Final Report

Exploring IPM compatible methods for spotted wing drosophila in berry crops

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Project code:

MT18010

Project:

Exploring IPM compatible methods for spotted wing drosophila in berry crops (MT18010)

Disclaimer:

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Content

Summary

The highly invasive Spotted Wing Drosophila (SWD; *Drosophila suzukii*) has emerged as a serious pest of international significance to global fruit production in the last decade as it lays eggs in ripening fruits of more than 145 plant species, including economically important stone fruits and berries. It was first detected in Europe and North America in 2008, and since 2012 it has also been found to be widespread in South America. Most recently, SWD has been detected on the African continent. Estimated yearly losses due to SWD exceeded 500 million US dollars in just three states of the US, and in Europe SWD has been shown to infest up to 80% of fruits in some site.

While SWD is not known to be present in Australia, fruit industries are valued at $4.8 billion at the farmgate, and remain highly vulnerable to an incursion. Independent studies modelling the potential global distribution of SWD have concluded that there are substantial regions of Australia with high climatic suitability. However, at a more fine-grained resolution, seasonal fluctuations of SWD in trap catches vary widely across geographic regions and climates, crop management strategies including trapping and pesticide application, and adjacency to non-crop host plants. MT18010 presented an opportunity to explore the general processes underpinning seasonal population dynamics of SWD across its international distribution.

During MT18010 the project team compiled data on international seasonal abundances on SWD for different climates, crops, and management contexts to identify patterns to improve predictability of seasonal population dynamics covering the major geographic areas of both native and invasive occurrence. Specifically, the project investigated how climatic variation and management factors explain variation in seasonal abundance of SWD through time.

In relating seasonal abundances to environmental predictors, specifically temperature, the project found strong negative effects of exposure to high (>25°C) and low (<5°C) temperatures during the preceding month. Unlike most studies on SWD phenology that focus on temperature in the physiological development range (i.e., between 5°C and 25°C), project findings show that exposure to thermal extremes are an important driver of seasonal population fluctuations. These findings, therefore, have implications for predicting seasonal abundance at a regional level.

Insecticide resistance and issues with secondary pests have been challenges encountered in regions infested with SWD overseas. Following the serious incursions of SWD into North America and Europe, growers have relied almost entirely on insecticides to control this destructive pest. In invaded regions local larval parasitoid species of *Drosophila* spp. have not been successful in parasitising SWD because of the highly developed immune response of the invading fly. Only local pupal parasitoids show some potential. Effective parasitoids for the biological control of SWD have been sourced from East Asia and progress is being made for their importation to North America and Europe. Biological control should play a key role as part of an areawide approach to management of SWD.

A literature review of parasitoid wasp control options for SWD was undertaken and highlighted at least two endemic parasitoid wasp species that may be candidates for SWD control, through augmented releases or strategic stewardship of these species in the field. This review makes several priority recommendations that will be important for furthering this work. In addition, activities to raise awareness about SWD among at-risk industries has continued on from the campaign initiated in MT17005. Resources on SWD have been centralized and made available through a Hort Innovation project page, and two SWD PestCase videos have been complemented by several articles and a SWD management fact sheet.

The activities undertaken throughout MT18010 will further support at-risk production industries in pre-emptively planning best strategies for eradicating or managing SWD in the event of an incursion. Indeed, in a previous Hort Innovation investment (MT17005) it was reported that time since an incursion has a negative relationship with average industry yield losses from SWD. Improved knowledge of SWD phenology, refined management activities, and a higher availability of decision-aid tools in affected countries are likely contributors to this relationship. Therefore, assessing best management options that may be employed in an Australian context, at a regional level, will be an important contributor towards limiting unnecessary profit loss in the event of an incursion and establishment.

Keywords

Spotted wing drosophila; *Drosophila suzukii*; integrated pest management; IPM; biological control; seasonal abundance

Introduction

Spotted wing drosophila (SWD; *Drosophila suzukii*) is a new and significant pest of a range of soft, thin-skinned fruits including blueberries, caneberries (e.g. blackberries, raspberries, loganberries and youngberries), cherries, strawberries, summerfruit, and table grapes. While SWD was first described from Japan in 1931 and is present throughout several Asian countries, its potential importance as a production pest was only fully realised after incursions into the US in 2008 and Europe in 2010.

In contrast to most *Drosophila* species, SWD is capable of laying eggs (ovipositing) into ripe and ripening, undamaged fruit. Due to the apparent insignificance of other Drosophila as pests in commercial production, initial reports of fruit damage in the US were largely overlooked, allowing the pest to expand its geographical range unchecked. The observed impact of SWD in the US and Europe is highly variable depending on crop and region. Losses as high as 80% have been reported in caneberries, strawberries and cherries, however 20–40% losses are more commonly seen (Maino et al. 2020). The damage caused by larvae makes fruit unsuitable for markets, meaning there is no practical option for treating infested commodities or redirecting them to alternative markets.

