Final Report

Macadamia pollination gap analysis and industry opportunities

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Project code:

MC24002

Project:

Macadamia pollination gap analysis and industry opportunities (MC24002)

Disclaimer:

Funding statement:

This project has been funded by Hort Innovation, using the Macadamia research and development levy and contributions from the Australian Government. Hort Innovation is the grower-owned, not-for-profit research and development corporation for Australian horticulture.

Publishing details:

Published and distributed by: Hort Innovation

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North Sydney NSW 2060

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www.horticulture.com.au

Contents

Public summary

The objective of this project is to gather knowledge about macadamia pollination and practice in Australia and other leading producer countries. In support of this objective, we have conducted a comprehensive review of published literature and complemented this with survey and qualitative interviews to gather information about perspectives and practices in the Australian macadamia industry. Our literature review summarises the information from 150 published sources, while our survey garnered responses from 26 macadamia growers, 11 industry professionals, and 8 beekeepers. We have produced a 'research compendium' that will help readers to find the publications that were used in this literature review. This compendium will be made available on the Australian Macadamia Society web site.

We found a rich body of research on macadamia pollination that the key details of the process and how these influence outcomes for growers. The following points emerge as very well documented and significant for production:

- Macadamia relies on cross-pollination to support good yield, with self-pollination accounting for a relatively small proportion of nuts
- Most pollination is achieved by bees, with honeybees the most widely important and stingless bees important in some locations
- Large blocks of trees of the same variety generally have a lower nut production because the opportunity for bees to move pollen between different varieties (i.e. cross-pollination) is limited
- Wild insect pollinators are significant and they are more abundant in orchards close to native vegetation

Macadamia growers that we surveyed and interviewed had a number of perspectives on macadamia pollination that did not always align with the research. Although there was a diversity of views, it was surprising the extent to which many had the view that self-pollination was playing an important role; that modes of pollination included wind and moths, and that single variety blocks did not compromise yield.

Given this pattern our primary conclusion is that gaps relate more to understanding and implementation, rather than knowledge per se. Working to reduce this gap will help the industry reduce the risk of low yielding orchards and increase the resilience of the industry to variability in pollinator supply. We make the following recommendations to address this challenge:

- Focus on activities that demonstrate or reveal "best practice" in a real farm context
- Learn from macadamia growers in other regions (e.g. South Africa, China, Brazil) and from growers of other tree crops in Australia
- Support case study research on blocks that have been adjusted from single cultivar blocks to modified blocks with areas of replanting that introduces other cultivars
- Communicate directly with growers regarding "What we know about Macadamia Pollination" to reduce the risks of significant misunderstanding
- Treat ease of pollination as an important trait when working on improved cultivars
- Conduct a risk analysis that models possible impact scenarios in terms of loss of pollination from feral honeybees, increased charges for honeybee hives and the capacity for the managed stingless bees to fill gaps

Keywords

Macadamia; pollinator; pollination; outcrossing; gap analysis; honey bee; yield; variety

Introduction

The objective of this project is to gather knowledge about macadamia pollination and practice in Australia and other leading producer countries. In support of this objective, we have conducted a comprehensive review of published literature and complemented this with survey and qualitative interviews to gather information about perspectives and practices in the Australian macadamia industry. An assessment of this information provides the foundation for a gap analysis and identification of opportunities for future work. The project will also compile an on-line compendium of available materials that will serve as a one-stop-shop for macadamia pollination information.

Previous work indicates that managed honeybees, feral honeybees and native wild insects (including stingless bees) all contribute to pollination (see HA21005). The establishment of Varroa mite in Australia (declared in 2023) is expected to reduce the abundance of feral honeybees and to increase the cost of pollination services using managed honeybees (see MT13060). The project will support industry capacity to adapt to this event and to support sustainable production.

The industry strategic investment plan for 2022-2026 identified that one of the four key outcome areas (i.e. Industry supply, productivity and sustainability) will require *Securing pollination for industry through robust honey bee health, pest and disease mitigation and investigation of alternate pollinators* and further noted under the extension and capability outcome area that pollination was one of the areas in which communication and extension was required. This project will provide insight into the dependency on insect pollinators for crop success and highlight opportunities for international and across industry collaboration in further research and development.

Methodology

The project was completed as two complementary streams of work: The compilation of a comprehensive literature review on macadamia pollination was supported by qualitative data gathered about the state of the industry in Australia through a survey and semi-structured interviews.

Literature Review

To compile a comprehensive literature review on macadamia pollination, we conducted systematic searches across the online databases Google Scholar, Web of Science, and Scopus. Whereas Web of Science and Scopus specialise in peer reviewed literature, Google Scholar has a broader pool including more work that is not peer reviewed. We used the search terms "Macadamia" AND "Poll*" to capture research related to pollination in macadamias. In addition to these databases, we also searched for grey literature using these terms, targeting online repositories of research theses from domestic and international universities. To ensure broad coverage, we included industry- and practitioner-led research in our review, such as studies produced by government agencies, agricultural research bodies, and private industry. Research was initially screened for relevance first by Title, and then by Abstract, to ensure only relevant literature was included. To further ensure comprehensive coverage, we employed the snowball method, also known as citation chaining, by examining both the references cited within key studies and the studies that cited them. This process allowed us to identify additional relevant material that may not have been captured in the initial searches.

We also reached out to experts in the field of macadamia pollination and horticultural pollination more broadly to identify additional resources that may not have been captured through database searches. This outreach focused on unpublished grey literature and resources in languages other than English. The 19 experts consulted were based in key macadamia-growing regions, including Australia, Brazil, South Africa, the United States (California and Hawaii), and Thailand.

Our review seeks to comprehensively synthesize the most accurate, recent knowledge on best practice in macadamia pollination. While all resources relevant to macadamia pollination are included in the scope of our report (and accompanying compendium of resources), we have prioritised information so that resources backed by empirical evidence, such as through experimental manipulation or direct observation, is given precedent over speculative claims, information obtained by inference from other crops, or anecdotal information. We have made efforts to make these distinctions clear throughout, to best represent the current research informed literature on macadamia pollination. To ensure all relevant resources are included, in some cases grey literature, such as industry research reports or news bulletins, are cited alongside associated peer reviewed publications.

Surveys and Interviews

For the purposes of integrating the finding of the Literature Review component against the current context and practices of the macadamia industry in Australia, a qualitative component of this research project was undertaken in the form of:

An online survey designed to gather data about practices and perspectives on the role of pollination in macadamia production, and

A small set of semi-structured interviews with purposively selected growers and industry professionals, intended to access the diversity of experiences and perspectives on pollination in the macadamia industry.

Ethical approval for the survey and interview components of the projects was received from the ANU's Human Research Ethics Committee under Protocol H/2024/1096 prior to conducting any data collection.

The survey instrument was developed in consultation with the Project Reference Group to target three relevant sample groups: macadamia growers, macadamia industry professionals, and professional or amateur beekeepers. The survey was designed to gather information about several topics related to the question of knowledge and practices surrounding macadamia pollination in Australia. Specifically, the survey asked about:

- Orchard design and pollination considerations
- Pollination services (paid and unpaid)
- Pollination knowledge and practices

The survey was initially piloted with contacts of the researchers with relevant survey design knowledge, and then also with contacts with relevant macadamia and beekeeping industry knowledge. Once finalised, the method of sampling for the survey was a convenience sampling, and respondents were sourced via an in-person stall at the Industry Conference and via distribution through the AMS newsletter. To obtain responses from beekeepers, the survey invitation was also sent out privately by individuals within the macadamia industry to beekeepers known to them.

Alongside the survey development, preliminary discussions were had with growers and industry professionals at the AMS Conference and via site visits in the Northern Rivers region of NSW in late October 2024, and eleven semi-structured interviews were conducted over the course of a two-day fieldtrip to the Bundaberg growing region in mid-November 2024. These interviews were mostly conducted on-site at orchards and were intended to draw out the diversity of views held in the industry regarding pollination of macadamia as a crop. The participants for these interviews were selected by a representative of AMS and were constrained by time, geography and the availability of individuals.

Overall, the survey received 45 responses. Broken down this equalled 26 macadamia growers, 11 industry professionals, and 8 beekeepers. Given this number of responses, the results from the survey cannot be understood as statistically significant representations of the industry at large. The survey responses can, however, shed light on key themes or issues that can be explored in more depth through further research.

Report Structure

Informed by both our literature review and survey and interview data, we have structured this report according to the most salient questions for contemporary Australian macadamia growers. Each of these sections below begins with an explanation of the research and literature on that topic, followed by details from the survey and interview data where relevant. Insights derived from the interviews and survey is in *italics*. We then conclude each section with a summary of key takeaway points and knowledge gaps.

State of knowledge

Industry Overview

The Australian macadamia (*Macadamia*, Maiden and Betche) industry, comprised of approximately 800 growers 41,704ha of production area (1), is primarily located in the northern rivers region of NSW and in the Bundaberg area of QLD. Northern NSW farms are typically smaller and older, while the macadamia industry in the Bundaberg region is more recently developed, with larger-scale farms (2). In the year ending June 2023, production reached 48,400 tons (in-shell weight, 3.5% moisture) with a kernel weight of 15,972 tons valued at $104 million. The industry is primarily driven by the international market, with 75% of Australian macadamias exported overseas (1). Overseas, the largest producers of macadamia in 2024 were South Africa (92,000 tons), China (68,500 tons), and Kenya (41,150 tons) (3, 4). Macadamias are also grown in Zimbabwe, The United States (including Hawaii), Israel, New Zealand, Vietnam, Guatemala, Malawi, Colombia and Brazil (5).

Global Pollination Research Timeline

While wild macadamia is endemic to Australia, much of the initial research into macadamia pollination started in Hawaii, where the plant was first cultivated at scale following the First World War (6-8). Urata (9) published the first pollination research on macadamias, examining the pollination requirements of macadamia crops by studying the plant's floral biology, self- and cross-pollination potential, pollen movement and insect pollination. Ito et al. (10) conducted early studies on self- and cross-pollen compatibility of six cultivars, while Ito et al. (11) examined the effects of cross-pollination on initial and final nut set and yields. Shigeura et al. (12) and Gary et al. (13) examined the role that honeybees (*Apis mellifera*) played in pollinating Hawaiian macadamias, including their flight range, distribution within orchards and the role of feral honeybees as pollinators. Ito et al. (14) determined that mixed block plantings averaged 16kg more yield per tree than pure block plantings. Tavares et al. (15) examined visitors to Hawaiian macadamia orchards following the arrival of the Varroa mite (*Varroa* destructor) and found that honeybees were still the most abundant visitor. Following early foundational studies, Hawaiian macadamia pollination research output has slowed, consistent with the growth rate of the industry in Hawaii which peaked in 1990 and has since declined (16).

Macadamia cultivars initially developed in Hawaii were subsequently brought to Australia, where the industry began to expand and more pollination research was undertaken (17). Research in Australia began in earnest in the 1980s (18), continued alongside the expansion of the Australian industry in the following decades, and is still very active. Because of the extensive Australian literature on macadamia pollination, we refer briefly to some key authors and papers here, with research outlined in subsequent sections below. Sedgely conducted early Australian macadamia pollination research in the 1980s including on the development of the macadamia ovary (19), self- and cross-compatibility by assessing pollen tube growth (20), and cross-cultivar compatibility (21). Moncur et al. (22) assessed the floral development of flowers under Australian conditions, by examining several Hawaiian varieties and early Australian varieties. Rhodes (17) undertook early assessments of insect pollinator efficacy in macadamia orchards, including honeybee hive placement and foraging distance. Vithanage et al. (23) examined key flower visitors to Australian macadamia orchards, with honeybees and stingless bees (*Tetragonula* spp.) most common. Stace (24) examined the foraging behaviour and subsequent hive development of honeybees on macadamia flowers. McConchie, Meyers and Vithanage and coauthors focused on pollen parentage and appropriate selection of cultivars to maximise outcrossing (25-27). Heard and coauthors conducted several studies of insect pollinators to macadamia crops, with particular focus on stingless bees (28-32). Trueman and coauthors have published extensively on pollination in Australian (and more recently, international) macadamias, with focus on limitation to fruit set arising from poor pollination (for example: 33, 34-42). Wallace and coauthors have focused on macadamia pollination and pollen-parent affects on fruit set and yield (for example: 37, 43, 44-48). This Australian body of work points towards the key insect vectors of Australian macadamia orchards, the benefits of ensuring adequate cross-pollination between cultivars, cross-cultivar compatibility, and resultant orchard management practices to maximise pollination services. Active Australian research in macadamia pollination continues, including through collaboration with other key growing countries such as South Africa (40).

