have been found to attack fall armyworm in sweetcorn. In the regions, a total of 3285 FAW larvae and another 468 egg masses were collected during March 2021 to April 2022 and reared to recover parasitoid species. A total of 487 parasitoids were recovered with parasitism ranging between 1.3 and 25.3 % (Table 1). Hymenopteran parasitoid species that emerged from fall armyworm larvae were *Cotesia ruficrus* strain B, *Cotesia icipe*, two *Chelonus* spp., and two *Coccygidium* spp., *Eriborus* sp*., Microplitis abrs, Temelucha* sp. and unidentified Ichneumonid. Dipteran larval parasitoid were two tachinids (*Exorista xanthaspis and Drino* sp*.)* and one phorid (*Megaselia scalaris*). One egg parasitoid (*Trichogramma pretiosum*) was identified. In Bowen and Burdekin locations, *Cotesia ruficrus* strain B*, Chelonus* sp. *and Coccygidium* spp. were the common larval parasitoid recorded from all surveyed farms.

In Mareeba and Atherton, five larval parasitoids have been found to attack fall armyworm in maize and sweetcorn. A total of 170 larval parasitoids were collected from the 698 FAW larvae sampled yielding an overall parasitism rate of 24.3%. Hymenopteran parasitoid species that emerged from fall armyworm larvae were *Cotesia ruficrus*, *Coccygidium* spp., *Chelonus* sp., and *Eriborus* sp. One dipteran parasitoid was *Drino* sp.

SE QLD (Lockyer and Fassifern valleys) locations, one egg and six larval parasitoid species have been found to attack fall armyworm in sweetcorn. In the regions, a total of 489 FAW larvae and another 52 egg masses were collected during March to May 2022 and reared to recover parasitoid species. Hymenopteran parasitoid species that emerged from fall armyworm larvae were *Cotesia ruficrus* strain B, two *Chelonus* spp., *Microplitis abrs,* and *Temelucha* sp. The most common larval parasitoid found in all the sampling locations was the phorid, *Megaselia scalaris* (Diptera: Phoridae).

In NSW (Bonshaw and Glen Innes), the most abundant larval parasitoids found in both sampling locations were phorid flies, *Megaselia scalaris*, with parasitism ranging between 33 and 51%. No hymenopteran parasitoids were recorded from the samples

Northern Territory Survey: A total of 65 larval parasitoids were emerged from the 666 FAW larvae sampled from Darwin and Kathrine locations. Four larval parasitoids and one egg parasitoid species were recorded in all sampling sites. The most abundant larval parasitoids found in almost of the sampling locations were the Tachinid *Exorista xanthaspis* and the Braconid *Chelonus* sp1. The *Chelonus* sp., had an average percent parasitism of 12.38% but can reach as high as 25%. On the other hand, for the *E. xanthaspis* the average parasitism rate was at 9.13% and the highest parasitism was at 22%. Egg masses were only retrieved from the field in the Darwin region and of the total 73 egg masses collected only one egg mass was parasitised with egg parasitism rate of 27%. The egg parasitoid emerged matches the sequences of the genus *Telenomus* and the species is likely to be a *Telenomus remus* which believed to be introduced into Australia to control some lepidopteran pests (Michael *et al*., 1984) (detailed report in Appendix 3).

Table 1. Summary of the larval parasitoid sampling of Fall armyworm, *Spodoptera frugiperda,* across Australia.

Location	Host crops	Sampling Months (2021 - 2022)	Number of sites	Number of samplings	Total number of larvae collected	Number of larvae parasitised	Parasitism range (%)	Type of parasitoids (family, genus or species)
Kununurra WA	Maize	Jun – Sep 21	4	38	736	71	1 – 6.2	*Costesia ruficrus (strain B)* Eulophid sp. Tachinid sp1 *Coccygidium* sp1
Carnarvon, WA	Sweet corn	Aug– Sep 21	4	8	352	89	9 – 14.4	*Costesia ruficrus*; Eulophid sp. Tachinid sp1
Broome, WA	Maize	Sep 21	3	3	134	11	1.8 – 6.5	Tachinid sp1 and 2 *Megaselia scalaris*
Katherine, NT	Sorghum	Apr, 21 Mar, 22	2	2	84	8	2.7 - 14.9	*Exorista xanthaspis*; *Coccygidium* sp1; Cholopidae sp.
Darwin, NT	Sweet corn	Aug- Sep	3	10	582	57	0.0 – 24.6	*Chelonus* sp1; *E. xanthaspis*
Bowen/ Gumlu, QLD	Sweet corn	Mar- Dec 21	14	42	2114	146	4.0 – 39.3	*Chelonus* sp1 *Chelonus* sp2 *Coccygidium* sp1 *Coccygidium* sp2 *Cotesia ruficrus* (strain B) *Eriborus* sp. 1 Ichneumonid sp *Microplitis abrs* *Temelucha* sp. 1 *Driono sp.* *E. xanthaspis* *Megaselia scalaris*
	Sorghum; Sweet corn	Jan - Apr 22	3	8	524	76	4.3 – 12.6	
Burdekin QLD	Sweet corn	Jul – Sep 21	7	14	391	6	1.3 – 2.5	*Chelonus* sp1 *Cotesia icipe* *C. ruficrus* (strain B)
Lockyer Valley QLD	Sweet corn	Mar- Apr 22	2	2	96	5	0.0 – 11	*Chelonus* sp1 *Chelonus* sp2 *Microplitis abrs*
Fassifern Valley QLD	Sweet corn	Mar– May 22	4	6	255	27	3.5 – 36.6	*Cotesia ruficrus* (strain B) *Megaselia scalaris* *Temelucha* sp. 1
Texas, NSW	Sweet corn	Mar 22	2	2	80	36	36-51%	*Megaselia scalaris* (Phorid fly)
Mareeba, QLD	Maize	Mar-Sep 21	3	5	427	105	12.6- 43.6	*Coccygidium* sp1 *Costesia ruficrus* *Chelonus* sp1 *Drino* sp. (tachinid)
Dimbulah QLD	Rhodes grass	Feb 22	2	2	53	26	42.4 - 60	*Drino* sp. (tachinid)