In response to reports of SWD affecting crops in western North America in 2009, Australia's department of agriculture commenced a pest risk analysis for SWD in 2010 to identify import pathways and management options to mitigate the risk of a SWD incursion in Australia. The report identified key import conditions that would help to mitigate risk of importing SWD contaminated commodities. The analysis also highlighted that while Australia is relatively well protected by its natural isolation and rigorous approach to biosecurity, the spread of SWD indicates that this pest can successfully invade new countries. The pest can rapidly reach economically injurious levels, and the lack of an established control program means that the impact on horticultural industries could be significant. Based on the host range seen overseas, within Australia, the potentially affected industries have an estimated value of production in excess of $1.6 billion.

Project MT17005

To minimise the impact of an incursion MT17005 (*Improving the biosecurity preparedness of Australian horticulture for the exotic spotted wing drosophila (Drosophila suzukii*)) was launched in 2018 to ensure Australian governments and industry understand trapping, surveillance and control options that support suppression, containment, and potential eradication of SWD. MT17005 project partners are currently consolidating available information on SWD across a range of environments and crops and, are applying this information to models to predict how this pest is likely to behave in Australia. Ultimately, MT17005 will provide insights for containment or management while best drawing upon international experience. By synthesising existing data on SWD and capturing biological processes in a quantitative framework, gaps in knowledge for Australia are currently being identified to help direct future investments.

Through completion of MT17005, our collective understanding of SWD risk to Australia industries was improved and resources to better prepare at risk industries were delivered. MT17005 resulted in the following outputs:

- Report on modelling for spread and establishment of SWD.
- Report on potential impacts of SWD.
- Report on modelling potential pathways for entry and spread.
- Report on the surveillance and quarantine of SWD.
- A desktop review of Invasion history, biology, trapping for surveillance and control of SWD
- Control methods review.
- SWD preparedness plan.
- Extension and communication outputs, culminating in development of an extension pack for industry educators and knowledge brokers.

Importantly, MT17005 resulted in a series of recommendations which spanned prevention, diagnostics, surveillance, preparedness for management, engagement and awareness. These recommendations, which have been developed as a roadmap for limiting the impact that an SWD incursion would have on at-risk industries, can be viewed in the MT17005 final report. They may be considered in conjunction with the recommendations made in this report.

Project MT18010

MT18010 (*Exploring IPM compatible methods for Drosophila suzukii in berry crops*) was launched as a complementary project to MT17005, with the purpose of providing research-based insights into management options for SWD in Australia, as well as continuing awareness activities with key stakeholder groups. MT18010 was split into three distinct work areas: predictive modelling of seasonal abundance, review of biological options; and SWD awareness activities.

Predictive modelling of seasonal abundance

At the outset of MT18010 it was apparent that international research had accumulated on the population biology of SWD since its emergence as a global pest, however, there had been no attempt to synthesise this data to understand broader patterns across the diverse climates, commodities, and management contexts in which SWD currently occurs. The MT18010 project team recognized that this gap would limit the ability of at-risk Australian production industries, such as grape, stonefruit and summerfruit industries, to forecast how SWD is likely to behave in terms of its seasonal activity in key production areas. It was agreed that this large pool of data presented an opportunity for a meta-analysis on the general processes underpinning seasonal population dynamics of SWD across different contexts. The intended outcome of this component would be improved predictability of population dynamics to enhance SWD management in production areas through more precise monitoring and application of management strategies (in the event of incursion and establishment). With the above in mind, the modelling component investigated the following research question: *Based on accumulated international trapping data*, *what can we expect from seasonal activity of SWD in Australian horticulture?*

This analysis had not been possible in MT170005, as modelling outputs in that larger project has focused on spread, establishment, determining economic impact, and surveillance grid design. However, activities completed in MT17005 gave the project team a solid foundation for undertaking this research.

Review of biological control options

Information on beneficials, such as native and endemic parasitoid wasp species, in Australia can be difficult to access and compile without a dedicated effort. However, such an activity can be highly useful. As an example, findings from the Hort Innovation funded project MT16004 (*RD&E Program for Control, Eradication and Preparedness for Vegetable Leafminer 2017-20*) highlighted the existence of the parasitic wasp *Diglyphus isaea* in certain regions of Australia, which is a parasitoid of vegetable leafminer overseas. This finding was made through extensive review of Australian scientific literature, which culminated in a detailed 2018 report for Hort Innovation '*Prospects for biological control of the vegetable leafminer, Liriomyza sativae, in Australia'*.

