Final Report

Secure Pollination for More Productive Agriculture: Guidelines for effective pollinator management and stakeholder adoption

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Securing Pollination for more Productive Agriculture: Guidelines for effective pollinator management and stakeholder adoption

Final Report

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AgriFutures™ Securing Pollination

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Introduction

The reliability and security of crop pollination services is at risk, for two main reasons:

- A decrease in floral support for pollinators in the landscape due to habitat clearing, agricultural intensification and climate change, leading to increased and more intense droughts and heatwaves;
- An increase in the reliance on a single pollinator species for crop pollination services.

To enhance pollination security, now and in the future we need to diversify our pollinator portfolio and reduce threats to existing pollinator species. Achieving that requires evidence-based decision making. This project aimed to collect and disseminate the background information needed to design meaningful action to enhance pollination security and resilience for farmers of pollination dependent crops, by developing:

- an understanding of the identity, density and efficacy of a diverse range of insect flower visitors of eleven pollination dependent crops;
- an understanding of the nature and extent of the main threats to pollination security;
- crop and landscape management strategies to secure pollination services in the future.

Outcomes and conclusions

We identified a wide range of insects that visited the crop flowers, and found that the most efficient and abundant pollinators differed per crop, per region and over time. What they have in common is that they depend on the presence of flowering plants in the landscape. We found that the proximity and composition of native vegetation influences the abundance and diversity of crop pollinating species, with effects noticeable up to ~200 m into the crop. Feral honey bees play a major role in crop pollination, in particular in dryland lucerne and apple. However, in less forested areas, their densities are not high enough to provide all the pollination required, because, in addition to nectar and pollen, their presence depends on the availability of nesting hollows and water.

All pollinating species rely on the presence of floral resources, i.e. pollen and nectar. Different species are active at different times of the year - also when the crop is not in flower. Therefore, to enhance the health and diversity of pollinators and ensure that pollination services remain reliable and resilient now and in the future, floral support should be available nearly year-round, in close proximity to the crop. Most crop pollinating insects, including honey bees, are generalist feeders that have a broad diet, and require the presence of a variety of pollen and nectar sources. Therefore, our advice is to plant a wide range of local, easy to grow native species. Planting designs can focus on understorey species, hedgerows or whole area plantings. These plantings also convey a range of other benefits for farm productivity.

In addition, nesting substrate for volunteer pollinators can be provided in various ways. This includes bundles of sticks-with-pithy-stems for reed bees; open, compacted well drained soil for ground nesting furrow and nomia bees; and leaving old paddock trees in place as they provide nesting hollows for feral honey bees and stingless bees.

Outputs

With a focus on the farmers of pollination dependent crops, we promoted the insights into density, numbers and identity of crop visiting insects, the importance of native vegetation for their presence and crop productivity, and planting advice to enhance their presence. We did this using a large variety of approaches including fact sheets, websites, industry newsletter articles, videos, oral presentations to industry groups, scientific publications, and even a pollinator song. Links to many of these outputs are provided in this report.

To enhance future and geographically wide-ranging adoption by primary producers we recommend:

- Further assessment of the pollination efficacy of a suite of pollinators for a range of crops;
- Research and formulation of planting advice that complements additional crops and cropping areas outside of South Australia, as the advice produced in this project is limited to three cropping regions in SA;
- Research and formulation of planting advice that can provide a range of co-benefits additional to pollination, for example: shade and shelter for livestock, erosion control, fire retardancy;
- This report be brought to the attention of industry organisations of all pollination dependent crops.

Future research should provide experimental evidence of the additional co-benefits of floral resource management and plantings, not only for pollination services, but also for biological control, carbon sequestration, sun and wind protection for stock, protection from snail invasions and erosion prevention.

Abbreviations and glossary

Provide a list of abbreviations and description of key words if used frequently throughout the report.

Delete if not applicable.

AB	Almond Board
ANU	Australian National University
APAL	Apple & Pear Australia Limited
APGASA	Apple and Pear Growers Association South Australia
B	billion
BOLD	Barcoding Life
DEW	Department of Environment and Water (South Australia)
GA	Greening Australia
Ha	hectare
km	kilometre
LA	Lucerne Australia
m	metre
NBCI	National Centre for Biotechnology Information
NRM	Natural Resources Management
NSW	New South Wales
NT	Northern Territory
QLD	Queensland
SA	South Australia
SAAA	South Australian Apiarists' Association
TAS	Tasmania
TERN	Terrestrial Ecosystems Research Network
TfL	Trees for Life
UNE	University of New England
UoA	University of Adelaide
Usyd	University of Sydney
YP	Yorke Peninsula

1 Project rationale and objectives

Annually, crop pollinators contribute about AU$14B to the Australian economy (Clarke and Le Feuvre 2020). The pollinators include managed and feral honey bees, native bees and a range of other insects. The produce that depends on pollination includes 35 species of fruit, vegetables, nuts, cotton, as well as oil and pasture seeds. Due to the economic and nutritional value of these products, safeguarding pollination services serves the interest of both the farmers and the consumers of pollination dependent crops.

The security and resilience of pollination services are increasingly under threat. Increasingly, combinations of agricultural intensification, land clearing, and more frequent and intense droughts and bushfires, reduce the resource base for unmanaged and managed pollinators. The security and resilience of crop pollination is further threatened by the expected establishment of the Varroa mite, which will lead to a sharp decline in free pollination by feral honey bees.

This project aimed to secure and enhance crop pollination services by designing ways to support pollinator density and diversity to create a resilient pollinator portfolio.

Resilient systems are able to bounce back from future short-term shock and optimise long-term trends. They are consistent in their performance over time through diversification, risk awareness and flexibility. In the financial world, enhancing the resilience of an investment portfolio requires a profound understanding of the available capital, the risk that capital is exposed to, and the investment landscape. Similarly, a resilient pollinator portfolio requires an understanding of the capital, the threats and investment options.

The main objectives of the project were, therefore, to investigate:

(1) **Our capital** – identification of the crop visiting species and assessment of their efficacy as pollinators.
   a. <u>Justification</u>: Strengthening pollination security requires (a) improved understanding of the contribution of various species of insects (native pollinators, hived honeybees and feral honeybees) to the pollination of crop species across different regions, and (b) improved recognition and identification tools.

(2) **Risk and opportunity** – identification of the threats to crop pollination, and the possible actions that can reduce risk and enhance security.
   a. <u>Justification:</u> Any incursion of honey bee diseases poses a risk for pollination services. In Australia, this risk is still not well understood, because it is unknown what part of crop pollination services are delivered by feral honey bees and by other unmanaged pollinators. In addition, the landscape elements and resources that support crop pollination services need to be identified to explore opportunities for enhancement of pollination security.

(3) **The investment landscape** – the economic feasibility of investments that can reduce risk and enhance resilience in crop pollination.
   a. <u>Justification</u>: Pollination security, that is, the reliability and resilience of pollination services, can be increased by enhancing the abundance and diversity of volunteer pollinators in cropping areas as well as the health of honey bee hives. This requires the presence of adequate floral resources and nesting

opportunities. To enhance the reliability and resilience of pollination services now and in the future, we need to understand the costs and benefits of tailor-made approaches to support their presence and abundance in the cropping environment.

Lastly, a major aim of this project was to increase the uptake of improved management for pollination security. To this end, we aimed to use established communication channels with industry stakeholders, on-farm demonstrations, and develop web-based tools to provide cost information and planting advice for farm business planning.

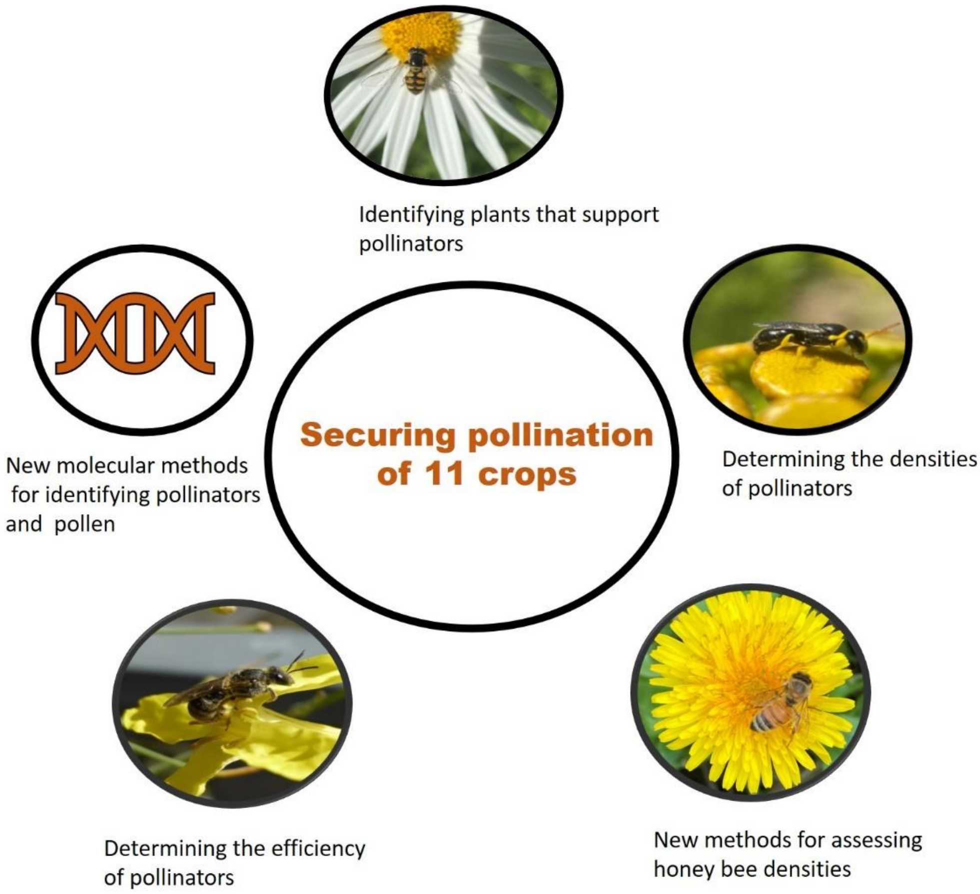


Figure 1. Graphical summary of the project

2 Methods and project locations

2.1 Introduction

To provide growers with an understanding of the pollinators of their crop and their reliance on the availability of food and nesting opportunities in the cropping landscape (Figure 1), we focussed on:

- **Assessing our capital**: the crop pollinators;
- **Understanding the threats** to pollination security;
- **Designing an investment strategy** to support pollinator security and resilience.

2.2 Assessing our capital: the crop pollinators

The identity of crop visiting insects, their abundances and pollination efficacy

We identified the crop visitors and assessed their abundances on a range of pollination dependent crops, including almond, apple/pear, avocado, blueberry, canola, cauliflower, lucerne, mango, pear, raspberry, and watermelon using standardised methods (all research groups). Of these eleven crops, data on visitation are presented for nine, i.e. all apart from almond (exclusively honey bees), and cauliflower. The visitation data for the latter crops are available from the authors on request. On apple, blueberries and raspberries, we investigated the pollination efficiency of the most abundant pollinators.

2.3 Understanding the threats to pollination security:

Assessing the density of feral honey bees

The density of feral honey bee hives was assessed at various locations in south-eastern Australia, and the method was validated in Urrbrae, South Australia.

Assessing the importance of natural habitat for crop pollinators and their services

We investigated the effect of the landscape on the presence and abundance of crop pollinators of apple in Victoria, apple and berries in QLD and NSW, and apple and lucerne in SA. Furthermore, we investigated the importance of the presence of woody vegetation in the surrounding landscape for apple quality and lucerne set, as well as the effect of inter-row flowers on almond visitation. Furthermore, we examined the nesting resources that support stem-nesting bees that pollinate *Rubus* crops, both in the orchard and in nearby forest habitats.

2.4 Designing an investment strategy

Revegetation design: plant selection

Using a combination of field observations, visitation data, and analysis of pollen carried by honey and native bees, consultation with beekeepers and information from the literature about honey bee floral resources we identified the local plants that constitute food and nesting substrates for native crop-visiting bees of apple, berries and lucerne. To identify the pollen carried by bees, we created a repository of DNA sequences of South Australian crops and native plants. To improve plant selection in our revegetation plantings, we investigated the importance of plant diversity for native bee abundance and diversity. We then designed revegetation strategies together with participating growers and revegetation specialists, and implemented demonstration plantings on 5 farms (SA).

Value, benefits and costs of plantings

We used a reverse conservation auction to reveal the costs of diverse plantings in general and the perceived value of plantings for pollinators in particular. A reverse auction is a tender process - bidders are invited to estimate the cost of delivering a service, such as revegetation, to a certain standard. The bidder that provides the highest value for money is then offered a contract to deliver this service. The height of the bids therefore reveal the price of the service. We also documented the costs of our demonstration plantings, and modelled the longer term benefits using existing software (SA).

2.5 Outputs and extension

The outcomes of this project are detailed in a range of scientific papers, and we provide links to these in the chapters below. We have presented the outcomes in person at a wealth of grower and beekeeper conferences, field days, workshops, and via the media, including appearances on television, radio, and in newspapers, as well as contributions to crop specific magazines and social media platforms). A list of the extension activities is provided in the report, and examples can be found in the Appendix, which is made available by AgriFutures upon request.

To help farmers and scientists recognise and identify pollinators, we created:

- A factsheet with the main pollinators found in each crop and region;
- A pollinator recognition app;
- A repository of molecular barcodes of crop pollinating bees ("AUSBS" project under the Barcoding of Life Databases, BOLD) and plants visited by bees (accessible though the National Centre for Biotechnology Information, NCBI)

To assist SA growers with strategies to support the security and resilience of crop pollination locally, we created:

- Nine crop specific fact sheets (available through UNE. ANU and PIRSA);
- Advice for the placement of nesting substrate on the farm;
- An animation that directs growers to the Pollin8 website;
- The Pollin8 website which assists growers to:
    - Create a planting list that is suited to the region
    - Find local revegetation specialists, native nurseries, state sustainable agriculture officers
    - Model the estimated pollination benefits from plantings over time
    - Consult a flowering calendar
- Demonstration sites (5 ha) with pollinator habitat were created on five South Australian farms.

The fact sheets are available through AgriFutures. We also produced a pollinator song and various short video clips to promote the project and the pollin8 website.

2.6 Regions, crops and locations

The project encompassed honey bee density assessments and identification of visitors to 10 pollination dependent crops in six regions, at 82 sites (Figure 2). In addition, and not shown on the map, The University of Adelaide performed a reverse auction in the south east of South Australia (Section 3.d.ii), and undertook revegetation at five farms (two in Yorke Peninsula, two in the South East, one in the Adelaide Hills; Figure 44). A full list of all 82 properties and their locations can be found in the Appendix, which is available from AgriFutures upon request.

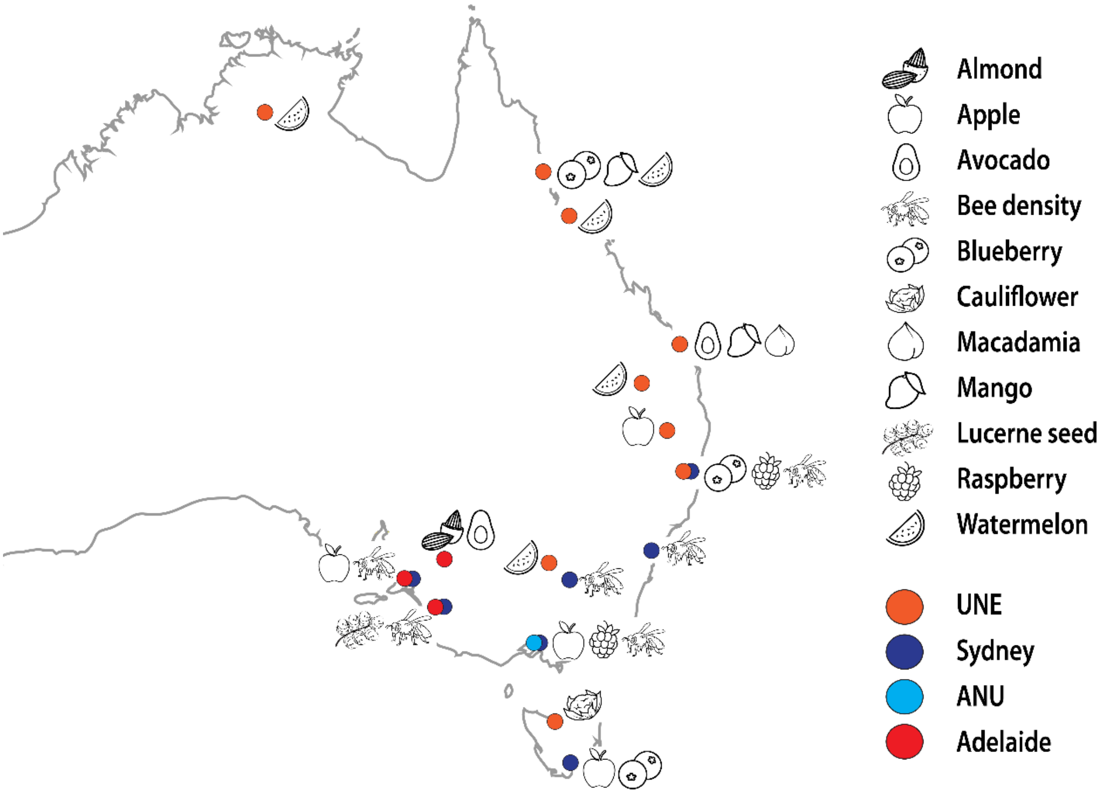


Figure 2. Project map. Map of project activities and crops, and involvement of different research teams. Research teams included UNE: University of New England; Sydney: University of Sydney; ANU: Australian National University; Adelaide: The University of Adelaide. The latitudes and longitudes of the 82 farms involved in this project can be found in the Appendix, which is made available by AgriFutures upon request. In addition to this, and not shown in the map, visitors to canola were assessed using the literature and data from Yorke Peninsula.

3 Project Outcomes

Here, we provide a combined overview of the main project level achievements. This chapter has three sections:

- **Assessing our capital**: the crop pollinators;
- **Understanding the threats** to pollination security;
- **Designing an investment strategy** to support pollinator security and resilience.

3.1 Assessing our capital: The Crop Pollinators

In this section, we find out what insect species visit and pollinate apple, avocado, blueberry, canola, lucerne, macadamia, mango, raspberry, and watermelon. There are three parts:

a. **Crop visitors:** Investigating the identity and abundance of the insects that visit the crop flowers in various regions;
b. **Pollination efficiency:** Assessing the pollination efficiency of the most abundant insect groups that visited the crop flower (apple, mango, avocado, macadamia, blueberry, and watermelon);
c. **Identification tools:** Developing the tools and outputs to assist in the identification of crop visitors.

a. Crop visitors

Introduction

Global production of pollination dependent crops is increasing, and this causes a great demand for pollination services worldwide (Aizen and Harder 2009). Pollinator declines cause lack of resilience in pollination services, and therefore expose farmers to high economic risk (Garibaldi et al. 2011, Potts et al. 2016). The resilience of crop pollination services is higher as the abundance and diversity of visitors and pollinators increase. Research performed overseas supports this notion (e.g., Klein et al. 2009, Winfree et al. 2009). However, in Australia, there is limited insight regarding both the identity of crop visitors, and the importance of diversity for crop pollination services. If we want to enhance and diversify the pollination portfolio, we first need to understand our resources: which species visit and help pollinate our crops?

Methods

We identified the flower visitors of nine crop species (apple, avocado, blueberry, canola, lucerne, macadamia, mango, raspberry, and watermelon), and used standardised methods to survey and quantify the flower visitors. These methods differed per crop and cropping system, but all methods involved registering and quantifying crop flower visitors, standardising the number of flowers scored and the time devoted to the surveys. In addition, we used sweep netting and traps (blue vane traps) to collect voucher specimens. These specimens were either pinned or preserved in ethanol.

For native bees, South Australian researchers removed a leg from some of the pinned specimens, to allow DNA barcoding (see section 3.1.c, below). The remainder of the pinned bees were treated as vouchers, and can be found in the collection of the SA museum.

Results

There was a wide range of insect visitors to the crops, which varied between crop species and location (Figure 3).

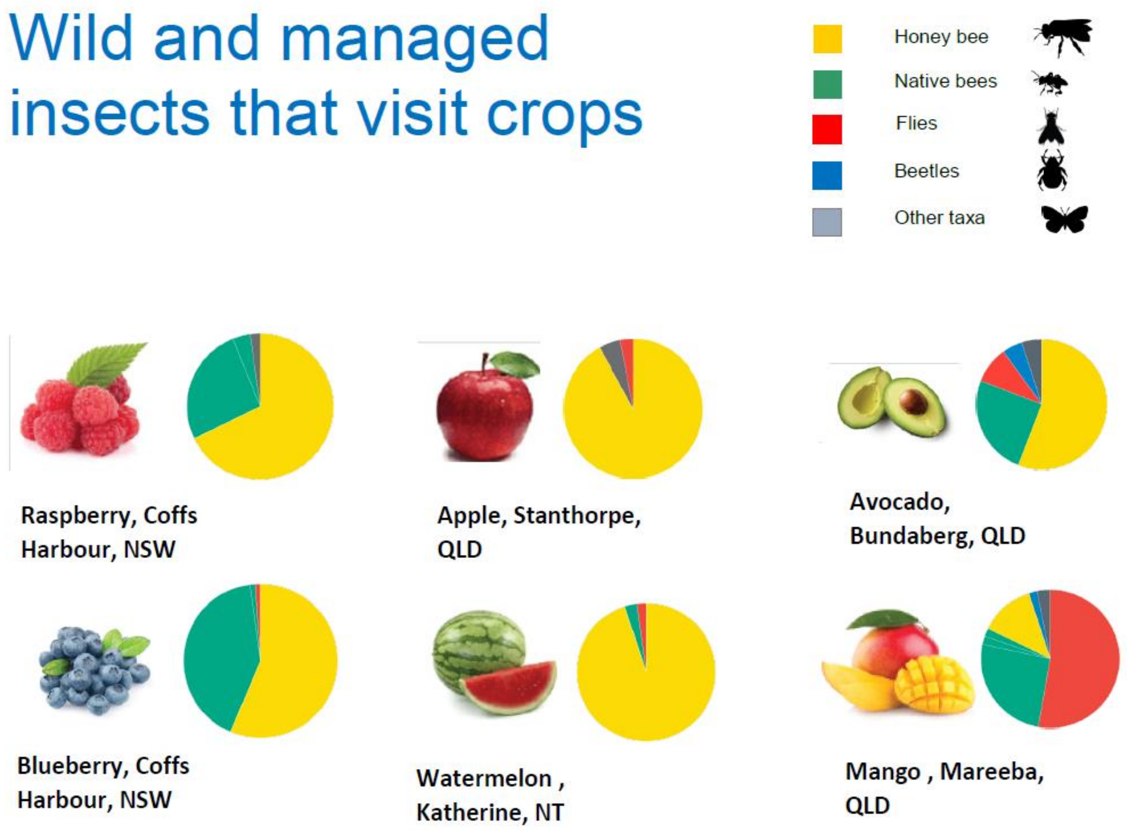


Figure 3. In northern Australia, the abundance and species of flower visiting insect taxa varied between crops.

Apple

Locations: Stanthorpe QLD, Yarra Valley VIC, Adelaide Hills SA, Huon Valley TAS (Figure 2).

We observed and collected insects visiting apple flowers at 14 sites across the Adelaide Hills production area, nine sites in Stanthorpe (QLD), six sites in the Yarra Valley (VIC) and in Tasmania (Appendix 1). While honey bees were the most abundant species in all orchards, other insect species accounted for nearly 40% of recorded visitors in some orchards (Figure 4. Proportion of visits to apple flowers by honey bees (orange) relative to all other insect flower visitors (blue) per orchard across the four production areas included in our study. Values included within each bar indicate the number of visits recorded by the respective group.). In Stanthorpe where orchards are commonly protected by hail-netting, visitors other than honey bees were relatively rare. The apple orchards in the Adelaide Hills, Huon Valley and Yarra Valley were predominantly unnetted and had a higher diversity and abundance of visitors.

Among native bees, the twig nesting reed bees (*Exoneura)* were the most common in the Yarra valley, followed by furrow bees *Lasioglossum (Chilalictus)*.

In Tasmania, honey bees made up the vast majority of visitors to apple (90%), with hoverflies (*Syrphinae* spp) and reed bees (*Exoneura* spp) the next most common, representing 2% and 3% of visitors, respectively. The bumblebee (*Bombus terrestris*) was notably absent from the majority of apple orchards, accounting for less than 1% of visits. Overall nine species of insect visited apple, two hoverflies (*Eristalinae* sp. and *Syrphinae* sp.), six bees (*Apis mellifera*, *Bombus terrestris, Exoneura* sp, and three species of *Lassioglossum*) and a muscid fly.

In the Adelaide Hills, furrow bees (*Lasioglossum*) and slender furrow bees (*Homalictus*) were the most diverse and abundant group after honey bees. Nest entrances of these ground-nesting bees were sometimes seen the soil beneath apple trees, in particular in herbicided headlands, which suggests that supporting their population with alternative floral resources before or after crop flowering could benefit apple pollination. The furrow bee *L. (C.) lanarium* is particularly widespread and occurs in nearly all production areas and crops in south-eastern Australia, making them a suitable target for management strategies that support their role as crop pollinators.

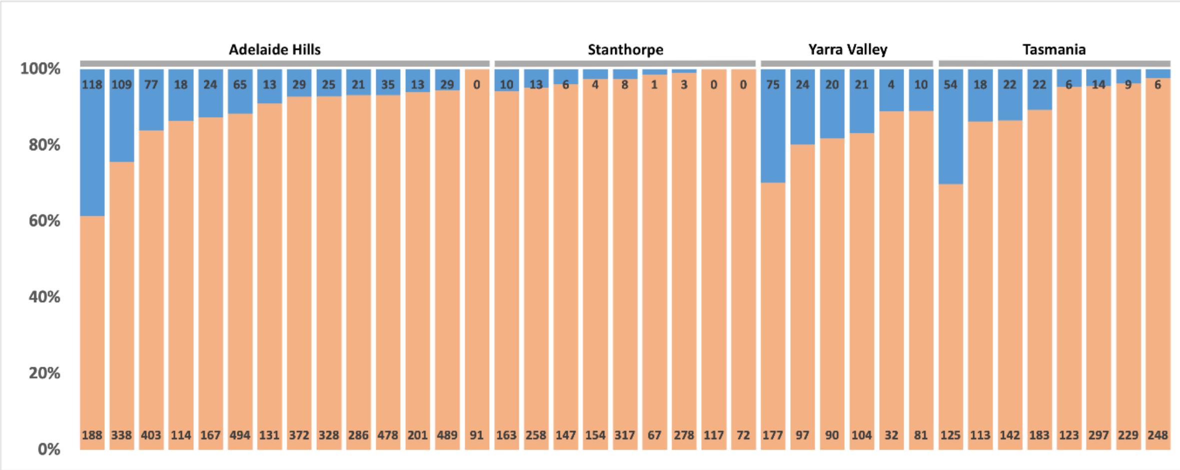


Figure 4. Proportion of visits to apple flowers by honey bees (orange) relative to all other insect flower visitors (blue) per orchard across the four production areas included in our study. Values included within each bar indicate the number of visits recorded by the respective group.

Avocado

Locations: Bundaberg QLD; Sunraysia & Riverland: Renmark SA, Mildura Vic,Coomealla NSW.

We observed and collected insect visitors to avocado flowers across 7 sites in Bundaberg, QLD and 15 sites in the Sunraysia region. Avocado flowers were visited by 38 taxa, including wild bees, flies, beetles, ants and wasps. In the Sunraysia region, flies were the most abundant group of visitors in total, accounting for a combined total of 52% of all visits (Figure 5.a). Hoverflies (Syrphidae) were the most commonly observed flies visiting avocado flowers (22% of visits), followed by blow-flies (Calliphoridae, 15% of visits). A ladybird beetle (Coccinella sp.) was the most frequently observed flower-visiting species, representing 25% of all visitation to avocado flowers. Honey bees accounted for only 3.8% of visits. Other insects observed visiting avocado flowers in low numbers included native bees, beetles, wasps, ants and butterflies, which accounted for a combined total of 5% of visits.

In the Bundaberg region, honey bees were the most frequently observed flower visitors, accounting for 37% of visitation (Figure 5.b). Ladybird beetles (Coccinellidae) were again well represented among flower-visitors, with four morphospecies contributing a total of 38% of visits. Rhiniid flies, *Stomorhina discolor* (Rhiniidae) and stingless bees, *Tetragonula carbonaria*, were also important visitors, contributing 10.5% and 4% of visits, respectively. Hoverflies were occasional visitors, accounting for 3% of visits. A variety of other flies, ants, native solitary bees, beetles and wasps accounted for the remaining 7% of visits.

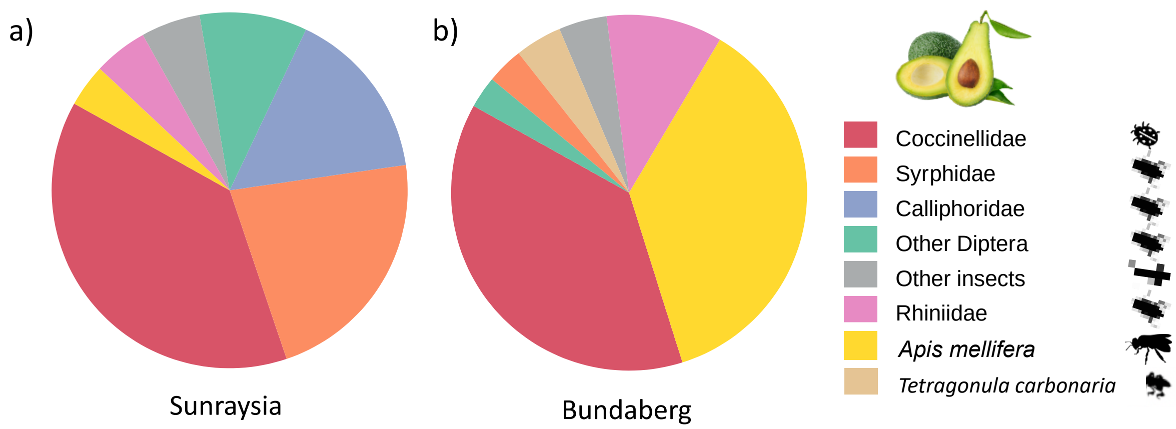


Figure 5. Relative proportions of visits to avocado flowers by different groups of insects in a) the Sunraysia region and b) Bundaberg, QLD.

Lucerne

Location: South East South Australia

Honey bees made up more than 90% of the insects visiting lucerne flowers. We found a total of 11 species of native bees visiting lucerne flowers in our study fields in south east South Australia (Figure 6), and nine additional species visiting flowers in the neighbouring vegetation. Captured bees were largely solitary, or primitively eusocial, ground-nesting species of the halictids bee genus *Lasioglossum,* or furrow bees*.* The two most abundant species, *Lasioglossum (Chilalictus) lanarium* and *L. (C.) chapmani*, are ground-nesting species that can nest in the irrigation banking, which is within close proximity to the crop. Larger species such as the blue-banded bee *Amegilla chlorocyanea* (Apidae; Figure 6) and a leafcutter bee, *Megachile obtusa* (Megachilidae) were also present, but collected in smaller numbers. Native wasps, including the pest lucerne seed wasp *Bruchophagus roddi*, were next most abundant non-*Apis* group after native bees. In the past, bee species collected on lucerne have included the nomia bees *Lipotriches australica*, and *L. flavoviridis,* and the leafcutter bees *Megachile quinquelineata*, and *M. nigrovittata* (Bray 1973, Hogendoorn and Keller 2012).

Research by the lucerne industry shows that 30% of dry-land lucerne seed producers do not add managed hives to their crop. This implies that they rely almost entirely on feral honey bee colonies for pollination. While European honey bees are the most abundant crop visitor, on an individual basis, they need to be placed in high densities, because they often harvest nectar without tripping the flower (Cane, 2002). In contrast, the native species *Lipotriches flavoviridis* has been found to be 30 times more efficient at pollinating lucerne flowers (Hogendoorn and Keller 2012).

The number and diversity of different species presence of different species varied with the presence of surrounding vegetation and paddock trees (Figure 26).

The blog 'The wild pollinators of Lucerne' provides more information lucerne visiting bees.

Figure 6. Flowering lucerne was visited mainly by honey bees. However, 10% of the visitors were native species. Blue-banded bees are among the most common native bee species seen in lucerne

Blackberry and Raspberry

Locations: Coffs Harbour NSW, Yarra Valley VIC

European honey bees are abundant pollinators of raspberries and blackberries, but native bees also play an important role that has been overlooked. Our study identified several native bee species visiting raspberry and blackberry flowers in the Yarra Valley, Victoria (Figure 35) and in Coffs Harbour region of NSW (Figure 7). The most common native bees detected visiting flowers and carrying pollen in Victorian rubus berry crops were reed bees (*Exoneura* species) and furrow bees (*Lasioglossum* species).

We also examined how important native bees are as pollinators, and how growers can encourage them. While some rubus berry cultivars produce fruit without pollination, all are likely to increase yield and fruit quality with bee pollination. We found that native bees are just as effective as honeybees at pollinating blackberries. A single visit by any bee species (honey or native bee) triples the number of drupelets, therefore increasing fruit size.

In the Coffs Harbour region, NSW, honey bees were the main visitors to raspberry flowers, accounting for 71% of flower visitation (Figure 7). Stingless bees, *Tetragonula carbonaria*, were also frequent visitors to raspberry flowers, providing 26% of visits. The ground-nesting solitary bee *Homalictus urbanus,* an occasional visitor, contributed the remaining 3% of observed visits to raspberry flowers. Both stingless bees and ground-nesting bees may be suitable species for targeted farm management practices to increase nesting habitat and nutritional resources to enhance crop pollination service delivery by wild pollinators.