Table 2. Summary of the egg parasitoid sampling of Fall armyworm, *Spodoptera frugiperda,* across Australia.

Location	Host crops	Sampling Months	Number of sites	Number of samplings per site	Total number of egg mass collected	Number of egg mass parasitised	Parasitism range (%)	Taxonomic group
Kununurra WA	Maize *	Jun - Sep	1	13	144	9	6.25	*Trichogramma pretiosum*
Katherine NT	Sweet corn	Aug- Sep	2	1	8	0	0	
Darwin NT	Sweet corn	Aug - Sep	1	1	14	0	0	
	Sweet corn #	Sep	1	1	7	4	41.5 -79.1	*Telenomus* sp.
Bowen QLD	Sweet corn	May	2	2	120	0	0	
		Sep	1	2	21	0	0	
		Oct	1	2	53	6	11.3	*Trichogramma pretiosum*
Burdekin QLD	Sweet corn	Jul	2	2	42	0	0	
Fassifern valley QLD	Sweet corn	Mar 22	2	2	52	3		*Trichogramma pretiosum*

*FAW Egg masses glued on cards (sentinel card) were clipped to maize plants and recovered after 24 hours for assessing parasitism

Potted sweetcorn plants with FAW eggs (sentinel plants) were exposed for 24 hours in the field and assessed egg parasitism.

2. A comprehensive literature review of FAW parasitoids

A literature search was undertaken using key search terms within national and international publication databases and search engines. This search yielded 124 full length peer-reviewed articles and 2 technical reports. For each of the 113 parasitoids meeting the criteria, we reviewed the nomenclature to resolve any duplication, and gathered additional information regarding the host range, climate, distribution. From this source dataset, a list of 87 parasitoid species that are known to attack fall armyworm overseas was identified. A second list was compiled of fifteen known parasitoid species found as either endoparasitoids or ectoparasitoids of fall armyworm that are already present in Australia parasitising key lepidopteran horticultural pests. Existing parasitoid species of well-established noctuid pests were evaluated for the prospect of being a plausible (either conservation or augmentation) biological control agent for *S. frugiperda* in Australian horticultural systems. We also evaluated the potential of seven parasitoids that are not currently present in Australia but demonstrated efficacy in managing fall armyworm overseas. The prospects of classical biological control through the introduction of those parasitoid species into Australia from their native range is unlikely for any of the identified parasitoids, given their lack of host specificity and difficulty in mass rearing. However, two key egg parasitoids (*Trichogramma pretiosum* and *Telenomus*, especially *Telenomus remus)*, larval parasitoids in the genus *Cotesia* especially *Cotesia ruficrus*, egg-larval parasitoids in the genus *Chelonus* were evaluated as key candidates for biological control of fall armyworm in Australia. (see full report in Appendix 4). Further research is required to evaluate these groups of parasitoids for their potential efficacy and use in augmentative or conservation biological control of FAW.

3. Economic Impacts of Fall Armyworm on vegetable crops in Australia

This report details the results of economic modelling on the impact of FAW in Northern Australia and the potential benefit of integrated pest management. Two scenarios are modelled: Production shift to next best crop, IPM not economically viable; As per Scenario 1, with R&D investment generating either new varieties, chemicals or biocontrol by year 10.

Results indicate economic losses from Fall Armyworm to be between $1.3 and $1.7 billion across Northern Australia with 79 per cent of the losses originating in Queensland. The majority of losses occur in the first 5 years after infestation whilst producers shift to the next best commodity, that is either non-susceptible or less susceptible to Fall Armyworm. In the first-year losses total $409 million or 23 per cent of total losses. However, once industry adjustment occurs losses are dramatically reduced with an estimated annualised loss of $59 million across Northern Australia (full report Appendix 5).