At the outset of MT18010 the project team proposed that a short review of potential SWD biological control options for SWD in Australia be undertaken to support management planning at the farm and industry level. It was recognized that there was potential to include information on beneficial species that impact on closely related *Drosophila* species in Australia in order to specifically identify candidate species that may aid in SWD suppression, without the need to import new parasitoid species. Therefore, the beneficial review component investigated the following research question: *What beneficial species currently found in Australia are best candidates for contributing to SWD control?*

SWD awareness activities

MT17005 involved rolling out an extension and communication program with the aim of increasing industry awareness of SWD and sharing research findings from the project. Communication activities for MT18010 were undertaken to complement those undertaken through MT17005. This integration of activities increased cost-effectiveness by leveraging existing activities and stakeholder contact lists.

Methodology

MT18010 was split into three distinct work areas:

- predictive modelling of seasonal abundance;
- review of biological options; and
- SWD awareness activities.

Predicting seasonal abundance

Cesar Australia modeller, Dr James Maino led this component of the project, which was supported by two important enabling factors. Firstly, previous data on SWD abundance that had been largely compiled during MT17005 was available for use at the outset of MT18010. Secondly, a significant achievement was providing support to secure an international fellowship for ecologist and SWD expert Dr Michael Ørsted (Section of Biology and Environmental Science, Department of Chemistry and Bioscience, Aalborg University, Aalborg E, Denmark) who plans to travel to Australia in 2021 (restrictions allowing) to develop improved predictive capacity for SWD seasonal risk and abundance. Therefore, during late 2020 to early 2021 Dr Ørsted collaborated with Dr Maino to progress our understanding of expected seasonal abundance.

Abundance data was compiled from an international review of field studies of SWD in which seasonal abundances were measured through trap catches, covering the major geographic areas of both native and invasive SWD ranges. Data was compiled from source tables or, where unavailable, extracted from digitised figures. From each study, project researchers recorded the trap count of SWD, trapping method, date of inspection, trapping period, trap location, year of first regional detection, and main host plant. This meta-analysis underpinned development of a model to predict seasonal abundances of SWD in different climates.

To build climatic variables at the study locations and time period project researchers utilised Global Surface Summary of the Day weather data from the USA National Centers for Environmental Information, which were retrieved using the 'GSODR' R package (Sparks et al., 2017). Weather stations were selected based on their proximity to the study site, which resulted in over 80% of the compiled studies having available data from weather stations within 30 km of the study site.

To better interpret seasonal patterns in abundance across a range of trapping methods, growing conditions, and management contexts, trap counts were scaled by the maximum observed number for each unique study, crop, or trapping method. It has been previously noted that trap data for SWD do not represent pressures in field (Briem et al., 2018; Drummond et al., 2019), thus scaling by the maximum observed trap count also serves to minimise inference on absolute counts with more emphasis placed on relative changes through a season.

Environmental covariates for each monitoring point were constructed from the climatic data, including the mean temperature across the preceding 30 days, as well as the accumulated degree days below both 5°C and above 25°C (Kamiyama et al., 2020; Wiman et al., 2016). These temperature thresholds approximately represent the lower temperature bounds of development and the decreasing phase of population growth rate respectively (Maino et al., 2020). To calculate these covariates, available minimum and maximum daily temperatures were converted to hourly temperatures with an idealized daily temperature curve that uses a sine curve for daytime warming and a logarithmic decay function for night-time cooling with the 'chillR' R package (Luedeling & Luedeling, 2015). To analyse seasonal trends in SWD trap abundance a generalized additive mixed model was used.

Review of biological control options

Independent consulting entomologist, Dr Peter Ridland, led the development of this review. As a starting point, the review leveraged an important recent study published by Lee et al. (2019) to understand what control options were available to growers in currently affected countries overseas. Lee et al. (2019) identified and catalogued an extensive list of potential SWD parasitoids, predators and entomopathogens and represented the most up to date compilation of SWD biocontrol data at the outset of MT18010.

Due to time constraints, the review focus was confined to parasitoid wasp biocontrol candidates and did not include an assessment of SWD control by generalist predators, although Lee et al. (2019) and Wang et al. (2020) note the usefulness of generalist predator species, such as earwigs, damsel bugs, spiders and ants in field conditions.

A detailed search for records on the presence and distribution of known parasitoids and predators of *Drosophila* spp. in Australia was undertaken. Information on the status of known parasitoid species deployed for SWD control overseas was also integrated into the review.

During the review development, a relationship was developed with the Jan Hrček research group at the Institute of Entomology, Biology Centre of the Czech Academy of Sciences at České Budějovice in the Czech Republic, as well as the lead developer (and curator) of the Drosophila Parasitoid database (DROP)) at the City University of New York. Information on the set up and structure of this landmark database was recently published in Lue et al. (2021). In addition, Dr Ridland participated in the two-day online meeting of the North American SWD Biological Control Working Group.