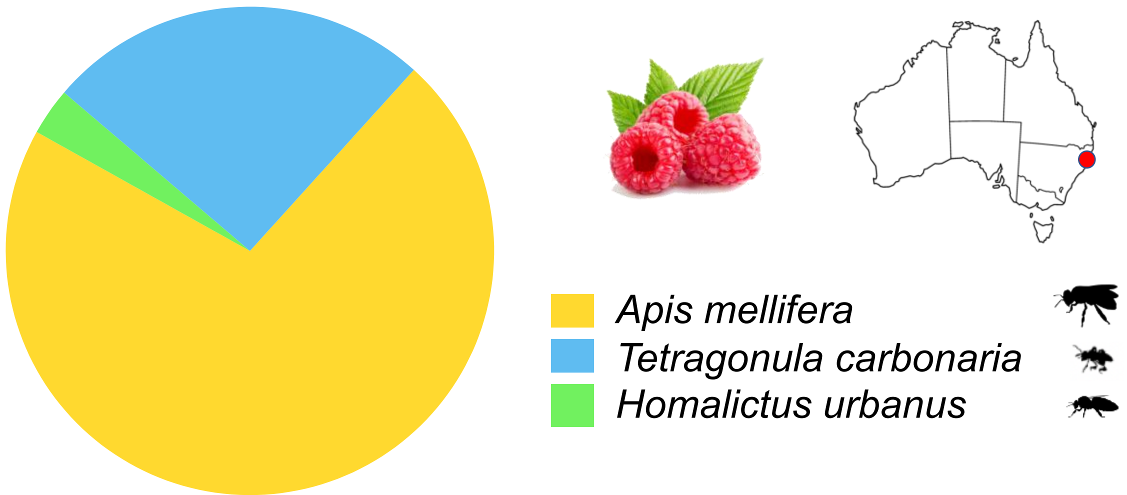


Figure 7. Relative proportions of visits to raspberry flowers by different groups of insects in the Coffs Harbour region of NSW.

Blueberry

Locations: Coffs Harbour NSW, Walkamin, QLD, Tas

Blueberry flowers were surveyed for insect visitors on farms in Tasmania, New South Wales and Queensland (Figure 2). Across all sites, bees were the most frequently observed group of visitors. In New South Wales, honey bees and wild stingless bees (*Tetragonula carbonaria*) comprised 99% of all recorded floral visitors to rabbiteye blueberry flowers. The remaining 1% of recorded visitors were native bees of three genera: *Exoneura*, *Lasioglossum* and *Xylocopa*, and hoverflies (*Austrosyrphus* and *Simosyrphus*). In southern highbush blueberry, managed honeybees and wild stingless bees made up 98% of all floral visitors. Hoverflies (*Austrosyrphus* and *Simosyrphus*) made up the remaining 2% of recorded visitors.

In Tasmania, honey bees accounted for 76% of blueberry visitors, while bumblebees accounted for 19% of visitation. Reed bees (*Exoneura*) were third most common, accounting for 4% of visitors. We observed a total of 11 visiting species of which 7 were bees (*Apis mellifera*, *Bombus* *terrestris, Exoneura* sp., *Leioproctus* sp., and three species of *Lassioglossum*). We also noted two hoverfly species (*Eristalinae* sp. and *Syrphinae* sp.) and two muscid flies (Muscidae sp.).

In Walkamin, Queensland, managed honey bees contributed 95% of visits to southern highbush blueberry flowers cultivated under polytunnels. Hoverflies, (Syrphidae) represented by two morphospecies, accounted for 3% of flower visits. Native stingless bees (*T. carbonaria*), butterflies (Lepidoptera) and muscid flies (Diptera) accounted for the remaining 2% of visits.

Both between and within each cultivar of blueberry, dominant pollinator taxa differed considerably in their abundance. In northern highbush, we observed 59% more honeybees than bumblebees. In rabbiteye, abundances of honeybees and stingless bees were similar (18% difference) but in southern highbush, we observed 42% more honeybees than stingless bees. The abundances of both honeybees and stingless bees were higher (76% and 83%, respectively) in rabbiteye than southern highbush. Honeybee abundance was similar between southern highbush and northern highbush (14% difference).

Canola

Location: Yorke Peninsula SA.

In canola, 99% of all visitors are honey bees. The crop was also visited by a range of fly species. Native bees that visited canola included, six species from the subgenus *Lasioglossum (Chilalictus): L. cognatum, L. eremaean, L. erythrurum, L. instabilis, L. occiduum, L. vitripenne,; L. (Parasphecodes) sulthicum and Homalictus urbanus.*

Macadamia

Location: Six sites in Bundaberg, Queensland.

We recorded 20 insect taxa including wild bees, flies, beetles and wasps. Honey bees were the most frequent visitors to macadamia flowers, accounting for 89% of visits (Figure 8. Relative proportions of visits to macadamia flowers by different groups of insects in Bundaberg, QLD. Bottom right: Stomorhina discolor.). The rhiniid fly, *Stomorhina discolor* (Rhiniidae) was the second-most abundant visitor after honey bees, contributing 3.5% of visits. Six other fly taxa, including hoverflies (Syrphidae) and blow-flies (Calliphoridae) contributed a combined total of 3% of visits. Five species of beetles from the families Lycidae, Cantharidae, Coccinellidae and Chrysomelidae, contributed a combined total of 2.5% of visits. Wasps and butterflies made up the remaining 2% of visits.

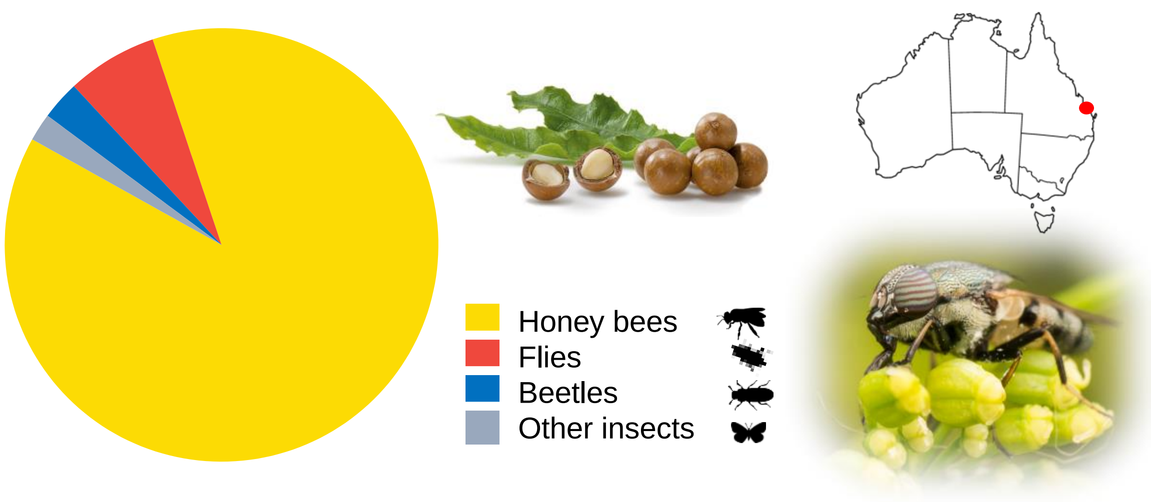


Figure 8. Relative proportions of visits to macadamia flowers by different groups of insects in Bundaberg, QLD. Bottom right: Stomorhina discolor.

Mango

Locations: Bundaberg QLD, Mareeba QLD

We observed and collected visitors to mango flowers at nine sites in Mareeba, QLD, and two sites in Bundaberg, QLD. Mango was visited by 76 taxa including 15 species of bees, 4 morphospecies of flies, 6 beetles, 5 moths and butterflies and one species each of true bugs and ants. In Mareeba, flies were the major group of visitors to mango flowers, accounting for a combined total of 62% of visits (Figure 9a). Stingless bees (*Tetragonula* spp.) were the second-most frequent visitors to mango flowers, accounting for 18% of visits. Honey bees provided 12% of visits, and other bees including the exotic bee *Apis cerana* and native solitary bees contributed an additional 3% of visits. The remaining 5% of visits were derived from beetles (2%), ants (1%), butterflies and moths (1%). Of the flies, hoverflies (Syrphidae, genera: *Eristalinus*, *Allobaccha*, *Mesembrius* and *Melanostoma*) were well represented, with 5 observed morphospecies accounting for a combined total of 40% of all visits. The other main fly taxa included blow-flies (*Chrysomya* spp.: 16% of visits), bibionid flies (*Plecia amplipennis*: 14% of visits) and rhinid flies (*Stomorhina discolor*: 14% of visits).

In Bundaberg, Queensland, the main floral visitor to mango was the rhiniid fly *Stomorhina discolor*, accounting for 46% of visits (Figure 9b). Honey bees were also frequent visitors, contributing 22% of visits. Stingless bees (*Tetragonula* spp.), soldier beetles (Cantharidae), hoverflies (Syrphidae) and blow-flies (Calliphoridae) contributed 5% of visits each. Ants and wasps contributed 2.5% of visits each, and the remaining 7% of visits were derived from blister beetles (Meloidae, 1.5%), ladybird beetles (1%), leaf beetles (Chrysomelidae, 1%), native bees (Halictidae, 1%), and other flies and beetles (combined total of 2.5% of visits).

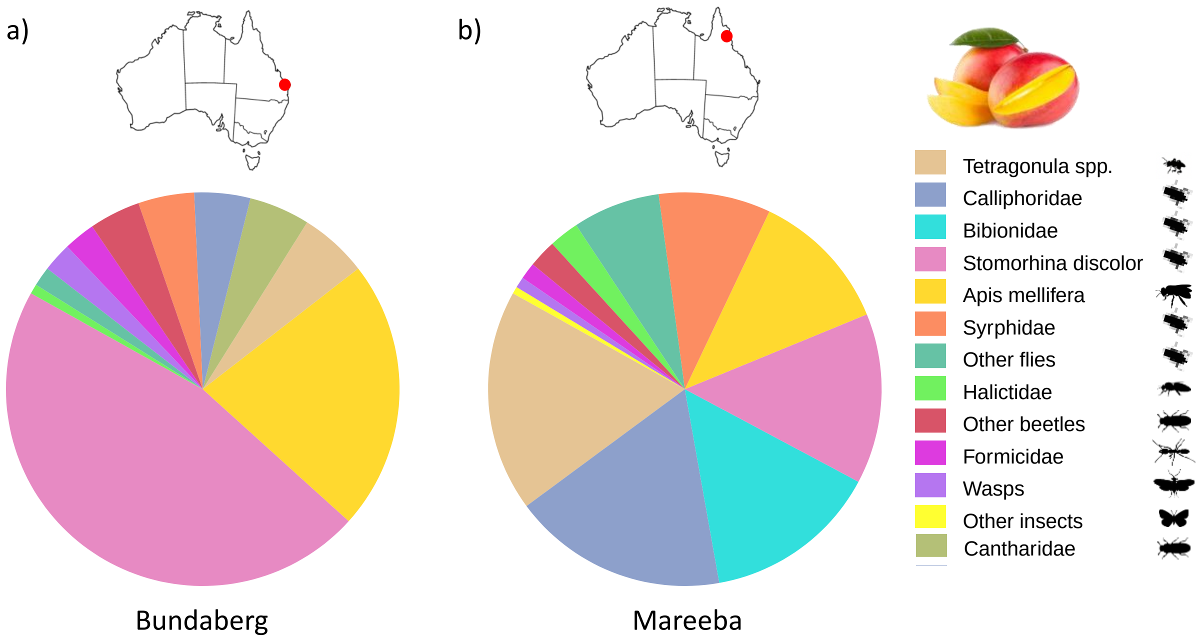


Figure 9. Relative proportions of visits to mango flowers by different groups of insects in a) the Bundaberg and b) Mareeba, QLD.

Watermelon

Locations: Coffs Harbour NSW, South East QLD, Katherine NT, Far North Queensland QLD

Riverina QLD

Species composition was significantly different among the regions with representatives from the orders Hymenoptera, Diptera, Lepidoptera, Hemiptera and Coleoptera in all five regions. Honeybees (*Apis mellifera* L.) was the most prominent flower-visiting insect species in all regions. Wild bees (including species of *Lasioglossum*, other halictids, and stingless bees) were found in all regions but they were prominent in Chinchilla (21%) and Riverina (18%) compared to other regions. Dipteran species (mainly family: Syrphidae) were present across the regions and their abundance was comparatively high in Lakeland (4%) while the lowest (0.3%) was recorded in Riverina. Species of beetles (family: Coccinellidae, Chrysomelidae, Melyridae and Staphylinidae) and true bugs (Miridae sp.) were found in the regions except Katherine and their relative abundance (beetles: 4.9% and true bugs: 0.7%) was high in Riverina. Relative abundance was low (<1%) in all other groups including lepidopterans (moths), wasps and other species.

Crop visitors: a summary

Most crops were visited by a wide range of insects (

Figure 10). In particular, wild bees, flies, beetles, moths, butterflies, ants and wasps were important flower visitors but abundance and diversity varied among crops, regions and even across blocks within sites surveyed. Honey bees (*Apis mellifera*) were found in all crops, regions and years but were not always the most abundant visitor. Two families of fly visitors, Hoverflies (Syrphidae) and blowflies (Calliphoridae), were present across all regions and crops. A single genus belonging to the blowflies (Calliphoridae: *Chrysomya* spp.) was present in all crops, comprising 5% of total visits.

Among bees, honey bees were the most abundant visitors to most crops and locations, which is not surprising as managed hives were placed in nearly all crops, and feral colonies reach high densities in several cropping areas (see below). We observed a diverse collection of Australian native bees, including stingless bees, blue-banded bees, halictine bees of the genera *Lasioglossum*, *Homalictus* and *Lipotriches*, as well as reed bees (genus *Exoneura*). Their visitation alone could locally comprise 30% of all visits.

Numbers and species of bees varied between crops, regions and years. For example, in the cooler regions of Victoria, native apple visitors were predominantly reed bees (*Exoneura)*, in Tasmania bumblebees and reed bees were the most common visitors of apple, in the Adelaide Hills the majority were furrow bees (*Lasioglossum*), while in the north of the country, stingless bees (*Tetragonula*) and carpenter bees (*Xylocopa*)were part of the mix.

Figure 10. Most crops were visited by a range of insects. Wasps, native bees, flies and butterflies were commonly seen on all crops studied.

b. Crop pollination effectiveness

Introduction

A flower visitor is not necessarily a pollinator. To assess the importance of different taxa for crop pollination, we need to analyse the pollination effectiveness. Pollination effectiveness of a visiting species depends how abundant the visitors are on the flowers and how much suitable pollen they deposit onto the stigma per visit. Suitable pollen is pollen that will grow a pollen tube and result in fertilisation, and hence seed and fruit production. The suitability of pollen depends on the crop species. For example, in apple, blueberry, cherry, and almonds, cross pollination with pollen from a different variety is needed to achieve fruit set, while watermelon, lucerne, mango, avocado and macadamia can self-pollinate but they need a pollinator to deliver the pollen to the stigma.

Methods

We used two methods to assess pollination effectiveness: pollen deposition and fruit set.

To quantify pollen deposition, we offered virgin flowers to the most abundant visitors in each of the crops. The flowers had been bagged before they opened to prevent any insect visitations. We then quantified how much pollen the visitors deposited on the stigma after single and multiple visits of in avocado, mango, apple and macadamia. To do this, we removed the stigma from flowers immediately after the visit(s), mounted it onto slides using basic fuchsin-gel (Kearns and Inouye, 1993) and counted the crop pollen grains of, under 200x magnification. We then calculated 'pollinator effectiveness' by multiplying visitation rate and mean number of pollen grains deposited after a single visit for the main flower visitors.

Results

Pollen deposition

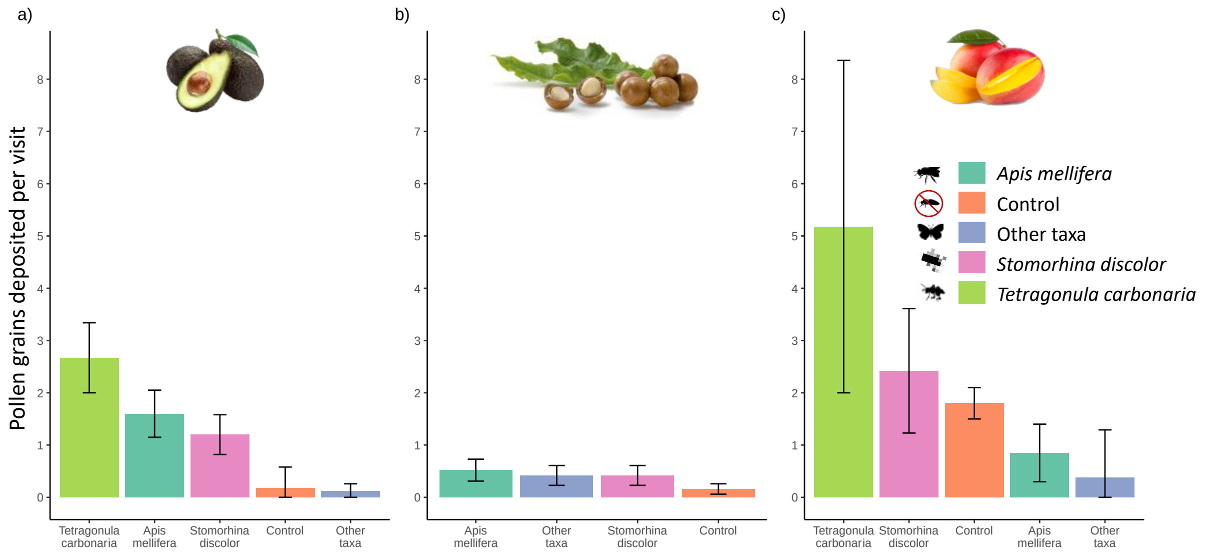


Figure 11. Number of pollen grains deposited on the stigma of (a) avocado (b) macadamia and (c) mango flowers by different groups of flower visitors

In **avocado**, stingless bees and honeybees were the most effective at transferring pollen in Bundaberg but flies were most effective in Sunraysia region (Figure 11a). Of the most dominant visitors to **macadamia** in Bundaberg, the honeybee was the most effective at transferring pollen (Figure 11b). In **mango**, stingless bees and *Stomorhina* sp. flies were the most effective at transferring pollen (Figure 11). We only obtained efficiency data on the most common taxa and did not obtain efficiency data for all flies and beetles due to the time and labour intensive approach. Future research needs to focus on efficiency of other wild taxa.

In **watermelon**, the number of pollen kernels deposited by honeybees was significantly higher than those deposited by wild bees (Figure 12).

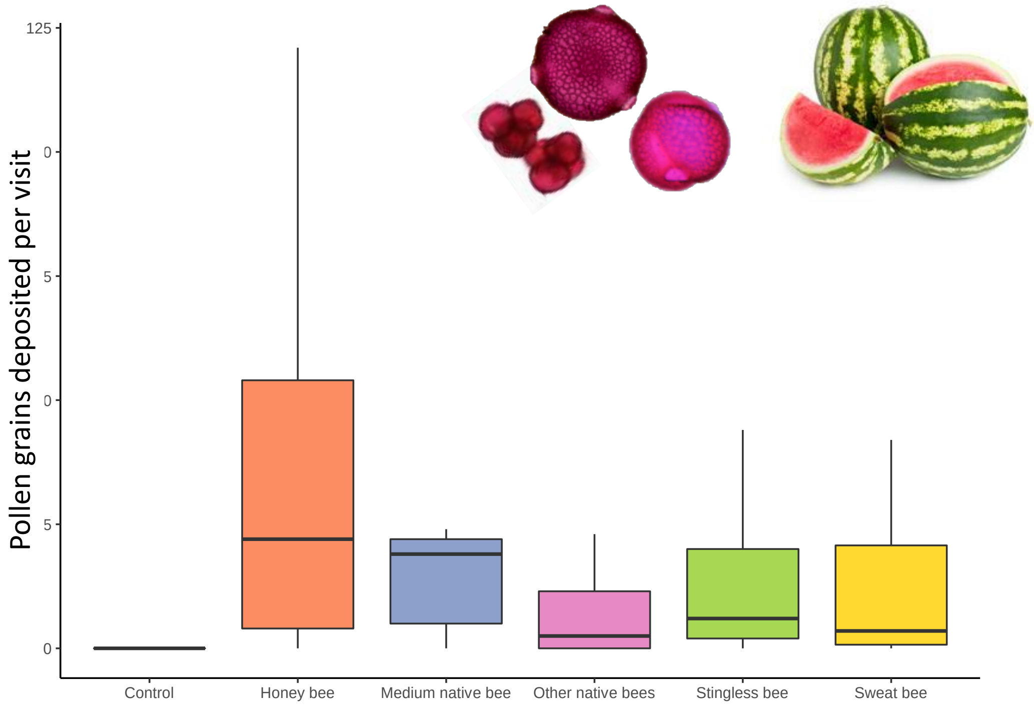


Figure 12. The average number of pollen grains deposited on the stigma of watermelon flowers after a single visit of bees from five groups.

Fruit set and visitation

In **apple**, multiple visits (up to 15) by honeybees were required to achieve 100% fruit set (Figure 13).

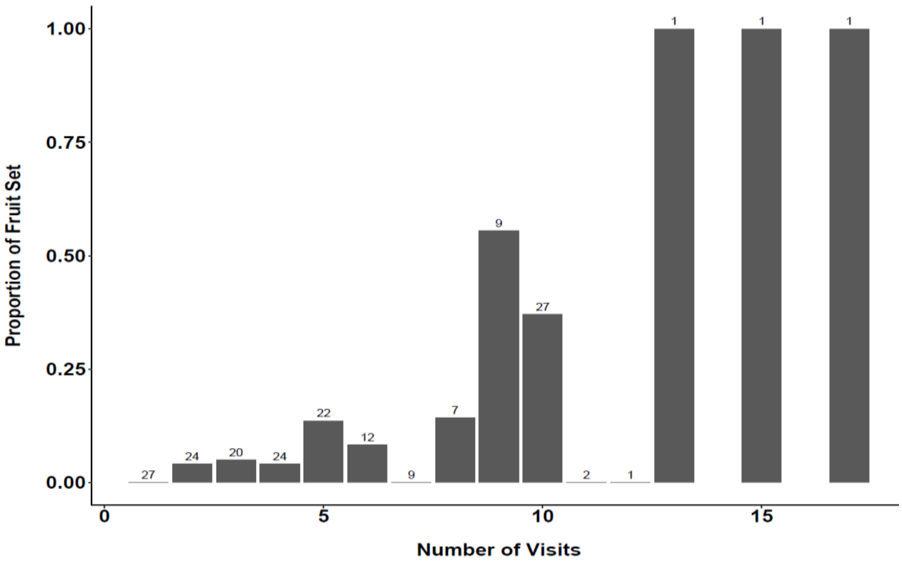


Figure 13. The proportion of apple flowers that set fruit relative to the number of visits they received from honey bees. The numbers above the bars give the number of flowers observed.

In **blueberry**, the pollination effectiveness of the dominant pollinator taxa differed considerably between blueberry types. In northern highbush, honeybees and bumblebees increased the probability of fruit set by 62% relative to un-pollinated flowers. In rabbiteye, neither honeybees nor stingless bees improved the probability of fruit set with a single visit relative to un-pollinated flowers. In southern highbush, honeybees and stingless bees increased the probability of fruit set by 59% and 41% relative to un-pollinated flowers.

Further observations on pollination effectiveness

The impact of the order of flower visitation in watermelon and berries

In **watermelon** crops, the order of flower visits to male/female flowers and the foraging behaviour (nectar or pollen) of pollinators impacted the number of pollen kernels deposited on stigmas. When pollinator species visited male flowers from diploid cultivars before visiting female flowers, we found significantly more pollen grains on the stigma. Further, pollinators foraging for pollen in the male flowers deposited significantly more pollen on the stigma than those that were foraging for nectar.

In **blueberry**, we found that insect identity was important to fruit set. Honey bees and stingless bees were the dominant pollinators of blueberry in Coffs Harbour. When both pollinator species visited blueberry flowers, fruit weight was influenced by which bee visited first. When the total visitation time was short (~1 min), blueberries from flowers visited first by stingless bees were 60% heavier than those visited first by honeybees. However, when total visitation time was long (~ 8 min), blueberry fruit were 24% heavier when initial visits were from honeybees.

Effectiveness of pollinators is different across different cultivars of same crop

In blueberry, we found differences in the dependency of different varieties on insect pollinators. Two varieties only required five visits to achieve 100% fruit set, however the third variety, required more than 15 to achieve 65% fruit set (Figure 14).

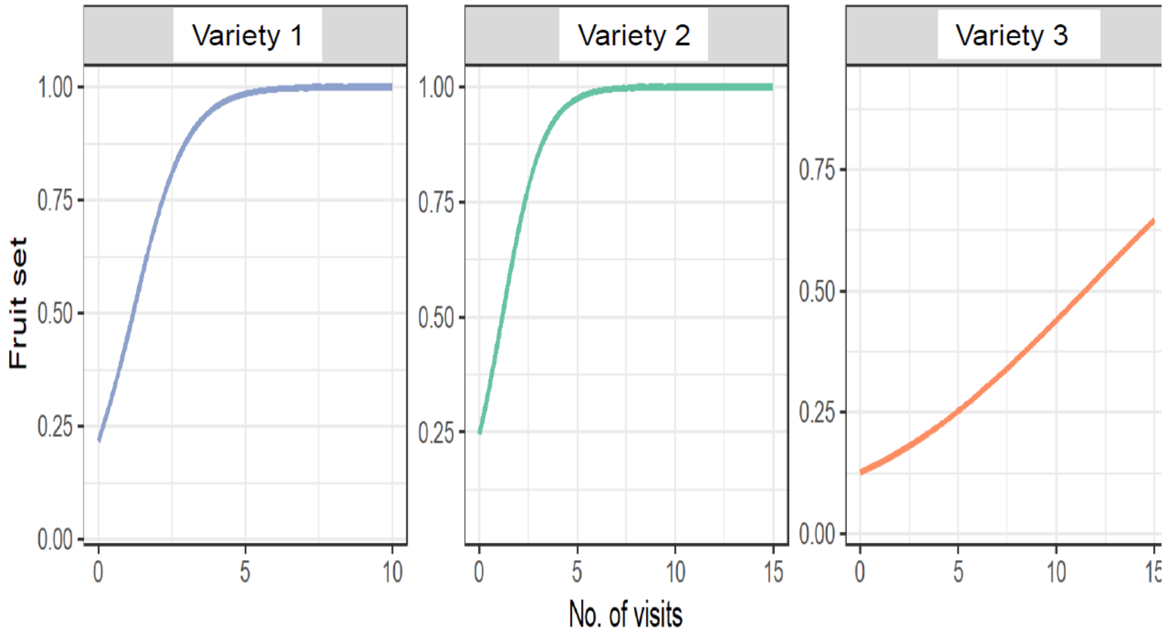


Figure 14. Average fruit set in three blueberry varieties relative to the number of visits received by insect pollinators.

Identifying shared species that use multiple crops

When comparing the insect visitors of macadamia, avocado and mango crops at Bundaberg, we found that there was a large overlap in visitors, in particular of locally abundant species groups, such as beetles (Coccinellidae) and stingless bees (*Tetragonula* spp; Figure 15). The identification of pollinators that provide services across multiple crops can be used to develop pollination management strategies that focus on the resource needs of these wild taxa.

a)

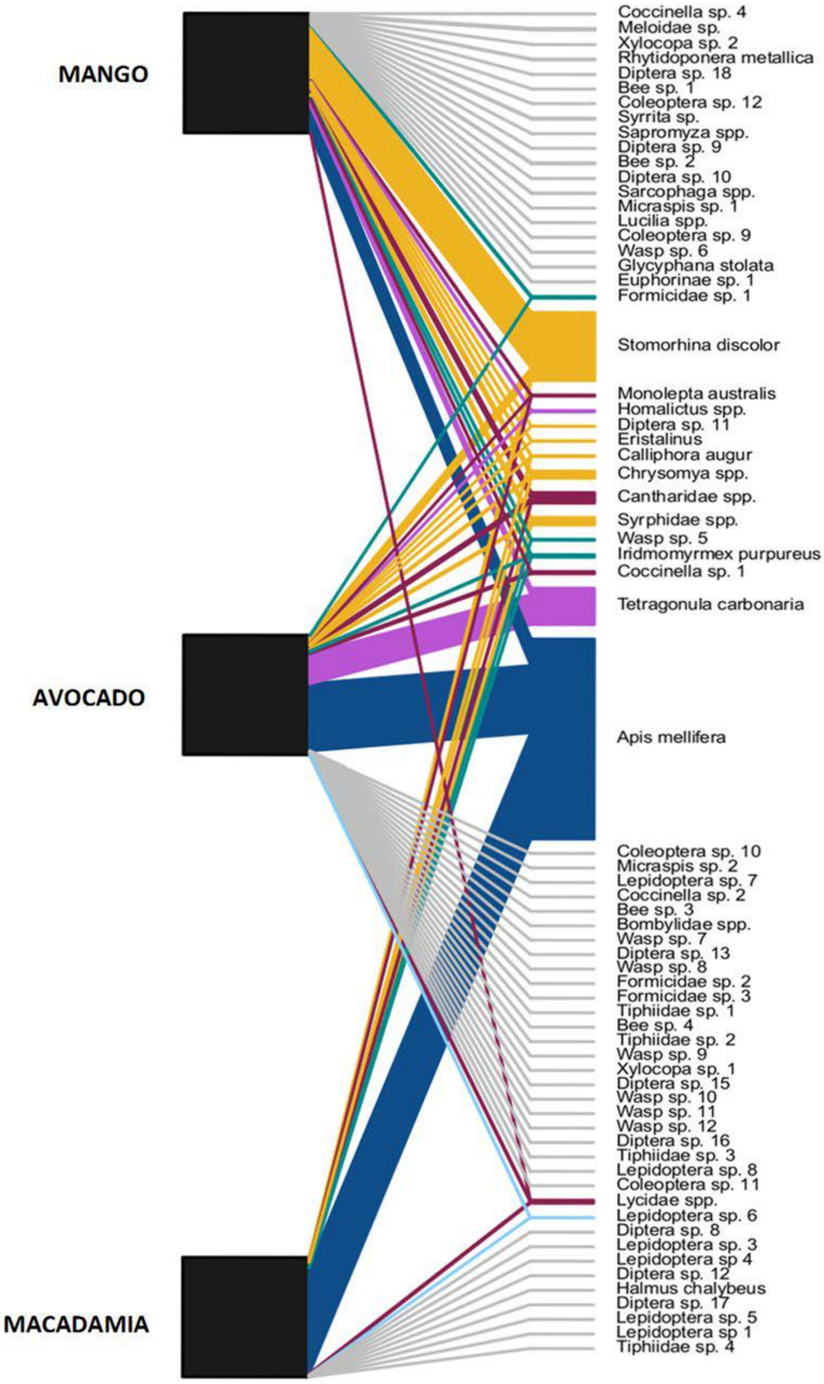


Figure 15. A visitation network of mango, avocado and macadamia in Bundaberg. The thickness of the connection between the insect taxa and the crops reflect the proportion of visits observed. The visitors that are shared across different crops are represented by different colours.

c. Identification of pollinators

Introduction

For researchers, identification of flower visitors and pollinators is crucial, as identification allows us to understand their needs and capitalise on their services by providing them with the necessary resources in the landscape. Many researchers lack the taxonomic skills for species identification, as the insect species groups are large and varied. Therefore, insects caught on crops are often identified only to genus or morphospecies. This is far from ideal, as it doesn't allow comparison of species between studies or regions, or historic interpretations, in particular when there are no voucher specimens.

To improve the potential for researchers to identify their specimens, we created a resource that allows the identification of crop pollinating native bee species using DNA barcodes – regions of the genome that are species specific for most species. This resource aims to allow identification using small amounts of biological material such as a bee leg or larva. This will substantially reduce the time and effort required for identification and allow reliable identification without expertise.

Farmers also have an issue with identification of the insects that visit crop flowers. While most take note of the many insects that visit the crop, they often don't know what they are or whether or not they are beneficial. This is especially the case when it comes to differentiating bees, flies and wasps. This is not surprising, because reliable identification of insects requires years of training. We aimed to make pollinator identification accessible in two ways. Firstly, we set out to design a pollinator identification app that would allow recognition of pollinators through machine learning. Secondly, we designed a leaflet to assist growers with the identification of the most common crop visiting insects. The leaflet also explains the threats to bees and other insects, the timing of their presence, where they nest and when they need food.

A barcode resource for identification of native bees

The open access DNA barcode resource contains genetic sequences of reliably identified native bees. These barcodes were generated through the Barcode of Life initiative, housed at the Canadian Centre for DNA Barcoding, in collaboration with a larger project at the South Australian Museum (https://www.boldsystems.org/, Project Code: AUSBS).

This project has resulted in DNA barcodes for 4327 Australian bee specimens, including approximately 800 species, representing all five bee families, from localities around Australia. In this project all five native bee families are represented. A subset of 35 species caught visiting crops in South Australia were included. Because crop-visiting species are typically the more common, widespread, generalist species, it is likely that the database includes the majority of species that visit introduced crops. This implies that most bee species that visit crops are now readily identifiable for researchers.

The bee barcode method and its development is further detailed in the following publications: Hogendoorn et al. 2015, Leijs et al. 2017, 2018, and 2020

One way to generate sequences of reliably identified specimens is to use museum specimens that have been identified by experts. The problem is that these specimens are often old, and the DNA becomes quite degraded over time, which can substantially reduce the lengths of the sequences obtained, and therefore the information contained in them.

To solve this problem, we generated a new way to obtain sequences from museum specimens. We used a single leg from the specimens for DNA extraction, so that each set of sequences can be related to a physically pinned voucher specimen. We successfully obtained the sequences of three gene regions from legs of species of *Lasioglossum (Chilalictus)* that had been in the pinned collection for up to 14 years. We selected this group because of its high representation among crop pollinating species. The group of 31 species for which we generated sequences contain 15 species that are regularly caught on crops.

This methodological improvement means that barcode reference sequences can be generated from pinned material, and do not necessarily require the collection and reliable identification of fresh specimens. The method is described in Akankunda et al. (2020).

Pollinator app

A small project was conducted with the aim of developing a prototype app to identify wild pollinators in crops. Several undergraduate and masters computer science students were involved in this project as part of unit delivery. However, during the development phase of this project, a commercial app was released that mirrored our objectives (see iNaturalist). This commercial platform was released worldwide and uses Google machine learning algorithms which far exceeded the small scale study we were conducting. Further, the cost of development and hosting far exceeded our budget for this component and without student assistance, we would not have been able to proceed. We thus completed the prototype and did not proceed with releasing the app. The following summaries of the results and outcomes of student projects in the development of the app are available online:

1. Student summary of project/s to develop prototype of pollinator app and web portal https://www.youtube.com/watch?v=iQ2njiPVCb4&feature=youtu.be
2. Link to demonstrate development of an online pollinator survey to gauge knowledge and interest from the community to compare to machine learning results https://www.youtube.com/watch?v=jHXCpOn1bd8#action=share

Guide to Australian crop pollinating insects

To assist growers in recognising the pollinators, we created a guide to the Australian crop pollinating insects (Figure 16). This combined output of the project provides a pictorial guide to a few of the most common native bee taxa and other pollinators that have been found in the different crops and regions. It provides background information about the nesting habits of the bees, the floral resources they benefit from and when they are present in the cropping area. The leaflet can be obtained through the AgriFutures website and can also be found in the appendix to this report, which is available upon request to AgriFutures.