Consistent with their growth as the largest producer of macadamias globally as of 2023 (3), much recent macadamia pollination research has come out of South Africa (but see earlier preliminary work by de Lange

(49), examining self- vs cross-pollination). For instance, studies have examined the spatial arrangement of honeybee hives in orchards (50), pollination limitation despite the use of managed honeybees (51), pest control and pollination ecosystem services provided by animals moving into macadamia orchards from the surrounding landscape (52-55), and effective orchard design to maximize pollination (5, 56-58). There is ongoing research in South African macadamias on: industry standards for pollination practices, including hive densities, placement and pollinator foraging patterns; cross-pollen compatibility of 12 macadamia cultivars; long-term viability of macadamia pollen storage, to enable artificial pollination (59). An article in The Macadamia Magazine (60) called for industry standards for honeybee hive acquisition and better relationships between growers and apiarists.

While macadamia pollination research in China is difficult to access potentially due to the language barrier and intellectual property constraints, recent patents lodged suggest ongoing research and development in line with the projected growth of China towards becoming the world's biggest macadamia grower in 2025 (61). These patents include a method for grafting three cultivars onto one tree to maximize outcrossing (62), methods and devices for manually hand-pollinating (63-67), a method for increasing pollination using application of a chemical pollination assistant (68), a method to delay flowering in *M. ternifolia* (69), and a method to promote earlier flowering (70). Kong et al. (71) also published research on flowering and fruiting characteristics of macadamias grown in China. As the macadamia industry continues to grow in China, it is likely that further development and research will continue.

Other countries where macadamia is grown commercially at smaller scales have also produced significant pollination literature. Research from Brazil examined the diversity of flower visitors to macadamias (72, 73), the foraging behaviour of honeybees to different parts of the canopy (74), pollination provided by butterflies (75), and the foraging habits of Brazilian stingless bees, which were shown to carry macadamia pollen (76). Kongpitak et al. (77) examined the foraging behaviour of stingless bees and honeybees to macadamia orchards in Thailand. Shivaramu et al. (78) studied pollinator activity on macadamias in India. Kenyan research has examined the role of macadamia visitors on nut set, retention and yield (79, 80), the diversity of insect flower visitors to macadamias (81), the effects of supplementary pollination on macadamia nut set (82). Masís et al. (83) have also conducted a study on the insects visiting macadamia flowers in Costa Rica.

Macadamia Pollination Biology

Macadamia is a mass-flowering tree capable of producing 2500 inflorescences per year. While there are four species in the genus, *M. integrifolia* is the primary species grown commercially, with *M. tetraphylla* also grown, but more rarely. Small white flowers develop along the stalk and form the inflorescence. Each inflorescence is arranged in racemes of 100 to 300 flowers, depending on the cultivar (36). Flowers typically open for one week, but are only attractive to insects for approximately three days (30), and develop into early-stage nuts three weeks later (34, 44). Macadamia flowers emerge already covered in self-pollen, which must be first removed by pollinators and then replaced with pollen from another plant (or better yet, another cultivar) for better yields (44). This floral trait is common to all plants in the family Proteaceae, such as *Grevillea* and *Banksia* (84). While a tree is capable of producing 750,000 flowers per year, only very few flowers reach final nut maturation (0.3-3%) (85), with most immature nuts abscising during the first 7-15 weeks after flowering (36). Overproduction of flowers is a common reproductive strategy across many different plants, and it is to be expected that the maximum number of nuts that a tree can ripen will be much lower than the flowers produced because of resource limits (86). Macadamia nuts fall from the tree after maturation and are harvested from the orchard floor (5). Because the stigma is only small, with little pollen carrying capacity (87), pollination may be limited by insects' ability to effectively deposit pollen on the stigmatic surface (88).

Is cross-pollination required to maximise macadamia yield?

Research clearly shows that adequate pollination services are an important factor in maximizing macadamia nut set, with high yields only achieved in macadamia through cross-pollination (36, 39, 83, 89-91). Pollinator exclusion trials indicate that insects are required to ensure pollen vectoring and suitable harvest yields (30). Hand cross-pollination experiments demonstrate that cross-pollen enhances fruit set (34, 44, 45, 92, 93) and nut weight (46). Furthermore, by hand cross-pollinating several whole macadamia trees, Trueman et al. (38) showed that cross-pollination increased nut-in-shell yield by 97%, kernel yield by 109% and fruit set by 92%, relative to open pollinated trees located in the first and 25th row adjacent to another cultivar block. The extent of pollen limitation varied depending on proximity to other cultivars, with 84-100% of fruit set occurring due to cross-pollination. Improved pollination in their study led to economically significant increases in yield of approximately 3720-7080 USD per hectare. Across several orchards in the Bundaberg Region containing Daddow, 816 and A4 cultivars, Trueman (39), (94) conducted genetic analysis of macadamia nuts and found that almost all nuts surveyed in their study resulted from cross-pollination, with only 0-3% of nuts (depending on the cultivar) evidencing self-paternity. Cross-pollinated nuts also had significantly higher nut in shell mass and kernel mass than self-pollinated nuts (except when the cross-pollen parent was from cultivar 741). They also found that cross-pollination positively influenced the quality traits including the mineral-nutrient profile of cultivar 816 macadamia nuts, increasing boron levels and decreasing aluminium levels. Similarly, another study showed that pollen parent affected the fatty acid nutrient profile of nuts (95). Grass et al. (51) showed that excluding pollinators from flowers reduced initial nut set by 80% compared to unbagged control flowers, while supplemental hand pollination increased initial nut set by 66% compared to unbagged control flowers. By hand pollinating wild *M. tetraphylla*, Pisanu et al. (96) also showed that nut set in wild populations (where there is a high diversity of genotypes compared to orchards of selected cultivars) was approximately 5-10 times greater in cross-pollinated versus self-pollinated flowers.

While all macadamia cultivars are likely to benefit from pollen outcrossing between cultivars, the degree of self-incompatibility varies between cultivars. Macadamia is partially self-incompatible, with degree of incompatibility varying among the approximately 20 cultivars grown globally, most of which are likely self-sterile (40). In an international study across Australia, Brazil and South Africa, Trueman et al. (40) sampled 19 macadamia cultivars across 23 sites and found that most cultivars required outcrossing. They found that outcrossed fruit had better kernel recovery, higher mass, and higher oil concentration, equating to differences of 433-841 USD per ton nut-in-shell. Kaur et al. (97) evaluated self-compatibility of four macadamia cultivars (791, 741, 344 and A16) by conducting experimental hand-pollination experiments. They found that 741 and 791 were partially self-fertile, while 344 and A16 were self-infertile. However, final nut set in partially self-fertile 741 and 791 cultivars was still higher in open pollinated flowers compared to self-pollinated flowers. Similarly, a study that compared nut set in open pollinated, hand pollinated and pollinator excluded flowers found that while some cultivars showed some self-compatibility, all cultivars set greater nuts after supplemental cross-pollination (98).

The evidence from the survey and interviews demonstrates some divergence within the industry with regard to both the importance of pollination altogether, and the importance of cross-pollination versus self-pollination. As illustrated in Figure 1 Figure 2 below, most (84.6%) growers surveyed were concerned about the risk of poor pollination on their orchard. Similarly, almost all (96.2%) agreed (either 'somewhat agreed' (30.8%) or 'strongly agreed' (65.4%)) that effective pollination is an important factor in the productivity of their crop, with one outlier strongly disagreeing about the importance of pollination. While three quarters (76.9%) of growers surveyed agreed that they were aware of the pollination needs of their crop, a diversity of perspectives on the value of pollination was present in the interview data, accompanied by a range of different ways that pollination was prioritised.

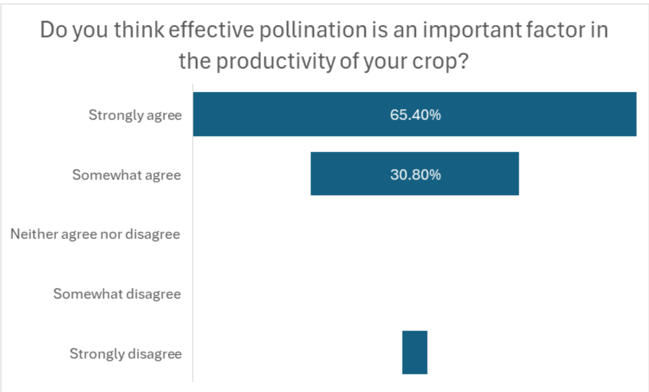

Figure 2: Grower perspectives on the importance of pollination for productivity (n=26)

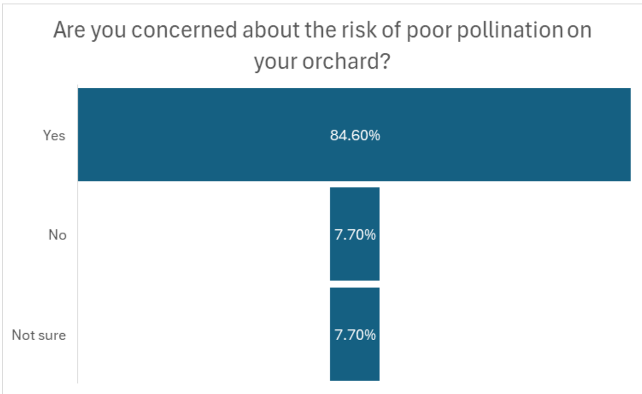

Figure 1: Grower concern about poor pollination (n=26)

All surveyed growers and industry professionals believed that effective pollination affected the quantity of nuts produced, with the majority (73% of growers and 91% of industry professionals) thinking it mattered 'a great deal'. Industry professionals also all thought that the quality of nuts produced was impacted by pollination, but there was slightly less consensus amongst growers: 80.8% believed 'a moderate amount' (34.6%), or 'a great deal' (46.2%) was contributed. However, 15.4% were unsure, and 3.8% considered there to be no impact at all.

In terms of accessing pollination services, 7 of the 26 growers surveyed indicated they paid for pollination services, while 5 still had hives on or near their orchards, and a further 6 indicated they managed their own hives (mostly stingless bees, with one respondent managing honeybee hives). 8 growers indicated they did not access pollination services. ***Error! Reference source not found.*** *below illustrates this variation. This reflects the point made by several of the interview participants, who saw pollination as less important in the matrix of decision-management than, for example, the costs/benefits of managing large single blocks. These interviewees cited limited difference in total yield observed across their large single blocks (See Box 1 below). Other growers interviewed discussed the challenges of accessing managed hives as a limiting factor.*

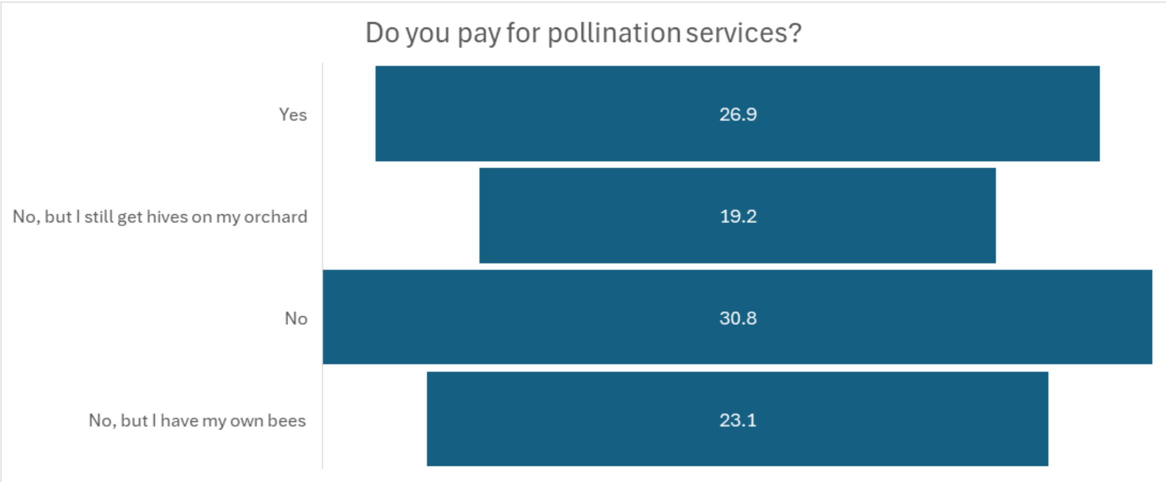

Figure 3: Pollination services accessed by growers surveyed (n=26)

> "We're getting reasonable quality yields… and I haven't seen enough evidence yet of … an improved yield, above what I'm already getting"
>
> "I haven't had enough evidence in front of me to identify that A) say we were paying for pollination, that the hives were of a quality to do the job, and B) do my varieties truly need crop pollination? And if they do, tell me with what?"
>
> "You can't just look at pollination in isolation. There's a lot of other factors that can play a part… your tree health… your irrigation… your nutrition…Pollination is a factor, but how much?"
>
> "Pollination…. Gets put in the too hard basket. I can concentrate on my fertiliser set-up, more than I can concentrate on pollination"

Box 1: Interview Quotes regarding value of pollination

Summary

Research highlights the critical role of pollinators in maximizing macadamia yields through cross-pollination, as self-pollination results in lower fruit set, nut weight, and kernel quality. Studies demonstrate that cross-pollination significantly improves nut-in-shell yield, kernel yield, and economic returns. Genetic analyses confirm that nearly all macadamia nuts in mixed cultivar orchards result from cross-pollination, with additional benefits such as improved mineral profiles observed in some cultivars. While macadamia has a low but non-zero rate of self-compatibility, the degree of self-compatibility varies across cultivars, with most requiring outcrossing for optimal yield and quality. Experimental studies reveal that even partially self-fertile cultivars achieve higher nut set with open pollination, underscoring the importance of pollination. Further research is needed on degree of self-incompatibility for common cultivars, and which specific cross-cultivar combinations are most beneficial.