SWD awareness activities

MT18010 awareness activities were integrated into the extension and communication plan for MT17005. Integration reduced duplication of efforts as project team members were able to share progress with a SWD industry steering committee set up through MT17005. At the conclusion of MT17005, education on the topic of SWD continued throughout MT18010, using key communication channels such as the Australian Berry Journal and the Urban Plant Health Network.

Outputs

Seasonality modelling key findings and recommendations

In relating seasonal abundances to environmental predictors, specifically temperature, we found strong negative effects of exposure to high (>25°C) and low (<5°C) temperatures during the preceding month. Unlike most studies on SWD phenology that focus on temperature in the physiological development range (i.e., between 5°C and 25°C), we show that exposure to thermal extremes are an important driver of seasonal population fluctuations.

While trap catches remain an indirect measure of infestations and must be interpreted carefully in terms of crop risk, our results will be able to support monitoring through enhanced knowledge of the climatic factors affecting SWD population activity. The negative impact of high temperatures suggests that late-season management strategies focusing on manipulating crop microclimates to temperatures above 25°C may be able to reduce SWD abundance. We show that early season abundance is modulated by climate, particularly the depth of cold extremes experienced in the preceding month.

For example, scaled seasonal abundance through time was simulated with relative SWD abundance predicted at 0, 5, 10, 50, and 100 accumulated degree-days below 5°C in a vineyard scenario using apple cider vinegar trapping scenario for a vineyard (this was the most common crop type and trapping method across studies). The predicted increase in abundance from mid-summer, with a peak at November or May for the northern and southern hemispheres respectively, are shown in Figure 1. The effects of 50 and 100°C/month accumulated degree-days below 5°C are shown as large reductions in both early and max abundances, while there was practically no effect of 5 or 10°C/month accumulated degree-days below 5°C compared to 0.

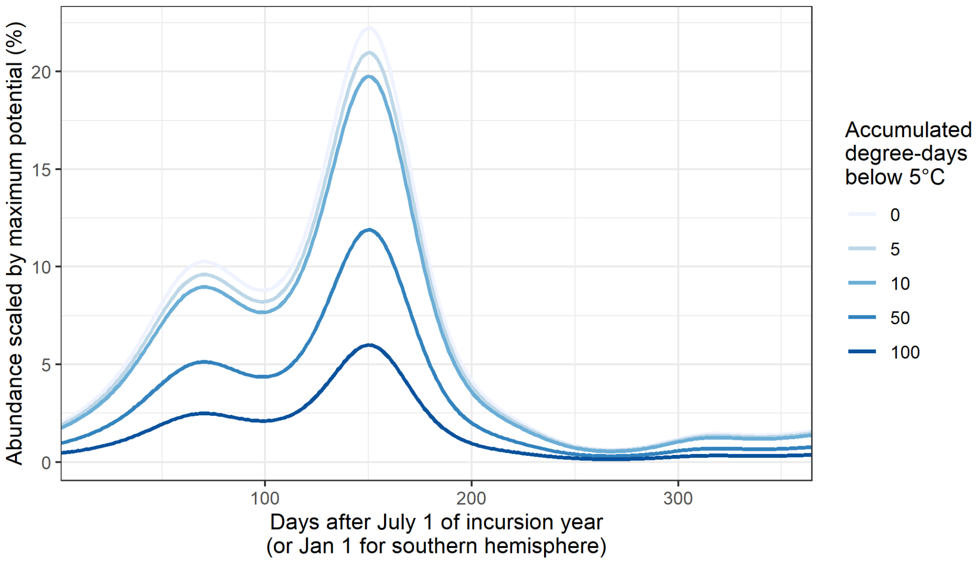

Figure 1. Predicted scaled seasonal abundance (the percentage of the maximum number able to be observed in a trap for a location), assuming a mean monthly temperature of 10°C, accumulated degree-days above 25°C of 10, accumulated degree-days below 5°C of 0, 5, 10, 50, and 100, using apple cider vinegar traps in a grape crop.

Our presented model has laid the groundwork necessary for growers to better predict the early season activity potential of SWD. We envisage such capacity will support, rather than replace, crop monitoring through the enhanced knowledge of how climatic factors affect SWD population activity.

Given that relationships were apparent in the diverse locations and conditions considered in this study, there may be some capacity to develop an early-warning system to improve management and biosecurity preparedness outcomes for Australian fruit production industries. The full research report with additional findings can be found in Appendix A.

Biological control key findings and recommendations

Drosophilids have many larval and pupal hymenopteran parasitoids in their native ranges (Carton et al. 1986). The larval parasitoids are koinobiont endoparasitoids: the wasp does not paralyse the host larva during oviposition. After the parasitoid egg hatches, the development of the parasitoid larva inside the host body does not accelerate until the host pupates. The adult wasp will then gnaw its way out of the host puparium. The generalist pupal parasitoids are idiobiont ecto- or endoparasitoids: the wasp paralyses the host pupa before oviposition. Ectoparasitoids such as *Pachycrepoideus vindemmiae* (Pteromalidae) lay their eggs between the puparium wall and host pupa. With endoparasitoids, the wasps insert their eggs into the haemocoel of the host (Lue et al. 2021).