Figure 16. Example pages from the Guide to Australian crop pollinating insects.

3.2 Understanding the threats to pollination security

General introduction

After identification and quantification of the main crop visitors and assessment of the efficacy of the main visitors in section 3.1, we need to understand the threats to pollination security, and therefore the factors that govern the abundance and performance in the crop, as this can inform actions to secure and improve the densities and diminish the threats to pollination services.

A prominent and widely recognised threat is the reliance on a single pollinating species, the European honey bee (*Apis mellifera*). Reliance on a single species for the supply of a wide range of produce involves high risk due as there is very little resilience in the system. Feral honey bees in particular are likely to experience negative effects from disease incursions and effects of climate change, as they have no beekeeper to look after them. Because the reliance on honey bees for most crops was high, and the reliance on feral colonies versus managed hives is unknown, we set out to assess feral honey bee densities in cropping areas.

Adding resilience means reducing reliance on a single asset. Our findings presented in section 3.1 showed that a diversity of unmanaged visitors and pollinators were present in all crops. For these pollinators, the landscape surrounding the crops provides additional floral and nesting resources, and their presence depends on the vegetation type and land use in the cropping area. Worldwide, habitat loss is recognised as one of the main causes of pollinator decline. Therefore, to explore opportunities for improving pollination security and resilience, we need to understand how landscape affects the presence, abundance and pollination services of unmanaged pollinators.

This chapter has two main sections:

a. Assessing feral honey bee densities:

i. Using drones to assess feral hive densities
ii. Assessing accuracy of density estimates

b. Landscape, bee abundance and crop pollination:

i. Landscape and native pollinator abundance and diversity
ii. Landscape and crop pollination

a. Assessing feral honey bee densities

Honey bees are among the most abundant pollinators for most Australian crops, and our observations presented above support this. Australia is unique, in that it has very high densities of feral colonies (Oldroyd et al. 1997). This unique position is the result of the fact that Australia has so far remained free of the parasitic *Varroa* mite. This mite host-jumped from *Apis cerana* to *Apis mellifera*, and became a vector and incubator of honey bee viruses. Wherever the mite has spread, it has caused large increases in viral diseases of European honey bees, which have led to sharp declines in feral honey bee densities.

Honey bees from both managed hives and feral colonies pollinate crops, but the extent to which crop pollination relies on feral honey bees is not known. To assess the impact of an incursion of Varroa mite on crop pollination services, and hence prepare for this threat, we need to know what proportion of pollination is delivered by feral colonies. For this assessment, we need to have a way to quantify the densities of feral colonies in cropping environments. These densities are very unlikely to be uniform, as, in cropping regions, they largely depend on the presence of nesting hollows in old *Eucalyptus* trees.

i. Using drone traps to assess feral hive densities

Assessing feral honey bee colony densities has long been a challenge for researchers as direct surveys are not feasible. Honey bee colonies tend to nest in cryptic and inaccessible locations. Williams balloon traps (Figure 17) have been used to assess honey bee populations in the past.

Lures impregnated with queen pheromone are placed inside a net, which is suspended from a weather balloon. When launched, male honey bees (drones) within flight range are attracted to the lures and become trapped in the net. Genetic analyses then allow us to group the drones into families based on their maternity, ie. how many males have the same mother and thus are from the same colony. In this way, we can obtain reasonably accurate population estimates without the need for direct surveys (Utaipanon, Schaerf and Oldroyd 2019).

Figure 17. A Williams drone balloon trap. Drones can be seen inspecting the lures (photo: Michael Holmes)

However, while the technique has been used for population estimates in the past, estimating population *density* is not possible without knowing the flight range of drones. We were able to measure the drone range using the below method.

Drone flight distance: the missing piece of the puzzle

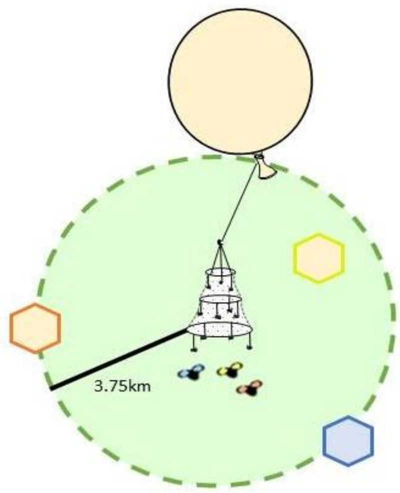


Figure 18. The area sampled by a Williams drone balloon trap (image: Patsavee Utaipanon)

Prior to our studies, there was no single reliable estimate of drone flight distance. We solved this with a simple yet effective field study in spring 2018 (Utaipanon, Holmes and Chapman, 2019).

We stimulated one of our colonies at USYD campus to produce drones during winter, then transported it to Lyndhurst, NSW, which has significantly later and cooler winters than Sydney. The local colonies had not yet started producing drones.

We paint marked thousands of drones from our focal colony, and then launched the balloon at 250m intervals in opposing directions (Fig 18). When a marked drone was caught (Fig. 19), we proceeded a further 250m from the colony, until no further marked drones were caught (Utaipanon, Holmes and Chapman, 2019).

Figure 19. A paint marked drone caught during our investigation of drone flight distance (photo: Michael Holmes)

Marked drones were caught at all intervals up to 3.75 km. At 4 km, several unmarked drones were caught, but no marked ones. Genetic analyses revealed that none of the unmarked drones caught at 4 km were from our focal colony. Thus we can reasonably conclude that drones fly up to 3.75 km when searching for a queen to mate with, but rarely fly further (Utaipanon, Holmes and Chapman, 2019).

KEY FINDING: This result is a breakthrough, as we now know the vital statistic required to assess population density. A circle with a radius of 3.75 km as an area of 44 km^2. If we find that the drone sample in our trap was produced by 100 queens, we know that there are at least 100 colonies within a 3.75 km radius, a population density of 2.27 colonies/km^2.

We have used this statistic in subsequent work to assess colony densities throughout NSW, as well as at locations in SA and Victoria. For our cropping areas, the hive densities inferred from drone captures at the Drone Congregation Area (DCA) are given in Table 1.

Table 1. Hive densities in cropping areas, estimated on the basis of assignment of drones, captured at a Drone Congregation Areas, into sib groups.

Location	Number of colonies inferred	Colony density (colony/ km^2)	Notes
Barra Brui, Sydney, NSW, -33.743, 151.175	119.7	2.72	Average from Nov 2019 - Apr 2020
Coffs Harbour, NSW, -30.000, 153.094	20	0.45	
Coffs Harbour, Coffs Harbour, NSW, -29.997, 153.109	50	1.14	There were 100+ commercial colonies at a distance of < 1 km from the DCA
Currawarna, Riverina, NSW, -35.015, 147.079	94	2.14	
Forest Range, Adelaide Hills, SA, -34.936, 138.798	N/A	N/A	We couldn't catch any drones, but it is 1.6 km from Mason, and 2 km from Swamp road
Keith, South East, SA, -36.232, 140.540	146	3.32	We located 60 feral colonies in an area with a radius of 1.5 km^2 from the DCA (i.e. 8.49 col/km^2)
Lenswood, Adelaide Hills, SA, -34.949, 138.814	68	1.55	
Mason, Adelaide Hills, SA, -34.922, 138.800	32	0.73	
Swamp road, 34°56'55.78"S 138°48'50.51"E	98	2.23	
University of Sydney, Sydney, NSW, -33.888, 151.185	125.5	2.85	Average from Oct 2018 - Mar 2019
Urrbrae, Adelaide, SA, -34.971, 138.641	56	1.27	We located 90 colonies within a radius of 1.5 km2 around the DCA (i.e. 12.73 col/km^2)
Wagga Wagga, Riverina, NSW, -34.760, 146.699	87	1.98	
Yarra Valley, Yarra Valley, Vic, -37.835, 145.252	322	7.32	

The density of feral colonies is rarely high enough to provide adequate pollination for most crops (Table 1), and as such, growers need reliable alternatives.

This work is further detailed in the following publications:

Utaipanon, P., Holmes, M. J. and Chapman, N. C. (2019) 'Estimating the density of honey bee (Apis mellifera) colonies using trapped drones: area sampled and drone mating flight distance', *Apidologie*, 50(4), pp. 578–592.

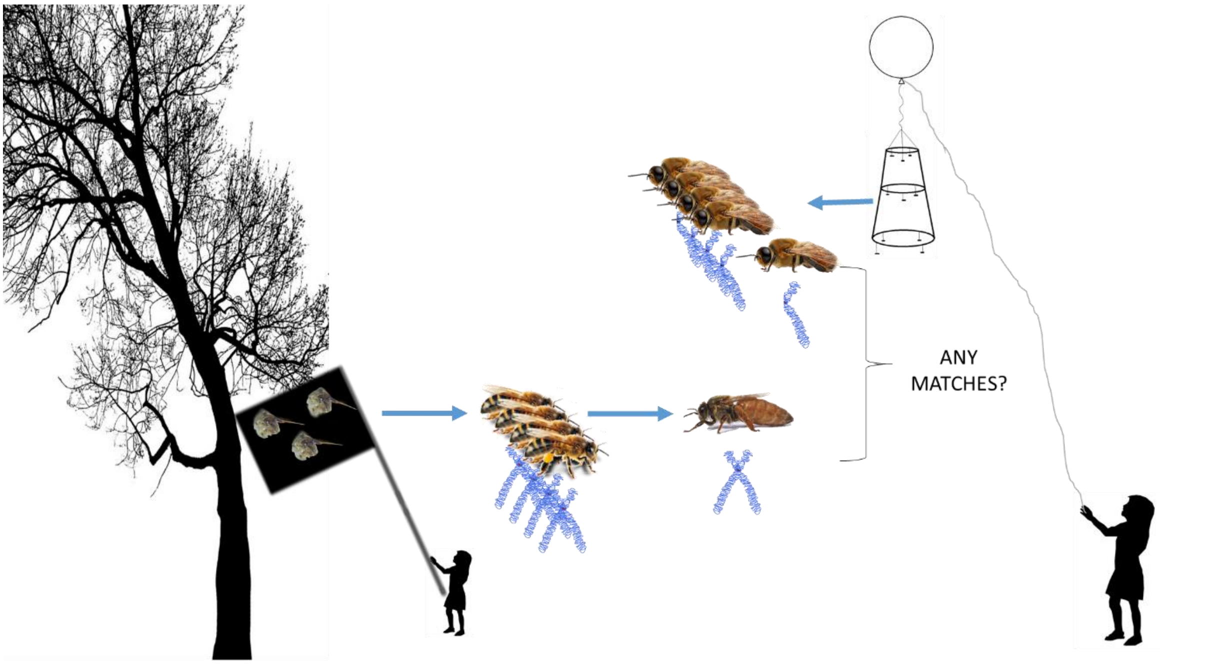
Utaipanon, P., Schaerf, T. M. and Oldroyd, B. P. (2019) 'Assessing the density of honey bee colonies at ecosystem scales', *Ecological Entomology*, 44(3), pp. 291–304.

Drone trapping can be seen in action at www.agrifutures.com.au/partnerships/rural-rd-for-profit-program/securing-pollination/.

ii. Using DCAs to estimate feral honey bee densities – A validation

To verify whether hive densities could be accurately quantified using trapped drones, we investigated whether all feral colonies that were close to a DCA were represented in drone samples. We also investigated whether the number of drones caught per feral hive was influenced by its size, or its distance to the DCA.

This study was done at the Waite Arboretum and Waite campus of the University of Adelaide, which we refer to as 'the Waite'. To investigate whether all colonies contributed to the drone sample, we first developed a method to obtain a DNA fingerprint of the queens from feral colonies (Williamson *et al.* 2019). Worker stings were collected by flagging a piece of cloth, mounted on a long pole, in front of located feral colonies in trees (Figure 20. To assess whether all feral hives were represented in the drone sample, we collected DNA from worker stings from feral colonies in the trees, deduced the DNA fingerprint of the queens from the DNA from the stings and then investigated which of the queens had contributed sons to the drone sample by comparing Queen DNA to the haplotypes of the drones. . We used the DNA from the worker stings to obtain the DNA fingerprint of the queen. We collected worker stings from located feral and managed hives in a radius of 1.6 km around a DCA, over two years. The drone sample sizes were large: 1565 in 2018, and 1484 in 2019. We then compared the inferred DNA fingerprints of queens from the known



feral colonies, to those of the drones captured at the DCA, to assess if any of the drones could have been the sons of any of the queens. The method is explained in Figure 20. To assess whether all feral hives were represented in the drone sample, we collected DNA from worker stings from feral colonies in the trees, deduced the DNA fingerprint of the queens from the DNA from the stings and then investigated which of the queens had contributed sons to the drone sample by comparing Queen DNA to the haplotypes of the drones. . We assessed relative hive size by counting returning foragers within 30 seconds on a single day when temperatures were above 25°C.

Figure 20. To assess whether all feral hives were represented in the drone sample, we collected DNA from worker stings from feral colonies in the trees, deduced the DNA fingerprint of the queens from the DNA from the stings and then investigated which of the queens had contributed sons to the drone sample by comparing Queen DNA to the haplotypes of the drones.

We sampled workers from 23 feral colonies in 2018 and 34 colonies in 2019. On average 64% of the colonies had contributed one or more drones to the sample taken at the DCA. Whether or not a hive contributed to the drone sample was not affected by the estimated colony size (Figure 21).

The distance of the feral hive to the DCA mattered. Colonies contributed more drones as they were closer to the DCA (Figure 21). In 2018, all colonies sampled were closer than 1.5 km from the DCA. In 2019, the five colonies that were further than 1.5 km from the DCA did not contribute any drones. This is a significantly higher proportion than expected if there was no effect of distance. The average number of drones contributed per colony was 5.1, which was lower than six, the number required to reliably recognise a brother group among drones captured.

For two areas (Waite and Keith), we also evaluated the number of colonies we located against the estimates using the drone capture. The visual location resulted in estimates that were 2.5 – 9 times higher than those measured using drone traps (Table 1. Hive densities in cropping areas, estimated on the basis of assignment of drones, captured at a Drone Congregation Areas, into sib groups.

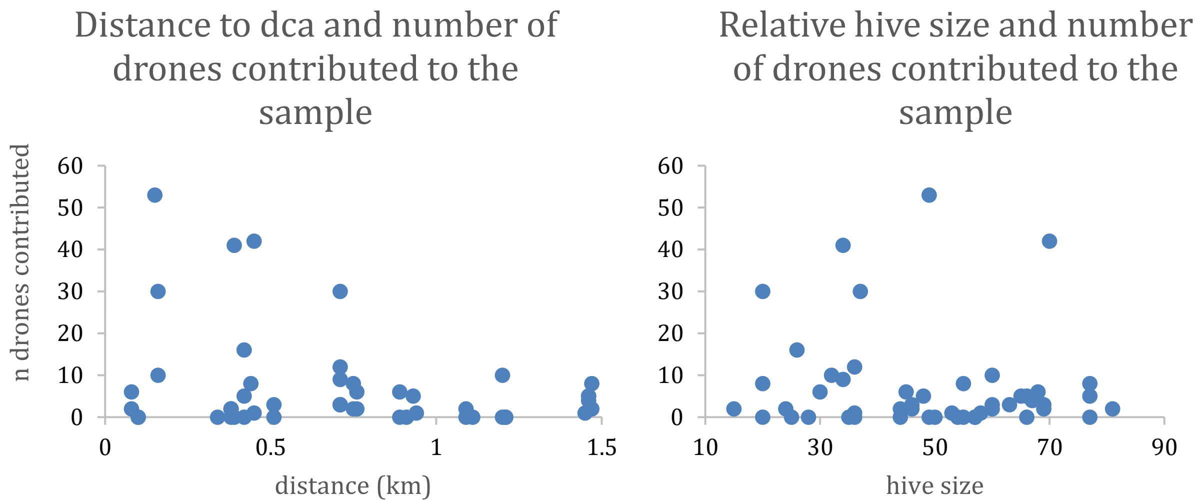


Figure 21. The number of drones contributed by feral hives to the sample caught at a Drone Congregation Area was (a) negatively correlated with the distance between the DCA and the hive (left), and not correlated with the relative hive size (right).

We conclude that sampling drones using a pheromone trap at a DCA did not produce a reliable estimate of the density of colonies because:

- Despite the large size of our drone samples, 36% of feral colonies were not represented by any drones;
- The number of drones contributed depended on the distance to the DCA, which leads to large underestimates at further distances;
- Only 19% of known colonies were represented by six or more drones, a minimum number required to recognise a group of brothers in a drone sample;
- The density of the feral colonies we found was substantially higher than estimated using the drone trapping method.

Therefore, both the general application of the method and the performance of the software used to analyse the data require further study, and it is likely that outcomes are influenced by the landscape.

This work is detailed in Williamson et al. (2019), the honours thesis of Elisabeth Williamson (University of Adelaide, 2020), and a nearly finalised manuscript.

Overall conclusion regarding feral honey bee densities

Despite the shortcomings in the method to assess feral honey bee colony densities, we can extract some general advice from our results. In areas with extreme high densities of feral colonies, the estimated density is about 150 colonies/km^2 (Oldroyd et al. 1997). The suggested density of hives for pollination of most crops is 3-8 hives/ha (Free 1972), which equates to hive densities of 300 – 800 hives/km^2.

KEY FINDING: This implies that maximally about half of the free pollination services would be lost after a demise of feral honey bee colonies due to an incursion of Varroa mite.

Such a substantial loss of free pollination services can be expected specifically in the regions that have high feral honey bee densities due to the high density of natural tree hollows in old *Eucalyptus* trees, for example in the Yarra Valley, Adelaide Hills and Keith. In other areas, the impact of a *Varroa* incursion will be smaller, because feral hive densities are much lower.

b. How the landscape supports pollinator abundance, diversity and crop productivity

Floral and nesting support in the landscape have been identified in Australia and overseas as major factors contributing to crop pollinator abundance, diversity and pollination services. Specifically, the proximity and coverage of woody vegetation has been shown to support crop pollination (Kennedy et al. 2013), and similar findings have been obtained in Australia (Blanche et al. 2006: macadamia and longan; Blanche and Cunningham 2005 : atemoya, , Arthur et al. 2010: canola). These findings would indicate that the recent and current losses of supportive habitat in Australia, due to climate change and clearing for agriculture and urban developments, could constitute a major threat to free crop pollination services. However, to further investigate the importance of woody vegetation for bee abundance and diversity, we investigated how bee abundance, diversity, and crop pollination services relate to the surrounding landscape. We did this specifically for apple and lucerne, as they depend on pollination for 100% of production and represent the highest gross domestic production value of the crops investigated in our project. We will first address the effect of the landscape on visitation, then address the link with crop productivity.

i. Landscape and bee visitation

a. Apple

To investigate how the vegetation surrounding the orchard can influence the visitation and diversity of floral visitors to apple crops, we collaborated between regions to assess the influence of different vegetation types on apple pollinators across regions and properties.

We sampled wild bee visitors to apple flowers in 2017 and 2018, and weeds and native plants in apple orchards in 2018. The samples were taken along landscape gradients of native vegetation and non-crop agricultural cover (open grassy areas, grazed or ungrazed) in three locations: Yarra Valley (VIC), Adelaide Hills (SA), Stanthorpe (NSW). We investigated whether type of vegetation within a radius of 200m surrounding the orchard land correlated with the wild bee visitation to apple flowers and weeds in the orchards. The non-crop land cover was classified as:

1) 'natural woody vegetation',
2) 'open grassy areas', and
3) or a combination of woody vegetation with open grassy areas ('semi-natural vegetation').

The dominant flower-visiting bees in apple orchards in all regions were soil-nesting, spring-active species of the family Halictidae, mainly furrow bees (*Lasioglossum*), slender furrow bees (*Homalictus*) and nomiine bees (*Lipotriches*). Their relative and absolute numbers on the flowers differed between regions (Section 3.1). However, across the three regions we found the same association between the landscape composition and the number of bees present on the flowers. Across regions, the amount of 'open grassy area' in a radius of 200m was a better predictor of the presence of these ground nesting bees than 'natural woody vegetation, or 'semi-natural vegetation'(

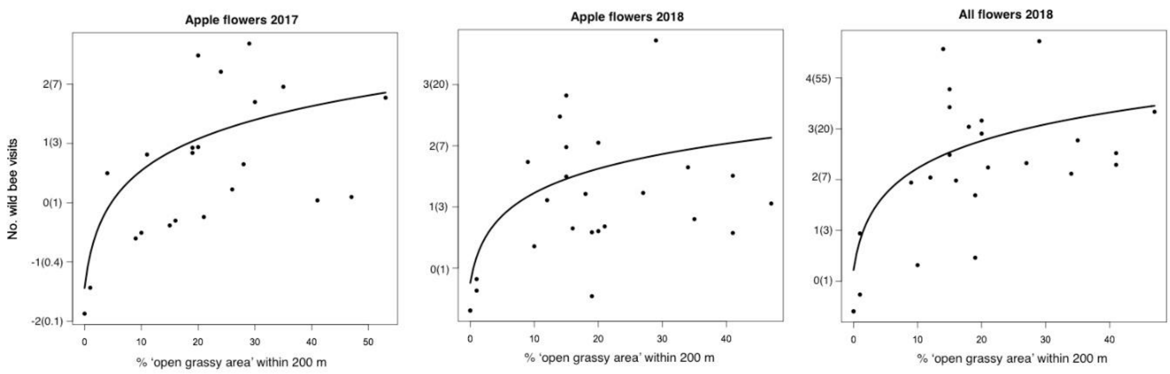


Figure 22).

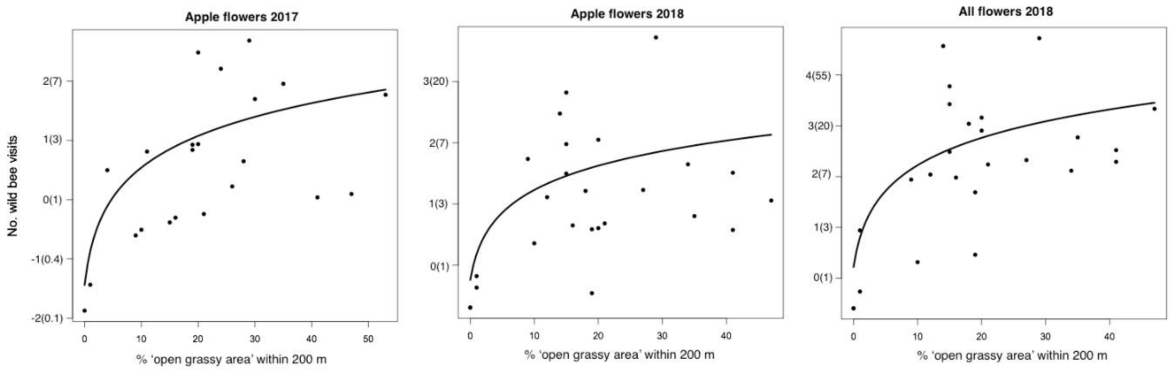


Figure 22. Partial regression plots from the models that best explained the number of wild bee visits to apple flowers in 2017 and 2018, and all flowers in the apple orchards in 2018. Values in parentheses on y-axis, and values on x-axis, are back-transformed from natural log-transformed predictor variables.

The importance of grassy areas for wild bee visitation is most likely a consequence of the fact that the dominant orchard-visiting wild bees in the cooler regions are soil-nesting species that can reproduce using the pollen and nectar from agricultural weeds such as dandelion (*Taraxacum*), African daisy (*Arctotheca*), and weedy brassicas (Figure 23, Figure 35).

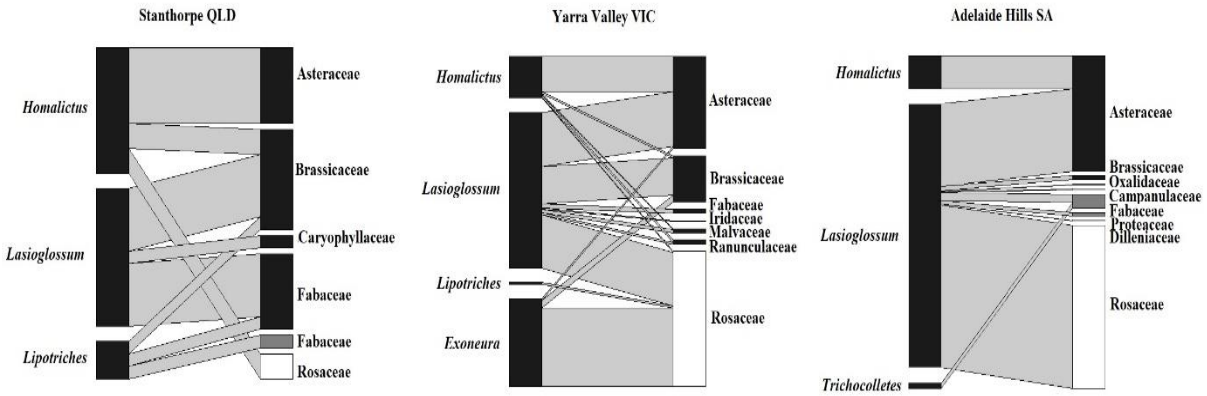


Figure 23. Quantitative bee – plant visitation networks in apple orchards for each region. The width of the connection between bee (left) and plant (right) species groups indicates the relative frequency of visitation. Plants are grouped into weeds (black boxes), native plants (dark grey boxes), and apples (white boxes).

Other regions are likely to have different land cover associations because of the biogeographic differences in bee fauna, and the particular ecologies of species in each region. For example, in northern NSW, stingless bees are relatively frequently observed in apple (Cook, pers. com.). Like feral honey bees, the presence of stingless bees depends on the availability of nesting hollows in native trees for nesting substrate, and floral resources throughout the year. Therefore, the presence of stingless bees and feral honey bees are expected to correlate with the availability of native woody vegetation.

Nevertheless, comparing different ways of classifying non-crop land cover types is an informative approach, revealing patterns not apparent in studies that only assess significance of a single non-crop land cover variable. This is because this approach allows for the identification of the best land cover predictor of wild bee visitation. However, the identification of a correlation between crop visitation by wild pollinators and any land cover type provides only a first step in identifying supportive action for enhancing pollinator diversity. An understanding of ecological factors which drive this correlation is required in order to design meaningful management process.

b. Lucerne

To understand the effect of surrounding vegetation and paddock trees on the flower visitors of lucerne, we analysed the abundance and diversity of bees relative to the amount of vegetation in neighbouring flood-irrigated lucerne seed blocks. Our trial sites were located within two properties near the township of Keith, approximately 250km southeast of Adelaide in South Australia. Lucerne seed produced in this area accounts for approximately 80% of total national production. Over two years we evaluated six flood-irrigated fields, three per year, of lucerne cultivar Siriver™.

We included three types of fields:

1) 'Absent': fields that were not neighboured by vegetation and contained no established paddock trees,
2) 'Adjacent': fields that bordered on one side with structurally diverse roadside vegetation including established Eucalyptus, and
3) 'Within': fields that included established Eucalyptus within the crop, as well as roadside vegetation.

We used multiple methods (sweep netting, direct observation, targeted sampling and blue vane trapping) to sample floral visitors to best characterise the visitation rates of a diversity of species over three transects. The transects were 100m apart, running perpendicular to the field edge with sampling at every 75m, totalling four sampling sites per transect and 12 per field. We observed 2031 and caught 1762 insects visiting alfalfa flowers, totalling 3724 records, with over 90% honey bees, and 150 other insects which included 11 native bee species, as detailed above.

The number of honey bee visitors in fields with established paddock trees was significantly higher than those in fields that had no native vegetation or bordered with road-side vegetation ($z = 6.64$, $p<.001$, and 5.20, $p<.001$respectively). In the fields with roadside vegetation, honey bee abundance was significantly higher at 75 and 150m than further in the field (z: 4.35, $p=.0008$; 4.508, $p=0.0004$, respectively; Figure 24).

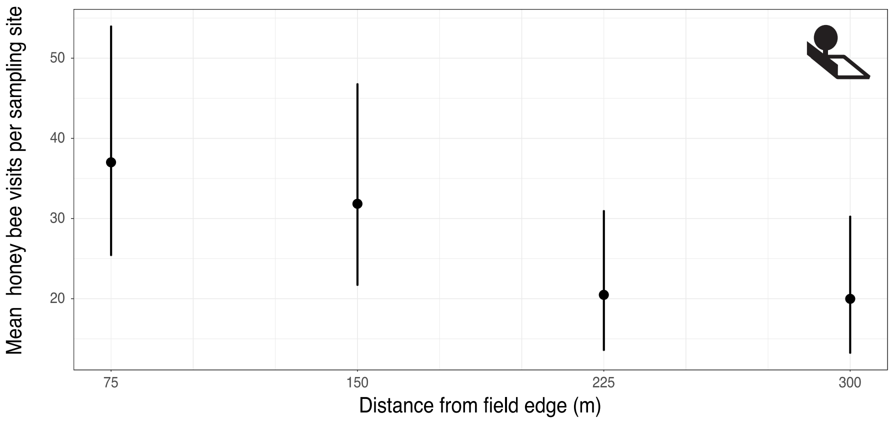


Figure 24. The average number of honey bees visits to one m² of flowering lucerne per three minutes (+/-95% C.I.) relative to the distance to an edge of native vegetation ('Adjacent').

The visitation by native pollinators was higher in fields with paddock trees than in those that lacked native vegetation ($z = 3.03$, $p=.007$), but did not differ from fields that had an edge of native vegetation ($z = 2.06$, $p>.05$; Figure 25). We found no effect of distance from neighbouring vegetation on native flower visitation.

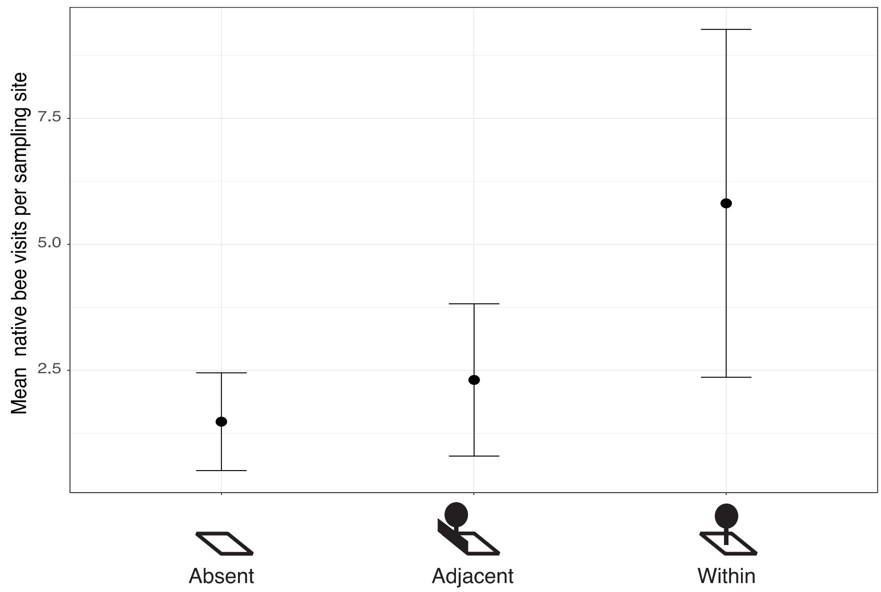


Figure 25. The abundance of native visitors of lucerne flowers (+/-95% C.I.) in fields that had paddock trees, native vegetation adjacent, and in fields without any vegetation in the proximity

The combination of these results suggests that feral colonies and native species found in and around Australian lucerne fields provide a substantial service to the production of lucerne seed, particularly in light of stocking rates of managed hives typically falling below recommended levels.

The presence of vegetation also influenced the abundance and diversity of native bees and other insects on the crop (Figure 26), with both of these higher in fields that contained paddock trees, than in fields that had no trees or an edge of native vegetation. However, we found no effect of distance from neighbouring vegetation on non-*Apis* floral visitor abundance.

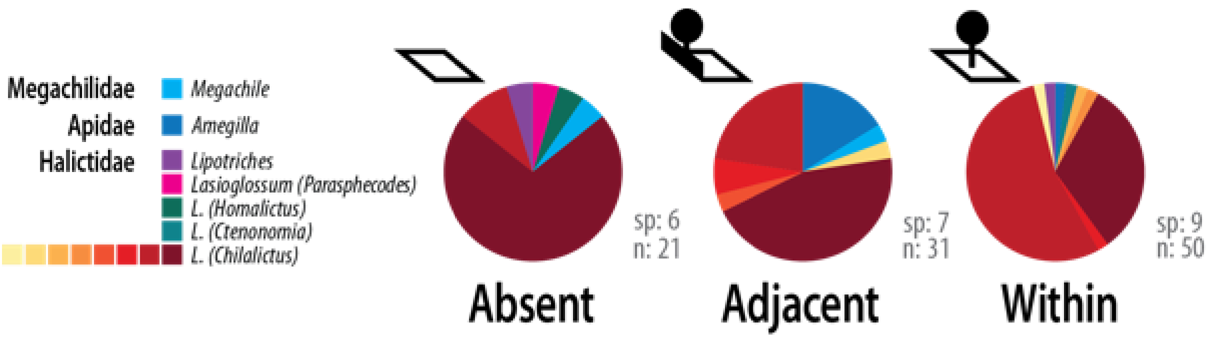


Figure 26. Species richness (sp) and abundance (n) of native bees within increasing integration of vegetation into crop fields.

KEY FINDING: In lucerne, paddock trees and native vegetation in edge of the paddock increased the abundance and diversity of native visitors to crops.

ii Landscape and crop productivity

Overall, we conclude that native vegetation close to lucerne crops and open grassland near apple orchards enhance crop visitation by insects. However, the proof of the pudding is in the productivity. Therefore, in the next section, we ask "Is there a link between supportive native vegetation productivity in apple and lucerne?"

a. Landscape and apple quality

Apple growers initially aim for good set, but then thin the crop as they aim to maximise quality over quantity. A top quality apple has high colour, no blemishes, is not too large or small, and is symmetrical. Of these quality aspects, pollination influences only symmetry, which is driven by even seed set in all carpels (Figure 28) and is achieved by sufficient visitation of the apple flowers (Figure 13). Therefore, in addition to assessing the link between native vegetation and pollinator presence and abundance, we also wanted to know whether increased pollinator diversity and abundance would translate into increased quality of the resulting fruit.