Despite relatively consistent data in the survey, the diversity of perspectives obtained through the interview component of the research suggests that there is a fragmented and inconsistent understanding of the value of pollination to macadamia yield within the industry. Receptiveness to pollination knowledge seems to be somewhat dependent on other perspectives about its value within the overall orchard management priorities.

What combination of cultivars should be planted to maximize pollination benefits?

Outcrossing between cultivars is essential for maximising pollination, but research shows that certain cross-cultivar combinations result in greater yield. There is some research on cross-cultivar compatibility of some cultivars, but many specific cross-cultivar combinations remain unreported in the published literature. For instance, 814, 816, 842, 849, A4, A16, A38, A203, Daddow and MCT1 cultivars are all considered self-sterile and need outcrossed pollen to maximise nut set (100). Conversely, 660, 741 (which are likely actually the same cultivar (101)) and 791 cultivars display limited self-compatibility (97, 102), with selfing rates of up to 40% (102). While this selfing rate appears higher than those observed in other studies, this trial is based on a small sample size of 10–12 nuts per cultivar, which introduces a degree of uncertainty in this result. Other studies also documented some self-fertility in 741 and 791 cultivars, though they still indicate that these cultivars produce higher nut set and larger nuts when outcrossed (40, 97). All cultivars will still produce higher nut set through pollen outcrossing, even cultivars displaying partial self-compatibility (100). Meyers (103) showed that pollen parentage influenced fruit retention and yield, with reduced compatibility in genetically similar cultivars. By demonstrating that some combinations of supplementary hand pollinated cultivars increased nut set more than others, Turnbull et al. (35) showed that cross-pollen identity is more important than pollen quantity. Their study included 151 combinations of common Australian macadamia cultivars, with most combinations exhibiting similarly intermediate levels of compatibility, mostly exceeding those seen in selfing. However, maternal-paternal combinations of 842-660 and 842-Daddow cultivars performed significantly better than other combinations, indicating that these may be promising cultivar combinations. Hort Innovation (104) have also developed a table indicating compatibility of common Australian macadamia cultivars following hand cross-pollination trials in Bundaberg. Farm managers should try to select cultivars with appropriate pollen donor compatibility (5), with higher yields available to growers with compatible mixed cultivar plantings (25).

Alongside cross-cultivar compatibility, other practical farm management considerations inform the choice of cultivar selection. To enable pollen outcrossing between varieties, it is important that flowering times overlap between each cultivar. While flowering time is largely an attribute of a given variety, it may also vary in terms of timing or length according to growing region, seasonal conditions and other orchard management factors (100). Hort Innovation (100) have provided an indicative guide of flowering time for many common Australian varieties. Other cultivar-specific differences may impact farm management practices such as pruning strategy and frequency, long term versus early nut production, tree and canopy size and shape, yield potential, timing and duration of nut drop, disease and insect susceptibility and heat and water tolerances (105).

The most important varieties listed by growers in the survey responses were 741 (19.2% of growers surveyed, n=26), and 246, 344, A203, and MCT1 (11.5% each). The varieties that were described in the survey as most important for pollination included 246, 741, 203 and M500 (related to the timing or length of flowering), and A38 (due to the large volume of nut set).

*Furthermore, 42.3% of grower respondents were unsure about the contribution made to yield by self-pollination within a single variety block, while 38.5% believed a 'large' (23%) or 'very significant' (15.4%) contribution was being made. Conversely, 73% of industry professionals who responded to the survey thought that self-pollination was only making a 'small' contribution to yield (see also **Error! Reference source not found.**).*

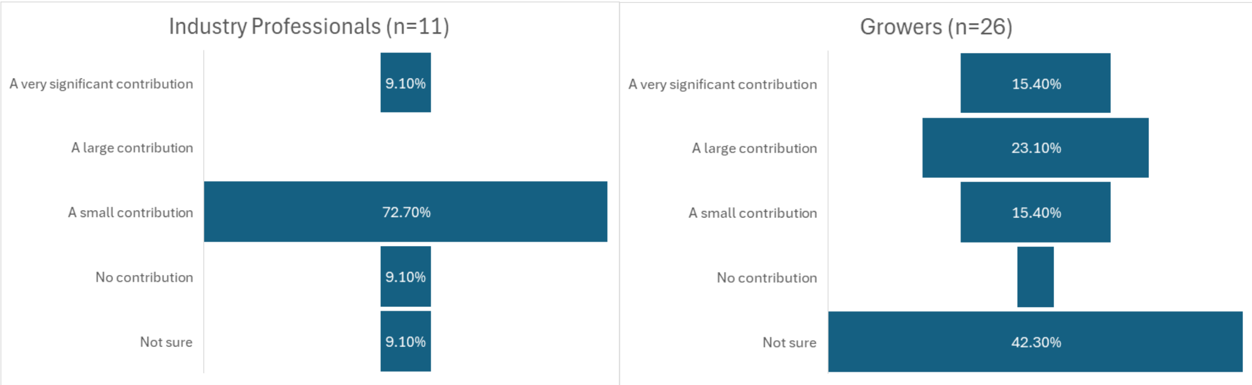

Figure 4: Growers vs Industry Professionals perspective on the contribution of self-pollination within a single variety block to macadamia yield?

These differences reflect the divergent interview responses noted above regarding the importance or value of pollination, and might contribute to explaining the prioritisation of single blocks of varieties over inter-row cultivar variation (i.e. if growers think ensuring cross-pollination is less important than the potential benefits of managing large single blocks). Some interviewees also discussed the challenges of being 'locked-in' by past decisions about varieties, and the potential for this to lead to wishful thinking that their orchards are not compromised by pollination problems arising from past decisions.

Summary

While certain cultivars exhibit partial self-compatibility, all cultivars benefit from pollen outcrossing. Because some cultivar combinations outperform others in nut set and yield, it is important that farm managers select compatible cultivar combinations. Alongside outcrossing compatibility, cultivar selection must also consider additional cultivar-specific traits that have implications for farm management practices, including flowering time and duration, yield potential, market value and disease susceptibility. Though research provides some indication of some suitable pairings, further research is needed to address knowledge gaps in cross-cultivar compatibility to inform effective planting. There is also little research on how to balance cultivar selection for outcrossing suitability with other farm management considerations that result from cultivar selection. It also may be possible to develop macadamia cultivars with higher selfing rates, as has occurred in other horticultural crops.

The survey and interview data shows that there is a degree of both uncertainty and disagreement amongst growers about the importance and value of cross-pollination. Furthermore, growers may have a variety of reasons for planting different varieties or may also be 'locked-in' to certain varieties and arrangements due to historical plantings. Improving understanding amongst growers of what knowledge is settled in the literature, and what knowledge gaps still exist, can help inform future planting decisions (such as how to replace storm-damaged trees, or when planning new plantings).

How should tree plantings be arranged spatially to maximize pollination?

One implication of the reliance on cross-pollination is that there would be a benefit to having different varieties planted sufficiently close together that cross-pollination rates remain high. This prediction has been validated by crop yield data, with higher yields harvested from blocks of trees containing multiple cultivars and a decrease in yield with increasing distance from other cultivar trees (5, 14, 27, 37). Trueman (39) showed that pollen limitation was affected by proximity to trees of another cultivar, with 84-100% of nuts developing after cross-pollination from another cultivar, even when that may be 200m away. Their results showed economically important improvements in yield from pollination, with an increase in farm-gate value of approximately 2950-5630 USD per ha. Kämper et al. (37) showed that macadamia tree yield decreased with increasing distance from a cross-pollen source so that crop production was reliant on transport of cross-pollen across orchards. By quantifying self- and cross-pollination rates at varying distances from a cross-pollen source, Wiebke et al. (57) showed that almost all nuts were cross-pollinated, even up to 23 rows from the cross-pollen source. McConchie et al. (25) showed that cross-pollination effects were greatest in rows adjacent to another cultivar and declined sharply with distance.

While recent research helps to inform a basis for developing guidelines for interplanting of cultivars, it remains unclear how many rows can be planted before nut yields begin to decline significantly (39). Kämper et al. (37) showed that the number of harvested nuts decreased 24m from the cross-pollen source. Vithanage et al. (27) showed that cross-pollination and yield increases were evident in the 5 rows of trees closest to another cultivar, with paternity tests demonstrating that pollen was able to travel across all 27 rows present in the orchard. These studies may indicate that interplanting of cultivars could be improved by planting within close distances of 24m (37) or 5 rows (27) of a cross-pollen source, but that some cross-pollination can still occur at distances up to 200m (39), 23 rows (57) or 27 rows (27) away from a cross-pollen source. While these findings provide some indication, further research is needed to determine suitable interplanting distances before nut yields decline (39). Hort Innovation (104) also suggest that because some pollinators (notably honeybees) prefer to move along rows of trees rather than between rows, it may be beneficial to plant different macadamia cultivars alternating within the same row. This advice appears to be based on observations from other crops, such as pear (106), blueberry (107) and strawberry (108) Orchard design guidelines that incorporate close interplanting of cultivars, possibly within the same row, are likely to maximize outcrossing and enhance yields. Alternating planting rows by different cultivars to ensure outcrossing and increase yield is also established best-practice in many other horticultural crops, such as apples (109) and almonds (110).

From the survey data, an equal number of respondents have trees arranged as blocks of one variety (38.5%) or with row variation (different varieties in each row) (38.5%). A smaller percentage have variation within rows (7.7%) or some other arrangement (15.4%). Half the growers surveyed said cross-pollination had been a consideration in the arrangement of their varieties, but a further 19% said ease of harvesting was considered more important. 19% said cross-pollination was not a consideration, and 12% provided 'Other' answers (mostly to provide detail about variation between older and more recent plantings where cross-pollination has been considered) (see Figure 5).

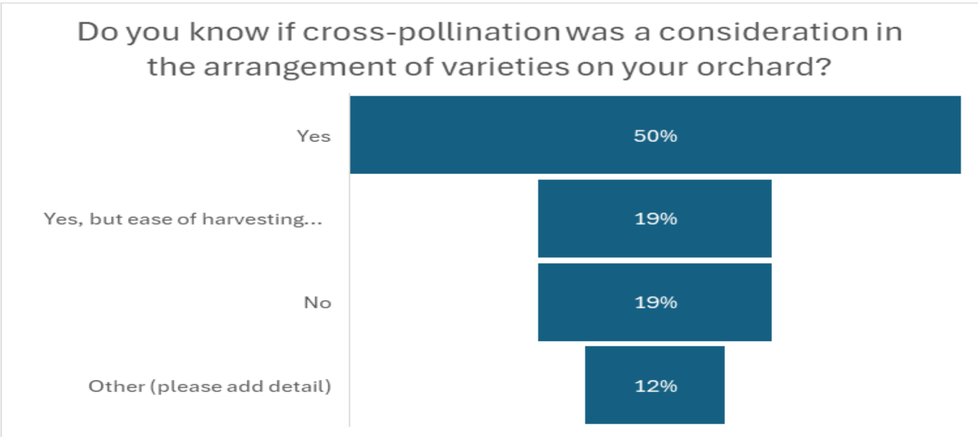

Figure 5: Pollination consideration in orchard design and varietal plantings

“I couldn’t come at the two rows of this, two rows of that…. What I really struggled with… is the contradictory information… I can find people who say “do 1 row of this, 1 row of this” and then other successful growers who say “it’s all a waste of time, just do blocks”. I don’t think we really know what the requirement is”

“It’s incredibly important. As far as pollination is concerned I think it’s essential. I can see where the A268s abut the A16s … the first four rows on either side, always has about 20% more production than those rows further away. So now we do 2 by 2 rows.”