This review has collated records of known Drosophilidae parasitoid wasp species in Australia. Through collection of primary source records of candidate larval and pupal parasitoid species. In all, the review found records of around 30 parasitoid species of *Drosophila* in Australia, with only six species identified to species and with the 15 species from Jeffs et al. (2020) having molecular data. It is highly likely that there will additional parasitoid species of drosophilids present in the Australian rainforest areas.

European and North American larval parasitoids have been mostly ineffective against the newly arrived SWD because of the highly developed immune response of the invading fly. Two candidate larval-pupal parasitoid species have been identified in eastern Asia for classical biological control of SWD. These species are (i) *Ganapsis brasiliensis* (Hymenoptera: Figitidae: Eucoilinae) and (ii) *Leptopilina japonica* subsp. *japonica* (Hymenoptera: Figitidae: Eucoilinae). The review was successful in identifying Australian records of wasp species from the *Leptopilina* and *Ganaspis* genera, although these samples have not been characterized to the species level. In addition, the review noted that parasitoids of the genus *Asobara* and *Leptolamina* are also found in Australia and represent candidates for SWD control. However, the immunological response of SWD to the Australian larval parasitoids from Australian horticultural areas needs to be assessed. Two specimens previously collected in Victoria, *Asobara persimilis* and *Leptopilina* sp. are shown in figure 2.

Figure 2. Parasitoid wasps that represent candidate species for SWD control in Australia: (A) *Asobara persimilis* ♀, (B) *Leptopilina* sp. ♀. Specimens were collected by Dr Peter Kriesner in Victoria. Ken Walker from the Museum Victoria supplied assistance with photographing field-collected specimens. Photo source: Kriesner (2017).

Importantly, several lines of larval parasitoid species (*Leptopilina* sp., *Ganaspis* sp. and an *Asobara* sp. reared from several endemic *Drosophila* species from north Queensland (Jeffs et al. 2020)) are being tested against SWD in the Czech Republic and have shown some level of parasitism, suggesting that immune response encapsulation might not be as high as with European larval parasitoids tested against SWD.

This review highlights the large amount of progress that may be made in the collective scientific knowledge base relating to parasitoid species from a relatively short field survey by Jeffs et al. (2020). The ground-breaking study of Jeffs et al. (2020) constructing bipartite *Drosophila*-parasitoid food webs from rainforest sites in the Australian Wet Tropics World Heritage using DNA metabarcoding and conventional molecular methods has greatly increased knowledge about the parasitoids of endemic *Drosophila* spp. in Australia. Even though the study was for only 1 month (mid-March to mid-April 2016), 15 parasitoid species were recorded.

The lack of records for the pupal parasitoids, *P. vindemmiae* and *Trichopria* spp., and larval parasitoids, *Asobara persimilis*, *Leptopilina* spp., *Ganaspis* spp. and *Leptolamina* spp., reared from Drosophilidae in Australia needs to be addressed, before other research plans are developed. Recommendations for next steps in the short term are included below.

1. Survey Drosophila species known to commonly occur in orchard settings (the cosmopolitan species: *D. melanogaster*, *D. simulans*, *D. immigrans*, and the endemic *Scaptodrosophila lativittata*) with the intention of rearing out and identifying the most common parasitoids.
2. A trapping program would ideally involve sentinel traps (using *D. melanogaster* pupae or late instar larvae) and fermenting fruit traps, as well as collections of fallen fruit from the field. Collections and trapping should be undertaken at several sites in the berry and cherry growing areas in spring, summer and autumn. Preparation of sentinel traps will require access to rearing facilities for host and parasitoids. Priority trapping activities would include: A survey for the pupal parasitoids: *Pachycrepoideus vindemmiae* and *Trichopria* spp. in regions most at risk from SWD and a survey for larval parasitoids: *Asobara persimilis*, *Leptopilina* spp., *Ganaspis* spp. and *Leptolamina* spp. in regions most at risk from SWD.
3. Conduct molecular testing and lodge voucher specimens of all parasitoid species reared (as well as specimens to hand from earlier studies) and contribute data to the DROP database. Further develop collaboration with US taxonomists coordinating DROP.
4. Obtain biological data for the larval and pupal parasitoids wherever possible.
5. Examine the potential for augmentative biological control of SWD using mass releases of endemic pupal parasitoids
6. Explore potential to export live samples of larval parasitoids for testing on SWD cultures overseas.
7. Explore the use of augmentoria (cages containing fallen fruit but where nets retain the flies but allow the escape of parasitoids) as a conservation biological control option for SWD while maintaining sanitation.

The full research report is found in Appendix B.