In three Australian apple production areas, Stanthorpe, Yarra Valley and Adelaide Hills, we assessed the number of floral visitors to apple flowers (per 100 flowers per hour). We then compared this to the number of seeds and the symmetry of the fruit at harvest to determine how pollinator visitation relates to crop quality. Orchards in Stanthorpe had a significantly higher honeybee visitation than the Adelaide Hills and Yarra Valley (Figure 27a). It is likely that this is caused by the fact that managed honey bee hives were placed under netting. We expected netting to have a strong negative effect on other flower visitors, but this was only borne out for native bees. The hourly native bee visits per 100 flowers was significantly greater in the Yarra Valley (Figure 27b). Overall, only in Stanthorpe were visitation rates sufficient to surpass the recommended target rate of 55 visit per 100 flowers per hour (Garibaldi et al. 2020).

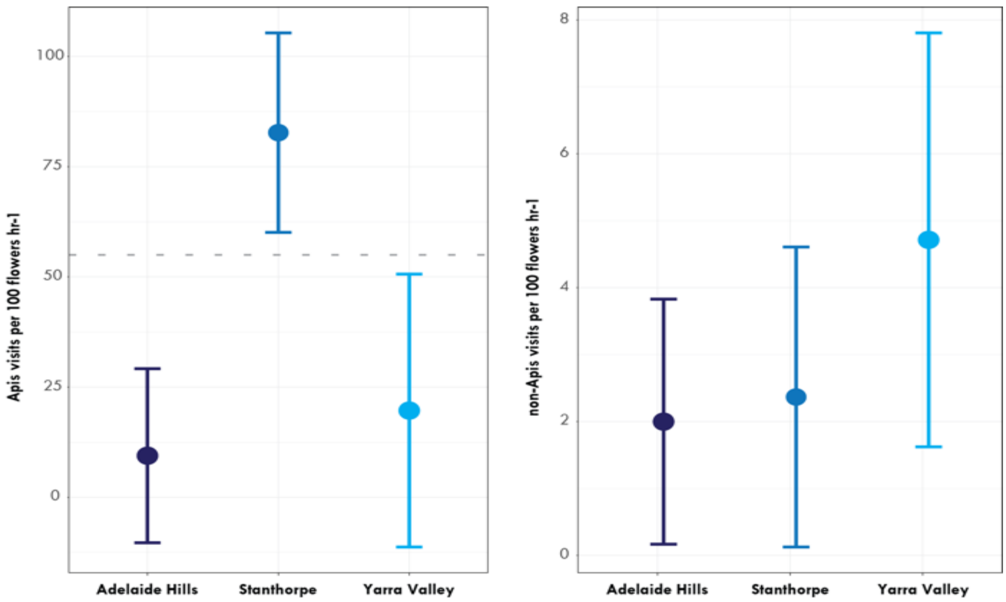


Figure 27. The mean visitation rates per 100 flowers per hour (+/-95% C.I.) in three production areas for honey bees (left) and other pollinators (right). The dashed line indicates the recommended visitation rate of 55 visit per 100 flowers per hour for adequate apple pollination (Garibaldi et al., 2020).

Despite these differences, we found little variation between the production areas in the mean number of seeds or empty carpels per fruit – two key factors that can each influence fruit symmetry (Figure 28).

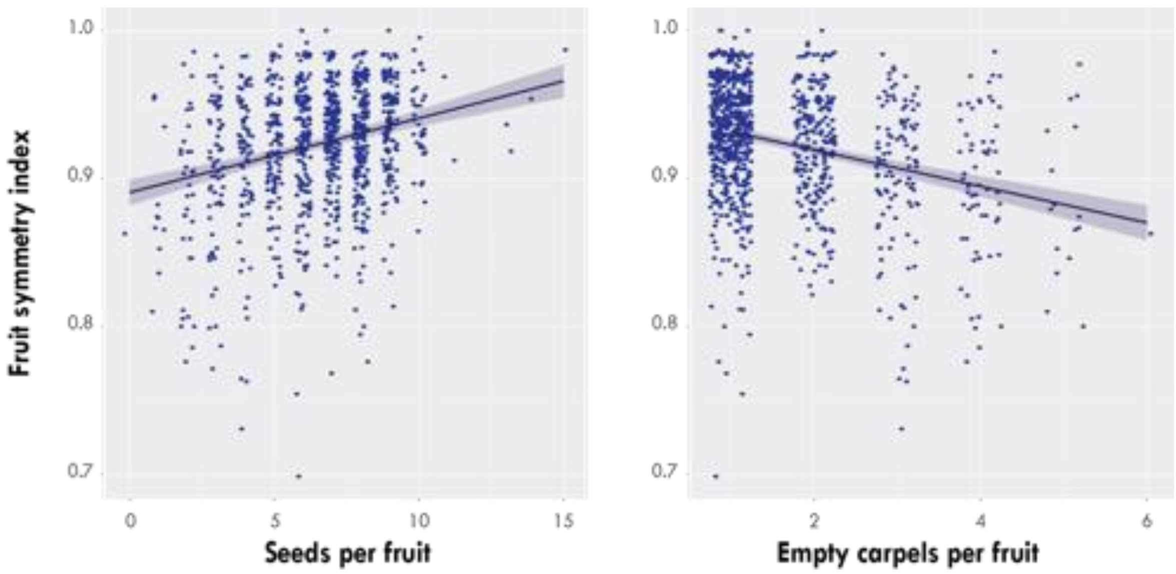


Figure 28. Relationship between fruit symmetry, measured by the difference between the shortest and tallest side of an apple, and the number of seeds per fruit and empty carpels (no seeds) per fruit.

Compared to wild insects, almost 12 times as many honey bees were observed visiting flowers. Increased visitation by honey bees significantly correlated with the number of seeds per apple (χ^2 = 3.04; p=0.04;

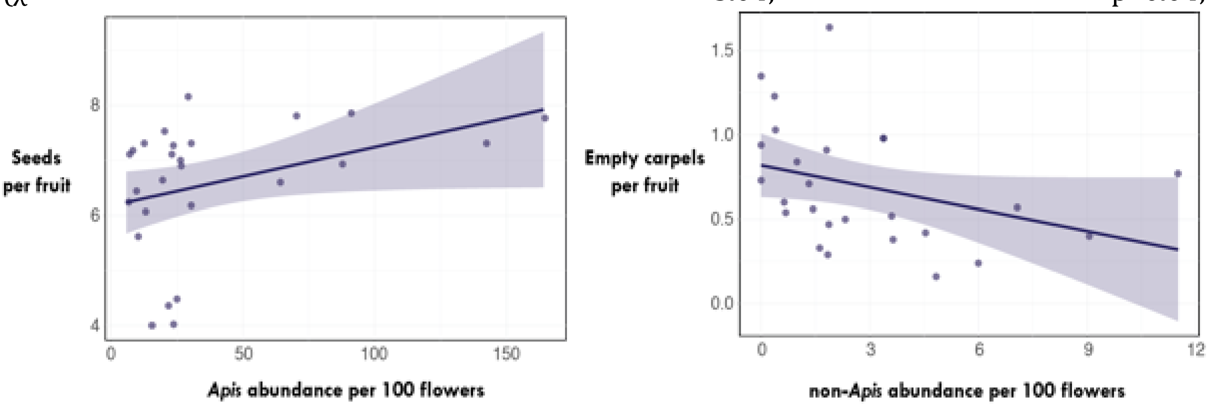


Figure 29a) as well as fruit symmetry ($\chi^2 = 7.21$, p=0.007). However, there was no effect on the number of empty carpels per fruit – another factor in the development of uniform fruit. By contrast, despite their relative rarity, visits by wild insects correlated with a reduction in the frequency of empty carpels (χ^2 = 4.02, p=0.04; Figure

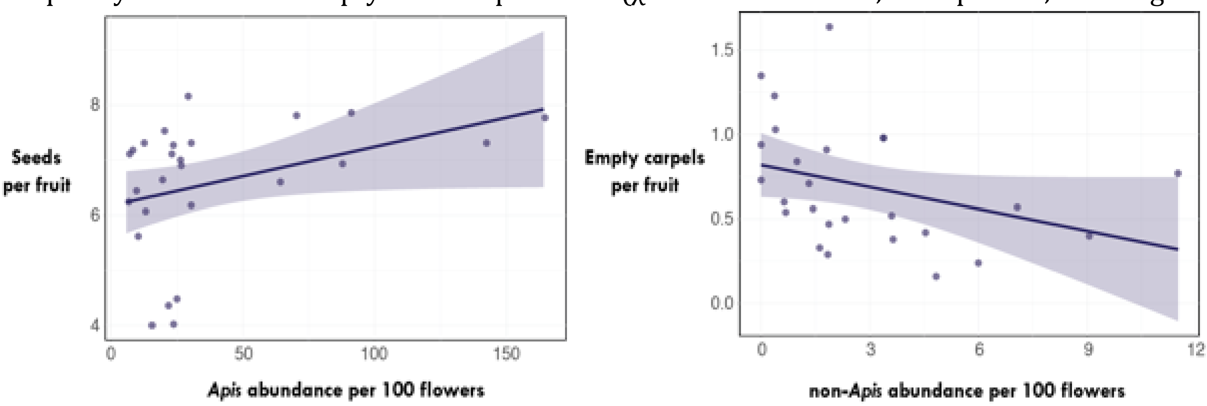


Figure 29b) but not with the number of seeds per fruit.

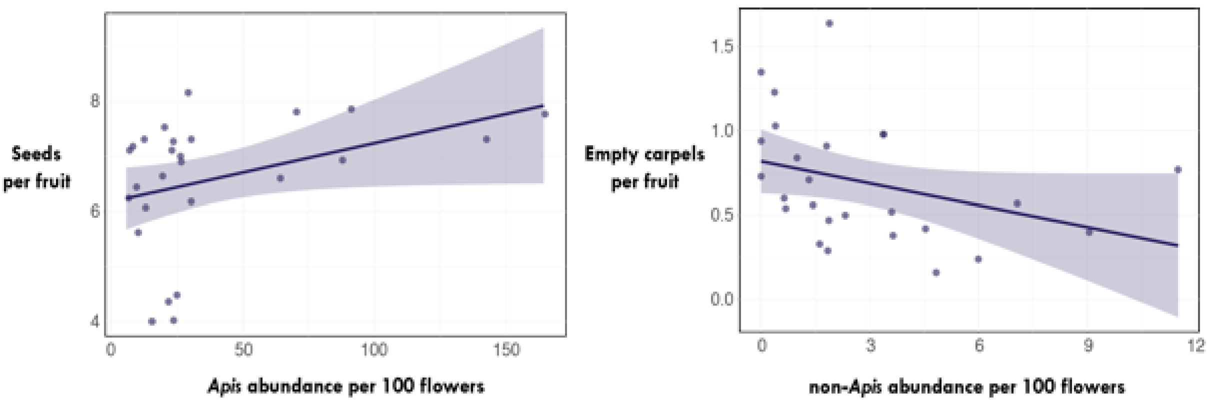


Figure 29: Association between (a) honey bee visitation frequency to apple flowers and the average number of seeds per fruit for each orchard; (b) the number of native insect visitors and the average number of empty carpels per fruit. Non-significant relationships between honey bee visitation and empty carpels, and native insect visitation and seed per fruit are not pictured.

In an industry facing increased competition for access to managed pollinators, these results suggest that supporting diverse pollinator communities through supportive landscape and sustainable production practices may help secure fruit quality. This is particularly true when an incursion of the *Varroa* mite would diminish free pollination by feral honey bees and consequential demands drive up the costs of managed honey bee hives.

b. Landscape and pod set in lucerne

After establishing a correlation between native vegetation and visitation within the lucerne blocks, described in the section above, we investigated whether the differences in visitation correlated with yield. From the sampling sites on our transects, we collected 100 flowering stalks per sampling distance, and then quantified the pod set by dividing the number of seed pods by the number of flowers on each stalk.

Going into the crop from the roadside vegetation, the pod set was higher was 10% higher at 75m than at 225m, and 8.7% higher than at 300m. At 150m the set was 8.4% higher than at 225m. In fields that lacked native vegetation and fields with paddock trees, there was no change in set with distance to the edge. In fields with paddock trees, pod set was on average 5% higher (0.47 pods per flower) than in fields that lacked native vegetation in the proximity (0.42 pods per flower).

Using a modelling approach to assess the parameters that were most important for pod set in lucerne, we found a major effect of the presence of native vegetation and distance to the edge. The estimated effect of the abundance of native pollinators (average effect size 0.27, which is classified as a small-medium effect) was larger than that of the abundance of honey bees (effect size 0.03, which is negligible). This surprised us, because the native pollinators constituted only a small fraction of floral visitors (8.5%). It is possible that this finding is caused by a higher pollination efficiency of native bees than of honey bees. This is supported by observations on *Lipotriches flavoviridis*, from the same family as the semi-managed lucerne pollinator *Nomia melanderi*. Females of this native Australian ground nesting species tripped 30 times more lucerne flowers per minute than honey bees because honey bees are relatively slow moving, often side-work the flowers, and are not collecting pollen from the crop (Hogendoorn and Keller 2012).

The native species depend on a diversity of floral resources aside from lucerne. Production areas typically comprise very few flowering plants. Furthermore, irrigation practices may hamper the ground-nesting species. In flood-irrigated fields, the dykes and roadside may offer the only potential nesting opportunities within the crop. The higher abundances of non-*Apis* insects in fields that contain *Eucalyptus* paddock trees could be the result of trees acting as islands, providing both alternative floral resources and elevated nesting substrate.

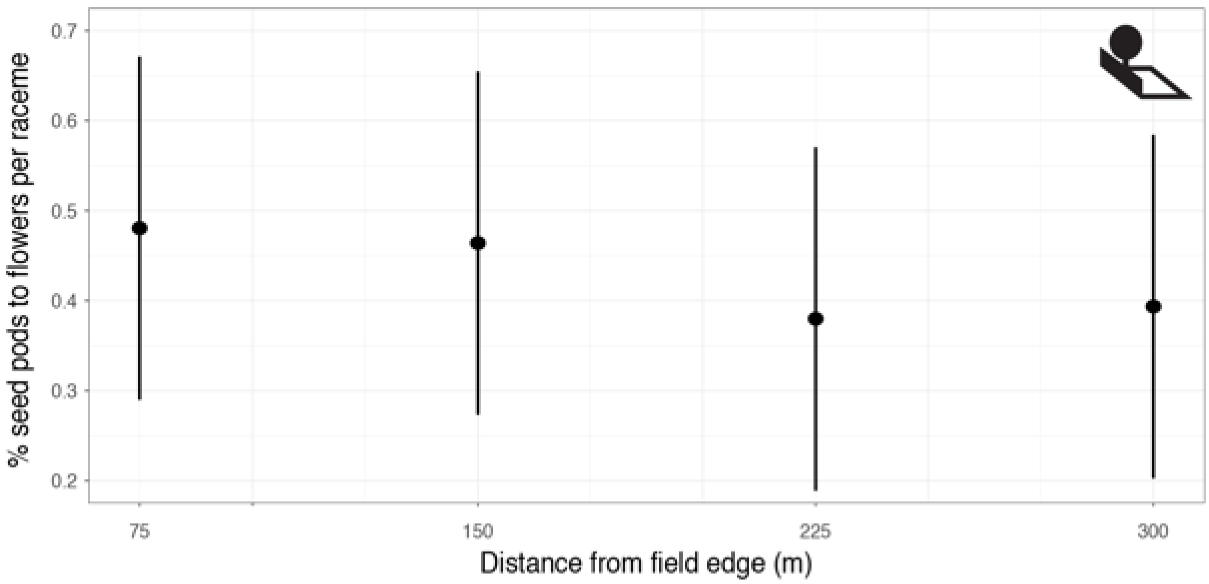


Figure 30. Mean proportion of flowers that produced seed pods per raceme (± 95% CI)

The importance of wild pollinators for lucerne seed production

Lucerne relies completely on insect pollination. A survey by Lucerne Australia shows that 66% of dryland lucerne seed growers did not run bees. Their lucerne seed production relied completely on free pollination by wild pollinators. The production of dryland lucerne seed varies, but in normal years about 30 – 40% of all seed is produced on dryland. Therefore, in GDP, the average value of dryland lucerne seed produced thanks to free pollination by wild pollinators is AU$20-25M per annum (Figure 31). Knowledge of the identity of these wild pollinators and of their requirements from the landscape will allow farmers to secure and even enhance these free services.

Figure 31. During normal years, wild pollinators contribute AU$20 – 25M to dryland lucerne seed production

ii. Overall conclusion regarding the landscape and bee crop pollination

For both apples and lucerne, we have shown that the landscape surrounding the crop influences the presence of feral honey bees and native pollinators, and that this translates to increases in productivity.

KEY FINDING: In apple, we found correlations between open grassy land and visitation by native halictid bees. The number of empty carpels decreased with increased native pollinator visitation, which increases apple symmetry and quality.

In lucerne, set was 5-8% higher in the presence than in the absence of native vegetation in close proximity. The presence of native vegetation was also associated with a higher abundance of honey bees and native pollinators.

Our conclusions correspond with findings throughout the world, regarding the effects of native woody vegetation and grasslands on visitors, as well as the order of magnitude of yield increases as a result of the presence of beneficial vegetation (e.g. Klein et al. 2012; Albrecht et al. 2020; Krimmer et al. 2019).

c. Threats to pollination security: Conclusions

Pollination security depends on the security and resilience of current pollination systems. Due to the pending incursion of the Varroa mite and associated effects on viral diseases, feral honey bees are the most important and vulnerable part of the system, in particular in cropping areas that contain high densities of old *Eucalyptus* trees, which provide nesting places. In addition, the strength and survival of feral colonies is likely to depend on the presence of fresh water and floral resources in a 2-5 km radius surrounding the crop (Beekman and Ratnieks 2000). The complete loss of feral honey bees, either due to loss of supportive vegetation or disease, could halve the crop pollination services by feral honey bees in landscapes of mixed farmland and trees. In areas that lack supportive vegetation, the pollination by feral honey bees is already likely to be minimal.

Estimates of the free pollination service from native pollinators depend on the crop, the region, floral resources and nesting opportunities as well as the pollination efficiency of particular pollinators. The estimates have wide margins but can be as high as 80%. Several pollinators rely on floral resources and nesting opportunities in native woody vegetation, while others benefit from open grassy areas. However, it is important to note that not all types or grassland support the latter pollinators in the same way: open unmanaged areas and native grasslands are likely to be much more supportive than intensively grazed pasture and frequently mown lawns.

Among the threats to free pollination services, this study has not assessed the impact of the higher temperatures and increased heat waves that are the result of climate change. This lack of information does not imply that the threat is small. Recent observations indicate that heat waves and higher temperatures cause a profound decrease in the floral resources, which, in the last few years, have substantially reduced honey yields from commercial hives (Le Feuvre pers. com.), and the densities of native bees in native vegetation (Hogendoorn and Leijs pers. obs.).

3.3 Designing an investment strategy to support pollinator security and resilience

So far, we have identified visitors, assessed their contribution to pollination, as well the threats to pollinator security and resilience. We identified the reliance on feral honey bees, as well as the absence of supporting landscapes as threats.

To better support pollination services, we need to know the specifics of how the pollinators relate to the crop and the surrounding habitat. This implies that we understand:

- when and where the pollinators need support (their lifecycle);
- how we can enhance their nesting opportunities;
- the plant species they use as food;
- whether such habitat enhancement is an economically worthwhile enterprise

a. Understanding the lifecycle

Pollinators are not only present in the cropping region when the crop is in flower. Native bees in particular are central place foragers, i.e. they have a home to return to throughout their lives, and females often re-use the maternal nest to reproduce. That makes them permanent residents on, or close to, the farm, Flies are more nomadic, and their offspring feeds on aphids (Syrphidae) carrion (blowflies), dung (*Eristalis*).

To design floral support for native bees and other crop pollinators, we need to know when the bees need support, i.e. understand their lifecycle, what plant species they use as food, and how we can enhance their nesting opportunities. This can then inform at what times, outside of crop flowering times, these pollinators need floral resources, and help to create advice for targeted plantings in close proximity to the crops.

Furrow bees (*Lasioglossum (Chilalictus)* and *Homalictus*) were among the most common native bees on the crops. They start their nest in early spring and overwinter as mated, adult females

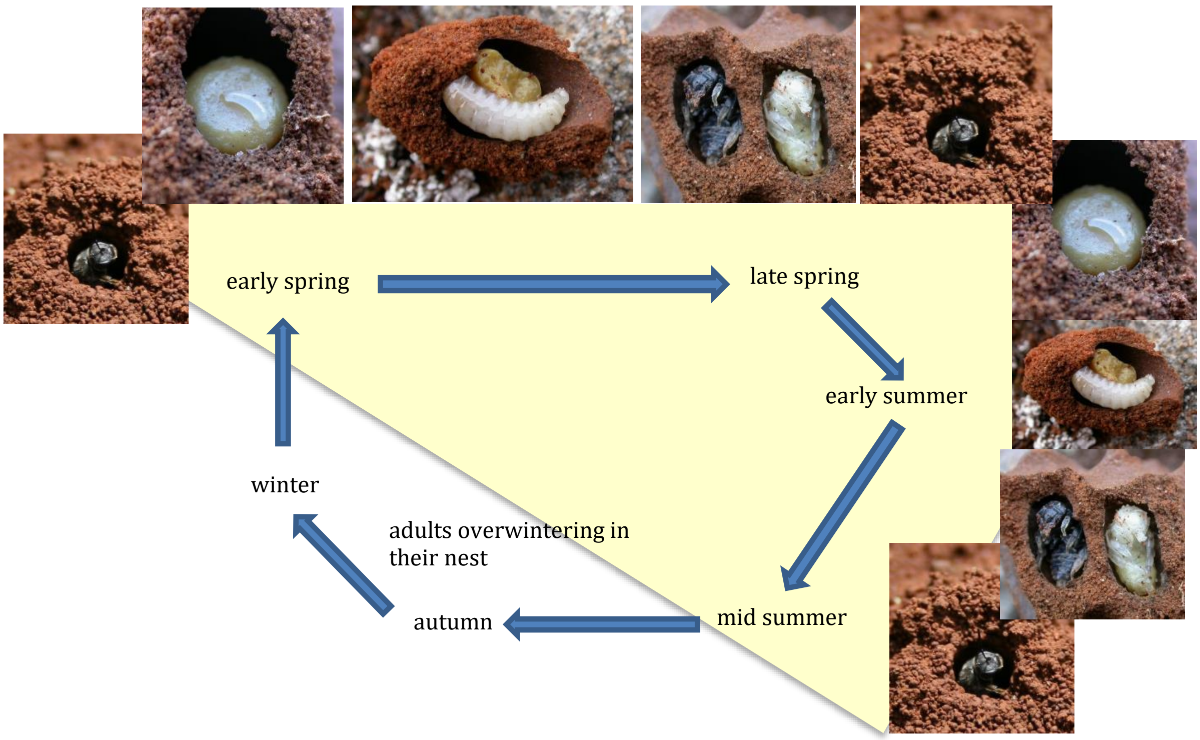


Figure 32. Typical lifecycle of a ground nesting furrow bee (Lasioglossum (Chilalictus)). Many of these species are communal and nest in aggregations. This implies that they can locally reach high densities. The light yellow background indicates the period of time is when furrow bees need food from the landscape: From early spring to late summer.

(Walker 1995). Many crop pollinating species have a second generation, and males and females emerge in mid-summer to mate, and require food during that time (e.g. Figure 32).

Reed, stingless, and honey bees have adults year round and will forage throughout spring and summer but also on warm days in autumn and winter. Blue-banded bees can have several overlapping generations between late spring and late autumn. Bumble bees occur only in Tasmania (where they are an introduced exotic), and queens may start new colonies in late winter after hibernation, but colonies are also known to survive through winter. In the south of the country, adult hover flies (Syrphidae) are particularly abundant in spring. Blow flies (Calliphoridae) are often seen in summer in the southern Australia, but throughout the year in the north of the continent. The overarching lesson is that the visitors and pollinators of crops benefit from having food year round, but specifically from early spring to late summer (Table 2).

Lucerne is a special case in this context. The period of lucerne flowering is between November and February, but the exact timing is variable, as it is the choice of the farmer to get the sheep off the crop. Because of this variability, the pollinators in the crop would benefit from support from late spring through to late summer.

Table 2. Times of the year when the main crop visiting bees require floral support in the landscape. Lighter colours indicate that adults will be out foraging on warm days, but the bees may hibernate in cooler areas.

bees	spring			summer			autumn			winter			presence
honey													all states
furrow bees													all states
blue-banded													all states
nomia bees													all states
resin/leafcutter													all states
reed bees													NSW,SA,TAS,VIC
stingless													NSW, NT, QLD
bumble													TAS

b. Nesting requirements

The native bees that visit the crops use a variety of nesting substrate.

Hollow nesters

A number of bees nest above ground. The most abundant species, the feral honey bees and, in the subtropical areas, the stingless bees, use existing nesting hollows in old trees. Because these bees can reach high abundance and provide substantial pollination services, it is important recognise the value of these trees.

For example, we found that the presence of paddock trees cause a more even, and higher set in lucerne fields (3.2b), and that stingless bees were supported by the presence of large native trees around apple, macadamia and berry orchards.

Twig and stem nesters

The berry and apple crops in the Yarra Valley and Tasmania had a high presence of allodapine bees (reed bees). They dig their own nest in pithy stems, and are supported by the crop and native vegetation (see inset - Reed bees live in berry crops, and pollinate them too!).

In lucerne, we observed many resin and leafcutter bees in the crop. These species use existing linear hollows in wood, often beetle bores, and are well-known users of bee hotels. The potential to enhance these bees using bee hotels in lucerne crops requires further exploration.

Figure 33. A reed bee visiting a Rubus *flower (photograph by Alison Hoelzer)*

Reed bees live in berry crops, and pollinate them too!

Reed bees were the most common flower visitor in some berry orchards. Reed bees are small (6 - 8mm long), and usually have a black head and thorax and a red-brown abdomen. There are many species in Australia, mostly found in wetter temperate regions. Reed bees are generalists and visit a range of crop (apples, blueberries, and more) and native plants.

The name 'reed bee' refers to the habit of females to dig a nest in pithy stems of plants such as tree ferns, and grass trees, although they rarely nest in reeds! The bees also nest in non-native plant species such as lantana, brambles and berry canes. Some species have social behaviour, where several females nest in a single stem and work together to raise and protect their brood.

Reed bees were found nesting in the canes of raspberry and blackberry. This means that the *Rubus* berry orchard environment provides both a home (nests) and food (flowers) for them! At one orchard, the density of bees was estimated at approximately 3,000 reed bees per hectare.

Reed bees will nest in dead canes that they can enter at a damage point or an opening created by pruning. New nests are established in spring, but they remain present in the orchard year round, and are re-used for several years. Because the bees do not tunnel through live tissue, they do not harm the plant. Bees prefer canes that are upright and not too thick (stems less than 9mm diameter were preferred). Further research is needed to find out which pruning strategy can help bee nesting. We encourage growers to make their own observations.

Areas of the orchard with more nests in canes also had more reed bee visits to flowers, confirming that the bees live and work locally. They also like nesting in tree ferns and so reed bees were more common in orchards when tree ferns were nearby.

Reed bees actively forage for most of the year (less so in winter; Table 2), and so require floral resources outside of crop flowering times. Reed bees forage on native plants such as *Acacia* and *Hakea* before crops were flowering, and *Kunzea* and *Pultenaea* after crops finished flowering.

Keep in mind that reed bees can forage as much as 1 km from their nest. Your local area may provide many of these flowering resources at different times of year – your local bushland can support your on farm pollination.

Soil nesting bees

Among the soil nesting bees, the furrow bees (*Lasioglossum (Chilalictus*)), also sometimes referred to as white-banded bees, were the most abundant in the majority of crops. These species are generalists that nest in open soil or areas with low vegetation cover. They do not nest in paddocks that are intensively grazed by sheep or cows, in lawns or in areas that are regularly flooded.

Blue-banded bees like to nest in cliffs and washouts, preferring soft, fine, sandy vertical substrate, that faces east-north-east. This knowledge can give lucerne growers an opportunity to stimulate these beautiful and useful bees in their crop, for example by finding and protecting existing nesting sites, or by building a blue-banded bee wall from besser blocks (Figure 34).

Figure 34. A wall made from besser blocks filled with dry, soft mud, can attract blue-banded bees and resin bees (Hogendoorn and Keller 2012).

The design includes star droppers through the side pillars to create a stable structure, an overhanging roof to prevent water dripping over the blocks and a backing of soil, which provides thermal mass to prevent overheating. Further advice regarding the filling of these blocks can be found at www.aussiebee.com.au/aussiebeeonline008.pdf.

c. The plant species and revegetation strategies that support pollinators

i. Networks and visitation

The visitation of bees on crops and plants in and surrounding the crops was investigated in two ways. In South Australia, the native plants that support crop visiting bees during and after flowering of canola (Yorke Peninsula), lucerne (South East) and apple (Adelaide Hills) were identified by collecting bees during these times. In addition, for the species that visited the crops, we constructed a database of all known flowers. The latter was done using information from the Atlas of Life Australia, Western Australian Museum and our data collected over the years (Appendix). This information was then used to inform revegetation strategies, see below.

In the Yarra Valley, the visitation of bees was assessed on all flowering plants in and around cherry, blackberry, blueberry, raspberry and apple orchards during crop flowering. The data show which species are abundant on the crops, and what plant species support the bees during crop flowering (Figure 35). This showed that, among native bee taxa, reed bees (*Exoneura* sp.) were the most likely to favour crops and that they did so at apple orchards, rubus and blueberry farms. The other two native bee taxa were less abundant overall and more frequently seen on weeds. This then informed strategies to enhance reed bee nesting substrate in the crops (see below).

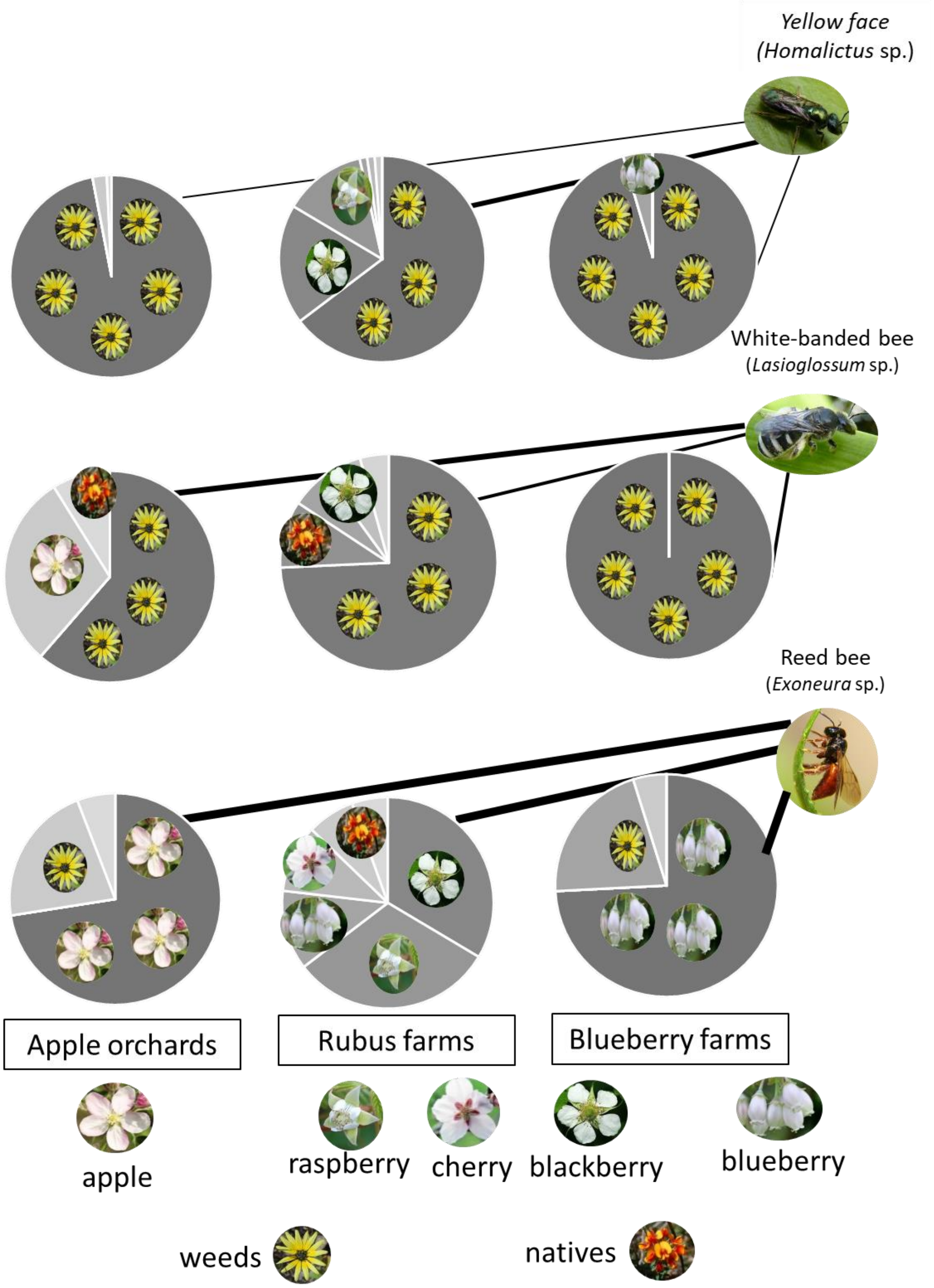


Figure 35. Flower visitation on farms of the three most abundant native bees in the Yarra Valley. The pie charts show the proportion of visits to the different flower types (five crops, weeds and native plants) considering observations made. Thicker lines reflect bees that were seen more often. Note that some black-/raspberry farms included cherry and blueberry, which were also visited.