Box 2: Interview quotes about varieties and cross-pollination

The importance of row-by-row/close alternating of varieties was questioned by some interview participants. This was discussed in the context of the trade-offs in management costs, and the path dependency of the time frames of plantings (i.e. growers being locked-in to certain patterns based on prior decisions/priorities). Conversely, other interviewees considered cross-pollination to be of paramount importance, and the driver behind many of their decisions (see examples in Box 2). This variation within the interviewees’ perspective reflects the nascent and evolving qualities of a young industry, as macadamia growing is, especially in the Bundaberg region.

<u>**Summary**</u>

Research clearly shows that proximity to a cross-pollen source is important for ensuring adequate pollination, with studies showing nut yield and farm-gate value increase with proximity to cross-pollen sources. While guidelines are not yet available for the optimal planting distances between cultivars, pollination services decreased over short distances (24m or 5 rows), showing benefits to close interplanting of cultivars. Further research is needed on how many rows of the same cultivar can be planted before nut yields decline.

Survey and interview data shows that while some growers are prioritising cross-pollination, others are focusing on other management priorities and input costs. Understanding the value (in terms of yield) and mechanisms (in terms of varietal arrangement) of cross-pollination will be important information for grower’s decision-making.

If multiple cultivars are required to maximise pollination, why are single cultivar blocks still setting nuts?

Acknowledging the need for cross-pollination from other cultivars, many macadamia orchards have switched from earlier single-cultivar orchards to several cultivars (20, 36), using alternating rows of different cultivars as the recommended strategy to increase yield (5, 17). However, some growers cite the management trade-offs of growing multiple cultivars as undesirable and still anecdotally report adequate yields with single-cultivar blocks. Some growers and researchers have suggested that there may be more sources of genetic variation present within the crop than expected (S. Trueman, personal communication, November 25, 2024). By determining genetic paternity of nuts, Trueman et al. (38) found high levels of outcrossing in single-cultivar blocks, speculating that outcrossed pollen may have come from trees of another cultivar that had been replaced following storm damage, through transfer of pollen from another orchard across large distances by bees, or in-hive transfer of pollen between honeybees. While it is difficult to measure its influence on yield, some in-hive transfer of pollen has been demonstrated in mangos, apples, sunflower and cotton (111-114). Whether or not in-hive pollen transfer contributes to cross-pollination in macadamia remains speculation only. However, Trueman et al. (38) also note that the single-cultivar blocks were still highly pollen limited, recommending closer interplanting of other cultivars to boost yield (38). It is also common for rootstock to grow unnoticed flowering shoots which can introduce outcrossed pollen, because scions are typically grafted onto rootstock of another cultivar (usually H2 in Australia) (S. Trueman, personal communication, November 25, 2024). Single-cultivar blocks may also be able to set nuts due to higher degrees of partial self-compatibility present in some cultivars, such as 741 and 791. However, Kaur et al. (97) demonstrated that nut set was still higher in single-cultivar blocks of these partially self-compatible cultivars when pollen outcrossing occurs. These results are consistent with other studies that show that yield in single-cultivar blocks is increased when outcrossing is enabled, with almost all nuts still resulting from cross-pollination in single-cultivar blocks (27, 36, 57).

Interview data reinforces the findings of the Literature Review, with several interview participants discussing the possibility of variation within assumed single-variety rows or blocks, either through misidentification or mislabelling from nurseries, incidental replanting with different varieties in storm-replaced trees, and rootstock flowering (see Box 3*).*

"there's lot of nursery mistakes"

"I can take you out in a 741 block….and we'll walk in there and I can say "well that's not a 741, and that's not a 741". But also, a 741, maybe it has enough genetic variation within the variety??"

"When they're young they're very hard to tell, but when they're old, they're very obvious"

Box 3: interview quotes about variation within single variety blocks

Summary

Although some growers have single-cultivar blocks, studies reveal that outcrossing remains critical for maximizing nut set and yield. Cross-pollination in single-cultivar blocks can be facilitated by factors such as storm-replaced trees, occasional pollen transfer over long distances by bees, or rootstock flowering and it is unclear which of these sources. *These theories are backed up by anecdotal on-farm evidence documented in the interviews.*

What are the pollinators of macadamia crops?

Observational surveys, both in Australia (32, 88, 115) and internationally (15, 51, 52, 72, 74, 76-78, 116), show that the predominant flower visitor to macadamia crops are honeybees. For instance, honeybees comprised 99% (51), 96% (72), 89% (115), 62.7% (15), 65% (52) and 60.8% (32) of visits to flowers in macadamia orchards. Because honeybees are an important managed commercial pollinator, with hives often placed in macadamia orchards (88), many of these bees come from apiaries. Research also shows that wild, unmanaged honeybees that nest in nearby native habitat can provide pollination services to macadamias in Australia (117) and South Africa (55), with higher abundance of honeybees found nearby to non-farm habitat. Because honeybees are often reported as the most abundant macadamia flower visitor, with studies suggesting macadamia pollen is highly suitable to honeybees (118), they are commonly regarded as the most important pollinator (88).

Stingless bees are also common visitors to macadamia flowers and likely play an important role in pollinating orchards in some regions. Globally, several stingless bee species (i.e. members of the taxonomic group Meliponini) have been observed visiting macadamia flowers, including in Australia (32), Thailand (77), India (78), and Brazil (76). In Australia and Thailand, *Tetragonula* species are among the most frequent macadamia flower visitors, second only to honeybees (32, 77). At 15 orchards along the east coast of Australia, Heard et al. (32) reported that stingless bees accounted for 35.8% of visits to racemes, though their visitation rate was more variable than that of honeybees, ranging from 0 to 10.7 visits per raceme per hour. Stingless bees have been shown to carry high levels of macadamia pollen in macadamia orchards, with macadamia pollen accounting for as much as 85% of bees' pollen load (119). Like honeybees, stingless bees preferred exposed flowers at the ends of canopies and exhibited peak visitation in the mid-morning (10–11 am) and early afternoon (2 pm), likely in response to nectar concentration peaks (Vithanage and Ironside, 1986). Stingless bees are also increasingly used as managed pollinators in Australian macadamia orchards (36), with hives either introduced seasonally or kept year-round on orchards (39). In 2021, Clarke et al. (120) estimated that managed stingless bee hives contributed 10% of the Australian macadamia industry's pollination needs, with their use expected to increase. Despite their potential significance, research on stingless bee pollination in macadamia crops remains relatively limited compared to honeybees.

While honeybees and stingless bees are both common visitors of macadamia flowers, their contribution to crop pollination services differs. Because they are unable to forage below 18°C (121), stingless bees have more limited foraging time than honeybees, which are able to forage longer on a given day and earlier in the spring flowering season (32). On the other hand, some studies indicate that stingless bees are more effective on a per-visit basis. Heard (31) examined honeybee foraging on macadamia racemes and observed that only 5% of honeybees were actively seeking for pollen (i.e. most were seeking nectar), and that they therefore rarely made contact with the stigma. Conversely, they showed that stingless bees more often foraged for pollen and contacted the stigma, suggesting that that may be more efficient pollinators per-visit than honeybees. They also showed that flowers within an exclusion cage, that excluded honeybees and allowed smaller stingless bees to visit produced a similar number of nuts to flowers open to all visitors, therefore indicating that stingless bees alone were adequate. However, they also suggested that because honeybees are more abundant and move between flowers more frequently, they may compensate for per-visit inefficiency with higher visitation rates (31). By counting pollen deposited onto macadamia stigmas, Howlett (122) and Evans (123) found that stingless bees were more efficient pollinators (rate of pollen transferred to stigma per visit) of macadamia flowers, compared to honeybees. However, Howlett (122) found honeybees to be more effective (efficiency multiplied by frequency) than stingless bees because they were more abundant at most study sites. Cook (124) placed stingless bee hives in a single cultivar macadamia block, as well as hives between two blocks of different cultivars, and identified 21-43% of stingless bees returning to hives were carrying macadamia pollen from different macadamia cultivars, suggesting that some foraging visits may lead to successful cross-pollination. Grass et al. (51) also showed that while 99% of visitors to their study orchard were honeybees, trees were still heavily pollen limited, and that nut set was lower in trees with a higher density of managed hives nearby. The authors suggest this may be because, in the absence of competition from other pollinator species, honeybees may have foraged over short distancers only as has been shown in a number of other crops (125), limiting cross-pollination potential between cultivars. It has also been suggested that the presence of both honeybees and stingless bees within orchards may lead to synergistic benefits. For instance, while larger honeybees may deposit cross-pollen on the style during a visit, smaller stingless bees may then transfer this pollen onto the stigmatic surface during a subsequent visit (31). Additionally, competition between the two species may lead to increased movement between racemes and cultivars, if a visit is disturbed by the other species (23). Practical considerations such as availability and price also determine the importance of each pollinator, with macadamia growers reporting that stingless bee hives are more expensive ($110/hive) and more difficult to source than honeybee hives ($50/hive) (1).

Studies have also observed various other pollinator species visiting macadamia flowers (i.e. other than honeybees or stingless bees), including various other bee species, flies, beetles, wasps, moths, butterflies and birds (32, 77, 83). Macadamia flowers display an open, 'generalist' floral morphology, making them accessible to a wide range of pollinator species (31). Day/night exclusion experiments have found that nocturnal pollination is rare, showing most pollination is carried out by diurnal insects (23, 80). In Australia, bees from the *Braunsapis*, *Lasioglossum*, *Leioproctus* (*Leioproctus*), *Hylaeus* (*Prosopisteron*), *Homalictus* and *Hylaeus* genera have been observed visiting flowers (23, 32, 122). While in Thailand *Halictus, Megachile* and *Andrena* bees and observed flies from two families have also been observed on racemes (77). Heard et al. (32) observed 26 species of flies visiting macadamia flowers in Australia, and hover flies (Syrphidae) in particular were also highly abundant on macadamia flowers in Hawaii (9). Ramotjiki (52) observed that 35% of visits to a South African macadamia orchard were from fly species. Whitehouse (115) found in Bundaberg QLD that 20 insect taxa visiting macadamia flowers. Most of visits (89%) were comprised of honey bees, while flies, beetles, wasps and butterflies comprised the other visitors. Santos et al. (75) found that butterflies were the most common visitor on macadamia racemes in Brazil, accounting for >50% of visits. In Australia, Willcox et al. (126) observed that the majority of insects (56.6%-94.1%) were bees in the Apidae family, with the remainder made up of flies (Calliphoridae, Syrphidae), beetles (Coccinellidae, Lycidae, Rhinidae, Chrysomelidae) and ants. Heard et al. (32) also observed four bird species visiting flowers in Australia, though they were much less common than insects.

While a variety of pollinator species have been observed visiting macadamia flowers, little research has examined the pollinator effectiveness of different species, with the exception of honeybees and stingless bees, as discussed above. Vithanage et al. (23) speculated that a beetle (*Metriorrhyncus rhipidius*) and a wasp (*Campsomeris tasmaniensis*) which were regularly seen visiting racemes may be viable pollinators. *M. rhipidius* was observed spending more than 30 minutes on racemes, then moving between trees carrying large amounts of pollen, while *C. tasmaniensis* were observed moving between trees carrying less pollen. By counting pollen deposited onto macadamia stigmas, Howlett (122) found that wild pollinators including lycid beetles (*M. rhipidius*), soldier beetles (*C. tasmaniensis*), nose flies (*Stomorhina discolour*) and scarab beetles (*Glycyphana stolata*) were capable of depositing pollen on stigmas. However, they suggested that these species are likely to contribute only incidentally to pollination, due to low abundance within the crop. Effective pollinators must both be efficient (capable of per-visit pollen transport) and abundant on flowers in the target crop. Where the abundance of a pollinator species is negligible, it is unlikely that they significantly contribute directly to crop yield (127). However, wild pollinator abundance varies regionally, and some orchards may benefit from significant abundances. For instance, in the Northern Rivers, Australia, Evans (123) showed that 70% of visits were from two beetle species (*Porrostoma rufipenne* and *Monolepta australis*), in South Africa, Ramotjiki (52) showed that 35% of visits were from flies, and in Brazil, Santos et al. (75) showed that 50% of visits were from butterflies. Santos et al. (75) also showed that visits from butterflies supported initial nut set equivalent to hand cross-pollination. These instances provide examples of non-honeybee/stingless bee pollinators that are likely to directly deliver pollination benefits.