4. Fall armyworm host plant status and crop losses

To collect FAW host plant data, the project team have used multiple approaches including direct field visits to commercial farms to conduct inspections and collect samples from vegetables crops, collating records of samples and phone enquires received from clients on FAW and discussion with local agronomists and crops monitors. During field visits, we have inspected between 80 and 120 plants for each crop as listed in **Table 3.** Since the FAW establishment in Feb 2020, amongst the vegetable crops, impact on sweetcorn crops was the most severe with major losses due to unmarketable cobs ranging between 15 and 70%. On few occasions, FAW has been found feeding on watermelon, rock melon, cucumber, heliconia flowers, ginger, turmeric and okra. It has also been recorded as a pest on sorghum, maize, Rhodes grass, cotton (non-Bt), sugarcane, and millet grown for fodder or grain.

In 2021 crop survey results also showed that FAW infestation in capsicum crops is widespread across several commercial farms in the Gumlu and Bowen region where fruit damage between 10 and 20% recorded in the field and packhouse. In 2022 season, FAW infestation is much higher in capsicum crops and more than 40% of harvestable size capsicum fruit had FAW larvae inside or feeding damage.

Table 3. Summary of FAW host plant surveys in horticulture production areas 2021 season

Sampling Month	Location	Crops	Planted area (ha)	No. of plants or fruit inspected	No. plant or fruit Infested	No. of Egg masses	No. of larvae
March	Bowen	Capsicum	5	120	6	6	NA
		Watermelon	4	80	2	2	0
		Mungbean	1	100	0	0	0
		Dolichos	1	100	0	0	0
Mid -April	Gumlu QLD	Capsicum	5	100	14	10	6
Late April	Gumlu QLD	Capsicum - field fruit	8	180	38	4	21
		Capsicum fruit	Packhouse fruit	54	19	2	16
	Gumlu	Cucumber	2	80	2	1	1
	Gumlu	Melons	4	100	1	1	0
April	Bowen	Capsicum	3	100	0	0	0
May	Bowen	Tomato	5	120	2	2	0
		Sweet corn	10	200	62	21	48
May	Gumlu	Capsicum	6	110	18	0	16
June	Gumlu	Capsicum	5	100	5	0	3
June	Bowen	Sweet corn	6	120	35	0	43
		Pumpkins	5	100	0	0	0
		Capsicum	4	120	0	0	0
July	Gumlu	Capsicum	5	100	1	0	1
August	Bowen	Capsicum	4	100	0	0	0
		Sweetcorn	4	120	25	15	38
Sep	Bowen	Capsicum	2	100	1	0	1
		Sweet corn	5	120	65	23	74
Oct	Bowen	Capsicum	4	100	2	0	2

		Sweetcorn	5	120	79	74	86

Outputs

Table 4. Output summary

Output	**Description**	**Detail**
Comprehensive national and international literature review on parasitoids	Literature review focused on parasitoid species associated with FAW and related Spodoptera occurring in Australia	Literature search yielded 124 full length peer-reviewed articles and 2 technical reports. A list of 87 parasitoid species that are known to attack fall armyworm was collated. The literature review report included Appendix 5.
Regional data on FAW distribution and damages in horticulture crops.	Host crop surveys were focused on vegetable and associated cover crops cultivated during the production season.	Crop survey conducted in NQLD for 2021 season is summarised in Table 3. FAW infestations and damage in capsicum and other crops reported.
Regional data on the presence endemic parasitoid	Extensive field surveys and sampling were completed in NQLD, WA, NSW and NT. Parasitoids reared for identification.	Endemic parasitoid species that are attacking FAW eggs and larvae were identified, and a list produced – Table 1 and 2. Full reports are in Appendix 2, 3 and 4.
Report on FAW risk analyses for horticultural crops	A Benefit Cost Analysis framework was used to estimate the potential economic losses of incursion of Fall Armyworm	Report on economic impacts of FAW on vegetable crops in Australia is completed and included Appendix 5.
A pictorial guide for FAW and its parasitoids	Regional data, information and images of endemic parasitoid and other beneficial species were collected to produce a grower guide	A pictorial guide of key and potential parasitoids associated with FAW in Appendix 6.
Industry communication – growers / industry meetings or webinar	Used webinars, industry meetings, growers guide to deliver project information.	Parasitoid information delivered to vegetable industry at various industry meetings, Hort connection conference and industry magazine Endemic parasitoids and predators results included in "FAW management guide" (Nov 2021 AusVeg publication)

List of Extension and communication activities:

1. FAW management in vegetable crops; Hort Connection Conference, Brisbane Jun 2021. Oral presentation by Siva Subramaniam (DAF).
2. *Management of fall armyworm in vegetable crops in Australia* (Nov 2021). Zali Mahony (AUSVEG) and Siva Subramaniam (DAF). https://ausveg.com.au/app/uploads/2021/12/Final-pdf-standard-faw-guide_compressed.pdf
3. Webinar presented by Siva Subramaniam (30 Sep 2021) *FAW management research update* as part of DAF's Vegetable Industry Webinar series hosted by Heidi Parkes.

   https://www.youtube.com/watch?v=2DENdz440sY&list=PL3dFDqBJiUG3iJV6LMh4BR4GMxnn6ePRh&index=6
4. Siva Subramaniam interviewed by Vegetables Australia for the article *Managing fall armyworm: a destructive, fast-moving pest* in the Vegetable Australia magazine Summer 2021/22 (page 88-89).

   https://ausveg.com.au/app/uploads/2021/11/AUSVEG_VegetablesAustralia_2021_Summer_WEB_100DPI_F01v1.pdf
5. FAW armyworm: Opportunities for integrated management. Queensland Horticulture Pest & Disease Workshops (AusVeg). Presentation by Siva Subramaniam at Ayr 20 July and Gumlu 21 Jul 2022
6. Talk on fall armyworm and parasitoids by Brian Thistleton at the The Northern Territory Farmers Association (NT Farmers)/DITT cropping field day at Douglas Daly on 25/11/2021
7. ABC NT Country Hour interview on fall armyworm and parasitoids, December 2021,
8. Discussions and demonstrations to growers on fall armyworm and parasitoids by Frezzel Praise Tadle and Brian Thistleton at NT Farmers vegetable growers workshops at Marrekai on 24/02/2022 and Humpty Doo on 03/06/2022
9. DPIRD Grains Portfolio and Farming Systems Innovation meeting, December 8 2021, Perth, Western Australia
10. Ord Irrigation Area pest and disease meeting with presentation on fall armyworm parasitoids, 22 November 2021
11. Workshop with Carnarvon and Wanneroo vegetable growers on fall armyworm management including the conservation of parasitoids March 2021.
12. Western Australia Grains IFS committee meeting to discuss fall armyworm parasitoids. October 22, 2021.
13. Seminar delivered to Applied Biosciences group at Macquarie University 3 August 2021.

Outcomes

Table 5. Outcome summary

Outcome	Alignment to fund outcome, strategy and KPI	Description	Evidence
Knowledge and information of potential parasitoids for future IPM program of fall armyworm,	Contribute to Vegetable Fund Outcome 1 Strategy 2 - Identify and support opportunities to improve productivity and sustainability through effective IPDM. KPI: Pest and disease management strategies are developed that mitigate crop loss in collaboration with growers	Change in industry knowledge and understanding suitability of endemic parasitoids for FAW management specific to growing regions	Completed crop surveys in major production areas of QLD, WA, NT and NSW and taxonomic identification 18 endemic parasitoid species. Five species recommended for further research and evaluations.
Better understanding of potential FAW parasitoids and biological control in Australia and overseas		Improved knowledge of researchers, agronomists indicating an increase in knowledge of biological control	Participatory approach - local farm agronomists involved in crop surveys of FAW and parasitoids. Ongoing field learning. Completion of parasitoid literature reviews – see report in Appendix 4. Key outcomes presented at Hort Connection conference 2021; National webinars; industry meetings. Contribution to FAW management guide
Evaluating the economic risk of FAW to Australian horticulture		Host plant survey in an FAW established location An economic risk analysis for relevant horticultural crops in Northern Australia	Vegetable and other FAW crops attacked or at risk identified and a list established (Table 3). Vegetable economic risk analysis completed – report in Appendix 6