Communication resources

Through additional resourcing provided by MT18010 two information videos were developed that explored the current status of SWD and its impact (PestCase 1), and how growers overseas are approaching management of the species (PestCase 2). At the time of writing these videos had elicited 130 and 79 views respectively.

In order to produce an initial output in time for 2019/2020 berry production Cesar Australia collaborated with NIAB-East Malling Research to film interviews of international growers and their reflections on what management of SWD means. The original video draft became quite sizable, and therefore the interviews were integrated into one of two ‘Pest Case’ videos. A third PestCase video had been planned, which would focus on management options, but was unable to be completed due to challenges that arose with COVID-19 and dependency on an aligned Hort Innovation research project.

The SWD PestCase episodes complement the SWD PestBites video, which was released in 2019 and focuses on identification. These videos supplement a SWD extension package for Australian growers that was developed during MT17005.

In addition to video development the project also provided resourcing support to the Urban Plant Health Network (UPHN) during SWD monitoring blitz during early 2021. As a result, MT18010 extension resources were integrated into the UPHN online platform, found here, and were featured in a UPHN social media campaign from January 4th until January 15th 2021 (see twitter.com/UrbanPlantHlth). On February 16th 2021 an UPHN podcast was released that featured the MT18010 project lead discussing the importance of urban biosecurity. One topic featured during the podcast was SWD, and the impact this pest could have on peri-urban food bowls.

At-risk industries continued to be kept up to date with project findings and new information on SWD through the Cesar Australia blog and the Australian Berry Journal. The following articles were published in the Australian Berry Journal since conclusion of MT17005:

- Spotted wing drosophila: Exploring biological control (Australian Berry Journal 2021 autumn edition).
- Spotted wing drosophila: go-to preparedness resources for time poor advisors (re-print from MT17005 into Australian Berry Journal 2020 summer edition).
- Spotted wing drosophila: What would management look like (re-print from MT17005 into Australian Berry Journal 2020 summer edition).

As a final output, a SWD management fact sheet was developed with the intention of improving grower knowledge about what management changes they could expect to make if SWD were to establish in Australia. This fact sheet is found as appendix C. During MT18010 the project team worked with Hort Innovation to ensure that all relevant educational resources were easily accessible on the Hort Innovation website. For searchability these resources were linked to the MT17005 project page, which was a more sizeable project. In addition, the SWD extension pack, currently hosted by Cesar Australia, is also linked to that project page.

Outcomes

MT18010 allowed the project to progress to several key recommendations made during MT17005 related to engagement and awareness, and preparedness. They were:

- Ongoing research on control methods used overseas to continue to collect and refine management advice within an Australian context to mitigate the impacts of SWD in fruit production systems in the case of an incursion and establishment. Action taken during MT18010: Biological control and seasonal abundance findings have progressed collective knowledge of how SWD populations will likely behave and may be managed strategically in Australia.
- Design and implement an awareness campaign directed at urban and peri-urban communities surrounding high traffic ports-of-entry. Action taken during MT18010: Communication support supplied to the UPHN on the topic of SWD.
- Maintain SWD engagement and awareness activities in raspberry, blackberry, strawberry, blueberry, cherry, table grape, and summerfruit industries. Action taken during MT18010: Awareness activities continued after conclusion of MT17005 through this project.

The research findings that have resulted from MT18010, as well as extensive preparedness activities undertaken through MT17005, contribute to our growing understanding of how SWD may adapt to Australian conditions. For locations preparing for possible incursions, such as Australia and New Zealand, improved predictability will provide insights into the likely seasonal behaviour of pest populations under different production contexts, such as climatic conditions, which will enhance pest management and preparedness. Integration of phenological prediction modelling into future recommendations for management of SWD in Australian regions will be important for producing regionally specific guidelines. In addition, project activities have culminated in the most up to date distribution map for SWD to date, which may be used for risk assessment purposes by government and trade bodies.

This project has also highlighted important information relating to potential biological control options for SWD, based on an assessment of known parasitoids of endemic Drosophilidae. Next research steps outlined in this review provide a roadmap for confirming the validity of identified parasitoid wasp species as biological control options in Australia. The review also provides an assessment of biological control options for importation, and key considerations relating to import of such species.

Relationships have been set up during MT18010 with international agencies and individuals that will become important research collaborations should further preparedness activities for SWD be undertaken in Australia. The continuation of Michael Ørsted's research fellowship offers an opportunity to extend findings to Australian fruit production industries. The relationship with the Hrček research group and DROP database curators represents an important opportunity for Australian production industries as evaluating lines of larval parasitoids reared from cosmopolitan Drosophila species in Australian horticultural areas against SWD overseas would provide valuable insights for Australia before any incursion.