However, research from other crops shows that wild pollinators can provide indirect pollination benefit even in low abundances. Honeybees and stingless bees leave notable gaps in the pollination services that they provide to macadamias, which wild pollinators may be better adapted to fill. For instance, Heard et al. (32) show that honey bees and stingless bees both prefer racemes near the outside of the canopy, potentially due to light intensity, while Howlett et al. (128) show that some wild pollinator species visit flowers at low light intensity in other crops. Other insect species may also be more tolerant of low temperatures and inclement weather conditions, allowing them a larger foraging window throughout the season and on an individual day (129). Greater pollinator diversity may also help to facilitate competition and increased movement between racemes, with different species interacting to disturb each other from flowers, as has been shown in almonds (125) and sunflowers (130). In the absence of wild pollinators, research shows that honeybees can restrict their foraging range in other crops, such as within single rows of trees (125), which may reduce outcrossing between cultivars (125, 130). As a result of all these factors, studies of many crops support the general pattern that diverse pollinator communities produce higher fruit set than any can be achieved by honeybees alone (131). Nevertheless, further research is needed on the relative contribution of different wild pollinator species to macadamia pollination in particular.

All survey respondents believed that wild pollinators were present on or near their orchards, citing mainly personal observation as the basis for that belief. Some comments also referred to nearby abundances of native vegetation as cause for assumption. Several interviewees also discussed the assumption that wild pollinators must be visiting and pollinating, due to the occurrence of decent macadamia yields. Survey data demonstrates this belief also, with growers acknowledging a moderate or great contribution from most pollinators (see Figure 6).

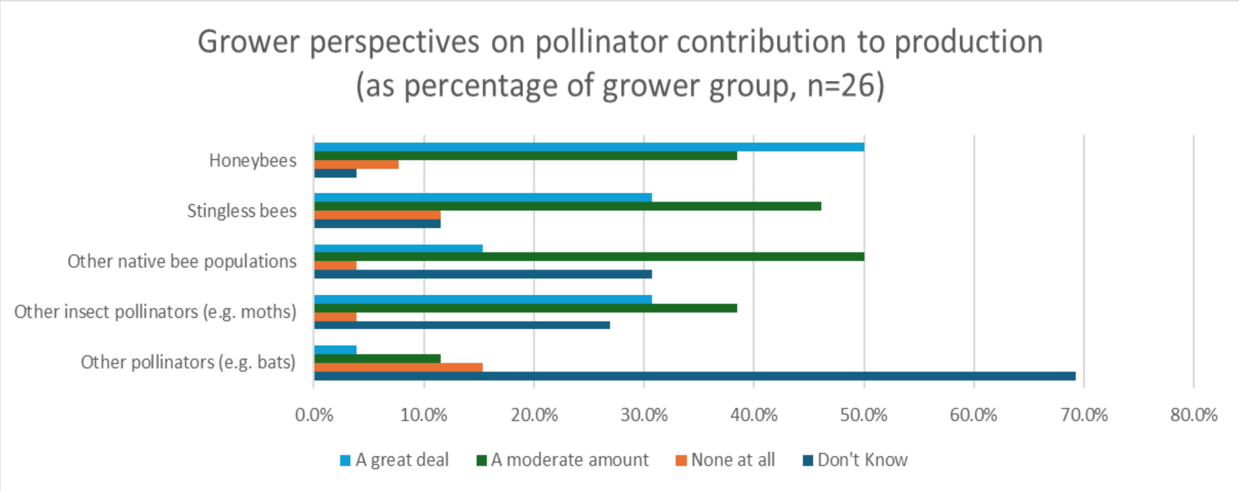

Figure 6: Grower perspectives on the contribution of different pollinator populations to their macadamia production

Several interviewees were also strong believers in the value of stingless bees, to the point of developing their own stingless bee hive capacity. Five of the growers surveyed also indicated they managed their own stingless bee hives. Interviewees generally were open to discussions about the need to modify management e.g. spraying behaviours to accommodate beneficial insects. Survey respondents also listed several actions they saw as the highest priority management change they thought could help improve pollination on their orchards, including "improving habitat for beneficial insects", "establishing native hives", and promoting "year-long floral diversity" on and around their orchards.

Summary

Observational studies across multiple countries indicate that European honeybees are the dominant flower visitors in macadamia orchards, often comprising the majority of recorded visits. While honeybees are widely regarded as the primary pollinators due to their abundance, stingless bees are also frequent visitors and are likely to be more efficient pollinators per visit. Honeybees compensate for their lower efficiency through higher visitation rates. Other pollinators, including various beetles, flies, and butterflies likely contribute to macadamia pollination, and in some regions comprise the most abundant pollinators. There is no evidence to support the idea that nocturnal pollination (e.g. moths) is important. The overall contribution of each species of pollinator to macadamia yield remains uncertain, highlighting the need for further research into their role in macadamia pollination systems.

The anecdotal observational evidence supplied in the survey and interviews suggests that growers do have an appreciation of the role of wild pollinators in the productivity of their macadamia crops. Further research into the contribution of different pollinator species, including stingless bees, could greatly support grower decision-making.

How will the spread of the Varroa mite impact the Australian macadamia industry?

With the recent arrival of the Varroa mite to Australia, there are growing concerns about reliance on honeybees for macadamia crop pollination. The impact of Varroa mite incursion on the Australian macadamia industry remains uncertain, though studies have predicted potential effects of honeybee declines on the broader Australian horticultural industry (123). Macadamia flowers attract a diverse range of pollinators, which may lend resilience to pollination services. A key unknown is the extent to which macadamia pollination currently relies on feral honeybee populations (i.e. unmanaged or wild honeybees), and how their decline due to Varroa mite will impact overall pollination rates. It is possible that Australian macadamias benefit significantly from feral honeybees, which are present in higher numbers in Australia compared to overseas (132), underscoring the potential loss of pollination services to Australian macadamias if feral honeybee populations decline. It is known that wild populations of honeybees are vulnerable to Varroa because they will not receive management from apiarists to control mites, with feral bee populations in other countries dramatically reduced by the incursion Varroa (133). At the same time, many small-scale and hobbyist apiarists are expected to stop beekeeping due to increased costs of managing Varroa, with remaining hives aggregating in larger companies and the risk of loss of services and reduced availability in some regions (133). While research has not directly quantified the relative pollination contribution from wild honeybees, a 2022 survey of Australian macadamia growers indicates that growers attribute 15% of their macadamia pollination to wild honeybee populations (120). Resilience to the spread of Varroa mite is likely to be regionally variable, with smaller Northern Rivers orchards adjacent to remnant vegetation expected to fare better than larger Bundaberg plantations with less intact habitat to provide alternative pollinators (1). While honeybees have been recorded as the most abundant and effective visitors to Australian macadamia crops (88), the proportion of these bees from wild versus managed hives remains uncertain, with wild hives likely playing an important role in some orchards (122). In Hawaii, after the loss of feral hives due to the arrival of the Varroa mite, growers had to shift towards reliance on managed honeybees, which were still the most abundant flower visitor, representing 63% of observations (15). To compensate for predicted declines in wild honeybees, growers may need to increase reliance on managed hives to maintain adequate pollination services or make efforts to increase stingless bee and other wild pollinator numbers (123). Based on insight from other countries where Varroa is present, it is expected that the cost of hiring honeybee hives in Australia will increase significantly due to rising hive management costs (134, 135).

Bundaberg interviewees noted that the demand for managed pollinators will 'skyrocket' over the next few years, as new plantings come online (see Box 4). The accessibility of hives was already noted as a limiting factor by several interviewees, and the increased demand would presumably only compound this challenge. Combining this increased demand with the potential impacts of Varroa on the beekeeping industry would suggest significant challenges for many growers in accessing adequate paid pollination services in the near future. Growers indicated in the survey and interviews that their interest in managing their own hives (stingless or honeybees) was a result of recognising the issue of accessing hives.

"Demand for bees is going to go through the roof… What's going to come online in the next 5 years is going to be massive."

"My neighbours are not convinced that they require… pollination services. They've developed a false sense of security because there is a lot of native vegetation and native insects around at the moment"

Box 4: Interview quotes regarding honeybees demand and accessibility

<u>**Summary**</u>

The arrival of the Varroa mite in Australia has raised concerns about the macadamia industry's reliance on honeybees for pollination. While macadamia flowers attract a diverse range of pollinators, the extent to which wild honeybees contribute to pollination remains unclear. Wild honeybee populations are expected to decline significantly, leading to regional differences in resilience, with some areas better positioned to maintain pollination services from other sources. Managed honeybee services may increase in price and decrease in availability. Growers may need to increase their reliance on managed hives or alternative pollinators to compensate for expected honeybee declines. The relative contribution of wild honeybees, managed honeybees and other wild pollinators to macadamia pollination remains a key knowledge gap, and will determine resilience to Varroa.

Accessibility of managed hives is already an issue for growers, and demand is expected to increase. Several growers have moved towards managing their own stingless bee hives as an input for their own orchards, and the industry could consider supporting such a move amongst other growers, as well as researching the contribution of different pollinator species to macadamia orchard productivity.

How can wild insect numbers be encouraged in macadamia crops?

Preserving nearby native vegetation provides an effective means of increasing pollination services provided by wild pollinators. This has been demonstrated in in large studies across many different crops (136, 137) and specifically for macadamias in Australia (117) and South Africa (55). Blanche et al. (117) showed that pollinator visitation rates to macadamia trees were higher nearby to remnant vegetation (tropical rainforest), and that this resulted in higher initial fruit set. Similarly, Anders et al. (56) found increased insect visitation and higher nut set in macadamia rows planted perpendicular to remnant vegetation by measuring yield from macadamia trees with increasing distance from remnant vegetation. Anders et al. (55) also found that pollination services increased in macadamia orchards where tree rows were placed nearby and perpendicular to natural habitat in South Africa. To assess this, these studies compared pollination rates and nut set between orchard rows that were planted parallel versus perpendicular to remnant vegetation. Perpendicular row planting relative to natural habitat may help to facilitate pollinator dispersal into orchards due to insects' tendency to follow orchard rows rather than move across them (56). Studies also show higher abundance of stingless bees in macadamia orchards when there is native vegetation nearby (23, 28, 32). These results are consistent with higher abundance of wild pollinators nearby to remnant vegetation in other cropping systems (131, 138), including almonds (139). Remnant vegetation provides pollinators with nesting substrate (140) and a diversity of year-round floral resources, promoting pollinator community health outside of crop flowering periods (141). Wilson et al. (48) also shows that stingless bee hives permanently located at macadamia farms are reliant on a diversity of plants present in the landscape outside of crop flowering season (142). With these principles in mind, Weier et al. (5) highlight the role of preserving adjacent natural habitat to improve wild pollinator activity in their recent review of macadamia farm management. Cunningham et al. (132) also document that feral honeybee hives have been detected in Australian *Eucalyptus* woodlands in high densities consistent with the hive stocking rate of some crops (69 hives/km^2), highlighting the value of preserving adjacent woodland habitat alongside crops that benefit from honeybees.

The use of pesticides has also been implicated in reducing wild pollinator numbers in macadamia crops. By surveying pollinator abundance in South African macadamia orchards, Linden (53) showed that bee abundance (mostly European honeybee, with some stingless bees) was reduced after pesticide application, and increased significantly with time after application. Pesticide spraying was also indirectly linked to the absence of native stingless bees in Queensland orchards, while honeybees were more resilient (27, 117). To reduce negative impacts on pollinators, pesticide application should be informed by regular scouting of pest levels to determine when pest populations surpass critical thresholds, and be based on, for instance, degree-day models of stinkbug growth stages (5, 143).