Monitoring and evaluation

Table 6. Key Evaluation Questions

Key Evaluation Question	Project performance	Continuous improvement opportunities
To what extent has the project achieved its expected outcomes?	Through the completion of surveys and sampling in 65 sites across Australia, valuable knowledge and information were gathered on list of endemic parasitoids, taxonomic identifications, distribution of species, and field parasitism levels. The parasitoid literature review has provided detailed information on the parasitoids associated with FAW overseas and parasitoids of closely associated noctuid already present in relevant Australian horticultural crops. Calculated the risk that horticultural crops in Northern Australia face from FAW populations now and provided predictions for next 5 years. Complied FAW host plant list. Knowing the host plant range will enable growers to manage cultivated crops.	Further taxonomic identification/ DNA barcoding is required to confirm the new species reared from FAW larvae and eggs. Three endemic parasitoid species found are unique to Australia. Established collaboration with Adelaide University for further identifications and descriptions of species. FAW infestations and damages to capsicum fruit was recoded in NQLD locations in 2021. FAW is continuing its adaptation to capsicum as damage level increased to over 40% in commercial farms during 2022 season.
How relevant was the project to the needs of intended beneficiaries?	Identification of endemic parasitoids associated with the new pest have provided valuable information for future biological control and areawide management of the pest.	Performance of the key parasitoid species need to be studied under field conditions and the way to utilise these for FAW management.
How well have intended beneficiaries been engaged in the project?	Information on the endemic parasitoid species were delivered through the Hort connection conference and industry webinars. Parasitoid and predator information included in “FAW management guide” with AusVeg.	Webinars were recorded and made available to wider industry via YouTube.
To what extent were engagement processes appropriate to the target audience/s of the project?	Farm agronomists who have participated in the field sampling received updated information. Project information was presented at industry meetings in NQLD and NT Industry articles on AusVeg magazine and Melon news	Latest information of the project (eg beneficial guide) will be delivered through Hort Innovation funded project VG20003.
What efforts did the project make to improve efficiency?	Planned field surveys in NSW and SE QLD was delayed due Covid and travel restrictions. Alternatively, we have collaborated with local agronomists for sampling of FAW and sent to DAF labs for rearing and identification of species.	Interacting with agronomists who are working with growers has provided more learning opportunities and better understanding of pest management issues

Recommendations

1. An efficient endemic egg parasitoid *Telenomus sp* was found in the egg sentinels used during surveys in Darwin. This egg parasitoid is a potential candidate for biological control for fall armyworm in Australia. *Telenomus remus* has been widely used against fall armyworm in America for many years and even effective against other species of Lepidopteran pest (eg Heliothis, *Spodotera litura*). Further research needs to be conducted in Australia to evaluate the efficiency of this egg parasitoid in controlling the fall armyworm.

2. In this survey, the egg parasitoid *Trichogramma pretiosum* was found to be attacking fall armyworm eggs used on sentinel cards in Kununurra and with mass release of *T. pretiosum* in Bowen, but parasitism levels were very low. As *T. pretiosum* is commercially available for Heliothis management in Australia, further research would be valuable to determine their parasitism potential and ecological interactions with other lepidopteran hosts in sweetcorn production system.

3. Among the 15 endemic larval parasitoids found in the field surveys across the production regions in Australia, three parasitoids (*Chelonus* sp., *Cotesia ruficrus* and *Coccygidium* sp.) were frequently recorded in most locations. These three genera have been reported as the key parasitoids of fall armyworms in other countries. These parasitoids, as biological control agents, need further investigation in terms of their parasitism levels in the field, potential for mass-rearing, ecology, and conservation in horticulture production systems.

4. Among the list, three species of larval parasitoids belong to the genus *Chelonus and Coccygidium* have not been taxonomically described and appeared to be unique to Australia. Further taxonomic studies are required to identify them at species level and publish taxonomic descriptions.

5. Industry recommendation: Diverse range of endemic parasitoids (including predators) were found attacking FAW in the cropping locations surveyed. They are slowly adapting to new host (FAW) and providing some level of control in the field. It is important to preserve the natural enemies as to regulate FAW populations in the cropping system. Recent resistance studies have shown that established FAW populations were highly resistance to broad spectrum inscectides such as carbamate organophosphate and pyrethroids. These products are very harmful to the parasitoid and predator species naturally occurring in the crops. It is recommended that broad-spectrum inscectides are not used during mid to late vegetative stages of corn crops, instead growers should consider using permitted softer products such as NPV (Fawligen/ Spodovir Plus).

Refereed scientific publications

Project has created sufficient data and information for the following publications. The project team members in collaboration with taxonomist Dr. Erinn Fagan-Jeffries at the University of Adelaide have already discussed writing two scientific journal publications, a taxonomic key hymenopteran parasitoids and taxonomic description for the potential new species of *Chelonus* found in this study.

1. Survey of fall armyworm (*Spodoptera frugiperda*) parasitoids in Western Australia and Northern Territory
2. Survey of fall armyworm (*Spodoptera frugiperda*) parasitoids in Queensland and NSW.
3. Potential parasitoids for management of fall armyworm in Australian horticultural systems: a review of the literature.
4. Description of new species of fall armyworm parasitoids in Australia (C*helonus* species).
5. A taxonomic identification key for the hymenopteran parasitoids associated with fall armyworm in Australia.

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Intellectual property

No project IP or commercialisation to report

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Appendices

Appendix 1: Sampling plan for FAW predators, parasitoid and entomopathogens

Appendix 5: Economic Impacts of Fall Armyworm on vegetable crops in Australia

Appendix 6: A pictorial guide of potential parasitoids associated with Fall armyworm

Appendix 1 Sampling plan for FAW predators, parasitoid and entomopathogens

1 Purpose

This protocol outlines the methodology and specifies detailed steps to survey for fall armyworm (*Spodoptera frugiperda*) predators, parasitoids and entomopathogens.