In Tasmania, native plants and weeds were sampled in and around apple and blueberry orchards during and after crop flowering. In apple, we found that the native reed bee *Exoneura* sp. primarily visited apple, and native shrubs post apple flowering. During blueberry fllowering, reed bees primarily visited native shrubs, such as *Pultenaea juniperina, Oxylobium ellipticum,*

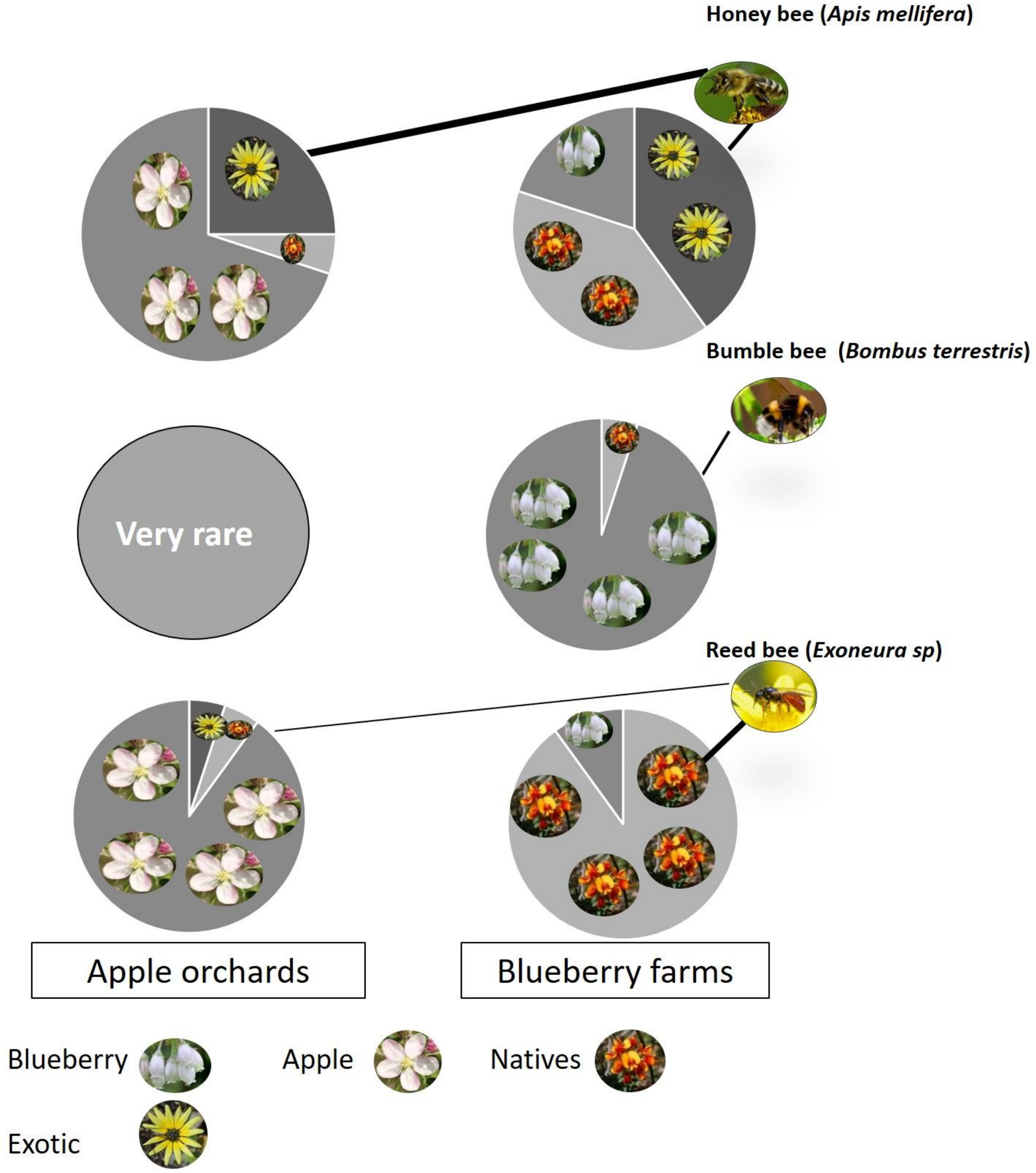


*Figure 36. Visitation patterns in apple orchards, blueberry orchards in Tasmania for the three most common insect visitors: Honey bees (*Apis mellifera*), bumble bees (*Bombus terrestris*) and reed bees (*Exoneura sp*). The pie charts show the proportion of visits to the different flower types based on our on-farm observations. Thicker lines reflect bees that were seen more often.*

Ziera *arborescens* (

Figure 33). Post blueberry flowering, *Exoneura* primarily visited native shrubs and raspberry bushes. In both apple and blueberry, *Lasioglossum sp* primarily visited wild brassicas and non-native forbs. Surprisingly, bumblebees were virtually absent from apple flowers. In blueberry, both reed bees and honey bees were less attracted to the crop than to native plants. Note that the difference painted by this picture may reflect the difference in abundance between the native plant species.

As pollen is often in short supply, identifying the pollen plants that support bees is of major importance to identify the plants that support crop pollination services. Therefore, in addition to flower visitation, we identified the pollen carried on the bodies of bees caught in the crop and on weeds and native vegetation surrounding the crop. In South Australia and Victoria, pollen identification was done visually. In South Australia, we also used the novel hybrid capture method that we developed during the project (see ii Plant barcode resource, below).

Figure 37 illustrates the importance of pollen analysis. While approximately 70% of the flower visits recorded for *Exoneura* in apple orchards were to apple flowers, the proportion of apple pollen it carried was very low (4% of all pollen). This suggests that apple is a nectar rather than a pollen source for these bees, and that *Exoneura* can be further supported in apple orchards by planting pollen sources (e.g. *Pultenaea* and *Goodenia*). By contrast, *Lasioglossum* (*Parasphecodes*) and to a lesser extent *L.* (*Chilalictus*) carried large amounts of Rosacea pollen (apple, cherry and black-/raspberry), and could be supported by allowing weeds to flower interrow. In blueberry orchards, *Exoneura* carried substantial amounts of crop pollen, suggesting that the enhancement of this bee may have major benefits for blueberry farms.

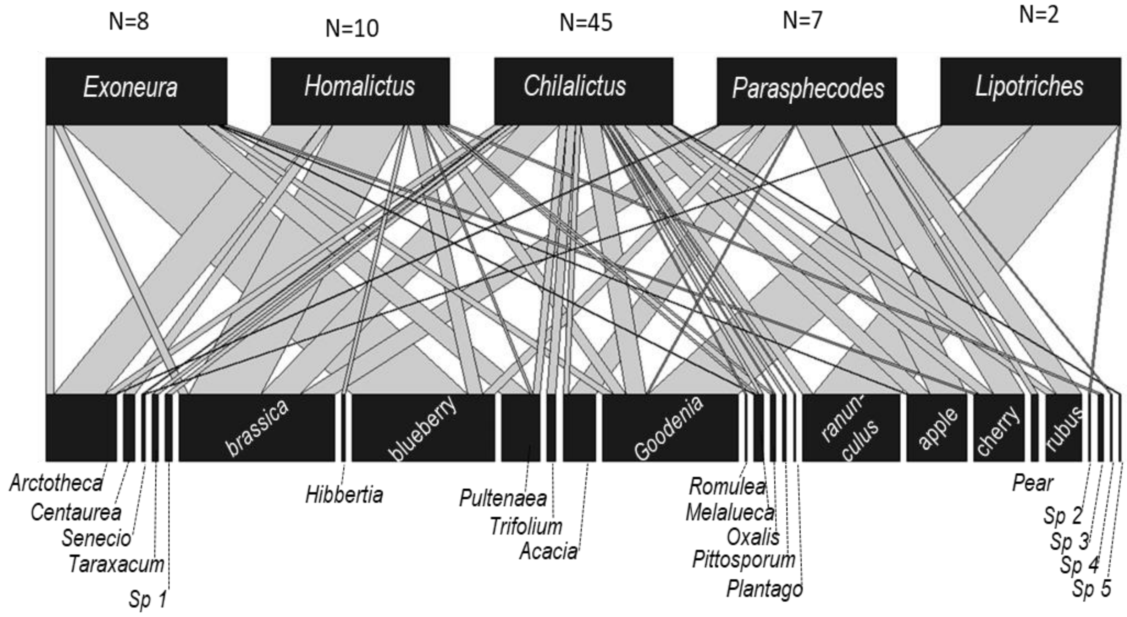


Figure 37. Pollen collected from the body of bees indicates pollen sources, rather than just observed visits. The network diagram shows the 5 bee taxa for which we had pollen carrying specimens (top row, N *ranging from 2 to 45) and the pollen types identified on their body (bottom row). The width of the connection reflects the total amount of pollen carried. As for the visitation analysis this study shows crop pollen prominent for all bees bar* Lipotriches *(where the sample size is small).*

To learn more about the diet width of the bees that foraged on apple and lucerne in South Australia, from the bees that were caught while foraging on the crop, we selected,, those that had a relatively full complement of pollen in their scopa. We then removed the pollen and identified it under the microscope.

In apple and pear, we caught only nine bees that carried a large amount of pollen, and of these, seven carried more than one species of pollen (Figure 38). The pollen species carried included apple/pear (crop), African daisy and wild mustard (weeds), *Leptospermum*, *Acacia*, native peas and *Eucalyptus* (native plants) and three species that we could not identify. The quantities that the bees were carrying of secondary and tertiary species make it unlikely that the mix of pollen was collected accidentally.

In lucerne, we caught 47 bees of four species, with a relatively full complement of pollen, while they were foraging in the crop. None of these bees carried a single species of pollen (Figure 39). All bees carried lucerne pollen, although for some (in particular blue-banded bees) this was not found in their scopa. The other pollen species were from native plants, crops, and weeds.

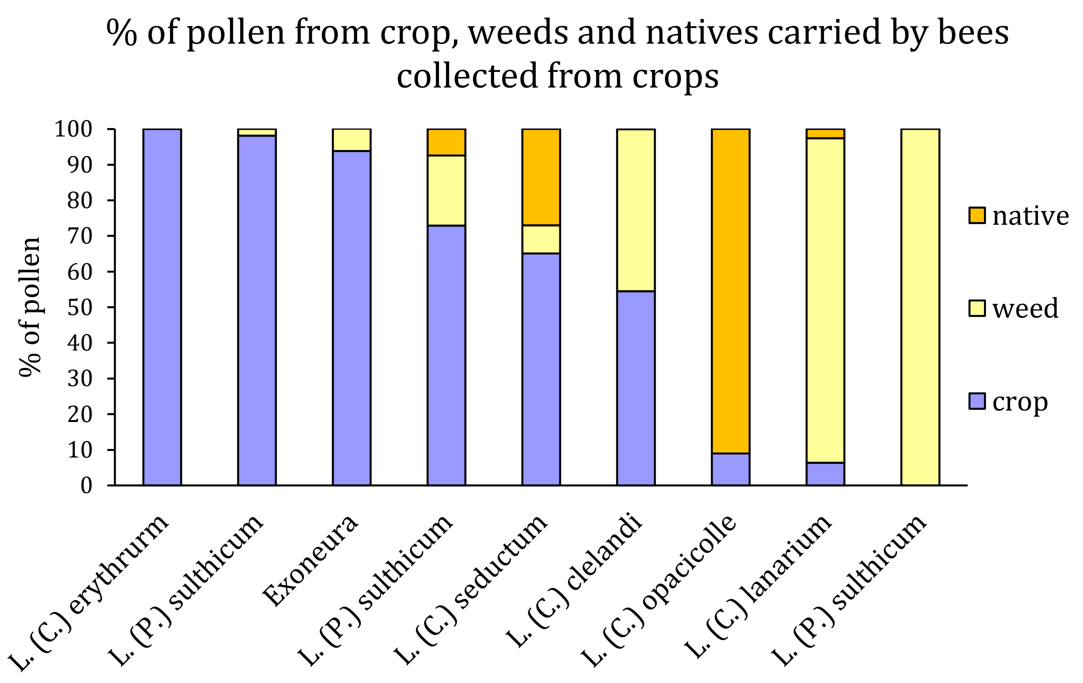


Figure 38. Individual bees caught foraging on apple and pear mostly carried pollen from more than one species of plant in their scopa. The percentage carried is based on a count of the pollen kernels present .

It is likely that the generalist bees that forage on introduced crops have a broad diet, and choose pollen from a mix of different plant species. This is an important novel finding in itself.

Our findings demonstrate that an in-depth analysis of diets is needed to understand how bees can be best supported in the landscape. The insight will allow us to ensure the bees have the right pollen and nectar available. Furthermore, the data suggest that the presence of a diversity of flowering plants is required at all times, not just when the crop isn't flowering.

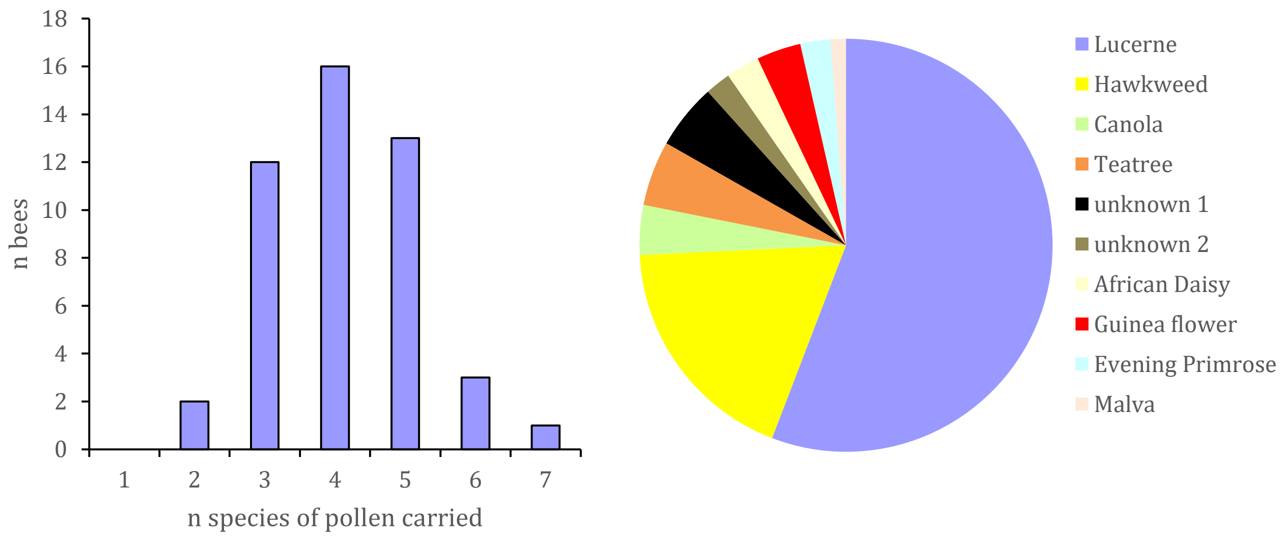


Figure 39. The number of pollen species carried by 47 native bees caught while foraging in lucerne (left) and the percentage of pollen carried.

iii. Plant barcode resource

Identifying pollen requires specialist knowledge, particularly if no voucher sample has been taken from plants in the field. To facilitate the identification of pollen sources, we developed DNA barcoding approaches. The barcodes (a selection of short DNA sequences) allow genus and species level identification from small amounts of pollen. The method reduces the time required for identification and improves the resolution to species level.

The first step was the development of robust DNA barcoding reference database pollen sources of flowering plants that grow in and around the cropping regions in SA. The method has been optimised to allow the identification of multiple species from a single sample, for example when several species of pollen are present on a single bee leg, as indicated above. This information can be used to evaluate the utility of pollen sources in the environment, including the target crops, and determine pollinator preferences.

The method, which uses RNA targeted baits (Figure 41) enables multiple chloroplast genes (approximately 20) to be assessed in a single analysis, including the standard plant barcodes Maturase K (matK) and ribulose-bisphosphate carboxylase (rbcL). In addition to the plant barcodes, RNA baits targeting bees were included in the bait set; this allows identification of both pollen origin and carrier bee in one single test.

Genetic reference data were generated for a total of 217 plant species (in triplicate, which includes subspecies and varieties) including natives, invasive species and crops that can potentially provide resources for pollinators. The 626 individual samples were collected from vouchered plant specimens in the South Australian Herbarium, or from wild collections, which were subsequently vouchered. From these samples, 626 genomic libraries (one per sample) have been sequenced successfully. These sequences obtained have been collated into a local BLAST (Basic Local Alignment Search Tool) database and to be lodged into the NCBI (National Center for Biotechnology Information) repository, the largest database for sequence data.

A full list of plants for which references have been generated can be found in the appendix. Additional to the Genomic Reference database, we mined NCBI for the targeted chloroplast loci (30 in total that were used in the hybrid capture design) for all flowering plants that are present in the Census of South Australian Plants, Algae and Fungi (http://www.flora.sa.gov.au/census.shtml).

Figure 40. The hybrid capture method allows simultaneous recognition of multiple species of pollen collected by honey bees,(left) or identification of bees and multiple pollen species from a leg (right; photo: Dona Kireta) in a single test.

For the analysis of mixed pollen samples, 16 test samples collected from honey bee hives in the study area (Figure 40) were successfully extracted for DNA and analysed through the hybrid capture method. Results showed expected diversity of pollen sources (up to genus level) and confirm the utility of the method for assessing plant resources utilised by bees. A further 221 pollen samples from native bees collected on crops have also been extracted, of which 31 have been sequenced, showing expected pollen diversity and bees successfully identified through their DNA barcode.

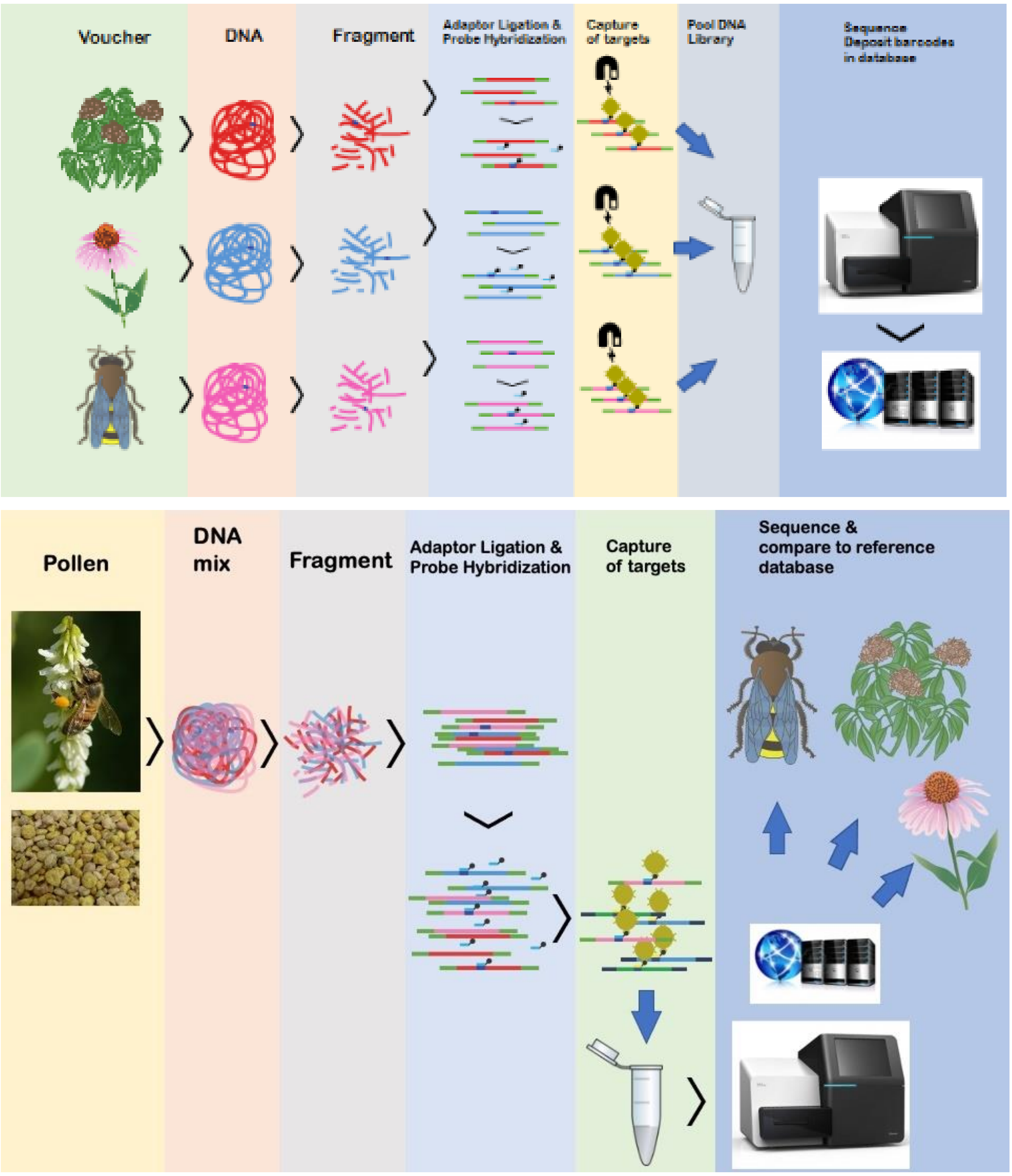


Figure 41. A graphical summary of the Hybrid Capture approach to generate Genomic Reference databases (top) and to identify pollen and bees by comparison against the genomic barcode reference database (bottom).

d. Habitat design: costs, benefits and the economic framework

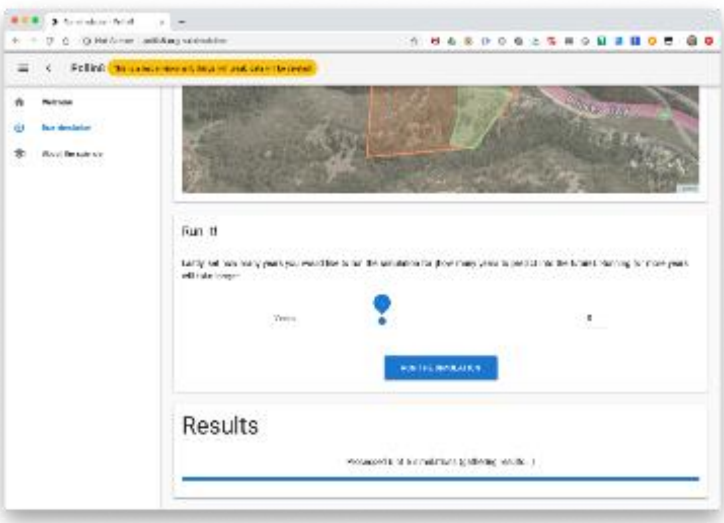
i. Modelling the benefits from pollinator habitat

Modeling using the Pollin8 planning tool allows growers to obtain insight into the pollination benefits of planned revegetation can offer, with associated impacts on crop yield. The model takes into account how much native vegetation is locally available. The tool's analysis considers the situation in which *Varroa* mite enters Australia and how much more of the crop pollination will need to be supplied by native pollinators.

The tool allows users to conduct "what-if" scenario analysis around options for revegetation and pollination services. These scenarios can be saved and compared, allowing land managers to make informed decisions on how pollination services can potentially affect their crop yields over time.

The planning tool is web-based, and makes use of a calculation engine which has been developed as part of the INVEST toolset (https://naturalcapitalproject.stanford.edu/software/invest-models/crop-pollination). The calculation engine's pollination model focuses on wild bees as a key animal pollinator, connecting the likely impact of an incursion of the *Varroa* mite on the free pollination services currently provided by feral honeybees.

The Pollin8 simulator has been updated with minor point releases of the underlying INVEST pollination engine, and the engine uses v3.70



We have integrated and calibrated a pollination re-vegetation maturity model, so that the delivery of pollination services can be appropriately taken into account when running multi-year scenario calculations. We are in discussion with the designers of the software to explore issues with the calibration.

The pollin8 web tool further includes:

- an example of a native been food calendar (http://www.pollin8.org.au/flowering);
- an explanation of the science behind the plant selector tool (http://www.pollin8.org.au/science);
- two videos that were made for the project (one to explain the project, the other to encourage growers to the use the plant selector (http://www.pollin8.org.au/project);
- the interactive revegetation planting guide (plant selector - below).

ii Auction and economic framework

Quality revegetation is costly, labour intensive, and with increasingly hotter conditions, risky. It is interesting to know the price growers are willing to pay. A reverse auction is a tool that allows us to understand the price of an action or service in relation to its quality. In this project we used a reverse auction with the aim of revealing the price of revegetation for biodiversity conservation (habitat restoration) and native vegetation plantings which enhance habitat resources for pollinators (pollinator-enhanced plantings). We anticipated that the landholder price for pollinator-enhanced plantings would be lower than for habitat restoration due to the larger proportion of private benefits expected from pollinator-enhanced plantings.

The auction (BuzzBids) was designed and run by O'Connor NRM Pty Ltd. The design included criteria for eligibility, contract design, communication strategy, revegetation templates, site preparation and management requirements, and bidding information requirements. Revegetation templates were developed for biodiversity (habitat restoration) and pollination (pollinator-enhanced plantings) outcomes, and were based on reference ecosystems and current knowledge of pollinator habitat requirements. Templates for pollinator-enhanced plantings included increased floral resources but was offset by reductions in other species not considered to provide important resources for crop pollinators (e.g. grasses). The templates specified minimum outcomes for species composition and richness, and planting density.

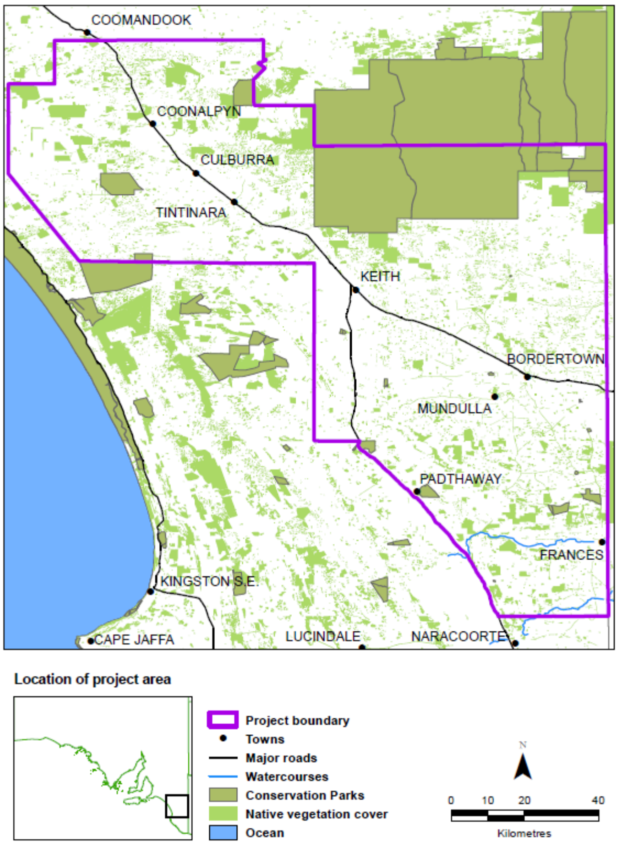


Figure 42. BuzzBids revegetation auction area capturing major lucerne growing areas within the Upper South East of South Australia.

The reverse auction was run in 2018/19 in the lucerne seed production area of the Upper South East of South Australia (see Figure 42).

The BuzzBids auction was promoted extensively to landholders and revegetation service providers within the project boundary (see Table 3). Information about the BuzzBids program was provided to key stakeholders, regional NRM and the community through staged advertisement, mail-outs and information sessions. Expressions of interest were opened on 20 November 2018; site assessments were conducted between December 2018 and April 2019 and bidding closed on 31 May 2019

Table 3. Promotional activity for BuzzBids revegetation auction

Activity	Date
Project brochure and factsheets produced	Oct 2018
Webpage created	Oct 2018
Newspaper ad (Border Chronical) - register of third party revegetation providers	Oct 2018
BuzzBids flyer circulated to >10 industry, local government, state government and community organisation contracts for further distribution	Nov 2018
Information provided to participants in BushBids (previous remnant vegetation protection auction in the same area)	Nov-Dec2018
BuzzBids flyer posted on local government Facebook pages	Nov-Dec 2018
Newspaper ads in Border Chronical (3) and Naracoorte Herald (1) re EOI opening and info sessions	Nov 2018 & Feb 2019
BuzzBids brochures sent to 7 agricultural outlets and nurseries for display on counter/notice board, and displayed on 8 community notice boards.	Dec 2018
Three information sessions	Nov 2018 & Feb 2019
Notification of EOI close circulated to industry, local government, state government and community organisation contracts for further distribution	Feb 2019

After the auction, the University of Adelaide undertook a survey of landholders to understand landholders' attitudes to revegetation and contracting, and their co-benefit interests, service provider engagement and bidding behaviours. The first phase of the survey used a mail and online questionnaire distributed to BuzzBids participants and Lucerne Australia members. The second phase of the survey used telephone interviews, with invitations to participate distributed to Lucerne Australia members.

In addition, a survey of revegetation service providers/industry was also conducted to identify a price for the provision of revegetation to a standard (including revegetation template and contract conditions) equivalent to that used in BuzzBids, and industry views about the revegetation standards and risk allocation. An online questionnaire was distributed to 133 revegetation service providers throughout southern Australia and had a response rate of 33% (44 responses).

The revegetation auction showed that:

- There is a thin market for high quality/high security revegetation in the BuzzBids area (see Table 4).
- The revealed price for high quality/high security revegetation in the BuzzBids auction was above $20,000 per ha (see Table 5). However, no contracts were entered into for BuzzBids revegetation.
- No landholders in the auction selected the pollinator-enhanced planting option (Table 4).

Table 4. BuzzBids revegetation auction stages and outcomes

BuzzBids Stage	Outcome
Information sessions	3 regional sessions
Expressions of Interest	17 people
Revegetation plans (habitat restoration)	8 landholders, 88.8 ha, 23 sites
Revegetation plans (pollinator-enhanced plantings)	0 landholders, 0 ha, 0 sites
Bids	6 bids, 18.8 ha
Successful bids	3 bids (sites), 7.1 ha, 1 landholder
Agreements signed	0 agreements, 0 ha, 0 sites

Table 5. Estimated price of revegetation in the BuzzBids revegetation auction and the revegetation industry survey.

	Price ($/ha)
BuzzBids auction[a]	
Mean (accepted bids)	$24,500
Range of accepted bids	$21,500-$29,000
Revegetation industry survey[b]	
Median (lower estimate)[c]	$25,000
Median (upper estimate)[d]	$30,000
Mean (lower estimate)[c]	$66,500
Mean (upper estimate)[d]	$68,000
Range	$600-$300,000

[a] 5 year contract, 27-35 species including herbaceous understory plants, 10,000 stems/ha
[b] 5 year contract, 35 species including herbaceous understory plants, 10,000 stems/ha
[c] lower estimates calculated using the minimum value when respondents provided a range
[d] upper estimates calculated using the maximum value when respondents provided a range

The associated landholder and industry surveys showed that:

- The revegetation industry considered the BuzzBids revegetation standard to be important for ecological objectives (82%), and achievable (49%), but above current industry standards (63%).
- The minimum cost of high quality/high security revegetation (similar to that offered in the reverse auction) estimated by the revegetation industry was $25,000-$30,000 per ha (median) and $66,500-$68,000 per ha (mean) (Table 5). These estimates are for revegetation provider costs and do not include transaction, management or opportunity cost for landholders.

The auction and industry survey provided an estimate of the price of high quality/high security revegetation for biodiversity conservation. This estimated price was substantially higher than prices paid by the Australian Government's recent 20 Million Trees program where standards for quality and security were lower (Collard et al. 2020). As there were no expressions of interest or bids for pollinator-enhanced planting, we were unable to estimate the value to landholders (or private benefit) from pollinator enhancement, however, establishment costs would be similar for the two revegetation templates which had similar species diversity and density. This suggests that in the auction area, it is not currently considered economic to revegetate for pollinator benefits alone. Possible non-exclusive reasons for the lack of interest in pollinator-enhanced planting are that participants:

- weren't lucerne seed producers (though the auction was open to all landholder types);
- did not have land available in proximity to lucerne crops;
- may have had other objectives for revegetation;
- were unaware or unsure about the total effects of pollinator plantings on crop production and profit;
- deemed the pollination-enhanced option to entail unacceptable risk.

The project was a formal collaboration with O'Connor NRM Pty Ltd and the Native Vegetation Council of South Australia. Collaborations also developed with the landholders and revegetation consultants who expressed interest and/or attended information sessions on the project. Lucerne Australia was an important collaborator and first point of contact for landholder engagement and contacts for project design and delivery. The Coorong and District Council and Local Action Planning Association were also involved in organising facilities for meetings and connecting landholders to the project.

The research is reported in peer reviewed manuscripts, one submitted for publication in Ecological Restoration, and one in preparation.

Reference

Collard SJ, O'Connor PJ, Prowse TAA, Gregg D, Bond AJ (2020) Objectives versus realities: Spatial, temporal, financial and social deficiencies in Australia's public revegetation investment model. Ecological Management and Restoration 21:35-41

3.4 Advice to enhance pollinators around crops

a. Nesting substrate:

In cooler areas in Victoria and Tasmania, the supply of bundles of rubus canes with pithy stems could enhance the activity and abundance of reed bees in the crop (see page 46).

In all crops, accessible, relatively undisturbed soil can assist the nesting of *Lasioglossum* and *Homalictus* species. In particular when headlands of orchards are treated with herbicide in winter, and/or orchard trees are planted in a mound, this can provide bees with an opportunity to nest in the orchard. Closely matted and regularly mown lawn and intensively grazed areas are unsuitable for ground nesting bees.

In lucerne, farmers could experiment with nest substrate for resin and leafcutter bees, in particular in flood irrigated areas, as this would remove ants from the system. In addition, walls for blue-banded bees could be considered (see page 47).

Paddock trees, in particular old *Eucalyptus* species, provide nesting substrate, and for feral honey bees, reed, leafcutter and resin bees. It is important that growers realise that they are a valuable asset for crop pollinators.

b. Planting advice

i. The Plant Selector

As has been shown above, a variety of bees will visit crops (section 3.1a). Some crop pollinating species are present year-round (feral honey bees), and others often have multiple generations per year (furrow and blue-banded bees). This implies that the local crop pollinating native bees need sustenance from early spring through to late autumn (Table 2. Times of the year when the main crop visiting bees require floral support in the landscape. Lighter colours indicate that adults will be out foraging on warm days, but the bees may hibernate in cooler areas. Based on the plant species that were visited by the crop pollinators (see section 3.2c), we formulated planting advice for native plantings around South Australian crops. This advice is available through the Plant Selector tool (http://www.pollin8.org.au/planting)

The Plant Selector is a simple (3 step) online tool designed in conjunction with TERN technical support to assist growers of pollination dependent crops and land managers in selecting native plant species that provide floral resources (pollen and nectar) for crop pollinating bees. The logic driving the tool is shown in Figure 43.

Feasibility filtering. From a master list of native plants we selected species that were visited by the crop pollinators (see section 3.2c above), had favourable phenology (the length of flowering) and operational feasibility (seed production, nursery availability and ease of growing). Once filtered these plants constituted the native species pool for the online Plant Selector.