Growers surveyed indicated a level of understanding about what practices can be undertaken to promote wild pollinators, with most respondents acknowledging that a sensitivity about the use and timing of insecticides, and the use of pesticide more broadly on the farm was important. There was slightly less evidence of practices related to pollinator-friendly plant combination, though protecting existing vegetation was recognised as worthwhile (see ***Error! Reference source not found.****).*

Interviewees also expressed a range of views on the importance of promoting wild pollinators, with some considering it to be one of their most important management actions, and others ranking it lower in their list of priorities (See Box 5 examples). Growers that discussed the limited accessibility of managed hives to provide pollination services acknowledged the importance of encouraging wild pollination services as much as possible. The cost of more targeted insecticides was noted by both interviewees and survey respondents as a key barrier to increasing pollinator-friendly practices.

> "(Paid) pollination is not a priority for me… I think there's enough wild insects… if the growers aren't spraying and knocking them out, at the flowering period, then we are getting some pollination from them. I'm not spraying open flowers, consciously"
>
> "I let all the beneficial plants grow in every other row, to look after the beneficial insects. And we only spray to thresholds, not calendar sprays"

Box 5: Interview quotes: practices to promote wild pollinators

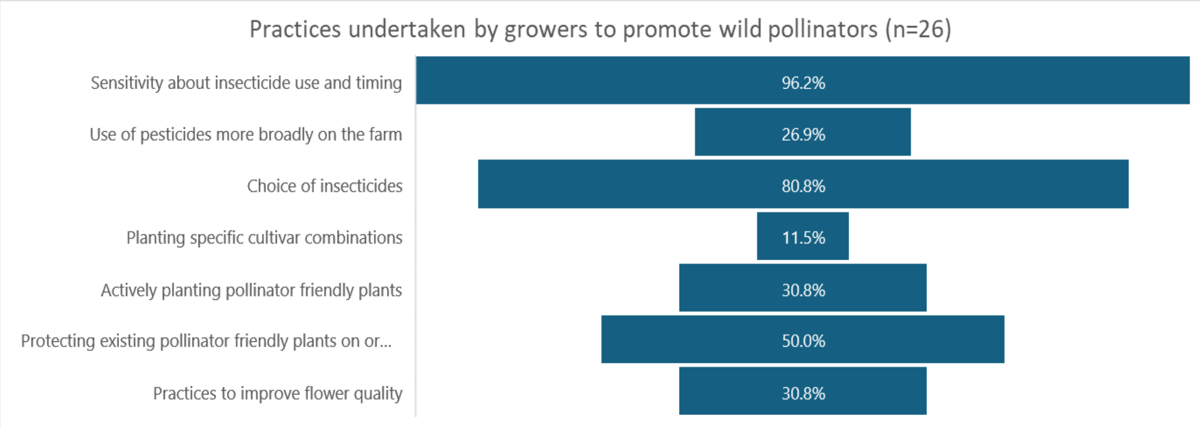

Figure 7: Practices undertaken by growers to promote wild pollinators

Summary

Consistent with findings in other crops, preserving remnant vegetation near macadamia orchards has been shown to enhance pollination services by supporting wild pollinators through nesting habitat and year-round floral resources. Studies in Australia and South Africa demonstrate that proximity to natural vegetation increases pollinator visitation rates in orchards, resulting in higher nut set and yield. Conversely, pesticide application negatively affects pollinator abundance, particularly native stingless bees, though honeybees show greater resilience. To enhance wild pollination services, farm management strategies should incorporate pollinator-friendly pesticide application and seek to conserve adjacent natural habitat. While there are some examples in the research, more studies are required to assess the impact of pesticide use on pollinator health to better inform guidelines for growers.

Some understanding is present about the value of promoting wild pollinators and the practices that do so. Building on this understanding by demonstrating the value and benefits of wild pollinators to crop yield may be an important aspect of increasing these practices.

How should managed bee hives be used to ensure optimal macadamia pollination?

Honeybees and stingless bees are both used as managed pollinators of Australian macadamia orchards (88), but approaches to managing pollinators in the macadamia industry vary. For instance, our grower surveys indicate that while some growers place hives in their orchards, the quantity of hives can vary greatly, and not all growers use managed bee hives. Although there is no direct research to inform industry standard honeybee hive stocking rates, the Australian Macadamia Society recommends between 2-5 hives/ha of Macadamia orchard (1), with other sources suggesting between 5-8 hives/ha (104, 144). However, these figures are estimates, with insufficient research directly measuring the impact of hive stocking density on macadamia yield. By examining nut set from trees at different proximity to honeybee hives, Grass et al. (51) also showed that nut set declined where colony density was too high, indicating that there may also be an upper limit. Because studies have demonstrated a correlation between honeybee visitation rates and macadamia nut set (17, 117), it is likely that optimizing hive stocking rates will improve macadamia yields. It is difficult to determine optimal hive stocking rates because many other factors also influence macadamia pollination outcomes (43). For instance, interplanting of cultivars (27, 36), the use of pesticides (27), hive strength (88), and the availability of nearby floral resources have all also been implicated in seed set resulting from pollinator visits (145, 146). Research into optimal hive stocking rates would help to inform clear guidelines that improve pollination farm management.

Alongside securing a sufficient quantity of bee hives, farm managers should also ensure that the arrangement of hive placement enables quality pollination services. To cover the macadamia flowering period, bee hives are required in NSW from the third week of August for about 7 weeks, and in QLD from the second week of August for about 6 weeks (1). However, by examining pollen carried by stingless bees in a macadamia orchard, Cook (124) found that placing hives within macadamia crops prior to crop flowering decreased their crop specificity compared to foragers from hives placed during flowering. They show that hives placed in orchards early were valuable for pollinating early opening flowers, but that sequentially introducing hives to orchards every two weeks ensures bees remain focused on foraging from macadamia rather than from other flowers (124). Research from other crops on honeybees also suggests that incremental introduction of hives throughout the flowering period can help to keep them focused on the target crop's flowers (146).

Hive spacing and arrangement is another important consideration in macadamia orchards, with different approaches needed for stingless bees and honeybees. Evans et al. (85) found that stingless bee abundance declined significantly within macadamia orchards with increasing distance from hive, with >96% of individuals recorded within 100m. They therefore suggest placing stingless bee hives at regular 100m intervals throughout orchards to promote even distribution of pollination services. While they did not find a similar distance relationship for honeybee abundance, they only sampled up to a maximum distance of 325m, with other studies indicating greater foraging distance for honeybees in macadamia (13) and almonds (147). By marking individual bees at increasing distances from the hive and then counting their return to the hive, Gary et al. (13) showed that honeybee foraging range within a macadamia orchard was likely within a 250-600m distance from the hive, but declined up to 750m away. In almonds, Cunningham et al. (147) surveyed flower pollen load and fruit set with increasing distance from honeybee hives, and found that honeybee foraging activity declined above 850m, suggesting hive placement of <700m apart.

The main limiting factors identified by survey respondents regarding the accessibility of managed hives included: the placement of hives, the availability of hives, and the timing of hives being on the orchard.

*Survey data also revealed an interesting discrepancy between the price per hive currently paid, and beekeepers expectations. The majority of growers report paying <$50 per hive, which aligns with the industry professionals believes about the price, and what was reported by the beekeepers surveyed see **Error! Reference source not found.** below. (Note: Only growers or beekeepers who indicated they were paying for pollination services answered this question, hence the reduced count. Industry professionals were asked what they thought growers were currently paying for pollination services).*

*However, when asked "What would you expect to pay/be paid for a professional pollination service with strong hives?", there was a clear difference between the groups, with the majority of beekeepers indicating they expected to be paid much more for their services, while most growers expected they could keep paying the same amount (see **Error! Reference source not found.**). (Note: more growers were asked this question than just those who indicated they currently pay for pollination services, hence the increase in total count).*

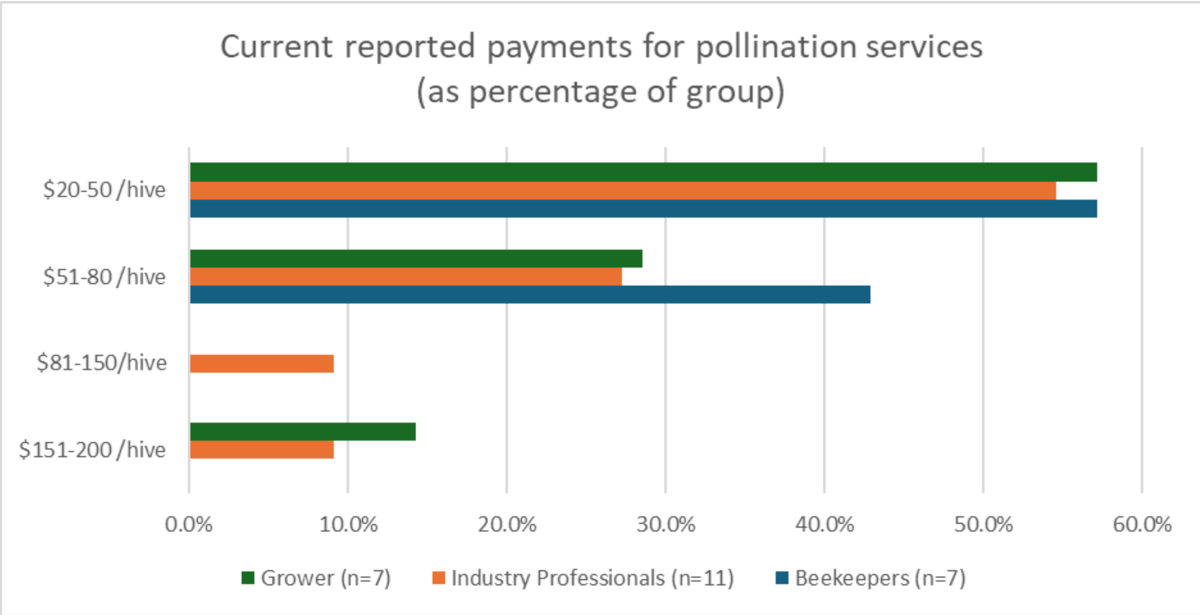

Figure 8: Current report payments for pollination services across the three groups surveyed, split by surveyed group (with different group *n* indicated in legend).

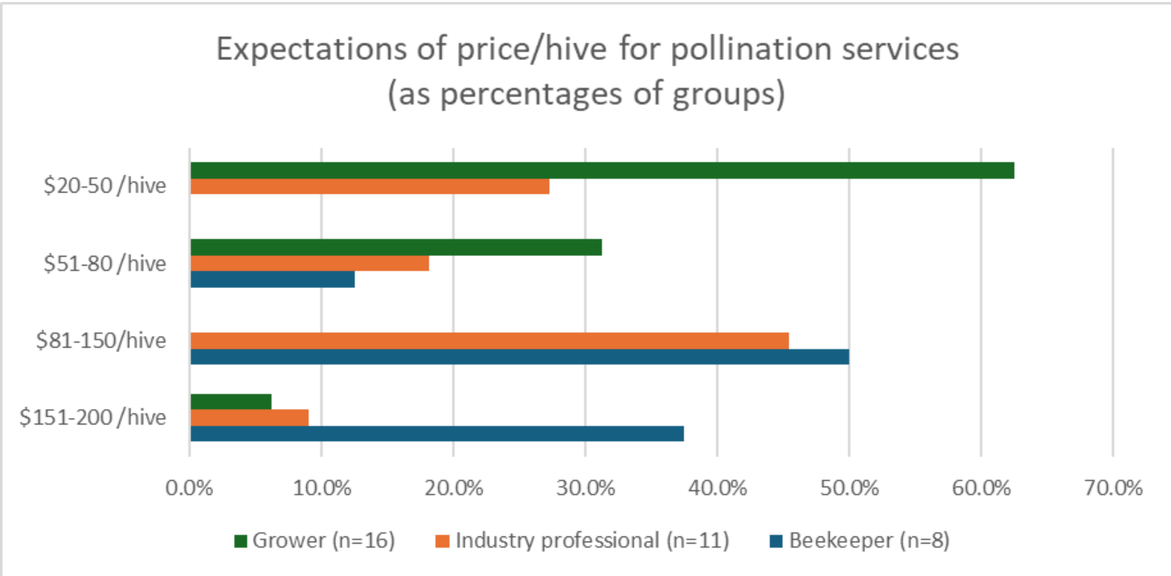

Figure 9: Expectations of price/hive to pay/be paid for pollination services, split by surveyed group (with different group *n* indicated in legend).