2 Scope

While the title of the project refers to identification of potential parasitoids of the fall armyworm, it also refers in the outputs and outcomes to knowledge of parasitoids and predators. It does not refer specially to entomopathogens, but for completeness these are considered in this sampling plan.

Likewise, while the funding is for vegetables, potential parasitoids may be found on other crops and native plants, so sampling should not just be limited to vegetables.

3 Procedure

These procedures detail each step to be undertaken for experiments with each species

3.1 Sampling locations

The surveys will be conducted in the following areas:

3.1.1 Queensland

Bowen (priority A)

Burdekin (A)

Gumlu (A)

Locker Valley (A)

3.1.2 Western Australia

Kununurra (A)

Broome (B)

Carnarvon (B)

3.1.3 Northern Territory

Darwin (A)

Douglas Daly (B)

Katherine (A)

3.1.4 NSW

FAW established and corn growing locations– Texas/ Bonshaw and Glen Innes

(arrangements to be made with local agronomists)

3.2 Crops

Priority of cultivated crops incudes sweetcorn, maize and sorghum (all priority A); and capsicum cucurbits and non-cultivated crops such grass weeds and cover crops (all B).

Collection of additional information on crops stages, crop varieties, infestation levels and crop losses in vegetable crops

3.3 Methods

Methods for collecting fall armyworm eggs and larval stages for detecting endemic parasitoids and entomopathogens.

Parasitoids

- For each priority A region and at least one priority A crop collect a minimum of 50 larvae covering small (1st and 2nd instars), medium (3rd and 4th instars) and large (5th and 6th instars) stages monthly.
- For each priority B regions and crops collect samples as opportunities arise.
- Also collect, where possible, a minimum of 25 egg masses for detecting egg parasitoid. Optionally put out egg masses (NT has exposed potted plants with egg masses for 24 hours and successfully recorded parasitism).
- Egg masses and larvae should be kept in the laboratory in small individual containers for emergence of parasitoids.
- For egg masses record the number of eggs, number of emerged FAW and no of emerged parasitoids.
- Where possible, rear the larvae on the plant species from which they were collected or sweetcorn cobs/tassels until pupation or parasitoid emergence.
- Use artificial diet formulation for rearing field collected larval stages under laboratory condition only when suitable hosts plants for are not available
- Guide to differentiate emerged parasitoids as egg, larval and pupal parasitoid and then curated and preserved for species identification.
- Collaboration established with Braconid taxonomist Dr Erinn Fagan-Jeffries School of Biological Sciences, The University of Adelaide for identification of parasitoids.

Predators/parasitoids field collection

- Suction sampling, beat trays and visual collections for potential predators and parasitoid adults in FAW infested crops and follow-up confirmatory feeding tests under laboratory condition.
- Use normal diagnostic processes (in house and networking with specialists) to identify predators (most will probably already be known locally from other studies).

Entomopathogens

- Collect sick and dead larvae from the field.

- Also record any larvae that die in the samples collected for parasitoid emergence.
- For fungal pathogens isolate on suitable media.
- For suspected viruses freeze samples and sent to Ian Newton

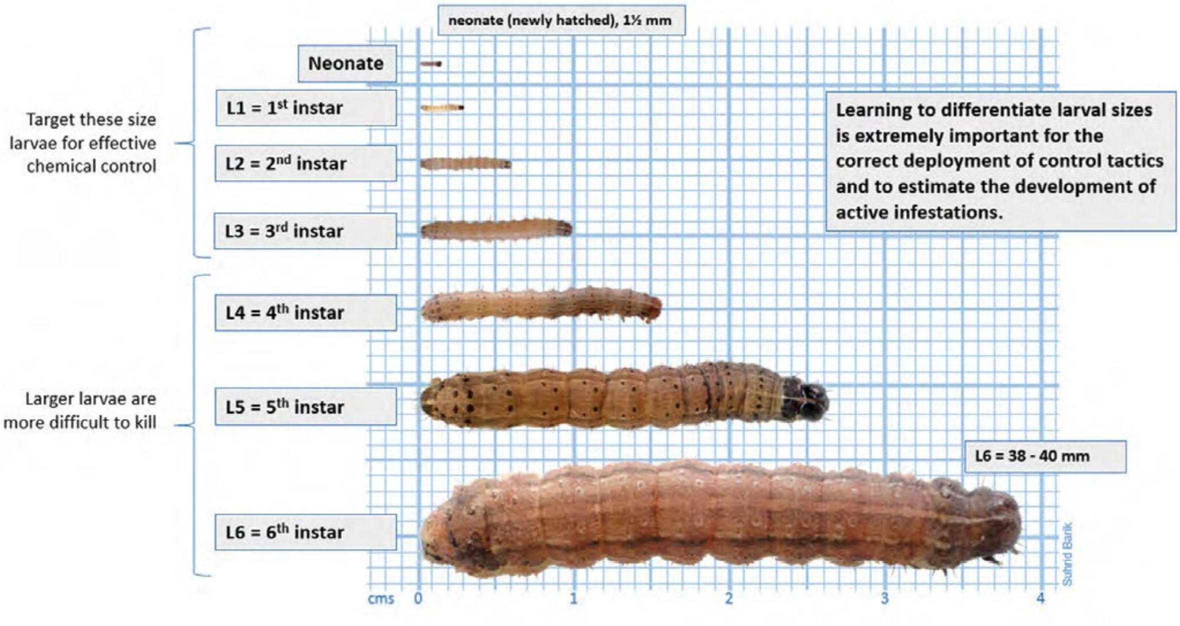
FAW egg and larval stages for parasitoid survey in the field.