Already, several lines of larval parasitoid species (*Leptopilina* sp., *Ganaspis* sp. and an *Asobara* sp. reared from several endemic Drosophila species from north Queensland (Jeffs et al. 2020) are being tested against SWD by the Hrček laboratory in the Czech Republic. If *Leptopilina* sp., *Ganaspis* sp. and an *Asobara* sp. can be similarly collected from high value soft fruit producing regions and likely high risk entry points (such as high traffic ports), they may be cultured and sent to the Czech Republic for testing against SWD.

In addition, this project has led to the development of a Master's student mini research project, to be conducted over April – June 2021, which will allow a pilot trapping study to be undertaken in temperate fruit growing regions around Greater Melbourne. This pilot trapping study may result in the culturing of both larval and pupal parasitoid species.

Finally, through communication activities conducted during MT17005 and MT18010 industries at risk from SWD have access to the most up to date extension resources in one central online location. These resources cover topics related to identification, establishment and spread, and best management practices. They form a foundation for continued awareness raising activities among industry into the future.

Ultimately, if the research findings of MT18010 are integrated into future management guidelines for SWD, and if priority next steps for investigating a biocontrol are undertaken, the outcomes outlined below will be realized in the event of an incursion:

- Growers will have guidelines to follow that will limit disruption of existing IPM strategies and achieve effective control of the pest;
- Growers will avoid excessive increases in production costs, particularly in relation to chemical purchase and use;
- The risk of insecticide resistance evolving in Australian populations of SWD will be reduced;
- Growers will have a method of retaining farm environmental credentials; and
- Risks associated with breaching Maximum Residue Limits will be reduced.

Monitoring and evaluation

Based on the MT17005 Monitoring & Evaluation plan, to which MT18010 activities were integrated, the project had the following key evaluation questions:

1. To what extent has the project achieved its expected outcomes?
2. How relevant was the project to the needs of intended beneficiaries?
3. How well have intended beneficiaries been engaged in the project?
4. To what extent were engagement processes appropriate to the target audience/s of the project?
5. What efforts did the project make to improve efficiency?

An internal evaluation of MT18010 is found in table 1.

Table 1. Project key evaluation questions and assessment from the project team

Key evaluation questions	Assessment
To what extent has the project achieved its expected outcomes?	At the outset, the project aimed to draw on activities begun in Mt17005 to undertake research activities that would support development of regionally applicable SWD IPM information. It also aimed to increase cost-effectiveness and reduce duplication by making use of the extension and communications program that had already commenced through MT17005. In line with the overarching aim of MT18010, the project was successful in progressing the collective knowledge about SWD phenology and biological control in order to contribute to the following objectives: • Developing and testing IPM compatible methods for SWD in the first year of the project, considering hygiene, surrounding vegetation, selective insecticides and relevant crop management strategies that could be transferred to Australia • Developing clear, user-friendly guidelines for IPM compatible methods, should guidelines be required in the future Due to COVID-19 challenges, the sister project to MT18010 was unable to collect overseas field trial data and supply it to Cesar Australia researchers that would have allowed contextualization of trial site results to the Australian context. However, the project team sourced a large amount of existing field-based data from international sources, enabling robust analysis of SWD seasonality and biological control options. Findings from these two project components are now available to support development of industry forecasting tools, further biological control development, and refinement of management guidelines.
How relevant was the project to the needs of intended beneficiaries?	Since stakeholder engagement activities were strongly integrated with those of the MT17005 project, the assessment here makes reference to MT17005 project activities. During the spotted wing drosophila preparedness roadshow in late 2018 seminar attendees were asked to complete an impact and feedback survey at the event. Aggregated impact data demonstrates a notable change in knowledge about spotted wing drosophila from an average of 2.38 before the seminar to 3.99 following the seminar (n = 57). The end of the MT17005 project webinar on 30 April 2020 represented another opportunity to track changes in knowledge as a result of project information delivery. One question was posed to attendees, preceding speaker sessions and following speaker sessions. The question posed was: *How would you rate your*

	knowledge of spotted wing drosophila? Results indicate that there was a knowledge level shift among attendees throughout the webinar. Figure 3 displays polling results, which show a greater number of attendees in the 'moderate' and 'high' categories when compared to the pre- webinar poll.
How well have intended beneficiaries been engaged in the project?	Through the many additional outreach activities undertaken during the project (details of which are included in the final report), at least 9.5 thousand individuals were indirectly engaged during the project through social media (YouTube and Twitter), magazine articles, conference presentations, farmer market and university information stalls, and newspaper articles. This is a conservative figure that does not take into account the readership of relevant newspapers in which articles were published, impressions made on Twitter throughout the project, and secondary distribution of products. It also does not take into account overlap of individuals.
To what extent were engagement processes appropriate to the target audience/s of the project?	While the researcher roadshow conducted during MT17005 attracted a predominately grower and agronomist audience, later outreach activities attracted individuals who play important capacity building roles within at-risk industries. Audience segmentation data captured during the Extension Pack Handover Sessions indicated that the majority of participants (N = 45) were industry development officers / extension personnel who would play a key role in preparedness education and response communication, as well as government personnel, who would conduct early detection surveillance and execute incursion response activities. Throughout the project the Australian Berry Journal was regularly supplied with articles to provide an update on project findings and general information about SWD. As a result of communication efforts, a You Pick strawberry farm in NSW made contact with the project team about a suspect SWD detection on the farm. The farm manager was supplied with resources from Mt17005 and MT18010 and ultimately made a report to the state department of agriculture. Fortunately, the suspect species was not SWD.
What efforts did the project make to improve efficiency?	Integration of MT17005 datasets and communication activities with those of MT18010 was successful and enabled the project to achieve the prescribed goals.