Beekeepers (n=7) were also asked what the most significant considerations or constraints were on them providing hives for pollination services. Price per hive was ranked as the top most significant consideration by almost half the respondents, and with 71% placing it in their top 3. Use of pesticides on orchards was also ranked in the top 3 by 71% of respondents, with competing honeyflows, preparation needed to provide hives, and timing of hives being required on orchard equally ranked in the top 3 by 42% of respondents.

Summary

Honeybees and stingless bees are key managed pollinators in Australian macadamia orchards, but optimal hive stocking rates remain unclear, with recommendations ranging from 2-8 hives per hectare for honeybees, and no recommendations available for stingless bees. Alongside hive stocking rate, research suggests that the hive introduction timing and hive arrangement is important. Sequential hive introductions during flowering improve pollinator focus on macadamia flowers. Stingless bees have a limited foraging range, and so hives should be placed at 100m intervals. Honeybees are capable of foraging at greater distances, so that hives should be spaced within 250-600m for effective foraging. More research is needed to fill knowledge gaps on adequate honeybee hive stocking rates, and may vary substantially depending on reliance on managed honeybees in region of interest and orchard layout. There is also no guidance on the use of managed stingless bee hives within macadamia orchards.

Achieving some consistency of expectations between beekeepers and growers regarding the value of a professional pollination service with strong hives may help to foster improved pollination services relationships between the industries.

Does wind pollination play a role in macadamia crops?

While some growers attribute crop pollination services to wind pollination, research indicates that wind pollination cannot transport sufficient cross-pollen between cultivars. Research has suggested that wind pollination is ineffective due to the large size of clumps of pollen released from flowers, and the small size of the stigmatic surface on flowers (43, 148). Early work by Urata (9) investigated macadamia pollen transport by wind by placing Vaseline slides nearby flowering trees. Based on the pollen that adhered to the slides, they calculated that approximately 4 flowers may be pollinated every 28 hours, concluding that while wind pollination may play an incidental role in pollination, insect pollinators are still the main pollen vector (9). To qualify this conclusion, incidental wind pollination would also only succeed if different cultivars were placed close together. For instance, Anders et al. (56) found that in multi-cultivar blocks, nut set increased in some flowers that were bagged to exclude insects, while this was not the case for bagged flowers in single-cultivar blocks. They suggested that some incidental cross-cultivar pollen may have been transferred by wind, but only in multi-cultivar blocks. Considering the limited influence of wind pollination indicated by these studies, it is unlikely that sufficient cross-pollination can occur from wind, with insects being crucial to maximising yield.

A large minority of growers surveyed (46%) believed that wind pollination contributed 'a moderate amount' (32%) or 'a great deal' (14%) to crop production. Conversely, the majority (63%) of industry professionals surveyed considered wind pollination to be making no contribution to macadamia production (see Figure 10 below). Along with the relatively strong beliefs identified above regarding self-pollination, this suggests a fragmented and inconsistent understanding within the industry about how macadamia pollination occurs, or the potential yield improvements available through prioritizing effective cross-pollination.

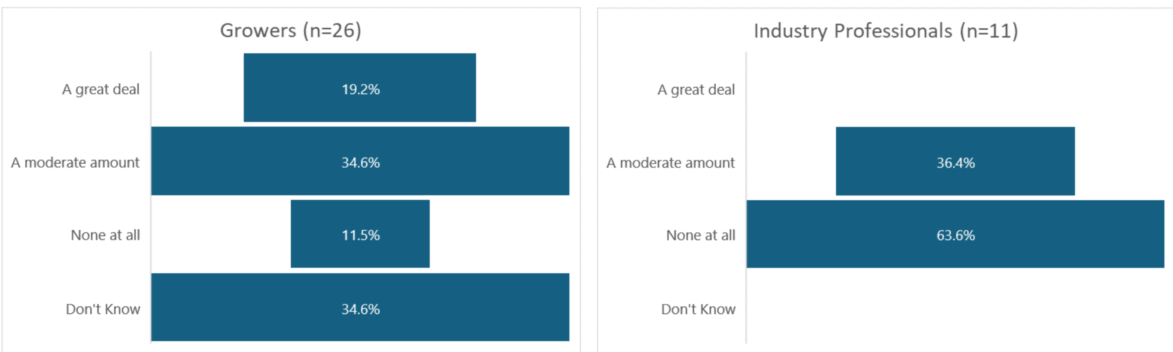

Figure 10: Grower vs Industry Professionals' perspectives on the contribution of wind pollination contribution to macadamia production

Summary

Research shows that wind pollination plays a minimal role in macadamia pollination, likely due to the large size of pollen clumps and small stigmatic surfaces on flowers which impede outcrossing by wind. Studies show that while incidental pollen transport by wind may occur, it is insufficient for ensuring effective cross-pollination between cultivars, even in multi-cultivar blocks. Overall, insect pollinators are essential for achieving sufficient cross-pollination and maximizing yield.

Encouraging growers to engage with the materials compiled through this research project may provide a better understanding of the basic pollination mechanisms of the macadamia plant, which might in turn affect their on-farm prioritisation and management processes.

What role does pollination play in premature nut drop?

Macadamia trees will set many small nuts during the initial stages of fruit development, many of which will then be selectively abscised or aborted before reaching full size. By genetically analysing the parentage of prematurely abscised nuts and nuts that reached maturity, recent research shows that many of the nuts that are dropped prematurely result from insufficient cross-pollination (41). While self-pollinated macadamia flowers will initially set nuts, these nuts are then selectively abscised by the plant before 10 weeks, so that 97% of nuts that reach maturity are cross-pollinated (41). This means that the nuts remaining on Australian macadamia trees by November, after initial drop of undeveloped fruit, are almost all cross-pollinated (149). By hand pollinating Beaumont cultivar flowers with 9 different cultivars, Lavi et al. (150) showed that some pollen donors had a greater impact on fruitlet retention 5 weeks after pollination, suggesting that cross-pollen compatibility also influences nut retention. These results further underscore the importance of ensuring adequate outcrossing between cultivars. While pollination plays an important role in retaining nuts to the harvest stage, nuts can also abscise early even when hand cross-pollinated (21, 34), due to factors such as resource limitation, predation and disease which also help to determine final set (36).

The data described above regarding growers' perspectives on the impact of pollination on the quantity and quality of macadamias may capture some understanding of general role of pollination in macadamia production. One interviewee also described originally noticing an earlier nut drop in the middle of their bigger blocks, but didn't necessarily ascribe this to a lack of cross-pollination, and they were subsequently satisfied with their total overall yield from the block. Overall, there was little evidence of a consciousness of mechanisms of the abortion of self-pollinated nuts within 10 weeks in the survey or interview data, suggesting that a more nuanced understanding of this detail may have significance for how growers prioritize pollination within their wider orchard decision framework.

Summary

Genetic analyses show that macadamia trees selectively abscise nuts that are not the result of cross-pollination, with nearly all mature nuts being cross-pollinated. While self-pollinated nuts may initially set, they are typically aborted within 10 weeks, highlighting the critical role of outcrossing between cultivars. Other factors, such as resource limitations, predation, and disease, also contribute to early nut abscission, underscoring the complex interactions affecting final nut set. It remains unclear whether macadamia cultivars that exhibit higher rates of self-compatibility may retain more selfed nuts or if farm management practices, such as optimizing soil or water conditions, could improve the retention of selfed nuts.

Given that this topic was not highlighted clearly in any of the interview of survey data, increasing general understanding amongst growers about the mechanisms of abscission in self-pollinated nuts may be a worthwhile component of any research project focused on this aspect of pollination.

Conclusions

There is a rich body of published research available on macadamia pollination that establishes many of the key details of the process and how these influence outcomes for growers. The following points emerge as very well documented and significant for production.

- Macadamia relies on cross-pollination to support good yield, with self-pollination accounting for a relatively small proportion of nuts. Self-pollinated flowers often initiate nuts, but these are subsequently aborted in favour of developing nuts from cross-pollination.
- Most pollination is achieved by bees, with honeybees the most widely important and stingless bees important in some locations. There is evidence that stingless bees are more effective pollinators than honeybees on a per visit basis.
- Given the importance of cross-pollination by bees, large blocks of trees of the same variety generally have a lower nut production because the opportunity for bees to move pollen between different varieties (i.e. cross-pollination) is less than in blocks with multiple cultivars in proximity to one another.
- Wild insect pollinators play a significant role in many macadamia orchards and they are more abundant and therefore influential in orchards that are close to native vegetation. Thoughtful use of insecticides can reduce harm to wild pollinators and therefore increase that benefit.

Macadamia growers that we surveyed and interviewed had a number of perspectives on macadamia pollination that did not always align with the research. Although there was a diversity of views, it was surprising the extent to which many had the view that self-pollination was playing an important role; that modes of pollination included wind and moths, and that single variety blocks did not compromise yield.

Disagreements between grower perspectives and published research can have many sources. In some cases it might be that the on-farm conditions are different from controlled experimental conditions so that growers lack confidence that comparison is appropriate. So, for example, it may be that blocks that are considered "single variety blocks" by growers in fact have other varieties represented in the form of shoots from roots stock or planted material with mistaken identity. Or it may be that experiments conducted using different cultivars or in different regions are considered by growers to be difficult to generalise to their circumstances.

Growers are unlikely to have the opportunity to read research papers directly and therefore do not have the opportunity to discriminate between observations that are supported by well replicated research (e.g. that out-cross pollen is much more important to yield than self-pollen) and other ideas that are speculative and not supported by appropriate data, but still be of interest to researchers (e.g. the possibility that honeybees might get cross pollen on their bodies while in the hive, rather than from visiting other flowers themselves).

It could also be that growers feel locked in to the selection and arrangement of cultivars in their orchards, and are therefore reluctant to accept the implication of research that suggests that yield is compromised by those past decisions. Or it could be that growers believe that the cost of those compromises is small relative to the advantage they believe they have in ease of management.

An important contributor to the different understandings is likely to be the different information requirements of researchers and producers. Whereas researchers commonly seek to understand processes and mechanisms, often by isolating them experimentally, producers are understandably more focused on seeing integrated outcomes in their own system, i.e. the macadamia orchard. Therefore, while a researcher might excited to document that there is a significant effect of distance between individuals of different cultivars in determining nut production, a producer might be more concerned to understand exactly how big that effect is, over what distance (i.e. planting layout) and whether the improved planting layout from a pollination perspective might incur increased costs in other management practices.

Project Outputs

Table 1. Output summary

Output	Description	Detail
Project logic and Monitoring and Evaluation plan	Milestone 102	Accepted by Hort Innovation in September 2024
Final Report	Final report comprising literature review and practitioner survey	This publication is the final report. After acceptance it will be made available by on the Hort Innovation web site.
Online compendium	Online compendium of published research relevant to macadamia pollination	This material will be submitted at the same time as this final report. It is anticipated that the Australian Macadamia Society will make this material available on their website.
Workshop	Zoom meeting with industry participants to discuss the final report	Currently being scheduled, subject to availability of the project reference group and other participants. Aiming for late March 2025. The PRG has also invited consideration of a broader face to face engagement to promote the results of this research in a key macadamia growing region. This would require supplementary funding for travel.

Outcomes

Table 2. Outcome summary

Outcome	Alignment to fund outcome, strategy and KPI	Description	Evidence
The key outcome of this project will be that representatives of the Australian Macadamia industry have access to a comprehensive assessment of the current state of knowledge regarding macadamia pollination.	Access to this information will be useful in guiding future research and development for the industry, including future collaborations (i.e. SIP outcome 2). In this way it will support strategy 11 *for improved profitability, efficiency and sustainability, which is to enhance crop pollination and resilience through improved pollination security*. It will also improve the capacity for the industry to extend evidence-based advice on practice for growers and beekeepers to support improved capability and an innovative culture in the industry (i.e. SIP outcome 3) in particular supporting strategy 1 to deliver communication and extension capability in areas of issues including pollination.	This final report documents the outcome of the literature review and the survey of growers. It is available to all macadamia industry members and the general public (via Hort Innovation web site). To enhance the industry understanding of major findings the work will also be presented and discussed in the on-line workshop.	This final report, the workshop and the on-line compendium each provide the relevant information for industry members. Evidence for the impact of this project on the state of understanding in the industry would have to be collected after release of the final report and the conduct of the workshop.