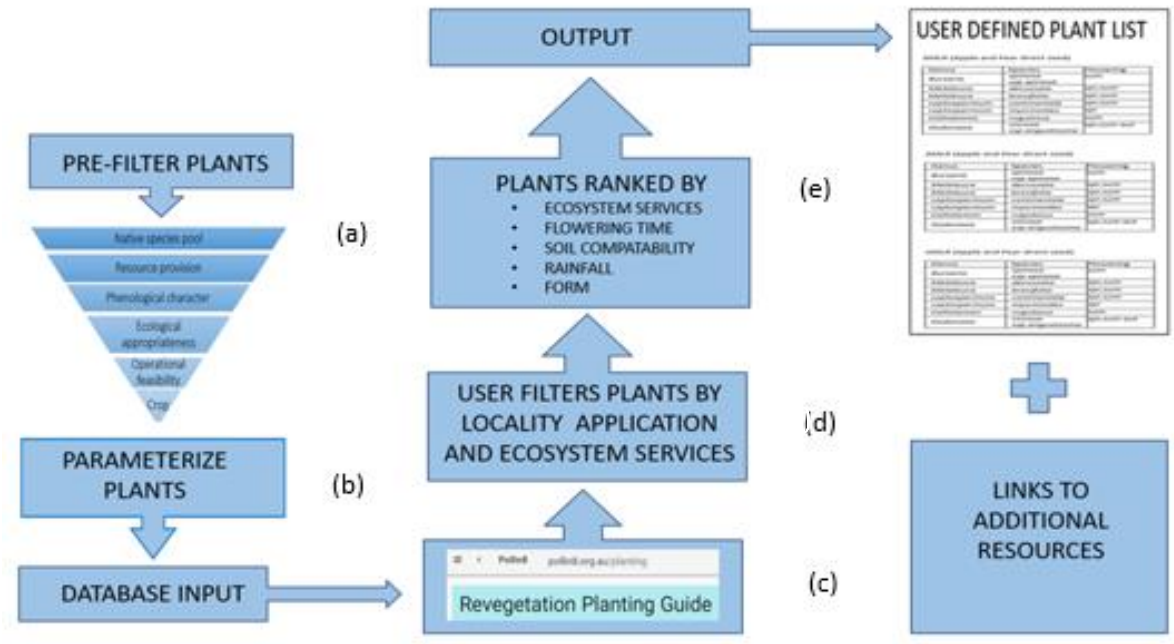
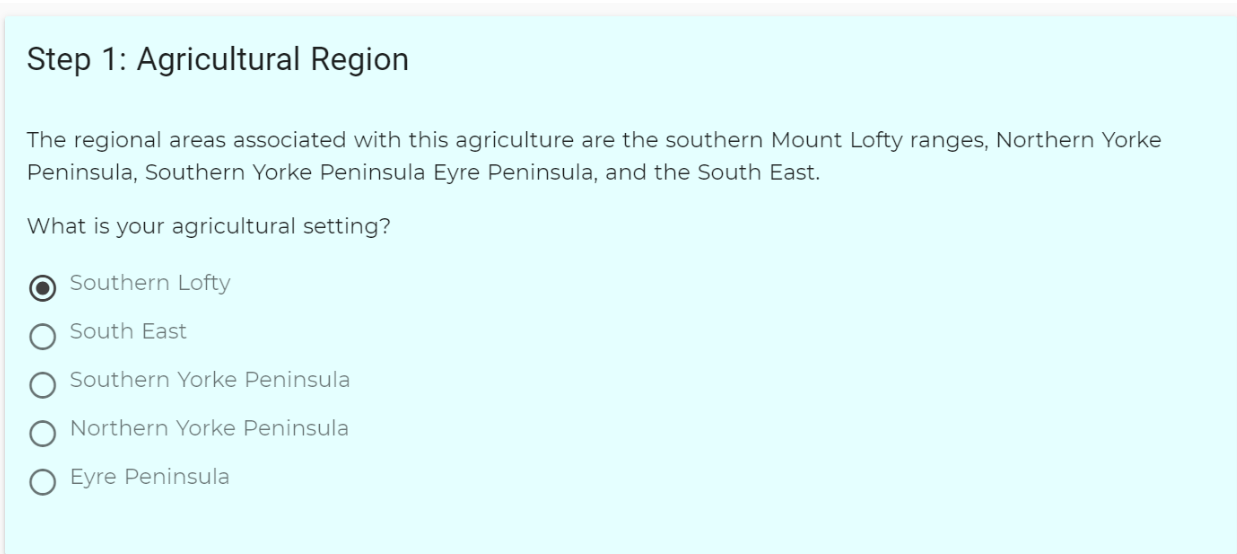
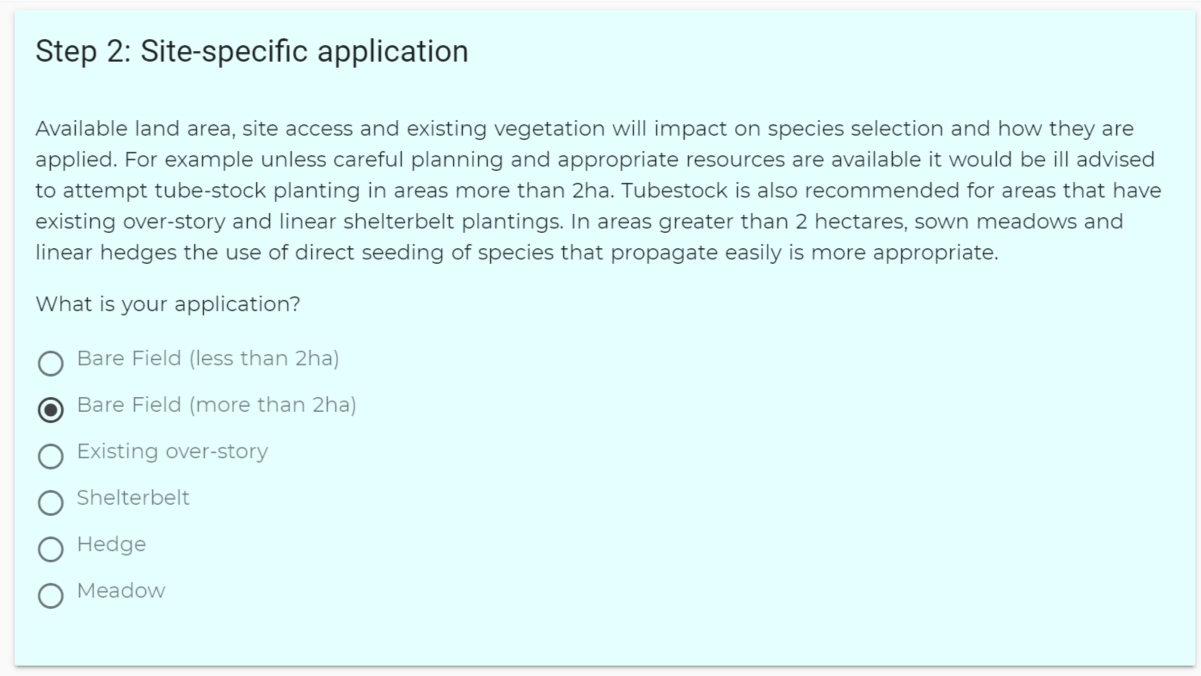


Figure 43. Online plant selector Logic and information flow started from (a) a pool of native plant filtered for feasibility, then proceeded to (b) select the planting application parameters (c) create an application programming interface for the planting scenarios (d) creating user input filters (e) rank plants according to criteria for planting.

Selecting the planting application parameters. The Plant Selector requires three stepwise inputs, which further determine the recommended plant selection:



The agricultural region further defines the species pool.



Step 2: Site-specific application

Available land area, site access and existing vegetation will impact on species selection and how they are applied. For example unless careful planning and appropriate resources are available it would be ill advised to attempt tube-stock planting in areas more than 2ha. Tubestock is also recommended for areas that have existing over-story and linear shelterbelt plantings. In areas greater than 2 hectares, sown meadows and linear hedges the use of direct seeding of species that propagate easily is more appropriate.

What is your application?

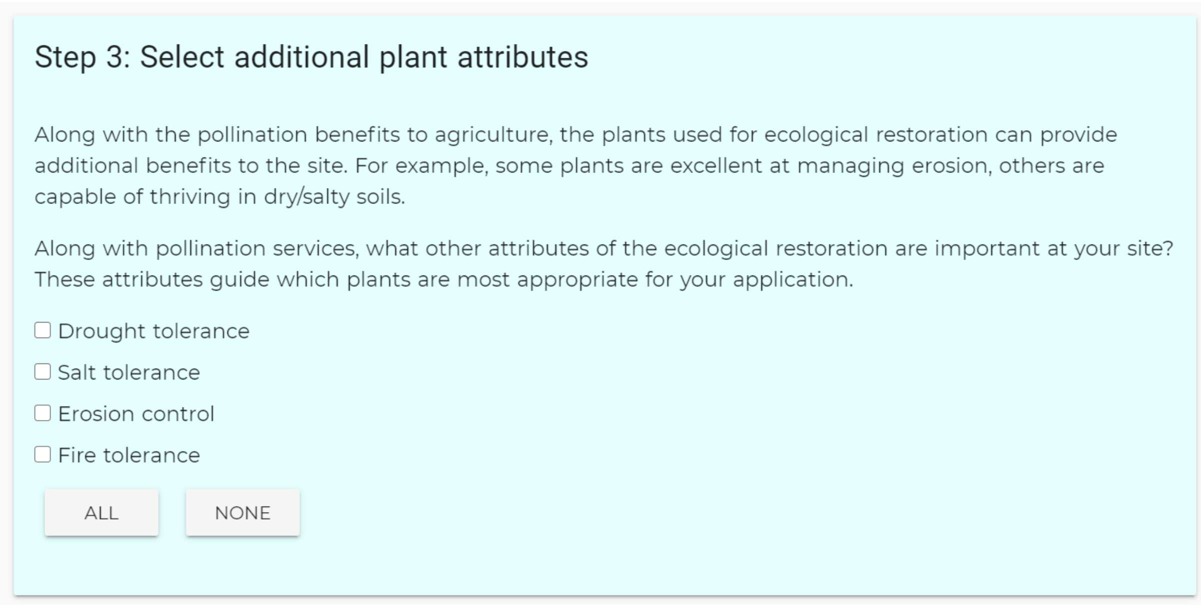
- ○ Bare Field (less than 2ha)
- ◉ Bare Field (more than 2ha)
- ○ Existing over-story
- ○ Shelterbelt
- ○ Hedge
- ○ Meadow

Site specific application. We based the information about site specific application requested in Step 2, results in further filtering and is based on the following rationale: In an agricultural setting land availability is at a premium so finding areas to set aside for restoration may be difficult. Wherever possible the plantings should be as large and as close to the crop as possible to get the most benefit. In general, orchard headlands, track sidings, degraded land and paddock voids are the most likely parcels of bare land available on a farm. In addition, existing overstorey or scattered vegetation can be enriched with supplementary plantings. The answers dictate plant selection.

- **Bare field >2ha (direct-seeding application)** A bare field provides many possibilities for revegetation. The selector tool will give an overview of plants that suit the soil type, aspect and rainfall of the site. The structure and number of plant species used in direct seeding can be maximised for resource provision and to minimise the effect of seeds not germinating. Because direct seeding is generally done mechanically sowing can follow contour lines of the site to retain moisture and avoid the seed washing out.
- **Bare field <2ha existing overstorey (tubestock application).** Available land area, site access, existing cropping and the existing vegetation obstacles may exclude the direct seeding approach and such areas may lend themselves for tubestock planting. An existing overstorey of trees will help the establishment of understorey tube stock plants by providing shade and wind protection. Plants that are easy to propagate from seed will be sold as the cheapest tubestock which (referred to as standard in guide). Plants need to be grown from vegetative growth (struck) or produce low quantities of seed are more expensive.
- **Shelterbelts (direct-seeding application or tube stock topically).** The benefits of shelterbelts include crop protection, livestock shading, reduction of soil erosion, salinity control, and soil moisture and biodiversity improvements. Paying attention to the length of the shelterbelt (the longer the better) the orientation (upwind of prevailing winds) and continuity (spacing) can improve the efficiency of a shelter belt.
- **Hedgerows (direct seeding)** are primarily made of a bushy shrub layer and do not include overstorey trees. Hedgerows might be suitable in areas where the risk of introducing roosting points for avian pest species into the landscape is too great (e.g. apples). Hedgerows generally begin flowering faster than most overstorey species in

shelterbelts. Direct seeding for hedgerows in linear plots will cost ca AUD$400 - $800 per kilometre.

- **Meadows (direct or broadcast seeding**) use only annual and perennial herbaceous understory plants that propagate well. This type of planting is ideally suited to between row planting in orchards and trellis. Depending on the region a species mix can also have weed suppression and erosion control benefits. Mass plantings of native meadows can produce bountiful and complimentary floral resources throughout the year for pollinators.



Once the plant list has been generated for the site, plants with particular traits, e.g. co-benefits, can be selected. This allows simultaneous enhancement of specific traits. For example, pollination services, health of soil and livestock, climate resilience and biodiversity. Some of the co-benefits provided by certain plant species are highlighted in the plant list and are listed below.

- **Fire mitigation.** Selecting plants that have a high moisture content, low levels of volatile oils, large hard leaves with simple margins will absorb heat from fires or be slower to ignite so may provide some fire resistance. Furthermore, some plants can trap the embers from fires such as *Carpobrotus rossii*, pig face, which acts as an arresting point to slow or change the velocity of the fires. Weed and understorey fuel management will also help to reduce the combustibility of plantings.
- **Salt tolerance.** Saline soils occur both naturally and as a result of land management in Australia. Dryland salinity (high alkalinity) in marginal cropping areas is often a consequence of the removal of deep rooted trees, which causes the water table to rise. Many Australian native species have evolved traits to exclude or tolerate salinised soils so it is worthwhile considering using these species to topically treat salt scolded land in agricultural regions. The species listed have a salinity tolerance of between 4-8 dSiemensm-1 for ground water and soil but mounding imported soil to approximately 10cm can alleviate also alkalinity for establishment.
- **Drought tolerance.** Some plants have adaptation to aridity (rainfall below 250mm annually) or varying degrees of specific drought tolerance. Particular leaf traits such as small leaves, waxy covering are efficient to conserve water and an indicator that the plant has evolved strategies to reduce evapotranspiration. Also, root architecture such as the deep tap roots and lignotubers of some Eucalypts help them to tolerate low water availability and drought conditions.

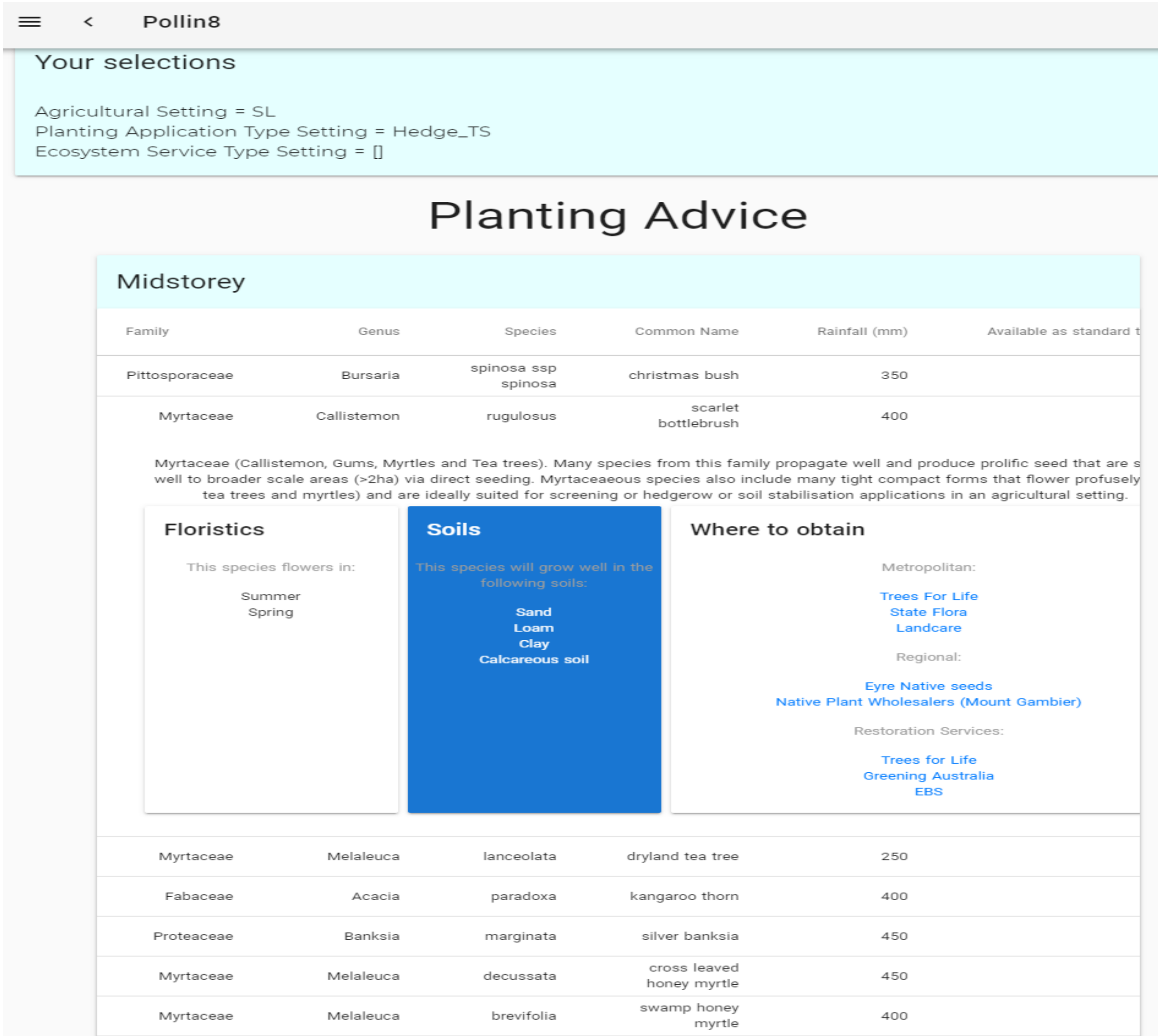
- **Erosion control.** Once established, the foliage of pollinator habitat will intercept rainfall, and decrease evaporative losses from the soil therefore reducing surface water runoff and erosion. If gullies are forming it is important to stabilise the soil by diverting surface water runoff by shaping the gully banks and fencing the affected area.

It should be noted that selecting some or all of the co-benefits drastically reduces the selection of plants and hence also has a downside.

As the filters are toggled by the end user, planting advice is generated. For example, the output for a selection of Adelaide Hills (apple) shelter belt would look as follows (This list is ranked according to the following criteria and in the following order):

- Resource provision (amount of pollen + nectar)
- Relative resource provision (plant size, flowering time)
- Breadth of soil type compatibility
- Availability of additional plant attributes and services

Furthermore by selecting an individual plant and clicking on it in the list (as in the Christmas Bush (*Bursaria spinosa* below) additional information and links about family traits, floristics, soil compatibility and availability are opened.



For further information see Plant selector http://www.pollin8.org.au/planting

c. Demonstration sites

To encourage adoption of pollinator habitat and create pollinator plantings, five demonstration sites of approximately 0.8 ha each were established during the life of the project.

The plantings were done on working farms in South Australia, two lucerne, one apple* and two canola farms (see Figure 44). The exact location and application of the plantings (hedgerow/ understorey/whole area plantings) was developed in conjunction with the growers.

Plant selection iterated the criteria formulated for the plant selector, i.e. the species: (a) occur naturally in the area; (b) provide pollen and nectar that is accessible for pollinators; (c) can be sourced; (d) will grow in revegetation plots; (d) combined, achieve a biodiverse outcome, with availability of pollen and nectar during large parts of spring and summer (Table 6).

Table 6. Species composition of pollinator habitat created through tube stock planting and direct seeding on farms of the Adelaide Hills (Apple& Pear), Yorke Peninsula (canola) and the South East (lucerne) growing regions.

Application	Apple and Pear	Canola	Lucerne
Tubestock	*Billardiera cymosa*	*Carpobrotus rossii*	*Banksia ornata*
	Calytrix tetragona	*Chrysocephalum apiculatum*	*Bursaria spinosa*
	Chrysocephalum apiculatum	*Dampiera rosmarinifolia*	*Chrysocephalum apiculatum*
	Cullen australasicum	*Eucalyptus oleosa*	*Eucalyptus leucoxylon ssp pinnosa*
	Daviesia leptophylla	*Eucalyptus porosa*	*Eucalyptus obliqua*
	Eutaxia microphylla	*Eucalyptus socialis*	*Eutaxia microphylla*
	Hakea rugosa	*Eutaxia microphylla*	*Kunzea pomifera*
	Hardenbergia violacea	*Hardenbergia violacea*	*Leptospermum continentale*
	Pultenaea largiflorens	*Leptospermum coriaceum*	
	Scaevola albida	*Melaleuca accumunata*	*Melaleuca brevifolia*
	Wahlenbergia stricta	*Melaleuca lanceolata*	*Melaleuca lanceolata*
	Bursaria spinosa	*Olearia pannosa*	*Olearia ramulosa*
		Pittosporum angustifolium	
		Scaevola albida	
		Senna artemisioides ssp	
Direct seeding	*Banksia marginata*	*Bursaria spinosa*	*Banksia marginata*
	Bursaria spinosa	*Callistemon rugulosus*	*Bursaria spinosa*
	Callistemon rugulosis	*Dodonaea viscosa spatulata*	*Callistemon rugulosus*
	Hakea rugosa	*Eucalyptus odorata*	*Eucalyptus arenacea*
	Hardenbergia violacea	*Eucalyptus phenax*	*Eucalyptus fasciculosa*
	Leptospermum coriaceum	*Eucalyptus porosa*	*Eucalyptus incrassata*
	Melaleuca brevifolia	*Eucalyptus socialis*	*Eucalyptus leucoxylon*
	Melaleuca lanceolata	*Melaleuca acuminata*	*Melaleuca brevifolia*
	Melaleuca uncinata	*Melaleuca halmaturorum*	*Melaleuca lanceolata*
		Melaleuca lanceolata	
		Pittosporum angustifolium	
		Senna artemisioides mixed subspecies	
		Templetonia retusa	

Tube-stock plantings

Tube-stock planting, ca 0.3 ha, was done at all sites. Tube-stock was grown in the commercial nurseries of our industry partners Trees for Life (for the apple and pear growing region) and Greening Australia (for the canola and lucerne regions). The planting days were organised between May and August in 2018 and 2019, and were used as an opportunity for outreach.

Each of the plantings involved around 20 volunteers, many from the local community. At each site approximately 1000 tube-stock of a diverse range of species were planted (Table 6). The very dry summers that followed the plantings done in winter 2018, necessitated follow-up planting of approximately 200 plants in late autumn 2019. Weed management and site maintenance has continued through spring-summer of 2019-2020.

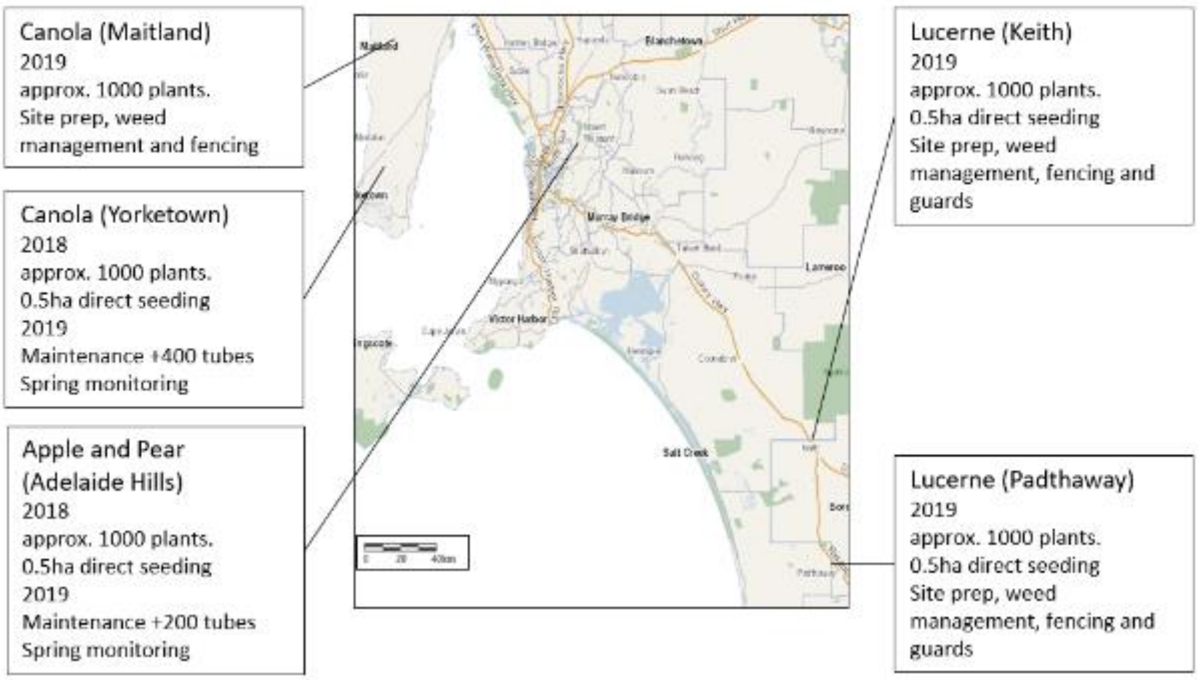


Figure 44. Pollinator habitat developed by the project in apple, canola and lucerne agricultural regions of South Australia

Photographic impression of planting days (all photos: Nick Gellie)

Adelaide hills (apple) 2018

Yorke Peninsula (canola) 2018

Padthaway (lucerne) 2019


Keith (lucerne) 2019


Maitland (canola) 2019

Direct seeding

In addition to tube-stock planting, direct seeding was undertaken by our industry partners Trees for Life on Yorke Peninsula (Yorketown - canola) and in the Adelaide Hills (Forest Range - apple). Greening Australia provided the direct seeding on the two south east properties. The direct seeding incorporated 1.5km of mid-story hedgerow direct-seeding distributed in rows. Due to the dry summer of 2018, the direct seeding of 2018 did not establish in the first year, however seeds can remain viable in the soil seedbank until conditions become more favourable for germination, which has happened in spring 2020. Upon consulting with Trees for Life, about the lack of results, we were informed that it had been a particularly bad year for direct seeding due to the lack of spring rains and the dry summer. Due to COVID-19 and budget restrictions, reseeding in 2020 was not feasible.

*A second property in the Apple region of the Adelaide hills had been tabled as a site for tubestock planting in 2020. Both COVID-19 and the fact that this site was affected by fire in late 2019, made involvement of volunteers in a May 2020 planting day unfeasible.

Planting Site at Yorke Peninsula May 2019 (above) and October 2019 (below).

“Nick and crew did a fantastic job in planting out 1000 different tubestock plants. We’ve had great establishment. Plants have flowered this past spring and the planting has motivated me to continue to plant out that section of scrub. If you are ever over this way, you really should call in to have a look.”

Jane Greenslade, Farmer, Maitland SA

4. Contribution to program objectives

4.1 The extent to which the activity achieved the project objective

This project developed a wealth of knowledge about the pollinator species of 11 crops, their regional distribution, and importance for pollination. In addition, it developed tools to identify pollinators and their food plants, to design plantings for pollinators and estimate the returns on investment from revegetation.

We have engaged with the industry organisations to deliver this information to the apple, berry, lucerne, apple, mango and almond industry, with a specific focus on regional area or areas for each industry (Figure 2. Project map. Map of project activities and crops, and involvement of different research teams. Research teams included UNE: University of New England; Sydney: University of Sydney; ANU: Australian National University; Adelaide: The University of Adelaide. The latitudes and longitudes of the 82 farms involved in this project can be found in the Appendix, which is made available by AgriFutures upon request.

Workshops, field walks and planting days have been held to identify and assemble specific actual and prospective outcome and impact information from the selected regional industries. Personnel from relevant natural resource management agencies in the specific region have been included in such workshops.

We have developed demonstration plantings at five farms in three regions for three crops with several cropping farmers in specific regions. Through interaction with the growers and growers organisation, we have developed a web-based tool that allow designing a revegetation strategy with co-benefits.

4.2 How the project contributes to the achievement of the overall program objective

The objective of the program was to design management strategies that increase pollination security, that will provide a resilient pollination portfolio, ensuring ongoing productivity and profitability for primary producers of pollination dependent crops.

The project has delivered what it set out to do. It has identified the main crop pollinators, evaluated the threats that crop pollination services are exposed to, investigated ways to manage these threats and increase pollination security, through protection and enhancement of nesting opportunities and floral support in the landscape, and delivered the tools to do this to individual growers and grower organisations. The project has:

- **Generated knowledge that benefits primary producers:**

  The project has generated a wealth of knowledge and tools to identify pollinators and their food, to design plantings, and calculate the potential revenue from investment from plantings for pollinators.

- **Strengthened pathways to extend the results of rural R&D, including understanding the barriers to adoption:**

The pathways for extension of the results were strengthened through the engagement with individual farmers, grower organisations, the general public, via a large number of outputs including mainstream media (radio, television, newspaper articles) on-line media (blogs and websites), contributions to industry newsletters, the creation of factsheets, videos, and web-based tools (see Chapter 6).

Plantings for pollination benefits alone are unlikely to be economically feasible, and this could be a barrier to adoption. However, the benefits from plantings are not restricted to pollination but include other ecosystem services, such as reduction in soil salinity, increased biological control, providing barriers to snails, improved soil aeration, erosion control and carbon credits. In addition to these ecosystem services, plantings for pollinators result in biodiversity benefits, which may be more difficult to capture in monetary terms, but that does not diminish its value.

These important ecosystem services, their interactions with the landscape and the combined benefits of interventions require further study. Increased evidence-based support for the role of the landscape and of interventions, such as plantings and provision of nesting substrate, could help to remove some of the existing economic barriers to adoption. Further adoption can be encouraged using incentives for farmers to protect native habitat and support its function, as is current practice in Europe and the USA.

- **Established and fostered industry and research collaborations that form the basis for ongoing innovation and growth of Australian agriculture:**

  We have built on this project by developing novel research collaborations that aim to improve the pollination outcomes for Australian pollination dependent crops, specifically by engaging in a new R&D for profit project on pollination in protected cropping (UNE and UoA), by collating results from work for the CRC for Honey bee Products with the outcomes of the current project.

  We fostered collaboration between primary industry organisations (beekeeping, almond, berries, apple & pear, lucerne canola, mango and watermelon), governmental departments of primary industries and the environments, NGOs delivering revegetation, and sustainable agriculture officers, by combining their inputs and capabilities in structuring and delivering the outcomes and outputs.

4.3 How the project recommendations improve pollination security and resilience

The project has provided a foundation for pollinator dependent industries to strengthen pollination security and resilience and optimise yield by identifying and demonstrating the insects that contribute to crop pollination and the way they relate to the landscape. This in turn has allowed the team to pinpoint revegetation strategies to support pollinator food and nesting resource needs. Primary producers that follow the advice formulated in this report should reap the benefits in increased pollination security. Innovative technologies and proven communication pathways have been used to facilitate adoption (Plant selector, Pollin8, newsletters, leaflets, contributions to blogs and social media, see Chapter 6 Extension and adoption activities).

As explained above, pollination benefits alone are unlikely to provide a return on investment for plantings. However, the associated biodiversity and ecosystem service benefits should be considered. Research is needed to investigate how the co-benefits stack up against the investments. As it stands, this project has identified correlations between the landscape and crop pollination services. The outcomes suggest that providing more landscape support will lead to increased pollinator diversity and numbers. Therefore, both protection of existing landscape support as well as plantings and provision of nesting substrate, increase the resilience and security of pollination services.

5. Collaboration

Early in the project, the researchers from the University of Adelaide established a steering committee in which all industry bodies (Almond Board, Canola growers, Lucerne Australia, Apple & Pear Growers Association SA, SA Apiarist Association), NGOs (Trees for Life, Greening Australia), and governmental organisations (NRM boards, Primary Industries and Regions SA, Department of Environment) and O'Connor NRM were represented. The South Australian steering committee met twice per year to present and discuss the progress. Meetings were very well attended and were held just before milestone reports were due to make sure the partners had an input in the reporting, and were fully up to date.

These collaborations will help greatly with the uptake of the project, because all the partners and industry representatives have been involved in developing the outcomes and outputs from the start. The project made connections between primary industries and environmental organisations by inviting them to exchange ideas. The individual researchers that were involved in the project have on-going collaborations with all of the partners involved (Hogendoorn with all of the industry partners, Lowe with NRM boards – now landscape boards, the department of Environment and Water and PIRSA, O'Connor with Greening Australia and Trees for Life, Gellie with Trees for Life and Groom with the Department of Primary Industries).

Members of the UoA research team have collaborated with a group of SA researchers that investigate ecosystem services (including pollination) as co-benefits of carbon sequestration ("Goyder project"). We are combining with this group to explore the INVEST model, which will be part of the Pollin8 tool to aid growers in exploring their farm and planning interventions for pollination services.

Our collaborations are leading to a barcode database for all Australian bees, not only of the bees on crops (funded by and output of this project), but country-wide of bees caught during various PhD projects, and during Bush Blitzes.

To take this further, we engage with other bee specialists in a country-wide bee genomics workshop. This will lead to a white paper that will outline the way forward, and with Taxonomy Australia and the Wheen Bee Foundation to explore funding to finish this project within five years.

The ANU research team is currently working with Victorian berry growers, local government, and the Wheen Bee Foundation with the goal of establishing a next phase project on native bees in peri-urban horticulture. An early target for funding with be the Australian Research Council's Linkage Program.

The University of Adelaide, has collaborated with the University of Sydney in assessing honey bee hive densities has this has resulted in an honours project. ANU, UNE and UoA have collaborated to draw together the observations of bees on apple and their relation to the landscape.

As a consequence of the project, problems with pollination in protected cropping have come to the fore, and researchers of UNE and UoA have been successful in obtaining funding through DAWE R&D for profit program to address these issues.

All project partners have collaborated to develop a guide to bees in crops as a major project output.

Cash contributors included: The University of Adelaide, UoA's Environment Institute, UoA's Waite Institute, APGASA, Trees for Life, DEW, PIRSA, O'Connor NRM, Greening Australia and Hort Innovation.