Recommendations

Predicting seasonal abundance

1. Investigate development of an early-warning system for critical monitoring periods to improve management and biosecurity preparedness outcomes for Australian fruit production industries.
2. Explore opportunities to further collaborate with Danish researcher Michael Ørsted during his research fellowship at the University of Melbourne. This may allow applied research outputs to be developed for Australian horticultural industries.

Biological control

3. Survey *Drosophila* species known to commonly occur in orchard settings (the cosmopolitan species: *D. melanogaster*, *D. simulans*, *D. immigrans*, and the endemic *Scaptodrosophila lativittata*) with the intention of rearing out and identifying the most common parasitoids.
4. A trapping program should involve sentinel traps (using *D. melanogaster* pupae or late instar larvae) and fermenting fruit traps, as well as collections of fallen fruit from the field. Collections and trapping should be undertaken at several sites in the berry and cherry growing areas in spring, summer and autumn. Preparation of sentinel traps will require access to rearing facilities for host flies and parasitoids. Priority trapping activities would include:
    a. A survey for the pupal parasitoids: *Pachycrepoideus vindemmiae* and *Trichopria* spp. in regions most at risk from SWD.
    b. A survey for larval parasitoids: *Asobara persimilis*, *Leptopilina* spp., *Ganaspis* spp. and *Leptolamina* spp. in regions most at risk from SWD.
5. Conduct molecular testing and lodge voucher specimens of all parasitoid species reared (as well as specimens available from earlier studies) and contribute data to the DROP database. Further develop collaboration with US taxonomists coordinating DROP.
6. Obtain biological data for the larval and pupal parasitoids wherever possible, including estimates of parasitism rates in the field.
7. Examine the potential for augmentative biological control of SWD using mass releases of endemic pupal parasitoids.
8. Explore potential to export live samples of larval and pupal parasitoids for testing on SWD cultures overseas.
9. Explore the use of augmentoria (cages containing fallen fruit but where nets retain the flies but allow the escape of parasitoids) as a conservation biological control option for SWD while maintaining sanitation.

Extension & engagement

10. Relationships with (i) the Hrček research group, (ii) the DROP database curators and (iii) the North American SWD Biological Control Working Group should be fostered as a priority. These relationships will be important in the context of undertaking further preparedness work for at-risk industries.
11. A continued focus on raising awareness of SWD among at-risk industries should be retained, and the extension pack created through MT17005 and MT18010 should be curated and continued to be updated for industry knowledge broker use.
12. Increasing the awareness of SWD in urban areas, with local council staff and 'green thumb' community groups should be a focus of next phase education as these areas are high risk entry points, but also high opportunity detection points.
13. As research continues, the SWD management fact sheet should be updated and expanded into a more comprehensive grower IPM guide with region specific information and advice.

Refereed scientific publications

No scientific publications have as yet been published from this project. However, the predictive modelling report had been converted into an academic paper for journal submission at the time of writing and it is intended that the biological control report be submitted to an academic journal for publication. Research from the previous project has recently been published:

- Maino, JL, Schouten, R, Umina, P. Predicting the global invasion of Drosophila suzukii to improve Australian biosecurity preparedness. J Appl Ecol. 2020; 00: 1– 12. https://doi.org/10.1111/1365-2664.13812

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Maino JL, Schouten R & Umina P. 2020. Predicting the global invasion of Drosophila suzukii to improve Australian biosecurity preparedness. Journal of Applied Ecology, https://doi.org/10.1111/1365-2664.13812

Wang X-G, Lee JC, Daane KM, Buffington ML & Hoelmer KA. 2020. Biological control of *Drosophila suzukii*. *CAB Reviews* 15, No. 054

Intellectual property, commercialisation and confidentiality

No project IP, project outputs, commercialisation or confidentiality issues to report.

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Appendices

Appendix A – 'Predicting spotted wing drosophila seasonal abundance' report (submitted as a separate attachment)

Appendix B – 'Parasitoids of Drosophilidae in Australia: Preparing for *Drosophila suzukii'* report (submitted as a separate attachment)

Appendix C – SWD Management Fact Sheet