FAW egg masses on corn

Third instar larvae

Fouth instar larvae

Fifth instar larvae



Economic Impacts of Fall Armyworm on vegetable crops in Australia

2021

Queensland
Government

This publication has been compiled by Karl Kloessing and Sarah Goswami of Industry Analytics and Systems, department of Agriculture and Fisheries.

Contents

Summary

Fall armyworm (FAW) was reported in North Queensland in 2019 and quickly spread to several locations in Qld, WA and NT. Establishment of fall armyworm in the production areas has caused major concerns for the sweetcorn and vegetable industries. Within the short period from the detection of FAW, significant crop damage (up to 50%) was recorded in organic and conventional sweetcorn crops in the Bowen and Burdekin areas. Pheromone trapping results from QLD, NT and WA production regions indicated that FAW moth numbers were higher from May through August. The rapid rise in FAW numbers has become a major threat to the existing IPM practices adopted by the horticulture industry.

This report details the results of economic modelling on the impact of FAW in Northern Australia and the potential benefit of integrated pest management.

Results indicate economic losses from Fall Armyworm to be between $1.3 and $1.7 billion across Northern Australia with 79 per cent of the losses originating in Queensland. The majority of losses occur in the first 5 years after infestation whilst producers shift to the next best commodity, that is either non-susceptible or less susceptible to Fall Armyworm. In the first-year losses total $409 million or 23 per cent of total losses. However, once industry adjustment occurs losses are dramatically reduced with an estimated annualised loss of $59 million across Northern Australia.

Background

Fall Army Worm (FAW) is an invasive pest which is currently damaging crop yields and farm profitability in vegetables and grains crop industries in Australia. This report has been requested by Hort Innovation, to assess the economic impacts of FAW.

Given the industry is still in the early stages of understanding the Fall Armyworm's resistance status in Australia, and international evidence of widespread insecticide resistance, the risk that chemical control options will not be effective must be considered. Thus, the risk analysis in this project focuses on the potential economic losses from "unmanaged" Fall Armyworm populations to horticulture crops across Northern Australia.

Prior economic modelling looking specifically at the farm level impact of Fall Armyworm on sweet corn production in Queensland found using current integrated pest management practices and chemicals to be economically unviable with negative returns.[1]

Current FAW situation in Australia

Queensland (QLD): Establishment of fall armyworm in the production areas Bowen and Burdekin has caused major concerns for the sweetcorn and vegetable industries. Sweetcorn is reported as a highly preferred host crop of FAW. Within the short period from the detection of FAW, significant crop damage (up to 50%) was observed in sweetcorn, maize and sorghum crops.

In QLD, commercial sweetcorn production is concentrated in the Bowen, Burdekin and Lockyer Valley regions and recently expanded to Bundaberg. In 2019, the Bowen and Burdekin sweetcorn production area was estimated at 2200 ha with a value of $90 million (Mullins and Subramaniam 2019). In the dry tropics, commercial vegetable production is significant (13,000 ha worth $620 million) with an extended season from February to November. The industry is concerned that FAW will move onto other crops.

Western Australia (WA): FAW was first collected in pheromone traps in WA in March, confirmed as present on 1 April 2020 with larvae detected in the field. An extensive trapping program is now in place across Western Australia, which has confirmed FAW presence in Broome and Carnarvon in April, with a singular a moth collected from a trap in the Geraldton area but no larvae have been found.

Numbers of FAW have steadily increased and been collected across the Ord River Irrigation Area (ORIA), with fluctuations and declines in the colder months. The damage, to date, has been restricted to grass crops, maize, sweetcorn, sorghum and Rhodes grass. Maize and sweetcorn have been badly damaged with reports of significant losses in Carnarvon crops. Whilst damage to other horticultural crops has been limited, there is concern that, as populations increase and the favoured host plants (maize/sweetcorn) decline the pest will move onto other crops. The primary means for management, at this point, is pesticides. There is concern that pesticide failure will occur due to genetic resistance. The presence of resistance alleles to the Group 1 insecticides in WA FAW has been confirmed in both Broome and ORIA.