In kind contributors were: The University of Adelaide, APGASA, Trees for Life, DEW, PIRSA, O'Connor NRM, Greening Australia, SA Apiarist Association, Almond board, Greening Australia, AEKOS/TERN, Northern & York NRM.

Research Partners were University of Adelaide, University of New England, University of Sydney, Australian National University.

6. Extension and adoption activities

Broadcast media:

- 5/12/2016 Live Radio (ABC Port Pirie) Hogendoorn interviewed about the importance of food for bees (10 minutes). Increased awareness of the importance of bee food in the landscape.
- 27/03/2017 Live Radio (ABC Riverland) Hogendoorn interviewed about the importance of food for bees (10 minutes). Increased awareness of the importance of bee food in the landscape.
- 02/04/2017 Live Radio (Radio Adelaide) Hogendoorn interviewed about the importance bees (30 minutes). Increased awareness of the importance of bee food in the landscape.
- 07/09/2017 Live Radio (ABC Adelaide) broadcast of Hogendoorn's talk about the importance of bee food at the royal show (15 minutes. Increased awareness of the importance of bee food in gardens.)
- 10/12/2017 Live Radio (Radio Adelaide) Hogendoorn interviewed about the importance bees (16 minutes) https://radioadelaide.org.au/2017/12/10/bees-trees-and-all-of-us/. Increased awareness of the importance of bee food in the landscape.
- 17/02/2018 television (Channel 10: Scope) Hogendoorn interviewed about the apple pollination (10 minutes). Raised awareness among children about the importance of insects for apple pollination and flowers for bees.
- 16/05/2018/ television (Channel 9 Weather cross) Hogendoorn interviewed about the importance bees . Raised general awareness.
- July 2018 Live Radio (ABC Nightlife) and talk back Saul Cunningham for 50 minutes (national show broadcast on ABC Local) https://www.abc.net.au/radio/programs/nightlife/the-latest-buzz-about-bees/9941370
- 21/07/2018 ABC rural news) The importance of food support in the landscape for almond pollinating honey bees. http://www.abc.net.au/news/rural/2018-07-19/beekeepers-call-for-more-forage-as-almond-boom-continues/10008254 Increased awareness that the landscape needs to be able to support bees, and provide a healthy diet.
- 02/09/2018 Live Radio (ABC Adelaide) broadcast of Hogendoorn's talk about the importance of bee food at the royal show (15 minutes). Increased awareness of the importance of bee food for food production.
- 05/09/2018 Live Radio (ABC Adelaide) Hogendoorn panel discussion about the importance of bee food at the royal show (20 minutes), Raised awareness of insects other than honey bees for crop pollination.
- 09/09/2018 Live Radio (ABC Adelaide) broadcast of Hogendoorn's talk about the importance of bee food at the royal show (15 minutes). Increased awareness of the importance of bees for food production and bee food in gardens.
- 25/11/2018 television (Channel 10: Scope) Elisabeth Williamson talks about feral honey bees and demonstrates drone capture (10 minutes). Raised awareness of the role of feral honey bees, and the importance of large *Eucalyptus* trees.
- 30/4/2019 Live Radio (ABC radio National: Big Ideas) Hogendoorn's presentation 'Bringing back the bees (54 minutes). Explaining what bee species are endangered and why people should care. https://www.abc.net.au/radionational/programs/bigideas/bringing-back-the-bees/11048898
- 2019 television (ABC Catalyst) (ABC TV) Tanya Latty co-hosted two episodes of' 'The great Australian bee challenge' focusing on bees and beekeeping. This program provided basic knowledge about pollination, bee biology and beekeeping.
- 25/5/2019 Romina Rader Radio interview on the key role of insects in pollination: https://www.abc.net.au/radionational/programs/scienceshow/the-key-role-of-insects-in-crop-pollination/11147648
- 7/5/2019 SBS news coverage of biodiversity extinction report (https://www.sbs.com.au/news/millions-of-animals-are-facing-extinction-here-s-what-you-can-do-

to-prevent-it). Saul Cunningham quoted regarding agricultural practice and farm chemicals as a consideration – article also mentions loss of bees as crop pollinators (Extinction.pdf)

- October 2019 "Outstanding in the Paddock" A presentation on the value of paddock trees, including the habitat they provide to support crop pollinating bees. Also on WIN News regionally (win news.wmv) though no mention of bees in the clip) 50 people present at the forum, from Shepparton region including farmers and land managers (CMA, DeLWP, Vic Dept Ag)
- November 2019 Prof Cunningham appeared on Brisbane Radio Local ABC radio, Saturday Breakfast show. A 12 minute interview on the role of bees in food production in Australia (https://soundcloud.com/anufennerschool/saul-cunningham-bees-abc-brisbane-saturday-breakfast)
- 7 and 9/02/ 2020 television (ABC Gardening Australia) Katja Hogendoorn about the importance of bee food https://www.abc.net.au/gardening/factsheets/bee-bnb/11943376
- 12/3/2020 Radio (ABC Radio National Late Night Live – Philip Adams) O'Connor, on 'The politics of trees' online audio https://www.abc.net.au/radionational/programs/latenightlive/the-politics-of-trees/12047342
- May-2020 television (ABC) Tanya Latty interviewed for World Bee Day
- 12/7/2020 radio (Australian Film, Television and Radio, School's radio show 'The World Around You') Michael J Holmes discussed pollination

General interest print media

- 25/05/2018 Article in the Barossa Herald Revegetation for pollinators https://www.barossaherald.com.au/story/5429657/plant-more-native-vegetation
- 9/08/2018 Article in the Yorke Peninsula Courier times to raise interest for plantings among YP farmers
- 2/08/2018 Article in the Stock Journal to announce the project
- 29/1/2019 Tanya Latty:' Native bees are powerful pollinators, and there's a simple way to help them'. ABC's Catalyst https://www.abc.net.au/news/science/2019-01-29/merits-of-native-bees-can-they-save-us/10749696
- 16/6/2019 Sunday Herald Sun (Saul Cunningham contributes to article on food and bee pollination in the lifestyle section, 16 June)
- 12/6/2019 Coffs Harbour Advocate "Working to save our bees"
- 14/6/2019 Daily Examiner, Grafton " Working to keep bees on the job"
- 12/1-/2019 The Australian newspaper https://www.theaustralian.com.au/nation/sting-in-the-tale-of-bees-in-crisis/news-story/a1ff7f75bd8106a62cf711ae51590f8f

Industry newsletter contributions

- March 2016. Willcox, B., Robson, A., and Rader, R and Howlett, B. Mango Matters, newsletter of the Australian Mango Industry Association, "Tree characteristics and pollination services", March 2016 issue https://www.industry.mangoes.net.au/resource-collection/2016/3/6/pollination
- July 2017. Willcox, B., Robson, A., Rader, R and Howlett, B. (2017). Can we increase avocado production via pollination? Talking Avocados Magazine, Winter 2017.
- March 2018 Hogendoorn, Spronk, Guerin, O'Connor and Lowe newsletter article for 'Around the orchard' (APGASA) 'Food for thought' 53 apple growers
- 2018 Kendall, L. and Rader, R (2018). Wild pollinators in blueberry orchards. Australian Berry Growers Journal 38, 19-22.
- 2018 Jones, J., Hall, M., Rocchetti M., Dempsey, R., Wright, D., and Rader, R. (2018). The behaviour and movement of insect pollinators visiting blueberry plants. Australian Berry Growers' Journal. 40, 22-25
- August 2019 Rader Good Fruit and Vegetables.com.au bees important to pollination
- 2019: Hall, M., Rocchetti M., Wright, D., and Rader, R. (2019). Bees visit less in the middle of poly-tunnels. Protected Cropping Australia Industry Trade Magazine, "Soilless Australia"

- March 2020 Hogendoorn, Gellie, Lowe newsletter article for 'Around the orchard' (APGASA) 'Food for bees https://apgasa.com/wp-content/uploads/2020/03/Newsletter-March-2020-Screen.pdf 53 apple growers
- 2020 Michael J Holmes The Cross-Pollinator (Australian Native Bee Association's monthly newsletter)
- 2020 Michael J Holmes How is Varroa like COVID-19? https://extensionaus.com.au/professionalbeekeepers/how-is-varroa-like-covid-19/
- 2020 Michael J Holmes Should growers pay for pollination services? https://extensionaus.com.au/professionalbeekeepers/should-growers-pay-for-pollination-services/
- 2020 Patsavee Utaipanon Is one food source good enough? Effects of monoculture on honey bees. https://extensionaus.com.au/professionalbeekeepers/is-one-food-source-good-enough-effects-of-monoculture-on-honey-bees/
- June 2020 Hogendoorn and Groom Newsletter article Lucerne leader :Bee snippet
- September 2020 Hogendoorn and Groom Newsletter article Lucerne leader :Bee snippet
- December 2020 Hogendoorn and Groom Newsletter article Lucerne leader :Bee snippet
- December 2020 Hogendoorn, Groom and Lowe article for The Australian fruit grower (APAL) https://apal.org.au/volunteers-in-the-orchard-and-how-to-look-after-them
- January 2021 Erandi Wijesinghe, Lisa Evans, Brian Cutting, Mathew Keir and Romina Rader. Honeybees and other insects visit watermelon flowers in Australia. Australian Melon Growers newsletter.

Fact sheets

- Rader, Cunningham, Hogendoorn – Know your bees: Crop pollinator guide for eastern Australia
- Brown and Cunningham - Native pollinators in *Rubus* (available here: https://fennerschool.anu.edu.au/research/projects/healthy-pollinators-healthy-food)
- Hogendoorn, PIRSA – Strategies to increase almond pollination in South Australia. Factsheet to direct SA almond growers to the plant selector at https://pollin8.org.au/;
- Hogendoorn, PIRSA – Strategies to increase canola pollination in South Australia. Factsheet to direct SA canola growers to the plant selector at https://pollin8.org.au/;
- Hogendoorn, PIRSA – Strategies to increase lucerne pollination in South Australia. Factsheet to direct SA lucerne growers to the plant selector at https://pollin8.org.au/;
- Hogendoorn, PIRSA – Strategies to increase apple pollination in South Australia. Factsheet to direct SA apple growers to the plant selector at https://pollin8.org.au/;
- Rader, Pollinators in Mango orchards, Mareeba, QLD.
- Rader, Pollinators in Watermelon, Riverina region, NSW
- Rader, Pollinators in apple orchards, Stanthorpe, QLD
- Rader, Native bees in blueberry, Coffs Harbour, NSW

Web content

- Rader, R., Saunders, M., Cunningham, S. Not just bees: the buzz on our other vital insect helpers. Article for The Conversation. Released online January 26, 2016 https://theconversation.com/not-just-bees-the-buzz-on-our-other-vital-insect-helpers-52373
- 30/3/2017 Farm Online interview with Katja Hogendoorn and Andy Lowe about the project https://www.farmonline.com.au/story/4559938/hope-for-native-bees-blooms-as-varroa-mite-looms/
- 15/10/2018 Rader and Cunningham ABC Fact check: Is two-thirds of Australia's food production reliant on bee pollination?https://www.abc.net.au/news/2018-10-15/fact-check-honey-bee-pollination/10365750
- 2018 Varroa threat to bees and pollination - Farm Biosecurity, web site news article (https://www.farmbiosecurity.com.au/varroa-threat-to-bees-and-pollination/), (Varroa threat to bees and pollination - Farm Biosecurity.pdf)
- 2018 – 2020: https://polli2017.wordpress.com Blog for lucerne growers: the wild pollinators of lucerne
- 2018 project web-page SA https://www.adelaide.edu.au/waite-research-institute/our-research/secure-pollination-through-revegetation July 2019 Story in GrainCentral.com "Why aren't bees all the buzz in broadacre crop pollination?" (https://www.graincentral.com/cropping/why-arent-bees-all-the-buzz-in-broadacre-crop-pollination/) (Why aren't bees all the buzz in broadacre crop pollination_ - Grain Central.pdf)

- 5/2/19 Adrian Dyer and Tanya Latty: Our 'bee-eye camera' helps us support bees, grow food and protect the environment. https://theconversation.com/our-bee-eye-camera-helps-us-support-bees-grow-food-and-protect-the-environment-110022
- 31-Dec-19 Manu Saunders, Tanya Latty, Tobias Smith, Mark Hall, Callum McKercher Aussie scientists need your help keeping track of bees. https://theconversation.com/aussie-scientists-need-your-help-keeping-track-of-bees-please-128932
- 5/12/2019 Yeates, Hogendoorn, Saunders. Scientist fear insect populations are shrinking. Here are six ways to help. https://theconversation.com/scientists-fear-insect-populations-are-shrinking-here-are-six-ways-to-help-128213
- 2020 Tanya Latty features on a facebook live event about bees and beekeeping https://www.youtube.com/watch?v=LnjQKHKIJz0
- 2020 https://pollin8.org.au/ contains two project videos, plant selector, planting advice, and calendar

Industry presentations, field days and public presentations

- 21/09/2016 Lowe presented the project at Lucerne Australia workshop in Keith 150 growers
- Oct 2016: Rader presented at the Queensland Entomological Society meeting Brisbane, QLD 1/11/2016 Hogendoorn presented the project at the Beekeepers Society of SA beekeeping industry 80 beekeepers became aware
- 13/02/2017 Steering committee meeting SA : progress presentations to representatives of all stakeholder groups involved (TfL, GA, SAAA, AB, LA, O'Connor NRM, DEW, NRM, PIRSA, APGASA)
- 31/03/2017 Hogendoorn presented at presentation and panel forum discussion at the Northern and Yorke Regional Development Alliance Landcare, 200 land carers, revegetation specialists NRM, State Government organisations and farmers
- May 2017: Rader presented at the Crop Pollination Association Annual Conference Ballina, NSW,
- May 2017: Rader presented at the Australian Mango Growers Association Conference Bowen, QLD
- May 2017: Rader presented at the Apple and Pear Growers Annual National R and D strategy meeting Launceston, TAS
- 6/06/2017 Hogendoorn presented at the SA Apiarist Association bee keeping industry 75 beekeepers became aware
- 28/06/2017 Hogendoorn met with almond board to discuss plantings for bees
- 26/08/2017 Hogendoorn presented a workshop for the Finniss Landcare group. 30 Canola farmers learnt about revegetation for pollinators
- 11/09/2017 Hogendoorn, Gellie and O'Connor led a field day with growers/revegetation specialists. 7 farmers became more aware
- 12/09/2017 Hogendoorn presented on behalf of all SA partners at the SA land care conference and raised awareness of land carers, NRM boards, farmers, State Government 150 people
- Sep 2017: Rader presented at University of the 3rd Age (U3A) Armidale, NSW
- 27/09/2017 Hogendoorn, Gellie and Spronk met with AHMLR NRM and APGASA delegates to discuss revegetation strategies and Ambers results
- Oct 17: Rader presented at the Department of Biology seminar series, University of Queensland Brisbane, QLD
- Oct 17 Liam Kendall presentation at the Australian Native Bee Association meeting Brisbane, QLD
- Oct 2017: Rader presented at Costa Group on pollination in berry crops Guyra, NSW,
- Nov 2017: Rader presented at Ecological Society of Australia postgraduate student day Hunter Valley NSW Honeybee certificate III information day: presentation on why it is important to do bee research
- 2017 Growing Regional Agricultural Science Students (GRASS) science teachers event: UNE – the science of pollination
- Nov 2017 Steering committee meeting SA : progress presentations to representatives of all stakeholder groups involved (TfL, GA, SAAA, AB, LA, O'Connor NRM, DEW, NRM, PIRSA, APGASA)
- 30/11/2017 Hogendoorn presented a community talk Strathalbyn Natural Resource Centre for farmers and gardeners 45 people became more aware of the importance of food for bees
- 5/04/2018 Hogendoorn presented a public talk about plantings for bees for Adelaide City Council 200 members of the general public became more aware of the importance of food for bees. https://www.facebook.com/watch/live/?v=1740848139269215&ref=watch_permalink

- 9/05/2018 Hogendoorn presented at a meeting of the Adelaide Hills and Mount Lofty Revegetation and Sustainable Agriculture officers (40 people)
- 25/05/2018 Steering committee meeting SA : progress presentations to representatives of all stakeholder groups involved (TfL, GA, SAAA, AB, LA, O'Connor NRM, DEW, NRM, PIRSA, APGASA)
- 20/07/2018 Hogendoorn meeting almond board, field day beekeepers almond growers Almond board almond industry beekeepers 25 almond growers and beekeepers
- 21/07/2018 Gellie lead a planting workshop in the Adelaide Hills 1000 bee plants in the ground, fenced, 25 members of the general public became more aware of the importance of food for bees.
- 28/07/2018 Gellie lead a planting workshop Yorketown: 800 bee plants in the ground, 25 members of local community became more aware of the importance of food for bees, fencing provided by farmer
- 12/09/2018 Gellie, Groom and Hogendoorn field walk and presentations for 20 NRM Sustainable Ag officers
- September 2018 Julian Brown Presentation to around 50 apple growers and associates at an APAL orchard walk
- Sept 2018 Brown presented "Pollinators in the paddock" Murrumbidgee Landcare field day, near Junee NSW. Approx. 20 landholders present (also reported in the Junee Southern Cross Newspaper)
- 21/10/2018 Hogendoorn gave a community presentation about revegetation for biodiversity and pollination Marion Bay YP, 60 canola farmers and general public became more aware of the importance of food for bees
- 25/10/2018 Hogendoorn organised a strategic planning meeting with CEO APGASA to plan extension
- August & Sept & Dec 2017 and 2018 Hogendoorn, Gellie and O'Connor had meetings with Trees for Life to discuss revegetation strategies and collaboration strategies
- 1/11/2018 Hogendoorn gave a 'Waite in the spotlight' Ted-Ex talk: What's the buzz about bees in Agriculture? UoA https://www.youtube.com/watch?v=EymufHxUyqU 150 members of the general public became aware of the issues with farmland biodiversity conservation
- 4/11/2018 Hogendoorn gave a community presentation at the Uraidla sustainability fair 50 land care and farm workers became more aware of the importance of revegetation
- Nov 2018: Steering committee meeting SA : progress presentations to representatives of all stakeholder groups involved (TfL, GA, SAAA, AB, LA, O'Connor NRM, DEW, NRM, PIRSA, APGASA)
- 7/12/2018 Gellie gave a presentation at a Farmer meeting for revegetation in Yorke Peninsula. 20 Canola growers became aware of the revegetation project
- 5/03/2019 Hogendoorn gave a presentation Barossa nursery 'Food Plants for bees' 30 land care managers became more aware
- 5/04/2019 Hogendoorn gave a presentation at the Ag Excellence alliance forum Maintaining bees and pollinations: 80 canola farmers form Yorke and Eyre Peninsula
- 9/04/2019 Hogendoorn presented at UoAs Research Tuesdays: 'The buzz about bees: Are bees in decline and what can we do about it?' https://www.youtube.com/playlist?list=PLrj2iJKdUdbwQleoFrMCh-Hw1tXUQboHi , 600 general public became more aware (plus 7,967 views on 1/2/2021)
- 14/04/2019 Hogendoorn gave a presentation at the Australian Plant Society fair about plantings for bees 50 gardeners became more aware
- 23/04/2019 Hogendoorn gave a presentation at the Orchid Society about plantings for bees 30 gardeners became more aware
- 5/05/2019 Hogendoorn gave a workshop on native bees at Grey box day, Community talks about plantings for bees and handout new leaflet. 150 gardeners became more aware
- 8/05/2019 Hogendoorn gave a talk at annual meeting Riverland Almond Growers and South Australian Apiarists, 40 participants became aware of the potential to plant for bees
- 24-25 May 2019 Ben Oldroyd invited presentation 'Mating biology and weird sex in bees.' Conference of the Bee Industry Council of Western Australia Perth WA
- 24-25 May 2019 Katja Hogendoorn Invited talk West Australian Beekeepers Association Plantings for crop pollinators: What's in it for the honey bee industry? Conference of the Bee Industry Council of Western Australia Perth WA May 2019

Presentation by Saul Cunningham in Bermagui, regarding the crop pollination by bees in Australia. Approx. 100 in attendance https://www.facebook.com/permalink.php?id=395534233846880&story_fbid=2385282804872003

- May 2019 Steering committee meeting SA : progress presentations to representatives of all stakeholder groups involved (TfL, GA, SAAA, AB, LA, O'Connor NRM, DEW, NRM, PIRSA, APGASA)
- Development of a song about wild pollinating insects see link on Raderlab.com.au
  - For World Bee Day in 2019, participation in a public scientific panel discussion at Parliament House in Canberra by the Embassy of Switzerland.
  - For World Bee Day in 2020, contribution to a video on behalf of Australia's peak horticultural industry body, Horticulture Innovation Australia
- 15/6/2019 Ben Oldroyd presents an invited talk titled Queens, drones and what they get up tofor the Victoria Association of Bee Clubs
- August 2019 Julian Brown and Katja Hogendoorn presented on "Native bees as potential crop pollinators, nesting substrate and habitat needs" for 3 Forums across eastern Victoria, attended by 250 farmers (organized by Port Phillip and Westernport CMA) https://www.ppwcma.vic.gov.au/native-bees-are-the-bees-knees-of-australian-ecosystems/ One apple grower has installed 1,000 artificial reed bee nests (bundles of bamboo) after learning from us that the bees visiting his apples might colonize these nests.
- October 2019 "Outstanding in the Paddock" A presentation on the value of paddock trees, including the habitat they provide to support crop pollinating bees. Also on WIN News regionally (win news.wmv) though no mention of bees in the clip) 50 people present at the forum, from Shepparton region including farmers and land managers (CMA, DeLWP, Vic Dept Ag)
- November 2017: Hogendoorn presented at the Apple and Pear Growers Annual National R and D strategy meeting Melbourne VIC
- 20/11/2019 SA science team presented at the Steering committee stakeholder meeting and had round-table on extension materials. Active involvement from all stakeholder groups
- February 2020 "Climate Variability and Pollinators" Prof Cunningham, invited presentation. Public Event at the Australian National Botanic Gardens, with Costa Georgiadis making a special appearance
- August 2020 Prof Cunningham delivers an on-line presentation on Bees and Pollination, including answering the questions of people in the Indigo Shire, Victoria (a Science Week event: https://www.indigoshire.vic.gov.au/Latest-news/National-Science-Week-2020)
- 8/8/2020 Hogendoorn and Groom organised a workshop for SA Apple growers workshop in Lenswood to present results, together with APGASA (30 growers attended).
- September 2020 Prof Cunningham delivers an on-line webinar on bees and crop pollination, for an event organized by the Sustainable Farms project (https://www.sustainablefarms.org.au/)
- 23 September 2020 Tanya Latty presents an invited public talk titled 'Bees in the city: toward pollinator friendly urban agriculture' University of Sydney https://youtu.be/RLJr3YzCy5A
- November 2020 Julian Brown and Saul Cunningham present in the "Wild Pollinators" webinar, Organised by Landcare with the Port Phillip and Westernport CMA

Scientific conferences

- 14/04/2018 Hogendoorn presented at the DEWNR NRM Science Conference 150 Government, scientist
- 1/7/2018 Saul Cunningham presented a keynote presentation at the Third Australian Bee Congress, Gold Coast, Queensland.
- 1/7/2018 July 2018 Hogendoorn presented a keynote presentation 'Tailoring revegetation to enhance crop pollination: timing, rewards and crop rotations' at the Third Australian Bee Congress, Gold Coast, Queensland.
- 1/7/2018 July 2018 Lowe presented a keynote presentation 'Working with native habitat to improve pollinator services' at the Third Australian Bee Congress, Gold Coast, Queensland
- 2/7/2018 July 2018 Lowe presented a keynote presentation 'Working with native habitat to improve pollinator services' at the Third Australian Bee Congress, Gold Coast, Queensland

- Plant pollination networks - DNA barcoding applications
- 2/7/2018 Julian Brown presented project findings from our first year of data collection at the 1st Australian Native Bee Conference, Gold Coast, July 2018.
- Sep 2018, Akankunda presentation in Australia for the Australian Entomological Society Alice Springs
- Sep 2018, Hogendoorn presentation in Australia for the Australian Entomological Society Alice Springs
- Nov 2018 Saul Cunningham delivered a Keynote presentation in a conference "Understanding the causes of low pollination in crops" Apimondia Symposium, Addis Ababa, Ethiopia (invited, *paid by conference host*) Approx. 500 international delegates present
- May 2019 Saul Cunningham delivered an Invited presentation at the Colombian Academy of Science (Bogota). "Plant reproductive Ecology, meet modern agriculture" (approx. 150 people)
- Jul 2019 Organiser of pollination session: Protected Cropping Conference, Gold Coast, Australia.
- Jul 2019 Rader invited presentation at the International Pollination conference UC Davis, USA
- Jul 2019 Hogendoorn presentation at the International Pollination conference UC Davis, USA
- Jul 2019 Groom presentation at the International Pollination conference UC Davis, USA
- Dec 2019, invited plenary presentation in Australia for the Australian Entomological Society https://www.aesconferences.com.au/2019-conference/keynote-invited-speakers-2019/
- Dec 2019, Groom presentation in Australia for the Australian Entomological Society Brisbane
- Dec 2019, Williamson presentation in Australia for the Australian Entomological Society Brisbane
- Dec 2019, Kireta presentation in Australia for the Australian Entomological Society Brisbane
- Dec 2019, Kireta presentation in Australia for the Metagenomics workshop at the Australian native bee conference Brisbane QLD
- Dec 2019, Kireta presentation in Australia for the Metagenomics workshop at the Australian native bee conference Brisbane QLD
- Dec 2019, Hogendoorn presentation in Australia for the Metagenomics workshop at the Australian native bee conference Brisbane QLD
- Dec 2019, Cunningham presentation in Australia for the Metagenomics workshop at the Australian native bee conference Brisbane QLD
- Dec 2019, van Dijk presentation in Australia for the Metagenomics workshop at the Australian native bee conference Brisbane QLD
- Dec 2019, Leijs presentation in Australia for the Metagenomics workshop at the Australian native bee conference Brisbane QLD
- Jul 2018 Invited presentation on honeybee crop pollination for the National Australian Bee Congress

Scientific publications

Akankunda T., To H., Rodriguez Lopez C., Leijs R., Hogendoorn K., 2020. A method to generate multilocus barcodes of pinned insect specimens using MiSeq. Molecular ecology resources. 20 (3):692-705.

Brown J, Barton PS, Cunningham SA. Flower visitation and land cover associations of above ground-and below ground-nesting native bees in an agricultural region of south-east Australia. Agriculture, Ecosystems & Environment. 2020 Jun 15;295:106895.

Cook DF, SC Voss, JTD Finch, RC Rader, JM Cook, CJ Spurr 2020. 'The role of flies as pollinators of horticultural crops: An Australian case study with worldwide relevance' Insects 11 (6), 341

Dainese, Matteo, et al. 2019. 'A global synthesis reveals biodiversity-mediated benefits for crop production', Science Advances (2019) Vol. 5, no. 10, eaax0121

Dormontt EE, Van Dijk KJ, Bell KL, Biffin E, Breed MF, Byrne M, Caddy-Retalic S, Encinas-Viso F, Nevill PG, Shapcott A, Young JM., 2018. Advancing DNA barcoding and metabarcoding applications for plants requires systematic analysis of herbarium collections—an Australian perspective. Frontiers in Ecology and Evolution. 13;6:134.

Garcia Bulle Bueno F., R. Gloag, T. Latty, I. Ronai. 2020. Irreversible sterility of workers and high-volume egg production by queens in the stingless bee *Tetragonula carbonaria*. Experimental Biology. Issue 223, Volume 18, jeb230599

Hall Mark A, Jeremy Jones, Maurizio Rocchetti, Derek Wright & Romina Rader 2020, ‘Bee Visitation and Fruit Quality in Berries Under Protected Cropping Vary Along the Length of Polytunnels’, Journal of Economic Entomology, vol. 113, no. 3, pp. 1337–1346, doi:10.1093/jee/toaa037

Kendall Liam K., Vesna Gagic, Lisa J. Evans, Brian T. Cutting & Jessica Scalzo et al. 2020, ‘Self-compatible blueberry cultivars require fewer floral visits to maximize fruit production than a partially self-incompatible cultivar’, Journal of Applied Ecology, doi:10.1111/1365-2664.13751

Rader, R, SA Cunningham, BG Howlett, and DW Inouye. 2020. 'Non-Bee Insects as Visitors and Pollinators of Crops: Biology, Ecology and Management', Annual Review of Entomology, vol. 65, no. 1, pp. 391–407, doi:10.1146/annurev-ento-011019-025055

Stavert Jamie R, Charlie Bailey, Lindsey Kirkland & Romina Rader 2020, ‘Pollen tube growth from multiple pollinator visits more accurately quantifies pollinator performance and plant reproduction’, Scientific Reports, vol. 10, no. 1, doi:10.1038/s41598-020-73637-5

Utaipanon P, Holmes MJ, Buchmann G, Oldroyd BP. 2021. Split or combine? Effects of repeated sampling and data pooling on the estimation of colony numbers obtained from drone genotyping. Apidologie, Under review. -..

Utaipanon P, Schaerf TM, Holmes MJ, Chapman NC, Oldroyd BP. 2021. Using trapped drones to assess the density of honey bee colonies — a simulation and empirical study to evaluate the accuracy of the method. Ecological Entomology, 46, 128–137.

Utaipanon, P., Holmes, M. J. and Chapman, N. C., 2019. Estimating the density of honey bee (*Apis mellifera*) colonies using trapped drones: area sampled and drone mating flight distance. Apidologie vol 50, page 578–592.

Utaipanon, P., Holmes, M. J. and Oldroyd, B. P., 2019. Queenless colonies contribute to the male breeding population at honey bee drone congregation areas. Insectes Sociaux vol 66, page 593–599.

Utaipanon, P., Schaerf, T. M. and Oldroyd, B. P. 2019. Assessing the density of honey bee colonies at ecosystem scales. Ecological Entomology volume 44, page 291–304.

Vesna Gagic, Lindsey Kirkland, Liam K. Kendall, Jeremy Jones, Jeffrey Kirkland et al. and Romina Rader 2020, ‘Understanding pollinator foraging behaviour and transition rates between flowers is important to maximize seed set in hybrid crops’, Apidologie, doi:10.1007/s13592-020- 00800-2

Wijesinghe S.A.E.C., L.J. Evans, L. Kirkland & R. Rader 2020, ‘A global review of watermelon pollination biology and ecology: The increasing importance of seedless cultivars’, Scientia Horticulturae, vol. 271, pp. 109493, doi:10.1016/j.scienta.2020.109493

Willcox, Bryony K, Brad G Howlett, Andrew J Robson, Brian Cutting, Lisa Evans, Linley Jesson, Lindsey Kirkland, Malou Jean-Meyzonnier, Victoria Potdevin, Manu E Saunders, and R Rader. 2019. 'Evaluating the taxa that provide shared pollination services across multiple crops and regions', Scientific Reports, 9: 1-10.

Williamson E., Groom S., Hogendoorn K., 2019. A new method to sample DNA from feral honey bee hives in trees. Transactions of the Royal Society of South Australia 143(1):92-6.

Further adoption can be achieved by funding more research and development in this area, as that keeps growers engaged and informed.

7. Lessons learnt

Governance

UoA has had enthusiastic support and from partner and industry organisations throughout the project. By establishing a steering committee involving all industry partners and stakeholder groups, and meeting twice a year, partners were kept engaged and informed. This input contributed to the outcomes of the project.

Start of the project

The assembly of a science team requires a clear discussion of the collaborations in the sub-projects, and include detailed project design meeting that involves only the researchers.

The milestone dates in the mother contract could be contingent on the date the subcontracts have been signed off, otherwise KPIs cannot be met and there is a setback from the start.

Media attention and communication with stakeholders is highly valuable at the start of a project. This implies that a media strategy needs to be in place at the time the subcontracts have been signed off.

The KPIs need to be designed to fit the pace of the research. In some cases, there cannot be any demonstrable progress until all data are collected.

The terms of reference of the mid-term evaluation need to be clear at the start of the project. They should not include the adoption by growers, as that can realistically only be achieved by the end of a research project (provided this is defined as an outcome or the project), or much later still.

Project meetings and collaboration between the research organisations

A key factor for successful collaboration has been regular, good communication. It is productive to set aside half the time for interactions between the researchers, and half for to presentations to the funding body. This allows researchers to streamline methods and align data, which is needed given the differences in both landscape and species composition between crops and regions, and variations in the focal questions of each research group.

In this context, it is important to find the right balance between increasing the number of collaborating institutions to increase the amount of data available for analysis, and not having too much complexity arising from the need to alter collaborative efforts in order to achieve each collaborator’s independent aims.

Outputs and extension

Successful collaboration to make industry change requires outcomes that can physically be adopted by growers, not those that are optimal or ideal necessarily.

In the last 1.5 year of the project, drought, fires, and COVID-19 have reduced contact with growers and industry representative bodies. Online presentations, newsletter contributions and Zoom meetings have been held but this is not the most effective way of delivering extension, and it does not capture all growers. We will likely need more time to deliver engagement and outreach to ensure it is of the highest quality and accessible to all growers.

Engaging Primary Industries and Regions SA has proven to be a good move in SA, as it has facilitated access to growers’ organisations and increased invites to speak at growers meetings. However, this was impacted by COVID-19.

8. Appendix - additional project information

Project, media and communications material and intellectual property

Include a summary of all material including research papers, journals and/or extension materials and all intellectual property created or arising during the period covered by the project.

All research papers and extension materials are listed in section 6, page 76 and following.

List all media, communications and activities over the life of the project. Where appropriate, photographs of project work should be provided.

Listed on page 76 and following

Imagery should be high resolution (at least 5 megapixels), along with caption and credit information, and description for web accessibility requirements.

Equipment and assets

List of all equipment or assets created or acquired during the period covered by the project.

University of Sydney:

VIOFLO 96, a handheld electronic 96 channel pipette, INTEGRA Bioscience AG, Switzerland

PIPETMAX®, an automated pipetting machine, Gilson, USA

Monitoring and evaluation

Attach the final project evaluation report in line with the project Monitoring and Evaluation plan. This should report on the project's outcomes against the program objective and include quantitative and qualitative information on outcomes achieved and expected.

See Chapter 4 Contribution to program objectives, and refer to Outputs below

Budget

Provide a statement of funds and contributions received and spent.

This will be supplied as a financial report by the different collaborating universities.

If practical, this section may be the final financial report (see grant agreement), containing:

- financial statements for the receipt, holding, expenditure and commitment of the grant, including a full reconciliation against the budget in the grant agreement and statements clearly showing expenditure against the grant

- a report of the receipt of other contributions (including the grantee's contributions), or if other contributions were not received as projected, an explanation of action taken in response to this shortfall
- the interest that the grantee has earned on the grant.