Monitoring and evaluation

Table 3. Key Evaluation Questions

Key Evaluation Question	Project performance	Continuous improvement opportunities
To what extent has the project informed industry leaders regarding the level of awareness of pollination requirements and practice among growers?	The outcomes of the quantitative survey and the qualitative interviews address this question and are reported here.	These survey approaches could be repeated in future to determine if there are changes in awareness, attitudes or practices
To what extent has the project improved access to knowledge of macadamia pollination requirements?	The compendium of literature produced in this project provides, for the first time, an entry point for industry members to examine the state of relevant research-informed literature.	This compendium is up to date at the time of publication. Over time new information will come to light and it would be possible to update the compendium.
To what extent has the project met the needs of industry levy payers?	The project questions and scope were set by industry in a RFQ process. A PRG (project reference group: industry representatives) monitored milestones to ensure the project stayed focused on needs.	The PRG group was an efficient mechanism for managing this need and our conversations were productive. Scheduling meetings for all to attend is time consuming and it may be better if more were scheduled well in advance.
Did the industry survey achieve adequate levels of participation?	There was initial concern that participation was lower than expected, which prompted us to discuss with the project reference group and others if there were opportunities to promote higher participation. A second effort (using personal networks and comms from AMS) brought participation to a level that was satisfactory and, according to advice, exceeded that for some other similar activities.	If the project timelines were longer then there would be more opportunity to drive involvement in the survey.
Is the PRG satisfied with the level of communication with researchers?	Feedback from meetings suggest that the PRG is satisfied.	
What changes to project delivery occurred from stakeholder insights?	Questions and comments from stakeholders, such as in the qualitative survey, shaped the way that we structured and synthesised the literature review.	A longer project time line would allow more time for interplay between feedback and conduct of the project.
Did the project deliver outputs and outcomes on time and on budget?	Project delivered on budget and final report delivered on time. Difficulty in scheduling the final workshop are likely to mean this output will be delivered after the agreed project end.	A longer project time line would allow more flexibility in scheduling events.

Recommendations

In this section we provide a gap analysis and recommendations for how the industry best addresses these gaps. This section builds from the synthesis presented under the sub-heading "Conclusions", where we identified gaps between the state of knowledge in published literature, and the perceptions of producers. We recommend the following actions to reduce these gaps.

Recommendation 1: Focus on activities that demonstrate or reveal "best practice" in a real farm context. These should focus on benefits relative to cost of integrated strategies (i.e. planting design and associated management) rather than the component variables that much existing research examines. In other words, rather than more research on a question like "how much self-pollination is occurring?" instead focus on demonstrating how to operate a block with multiple cultivars and then show the cost benefit analysis from a producer view point. If growers can be given incentives to share data on their own operations, including yield, then there would be many existing plantings that would generate valuable insights.

Recommendation 2: Learn from macadamia growers in other regions (e.g. South Africa, China, Brazil) and also from growers of other tree crops in Australia. While some challenges might be particular to Macadamias in Australia, most are not. For example, even though there can be a trade-off between the cost of management and the benefit of growing more than one cultivar, this challenge has been faced and resolved many times. Leading industry figures could benefit from study tours (both domestic and international) that give them the opportunity to learn and bring ideas back into the Australian Macadamia industry.

Recommendation 3: Support case study research on blocks that have been adjusted from single cultivar blocks to modified blocks with areas of replanting that introduces other cultivars. If it can be demonstrated that there are ways to modify single cultivar blocks that are less expensive than complete redevelopment then more growers might be open to the possibility of making changes to improve yield.

Recommendation 4: Whereas the focus of recommendations 1-3 is on learning by doing rather than pushing out more research-based information, there is still a role for communication of existing research. In those cases where the research is clear there may be benefit to the industry communicating more directly regarding "What we know about Macadamia Pollination". Such communication might encourage people to focus attention on management practices that are more likely to be rewarding

Recommendation 5: Although our primary conclusion is that gaps relate more to an understanding and implementation gap, rather than a knowledge gap per se, there are nevertheless research and development areas that remain important. Generation of improved cultivars is always important and ease of pollination should be considered an important trait for this crop. This could be achieved by increasing the rate of effective selfing, or increasing the cross-compatibility of productive cultivars or by making cultivars more uniform on their management requirements. Staying informed regarding developments in other producer countries is an important contribution here.

Recommendation 6: All pollination dependent crops in Australia need to consider risks to the managed pollinators, including the impact of Varroa. The macadamia industry has a unique profile because of the timing of flowering relative to other crops that require honeybees and the highly variable use of paid pollination currently. The industry would benefit from a risk analysis that models possible impact scenarios in terms of loss of pollination from feral honeybees, increased charges for honeybee hives and the capacity for the managed stingless bees to help fill gaps. This risk analysis should consider the economic benefit that might arise from pollinator friendly insecticide use. Although we can benefit by learning about paid and free pollination in other countries, the risk analysis must be tuned to the very particular set of circumstances for growers and beekeepers in Australia.

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Intellectual property

No project IP or commercialisation to report

Acknowledgements

We would like to acknowledge the generous support of growers, industry professional and beekeepers who contributed to this report. In addition to those who participated in the on-line survey, others were willing to engage in interviews that were vitally important in shaping this report. We also thank the project reference group for their on-going feedback and advice during the conduct of the research.

Appendix I: Summary of Survey Data

This appendix presents results of the survey additional to those that have been presented in the body of the report.

Overall attributes of the sample population

	Count	%
Role		
Macadamia grower	26	57.8
Beekeeper	8	17.8
Industry professional	11	24.4
Total	*45*	*100*
Age, years		
19-29	2	4.4
30-39	2	4.4
40-49	13	28.9
50-59	14	31.1
60 and above	12	26.7
Prefer not to say	2	4.4
Total	*45*	*100*
Gender		
Male	36	80
Female	8	17.8
Prefer not to say	1	2.2
Total	*45*	*100*

	Macadamia grower	Industry professional	Beekeeper	Total
Age, years				
19-29	0	1	1	2
30-39	1	1	0	2
40-49	5	4	4	13
50-59	9	3	2	14
60 and above	10	1	1	12
Prefer not to say	1	1	0	2
Total	*26*	*11*	*8*	*45*
Gender				
Male	21	8	7	36
Female	4	3	1	8
Prefer not to say	1	0	0	1
Total	*26*	*11*	*8*	*45*

Grower and orchard attributes

Note: "missing" indicates respondents were either not asked this question, or did not answer

Years as a grower	Count	%
2-5	3	11.5
5-10	8	30.8
more than 10	15	57.7
Total	*26*	*100*

Tree age, years	Count	%
0-5	1	3.8
5-15	7	26.9
15+	18	69.2
Total	*26*	*100*

ORCHARD PRODUCTION			
Nut in shell/ha	**Count**	**Total nut in shell**	**Count**
1t/ha	4	20t	2
>2t/ha	2	29t	1
>3t/ha	3	50t	4
>4t/ha	6	70t	1
>5t/ha	1	78t	1
Total	*16*	100t	1
		Total	*10*

These were asked as an open-ended text entry questions, and the answers have been categorized post-hoc. Although asked to provide answer as 'nut-in-shell/hectare' some respondents have answered with total production figures.

Q: How is the majority of your orchard arranged in terms of varieties?		
	Count	**%**
Blocks of one variety	10	38.5
Blocks with row variation (i.e. different varieties in each row)	10	38.5
Blocks with variation within rows (i.e different varieties within each row)	2	7.7
Other	4	15.4
Total	*26*	*100*

Q: Do you know if cross-pollination was a consideration in the arrangement of varieties on your orchard?		
	Count	**%**
Yes	13	50
Yes, but ease of harvesting was considered more important	5	19.2
No	5	19.2
Other	3	11.5
Total	*26*	*100*

Q: What are the first, second and third most important varieties in your orchard?			
Variety	1st (count)	2nd (count)	3rd (count)
741	5	3	
246	3	2	0.5
344	3	3	3
A203	3	3	4
MCT1	3	1	2
Daddow		3	1
A16	1	2	1
A4	1	1	2
816		2	5
A38	1	1	1
849	1	1	
842	1		
A268	1		
A29	1		
Nutty Glen	1		
M500		1	
660		1	
508			1
788			1
H2			1
333			0.5
NA	*1*	*2*	*3*
Total	*26*	*26*	*26*

Pollination knowledge

GROWERS: Would you say you are aware of the pollination needs of your crop?		
	Count	**%**
Strongly agree	11	42.3
Somewhat agree	9	34.6
Neither agree nor disagree	3	11.5
Somewhat disagree	2	7.7
Strongly disagree	1	3.8
Total	*26*	*100*

GROWERS: Do you think effective pollination is an important factor in the productivity of your crop		
	Count	**%**
Strongly agree	17	65.4
Somewhat agree	8	30.8
Neither agree nor disagree	0	0.0
Somewhat disagree	0	0.0
Strongly disagree	1	3.8
Total	*26*	*100*

GROWERS: Are you concerned about the risk of poor pollination on your orchard?		
	Count	**%**
Yes	22	84.6
No	2	7.7
Not sure	2	7.7
Total	*26*	*100*

Q: How much contribution do you think self-pollination within a single variety block makes to your yield?		
	Count	**%**
Growers		
No contribution	1	3.8
A small contribution	4	15.4
A large contribution	6	23.1
A very significant contribution	4	15.4
Not sure	11	42.3
Total	*26*	*100*
Industry professionals		
No contribution	1	9.1
A small contribution	8	72.7
A very significant contribution	1	9.1
Not sure	1	9.1
Total	*11*	*100*

Perceived contribution of wind pollination to production (as percentage of group)		
	Industry Professionals (n=11)	**Growers (n=26)**
A great deal	0.0%	19.2%
A moderate amount	36.4%	34.6%
None at all	63.6%	11.5%
Don't Know	0.0%	*34.6%*

GROWERS: Effect of effective pollination		
Quantity of macadamias produced	**Count**	**%**
None at all	0	0
A moderate amount	7	26.9
A great deal	19	73.1
Total	*26*	*100*
Quality of macadamias produced		
None at all	1	3.8
A moderate amount	9	34.6
Don't Know	4	15.4
A great deal	12	46.2
Total	*26*	*100*

Contribution of pollinator populations to crop production (percentages of grower group, n=26)				
	Don't Know	**None at all**	**A moderate amount**	**A great deal**
Wind	34.6	11.5	34.6	19.2
Other pollinators (e.g. bats)	69.2	15	11.5	3.9
Other insect pollinators (e.g. moths)	26.9	3.9	38.5	30.8
Other native bee populations	30.8	3.9	50.0	15.4
Stingless bees	11.5	12	46.2	30.8
Honeybees	4	8	38	50
Other				3.9

Paid pollination

GROWERS: Do you pay for pollination services?		
	Count	**%**
Yes	7	26.9
No, but I still get hives on my orchard	5	19.2
No	8	30.8
No, but I have my own bees	6	23.1
Total	*26*	*100*

BEEKEEPERS: Have you ever been paid to provide macadamia pollination services?		
	Count	**Valid %**
Yes	7	87.5
No, but I still put hives on or near a macadamia orchard	1	12.5
Total	*8*	*100*

Current payment/hive for pollination services + Expectations of fair price to pay/be paid for professional pollination service with strong hives						
	Grower paying (n=7)	Grower expect to pay (n=26)	Industry believe paying now (n=11)	Industry professional expect to pay (n=11)	Beekeeper Paid Now (n=7)	Beekeeper expect to be paid (n=8)
$20-50 /hive	4	10	6	3	4	0
$51-80 /hive	2	5	3	2	3	1
$81-150/hive	0	0	1	5	0	4
$151-200 /hive	1	1	1	1	0	3

Beekeepers: Most significant considerations or constraints on providing hives for paid macadamia pollination services (n=7)				
Ranking*	**1**	**2**	**3**	**Total****
Price received per hive	42.9%	14.3%	14.3%	71.5%
Alternative/competing honey flow for bees	14.3%	14.3%	14.3%	42.9%
Preparation needed to provide hives (e.g. extra feeding)	14.3%	0.0%	28.6%	42.9%
Timing hives are required on orchards	0.0%	28.6%	14.3%	42.9%
Placement of hives on orchard	14.3%	0.0%	0.0%	14.3%
Use of pesticides on orchard	14.3%	28.6%	28.6%	71.5%

*The percentages in this table relate to the proportion of beekeepers who ranked that factor as the 1st, 2nd, or 3rd most important considerations. Percentages for lower rankings have been omitted to save space.

** The total percentage indicates the proportion of respondents who listed this factor in their top 3 most significant considerations or constraints.