Northern Territory (NT): FAW was first detected in pheromone traps in NT at the end of March in the Darwin, Douglas Daly and Katherine regions. Numbers have fluctuated over the past few months and seem to have been driven by the crops being grown. Damage to date has been restricted to grass related crops. Sweetcorn and maize have been particularly badly damaged, and the pest has also damaged sorghum. The territory has a sizeable Asian vegetable industry and there is concern that, as populations increase the pest will move onto other crops. Over the past few years there has been a significant adoption of IPM by that industry and if increased spraying is required for FAW this would

[1] DAF (2020) Sweetcorn Production Analysis: Examining the Gross Margin Impact of the Fall Armyworm, Brisbane.

disrupt this system. DITT is currently conducting field and laboratory trials to determine the host range in the territory.

Methods

Economic Framework

A ***Benefit Cost Analysis (BCA)*** framework is used to estimate the potential economic losses of incursion of Fall Armyworm. In this method, the time preference of money (opportunity cost) is accounted for by discounting future benefits and costs to present values or compounding past benefits and costs to present values. A base year of 2021 is used. All dollar costs and benefits are expressed in constant dollar terms and discounted or compounded to that year.

Economic losses at the State and National level are measured using the investment criteria of Net Present Value (NPV). The NPV is the difference between the Present Value (PV) of benefits and the PV of costs.

A BCA assesses the change in losses resulting from the presence of FAW and compares it with the expected ***Producer and Consumer surplus*** in the absence of FAW.

Consumer surplus (CS) represents the excess of consumers' willingness to pay per unit of a commodity, above current market price whilst, producer surplus (PS) represents the excess of market price of a commodity above production costs. These metrics combined are a measure of total economic benefit.

In this report we examine the loss of PS/CS from the incidence of FAW over a 30 year horizon, using a discount rate of 5 per cent.

Scenarios

Two scenarios are modelled:

1. Production shift to next best crop, IPM not economically viable
2. As per Scenario 1, with R&D investment generating either new varieties, chemicals or biocontrol by yr 10.

Assumptions

Commodities susceptible to FAW and modelled herein are lettuce, tomatoes, rockmelons, capsicums, sweet corn, broccoli, watermelon, cauliflower and cabbage.

Data on production and prices received were sourced from the Australian Bureau of Statistics 2019-20 and Department of Agriculture and Fisheries, Queensland (DAF) to estimate PS/CS surplus. This was coupled with the latest data on variable costs from DAF to inform supply curve slopes for each commodity. On the demand side, an elasticity of demand of -1.5 was assumed. That is, for each per cent reduction in price, quantity demanded will increase by 1.5 per cent.

The costs of Integrated Pest Management are deemed to exceed benefits; therefore, this is not considered as a management option that producers would consider at this point.

Instead, it is assumed that producers will shift production to the next best alternative commodity, taking a reduction in PS/CS of 15%, or 5% after variety improvement. The shift out of FAW susceptible commodities is assumed to be a rapid shift, with 50% shifting to the next best alternative after 1 season, 75% shifting after season 3 and complete sector shift after 5 years.

Based on best available scientific knowledge yield losses are assumed at 50% for all commodities.

Given the likelihood of shifts to the next best alternative horticulture commodity, employment effects are expected to be limited. This is due to the similarity of labour intensity between horticulture crops.

Results

Fall Armyworm is a highly invasive damaging pest and as such it's incidence results in significant economic loss to producers. However, over a short time period producers will shift to alternate commodities to avoid negative profit margins. Table 1 shows estimated lost economic benefit by State for both scenario 1 and 2. This table shows that Queensland will bear most losses, in line with Queensland's current larger proportion of FAW susceptible vegetable production.

	S1 Lost CS/PS ($m)	S2 Lost CS/PS ($m)	Loss by state (%)
Qld	$1,406	$1,083	79%
NT	$108	$84	6%
WA	$260	$199	15%
Total	$1,774	$1,366	

Table 1: Economic loss from FAW, with shift to next best commodity and for S2 R&D benefit.

In the first year economic losses are greatest, with production response being limited. First year economic losses for Northern Australia are estimated at $409 million or 23 per cent of total losses over 30 years. Annualised economic losses over the entire analysis horizon are estimated at $59 million; $46.8 million in Queensland, $3.6 million in Northern Territory and $8.6 million in Western Australia.

There is a difference of just over $407 million in economic loss between scenario 1 and 2 indicating that to ensure a positive return on investment from FAW R&D, investment costs should be less than the benefits.

Due to the limited scientific data on yield losses from FAW, sensitivity analysis was conducted for Scenario 1 on the yield loss assumption. Results for yield losses of 20% are shown in table 2 below. Note the overall expected economic losses in this analysis are similar to that expected under Scenario 2 with the higher yield loss and R&D improvements.

	S1 Lost CS/PS ($m)	Loss by state (%)
Qld	$1,058	79%
NT	$91	7%
WA	$196	15%
Total	$1,345	

Table 2: Economic loss sensitivity