If not practical to satisfy requirements for the final financial report at the time of submitting the final report, please use this section to give a summary statement of the budget for the life of the project and submit the final financial report within 60 days of submitting the final milestone report.

Outputs

Below is the list of outputs as indicated at the start of the project with, briefly, the role of each teams in producing them. The outputs pertaining to the initiation and management of the project have been removed, as they a do not relate to the project.

B3. Communication and extension activities

Output 3(a) – Identify target audiences.

Growers and growers organisations for pollination dependent crops: apple, raspberries, blueberries, mango, watermelon, cherries, canola, lucerne, almonds, the beekeeping industry and industry organisations, organisations involved with revegetation and sustainable agriculture.

Output 3(b) – Implement communication and extension plan, and promote project activities and outcomes at regional and national conferences, workshops and seminars involving 9 crops (almond, Lucerne seed, apple, pear, blueberry, raspberry, mango, melon and canola) and beekeeping industries and the wider community].

The project participants have implemented the communication and extension plan and promoted the project activities and outcomes at all of the above. This is detailed in Section 6 Extension and Adoption Activities.

Output 3(c) – Publish research findings in journals, conference papers, industry publications, RDC publications and websites in a form accessible to producers.

The project participants have published the research findings in 19 scientific publications so far, presented 26 conference papers, produced 17 articles in industry publications, produced this report and 10 fact sheets to be incorporated in RDC publications, produced and contributed to 11 web pages, gave 60 presentations at industry and community meetings, promoted the conference via 24 radio and television appearances and in 8 articles in the general print media. The legacy is available through this report and fact sheets listed in Section 6 – Extension and Adoption Activities.

Output 3 (d) web based information tools (YouTube videos, planting guides) available via industry organisation websites.

We developed three videos, online planting guides, simulation models to investigate costs and benefits of revegetation, and a fact sheet "know your bees", all accessible via links in the Section 6 Extension and Adoption Activities.

Output 3(e) – Develop guidelines for vegetation management that are tailor made for different crops and regions to support the health of honey bees when moving from crop to crop.

Regionally specific planting guides were developed that support the health of native bees as well as honey bees and other crop pollinating insects (see: www.pollin8.or.au/plantings)

Output 3(f) – Develop guidelines to engineer pollinator habitat that are tailor made for different crops and regions, including an 'Ikea Kitchen' farm planning tool.

www.pollin8.org.au allows selection of plants in different cropping areas of SA via the plant selector, taking into account the regionally specific vegetation as well as the annual rainfall patterns. In addition, the website allows farmers to model the effects of pollinator habitat on the bottom line.

Output 3(g) – Develop a pollinator food availability calendar and maps.
The plant selector selects the areas where the beneficial plants occur, and indicates when they flower, so growers can make appropriate choices. See also the fact sheet: Food for native bees in the Adelaide Hills, in which the importance of flowering times is explained. Growers can select their farm on a map to simulate the pollination benefits of revegetating an area over time (See www.pollin8.org.au).

Output 3(h) – Develop factsheets of native pollinators, plant identification and husbandry/cultivation for farmers.
The project has resulted in a combined fact sheet about native pollinators, and what farmers can do to enhance their presence in the crop "Know your bees: Crop pollinator guide for eastern Australia" , as well as guidelines for plantings on www.pollin8.org.au

Output 3(i) – Develop best practice approaches to minimise the agricultural impacts of Varroa mite.
The combined fact sheet (Know your bees: Crop pollinator guide for eastern Australia) includes best practise advice

B4. Assess pollinator density and efficiency

Output 4(a) – Assess pollinator density in all targeted crops.
Pollinator density was assessed in all crops and regions see Section 3.1 Assessing Our Capital: The Crop Pollinators and Section 3.2.a Assessing feral honey bee densities.

Output 4(b) – Conduct pollinator surveys to identify the most effective pollinators
We have done this for the most common pollinators in apple, berries, mango and watermelon, 3.1 Assessing Our Capital: The Crop Pollinators.

Output 4(c) – Assess crop yields relative to observations on pollinator availability.
This has been done in this in apple and lucerne see Section 3.2.b. page 33b. How the landscape supports pollinator abundance, diversity and crop productivity .

Output 4(d) – Aggregate and analyse data from crop yield and pollinator observations.
See Section 3.2.b. page 33b. How the landscape supports pollinator abundance, diversity and crop productivity.

Output 4(e) – Analysis of bee movement and pollination distances
This report including Section 3.2.a Assessing feral honey bee densities and scientific publications (Section 6).

Output 4(f) – Collaborate with beekeepers and growers to develop plans for ongoing improvement of pollination outcomes
South Australian beekeeping industry has been consulted and demonstration sites have been designed in collaboration with growers see Section 3.4.c Demonstration sites.

Output 4(g) – Develop DNA barcoding data base for key pollinators and provide ID service
The database, 'AUSBEES' is a publicly accessible project under the Barcoding of Life Database, and, as a result of this project and collaboration with the SA Museum and Flinders University, now contains 1000 species of bees, including the main crop pollinating species (see Section 3.1.c Identification of Pollinators). A barcode resource for identification of native bees ID service had no future, as some taxonomist do it for free, and is easily achievable by most researchers.

B5. Assess pollinator habitats

Output 5(a) – Assess pollinator habitat for all crops INCLUDING competition/complementarity between crop and other flowers for pollinators
Pollen and nectar collection and surrounding vegetation for apple, lucerne and canola. See Section 3.3.c. - c. The plant species and revegetation strategies that support pollinators.

B6. Establish pollinator habitats

Output 6(a) – Conduct a literature review for flowering information on plants in cropping landscapes.
A literature review was performed for honey bee plants in the South Australia, as well as native bee visitation. The information was incorporated into the planting advice. See Section 3.4.c Demonstrations Sites - Table 6.

Output 6(b) – Establish the critical resources required to support pollinators (native, hive and feral) in the agricultural landscape, in particular vegetation for food and nesting opportunities.
Food plant species, the time they are needed, and nesting requirements were established for honey bees, stingless bees, reed bees, and furrow bees. See Section 3.4 3.4 Advice to enhance pollinators around crops.

Output 6(c) – Establish pollinator habitat around lucerne seed, apple/pear and canola farms to encourage alternative pollinators INCLUDING DEMONSTRATION SITES.
Altogether, five ha of demonstration pollinator habitat has been planted on two lucerne farms, two canola farms and one apple farm. See Section 3.4.c, Demonstration sites.

Output 6(d) – Conduct a conservation (reverse) auction to attract farmers to plant pollinator habitat.
The reverse auction was conducted. See Section 3.3.d.ii, ii Auction and economic framework.

Output 6(e) – Collaborate with cropping farmers who want to adopt landscape management strategies to support better pollination.
Collaboration regarding management strategies to achieve more resilient pollination has been amply provided to the apple, berry, lucerne, almond, mango, watermelon, canola s and beekeeping industry through advice, demonstration sites, at field days, at industry conferences (see Section 3.4 Advice to enhance pollinators around crops pages 60, 65, 76 and following, on advice about nesting substrate, demonstration plantings, and many industry presentations, articles in industry newsletters, workshops field days), and on a personal basis.

Output 6(f) – Develop socioeconomic framework to incentivise landholders to plant and adopt pollinator habitat options
The costs for revegetation for pollinators have been developed, as well as information sheets to make the growers aware of the community and NGO support structures that are available (www.pollin8.org.au/simulation and www.pollin8.org.au/planting).

Output 6(g) – Develop risk framework, including avoidance of perverse outcomes, for pollinator habitat establishment plan
The guidelines for the establishment of pollinator habitat include advice regarding the need to develop strategies to prevent consequences of drought, weeds, rabbit and kangaroo feeding during establishment www.pollin8.org.au/planting and www.pollin8.org.au/science.

Output 6(h) – Establish demonstration sites.
Refer Section 3.4.c Demonstrations Sites

B7. Develop a mobile phone app that provides farmers with look up table of different landscape designs, configurations and ability to support pollinators

Output 7(a) – Develop image learning algorithms for development of the mobile phone app.
See Section 3.1.c Identification of Pollinators - Pollinator app

Output 7(b) – Design mobile phone app (NEW) for easy presentation of field information on likely pollinator species to use for habitat-given location.
See Section 3.1.c Identification of Pollinators - Pollinator app

Output 7(c) – Conduct demonstrations of the mobile phone app with stakeholders.
See Section 3.1.c Identification of Pollinators - Pollinator app

Output 7(d) – Measure and report on the mobile phone app discovery and downloads.
See Section 3.1.c Identification of Pollinators - Pollinator app

Output 7(e) – Develop on-line resource for pollinator habitat info
See Section 3.1.c Identification of Pollinators - Pollinator app.

The plant selector and simulation of the benefits of pollinator habitat are now available (www.pollin8.org.au). This resource can guide the establishment of pollinator habitat in different South Australian cropping areas.

9. References

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A guide to Australian crop pollinating insects

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Saul Cunningham, Tanya Latty, Scott Groom and Jeremy Jones

AgriFutures™ Securing Pollination

Australian Government
Department of Agriculture, Water and the Environment

Know the pollinators in your crops

In Australia, a wide range of native insects provide pollination services to crops.

Many Australian fruit, nut and seed crops benefit from insects pollinating their flowers. Of these insect pollinators, the introduced European honey bees (*Apis mellifera*) are among the most well-known and widely utilised, yet Australia is home to over 1600 species of native bees. Becoming familiar with native bees and other insects that pollinate crops will help to us to provide habitats and resources that support these species into the future.

Native bees that visit and pollinate crops require local nesting opportunities and food. Their nesting habits are diverse. For example, several bee species dig burrows in the ground and need access to open soil, others use narrow crevices, dead hollow canes or beetle bores in dead wood, or they dig their own nest in plant stems or dead branches. Pollen and nectar from flowers are the main food sources for bees, so they benefit from access to a diverse range of flowering plants.

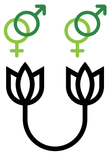
The vast majority of Australian native bees that visit crops are wild bees. Only a very small number are currently managed for crop pollination. In northern parts of Australia, the native stingless bees (*Tetragonula* and *Austroplebia*) are managed and utilised for crop pollination. Hives of these bees can be purchased or hired.

In addition to native bees and honey bees, crops are visited and pollinated by a vast range of other insects including flies, butterflies, moths and beetles. These other species may visit crop flowers more frequently than bees. For example, flies are the most abundant flower visitors in avocado crops in the Sunraysia region (VIC, NSW & SA) and mango crops in the Mareeba region (QLD).

Very little is known about just how important these other insects are to crop pollination, but given their abundance in some regions, more research is required to understand this and the habitats and resources needed to support them.

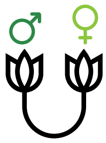
Recent research on Australian crops has shown that many native bees and other insects play an important role in crop pollination.

Plant breeding systems



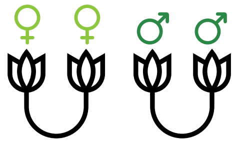
Hermaphrodite

Each plant has individual flowers that are **both** male (produce pollen) and female (produce ovaries). These flowers often require insects to move pollen from the male parts of the flower to the female parts to set fruit. Fruit set can also be limited by the degree of pollen self-compatibility. Examples include blueberry and apple.



Monecious

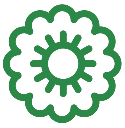
Each plant has individual flowers that are **either** male or female. These flowers often require insects to move pollen from the male flowers that are separate to the female flowers to set fruit. Fruit set can also be limited by the degree of pollen self-compatibility. Examples include watermelon and pumpkin.



Dioecious

Each plant has individual flowers that are **exclusively** either male or female. These flowers often require insects to move pollen from the male plants that are separate to the female plants to set fruit. Examples include kiwifruit and asparagus.

Pollen compatibility

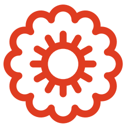


Self-compatible

Pollen self-compatible crops can successfully develop fruit and seeds when the flowers are fertilised with pollen from the **same** flower, plant or cultivar as the mother plant, or other compatible cultivars. The degree of self-compatibility can vary between cultivars. Many cultivars that are self-compatible still show increases in yield and/or fruit quality when cross-pollinated (pollen from a different plant, cultivar or variety).

Cultivar dependent

Different cultivars of the same crop **vary** in the degree of pollen self-compatibility. Some cultivars of a crop may require abundant pollen to be transferred from a different variety to successfully develop fruit and seeds, while other cultivars do not. The degree of cultivar-dependent pollen self-compatibility influences the extent of mixed variety plantings and the number of insect visits required to successfully produce fruit and seeds.



Self-incompatible

Pollen self-incompatible crops only develop fruit and seeds when the flowers are fertilised with pollen from a **different** cultivar to the mother plant. Pollen self-incompatible crops require mixed cultivar planting arrangements and often benefit from a high abundance of insect pollinators to transfer pollen between plants for successful fruit and seed formation.

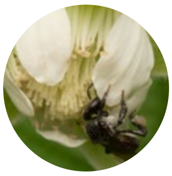
Nectar production

The quantity and quality of nectar a flower produces can influence how attractive the flower is to insect pollinators, as nectar is a major source of energy for many pollinators. The attractiveness of crop flowers to specific pollinators can in turn influence decisions such as hive stocking densities, placement timing and spatial arrangement in order to get the best pollination service to the crop.

Managed pollinators

***Apis mellifera* (European honey bees)**

Social. Present as managed hives or feral colonies that often nest in the hollows of old trees.
Can forage long distances.



***Tetragonula* & *Austroplebeia* spp. (native stingless bees)**

Social. Present as managed hives or wild colonies that often nest in the hollows of old trees. Found in warm areas of northern and eastern Australia.

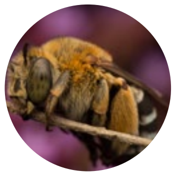
Australian native bee pollinators

***Xylocopa* spp. (Carpenter bees)**

Solitary. Tree nesting
(old, dead, soft timber).

***Leioproctus* spp. (Silk bees)**

Solitary. Ground nesting.

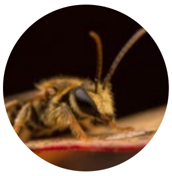


***Amegilla* spp. (Blue-banded bees)**

Solitary, sometimes aggregated.
Ground nesting (clay soil, mudbricks).

***Megachile* spp. (Leafcutter & resin bees)**

Solitary. Nests in the ground, hollow stems, beetle bores
and in narrow crevices.

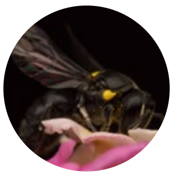


***Lipotriches* spp.**

Solitary or communal, occasionally subsocial. Ground nesting.

***Lasioglossum* spp. (Furrow bees)**

Solitary or communal. Ground nesting.



***Hylaeus* spp. (Masked bees)**

Solitary, sometimes aggregated. Diverse nesting strategies including stems, logs or ground nesting.

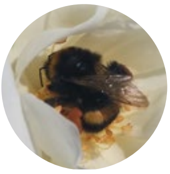
***Exoneura* spp. (Reed bees)**

Solitary, subsocial or social. Only occurs within certain habitats providing nesting resources (for example, dried tree ferns or berry canes).

***Homalictus* spp.**

Solitary or communal. Ground nesting.

Other Exotic Bee species present in Australia



***Bombus* spp. (Bumble bees)**

Social. Present as ground-nesting colonies.Found in Tasmania.

***Apis cerana* (Asian honey bees)**

Social. Present as colonies that often nest in the hollows of old trees.Found in Far North Queensland.

Bee Terms:

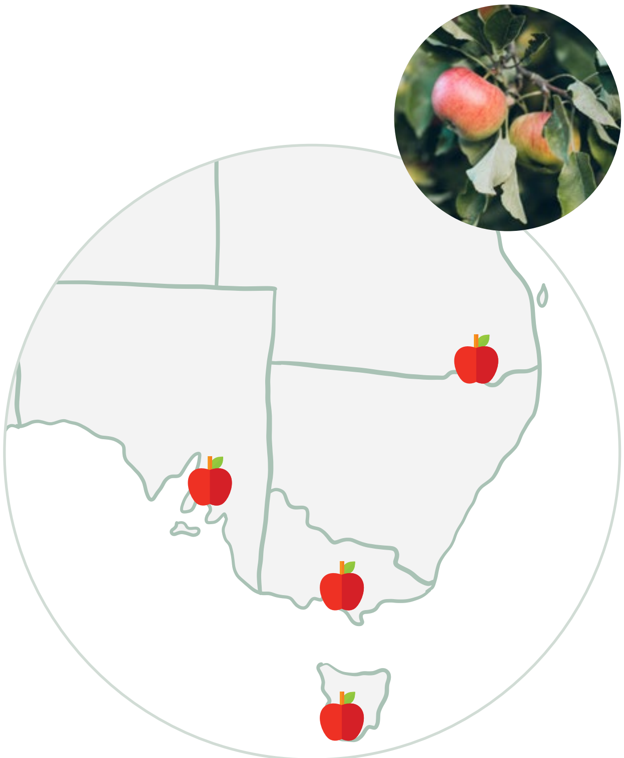
Social

Lives in a colony with a social structure consisting of queens and workers. Managed species live in hives; wild or feral (honey bee) colonies typically nest in tree hollows. Some native bees are 'subsocial' or 'semisocial' , with females sharing a nest with sisters or offspring but without a clear division of labour.

Solitary

Does not live in a colony. Females live and build nests alone, although some species have communal nesting habits where more than one female will share a burrow. Solitary nests can be found in aggregations, sometimes with hundreds of nests at the same site.

Apple:



Honey bees were the most common visitors across all sites. In the Adelaide Hills (SA), native bees could make up a third of all flower visitors. There were 16 species recorded, and they varied between orchards. The most common native bees were furrow bees, (*Lasioglossum* spp.), closely followed by Green and Gold Nomia bees (*Lipotriches australica*). These bees nest in soil in or around the orchard. Other occasionally common visitors were thynnid and scoliid wasps, and hoverflies.

On apple in the Yarra Valley (VIC), native bees could make up almost half of all visitors, though this varied between sites and time periods. Reed bees (*Exoneura* sp.) were the dominant native bees at some sites, while furrow bees (*Lasioglossum* sp.) were dominant at others. Reed bees were observed nesting in fern fronds and wild blackberry canes in some orchards. Green and Gold Nomia bees (*Lipotriches australica*) and slender furrow bees (*Homalictus* sp.) were occasional apple visitors.

On apple in southern Tasmania, a range of native bees including reed bees, *Exoneura spp.* and *Lasioglossum* spp. were observed, along with occasional visits from exotic bumble bees, *Bombus terrestris*. Flies also occasionally visited apple flowers.

Pear:

On pear in the Adelaide Hills (SA), honey bees were the most common visitors, but native bees could make up a third of all visitors. There were 16 species, and they varied between orchards. The most common native bees were furrow bees, (*Lasioglossum* spp.), but silk bees (*Leioproctus*) and Green and Gold Nomia bees (*Lipotriches australica*) were also observed. These bees nest in soil in or around the orchard. Other occasionally common visitors were thynnid and scoliid wasps, and hoverflies.

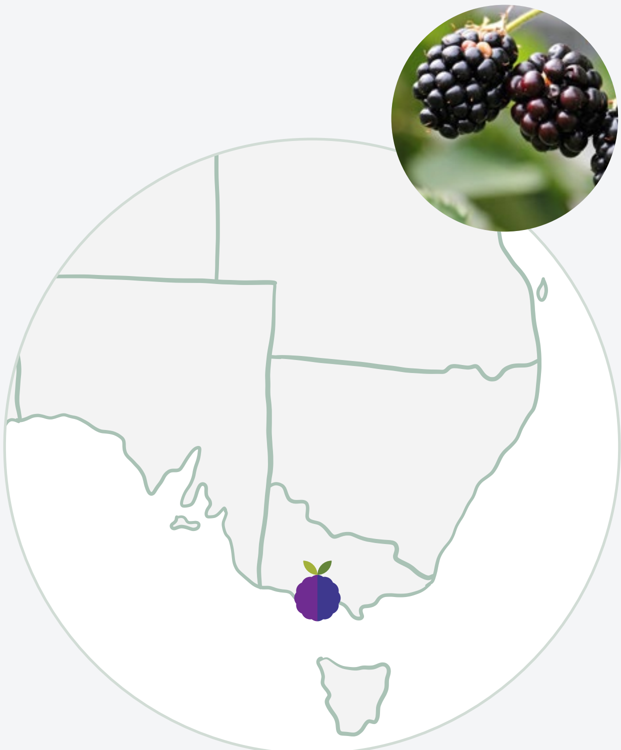
Raspberry:

On raspberry in the Yarra Valley (VIC), honey bees were the most common visitors, but at some sites native bees could make up more than half of all visitors. The dominant native bees were either Reed bees (*Exoneura* spp.) or slender furrow bees (*Homalictus* sp.), depending on the site. Reed bees were observed nesting in old raspberry and blackberry canes within crop rows. Green and Gold Nomia bees (*Lipotriches australica*) and furrow bees (*Lasioglossum* sp.) were occasional raspberry visitors.

In the Coffs Harbour region, honey bees were the most common visitor to raspberry flowers. Native bees, including *Tetragonula* spp. and *Homalictus* spp., were also observed visiting flowers.

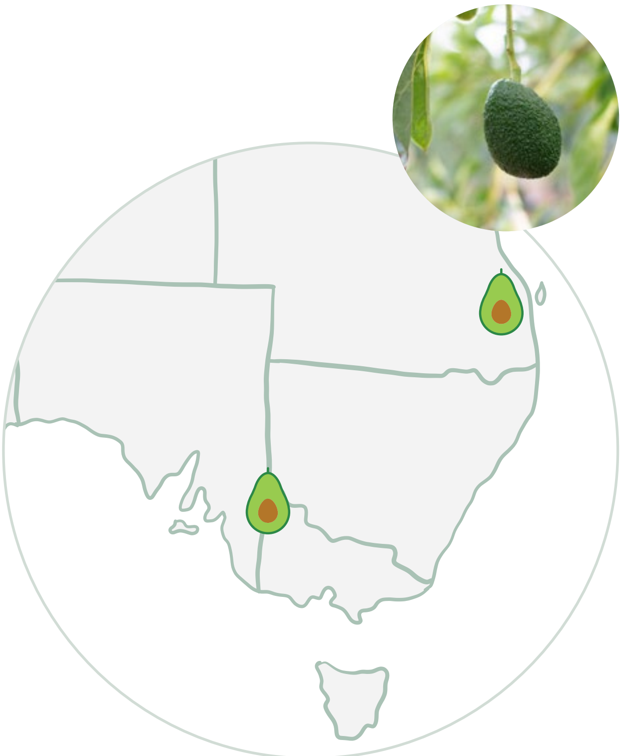
Blackberry:

On blackberry in the Yarra Valley (VIC), honey bees were most common but native bees could make up more than half of all visitors. Reed bees (*Exoneura spp.*) were the dominant native bees at some sites, while slender furrow bees (*Homalictus* sp.) were dominant at others. Reed bees were observed nesting in old blackberry canes within crop rows. Green and Gold Nomia bees (*Lipotriches australis*) and furrow bees (*Lasioglossum* sp.) were occasional blackberry visitors.



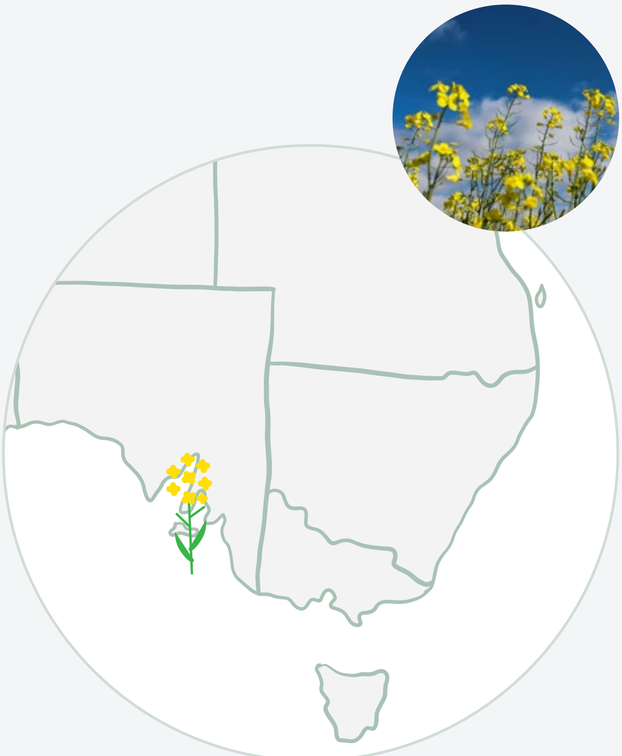
Avocado:

Avocado in Bundaberg (QLD) was visited by a range of pollinator species. Wild native stingless bees, *Tetragonula* spp., honey bees and a fly, *Stomorhina discolor* were observed regularly visiting flowers. In the Sunraysia region, flies were dominant visitors to avocado. However, honey bees and *Lassioglossum* spp. were occasional visitors.



Canola:

In canola on the Yorke Peninsula (SA), honey bees were the most common visitors. Furrow bees (*Lasioglossum*) and slender furrow bees (*Homalictus*) were the dominant native bees. *Leioproctus* bees, flies, beetles and butterflies were occasional visitors . The native bees nest in the crop, as the ground surface is easily accessible, but only in no-till areas. They would struggle to reproduce during grain rotations, and in particular in large fields with no surrounding flowering plants.



Blueberry:

In the Coffs Harbour region (NSW), the two most abundant pollinators on blueberry farms were managed honey bees and wild stingless bees (i.e. *Tetragonula carbonaria*, and to a lesser extent, *Austroplebeia australis*). Other species observed foraging on blueberry flowers included carpenter bees (*Xylocopa* spp.), reed bees (*Exoneura* spp.), allodapine bees (*Braunsapis* spp.) and very occasional flies and butterflies (eg. *Delias nigrina*).

On blueberry in the Yarra Valley (VIC), honey bees were the most common visitors, but native bees could make up over one third of all visitors. Reed bees (*Exoneura*) were the dominant native bees at all sites. Furrow bees (*Lasioglossum* sp.) and slender furrow bees (*Homalictus* sp.) were occasional blueberry visitors.

On blueberry in southern Tasmania, honey bees were the most common visitors, followed by exotic bumble bees and flies. Four species of native bees were observed visiting flowers including *Lasioglossum* (*L. mundulum* and *L. sculpturatum*) and two species of reed bees, *Exoneura* spp. (including *E. bicolor*).

Lucerne:

In South Australia, honey bees were the most common visitors to lucerne flowers. In total, lucerne was visited by 20 species, including blue-banded bees (*Amegilla chlorocyanea*), furrow bees (*Lasioglossum* spp.), resin and leafcutter bees (*Megachile* spp.), and several large mud dauber wasps (Sphecidae).

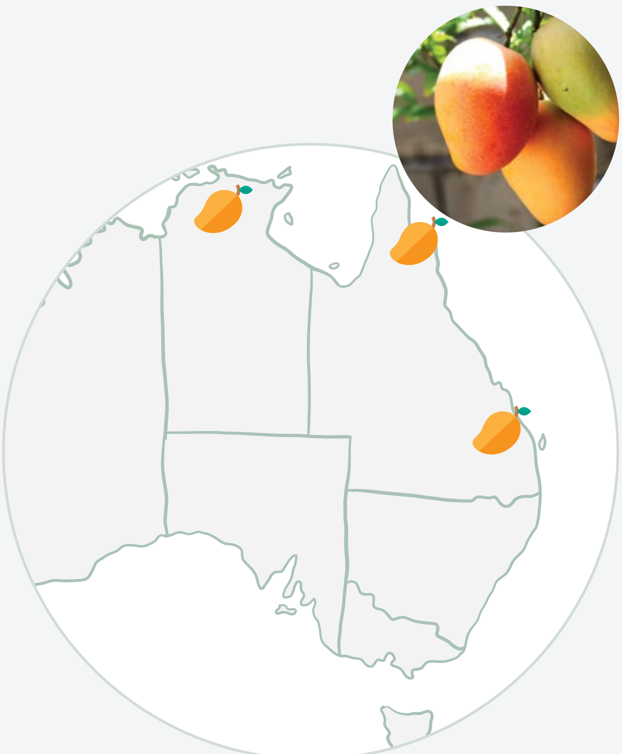
Cherry:

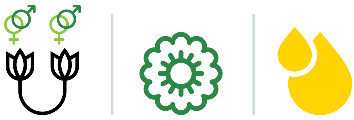
On cherry in the Yarra Valley (VIC), honey bees were the main visitors. Native bees could make up almost one quarter of all visitors. Reed bees (*Exoneura* spp.) were the dominant native bees, with occasional visits from furrow bees (*Lasioglossum* sp.).

In the Adelaide Hills (SA), honey bees were the most common visitors, followed by furrow bees (*Lassioglossum* sp.).

Mango:

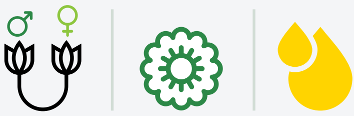
Wild native stingless bees, *Tetragonula carbonaria* (Mareeba & Bundaberg, QLD) and *Tetragonula mellipes* (Katherine, NT) were common visitors to mango flowers. Other native bees observed in mango orchards include *Homalictus* spp. (all regions), *Lasioglossum* spp. and *Megachile* spp. (Katherine), *Hylaeus* spp. (Mareeba) and *Xylocopa* spp. (Bundaberg & Mareeba). Flies were also frequent visitors to mango flowers in all three regions. Other less frequent visitors included beetles, ants and wasps. The exotic Asian honey bee (*Apis cerana*) was observed occasionally on mango in the Mareeba region.



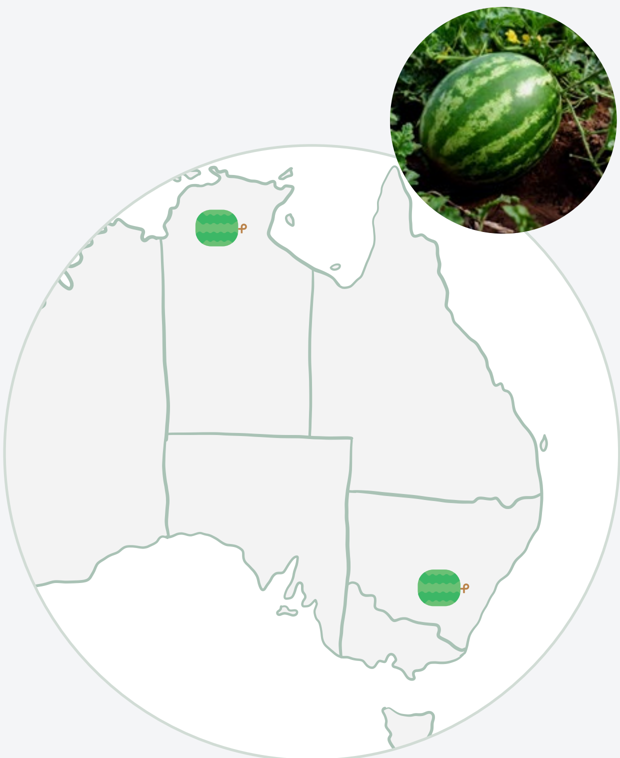


Macadamia:

Macadamia in Bundaberg (QLD) was primarily visited by honey bees, accounting for 80-90 % of visits. A range of flies, beetles and moths were also observed visiting macadamia flowers. Native stingless bees, *Tetragonula* spp., were only observed visiting flowers occasionally.

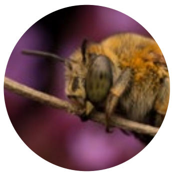


Watermelon:

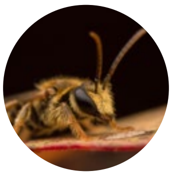
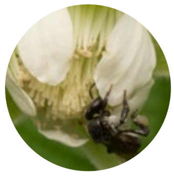


Honey bees were the most common visitor to watermelon flowers in both Katherine (NT) and Griffith (NSW). A range of native bees were found visiting watermelon flowers including *Homalictus*, *Lasioglossum* and *Megachile* species in Griffith (NSW), and *Homalictus*, *Megachile* and *Tetragonula* species in Katherine (NT).

What native bees should I expect to see in my crops?

Region	Crops	*Xylocopa* spp. (14-26mm)	*Leioproctus* spp. (4-16mm)	*Amegilla* spp. (7-15mm)	*Megachile* spp. (6-15mm)
Katherine (NT)	Watermelon				
	Mango				
Mareeba (QLD)	Mango				
Bundaberg (QLD)	Avocado				
	Macadamia				
	Mango				
Stanthorpe (QLD)	Apple				
Coffs Harbour (NSW)	Blueberry				
	Raspberry				
Griffith (NSW)	Watermelon				
Yarra Valley (VIC)	Apple				
	Blackberry				
	Blueberry				
	Cherry				
	Raspberry				
Tasmania	Apple				
	Blueberry				
Renmark (SA)	Avocado				
Keith (SA)	Lucerne				
Adelaide Hills (SA)	Apple				
	Pear				
Yorke Peninsula SA)	Canola				

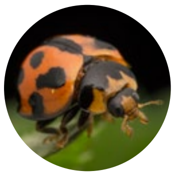
     

Lasioglossum spp. (<12mm)	*Lipotriches* spp. (6-11mm)	*Hylaeus* spp. (<10mm)	*Exoneura* spp. (<8mm)	*Homalictus* spp. (<8mm)	*Tetragonula* spp. (3-5mm)

What other pollinators should I expect to see in my crops

Flies


Region	Crops	Calliphoridae spp. (Blowflies)	Syrphidae spp. (Hoverflies)	Rh
Katherine (NT)	Watermelon			
	Mango			
Mareeba (QLD)	Mango			
Bundaberg (QLD)	Avocado			
	Macadamia			
	Mango			
Stanthorpe (QLD)	Apple			
Coffs Harbour (QLD)	Blueberry			
	Raspberry			
Griffith (NSW)	Watermelon			
Yarra Valley (VIC)	Apple			
	Blackberry			
	Blueberry			
	Cherry			
	Raspberry			
Tasmania	Apple			
	Blueberry			
Renmark (SA)	Avocado			
Keith (SA)	Lucerne			
Adelaide Hills (SA)	Apple			
	Pear			
Yorke Peninsula (SA)	Canola			

		Wasps	Beetles
			
inniidae spp. (Noseflies)	Bibionidae spp. Flies (Bibionid Flies)	Thynnidae, Scoliidae & Tiphiidae spp. (Flower Wasps)	Coccinellidae spp. (Lady Beetles)

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