Horticulture Innovation Australia MC16008

Insectaries in the macadamia inter-row - opportunities for maximising the presence and action of beneficial arthropods for the suppression of pest arthropods

Milestone 102 Literature Review 22.05.2017

Prepared by Dr Abigail Makim
BioResources Pty Ltd
Samford Qld 4520
www.bioresources.com.au
info@bioresources.com.au

Executive Summary

- This literature review is part of the larger Integrated Pest Management (IPM) Program for the Australian Macadamia Industry (Horticulture Innovation Australia MC16003-8) with different components.
- Arthropod pests including lace bug, sigastus weevil, banana fruit caterpillar, fruitspotting bugs and green vegetable bug cause significant yield and/or quality loss in the macadamia industry.
- Management strategies have been principally chemical. In recent years the effectiveness of these strategies has been circumscribed by the continuing emergence of new pests, chemical resistance, withdrawal of pesticides, and community and environmental objections.
- A major opportunity is now available for the industry to position growers and consultants to include inter-row insectaries in their IPM program.
- The primary function of the inter-row insectary is to incorporate vegetational species diversity within the orchard. Vegetational diversity is strongly correlated with arthropod species diversity.
- Insectaries can promote the presence of beneficial arthropod predators and parasitoids. Their proximity to the crop maximises arthropod interactions, which can improve the suppression of pests. Beneficial populations can provide a buffer in the system and give more time to make spray decisions. Refuges for beneficial arthropods can enable their quicker recovery after spraying.
- Insectaries have been trialled internationally and in Australia in a number of crops. There are promising results in terms of the increased presence of beneficials, suppression of pests, decrease in crop damage, and increase in crop yield.
- This review provides the first opportunity for the consideration of these issues within the specific context of macadamia orchards. In macadamia orchards, a range of inter-row practices are standardised including heavy regular mowing and heavy control of "naturalised weeds", which inhibit vegetational diversity. These practices have not been assessed in terms of their impact on arthropod ecology, and particularly beneficial insects.
- Vegetational diversity can be incorporated into the macadamia orchard through a process of "ecological engineering", ensuring "selective diversity". This means that vegetation is selected that provides the food and habitat requirements of benefical insects, and which will not harbour pests, diseases or be invasive, and which is suitable for the seasonal and operational requirements of the macadamia orchard.
- This review considers a number of strategies that consultants and growers can employ in orchards for cultivating vegetational diversity, which are based on reduced mowing, ripping and/or seeding.

- This document concludes by pointing to a number of areas requiring further work as part of a broader IPM strategy for the management of arthropod pests in the macadamia industry:
    - Review and confirmation of plant species suitable for inclusion in an insectary in the macadamia inter-row, factoring in regional characteristics of the Atherton, Bundaberg, southeast Queensland, northern NSW and Nambucca Heads growing districts.
    - Trialling strategies for establishing and maintaining an insectary in the inter-row.
    - Clarification of the current status of key beneficials, especially spiders, and their role in the macadamia orchard.
    - Clarification of the current status and role of "non-economic" alternative prey insects in the macadamia orchard.
    - Resources supporting consultants and growers in decisions for vegetative diversity in the macadamia inter-row.

Background

Why is this literature review being done?

Arthropod pests of macadamia include the sigastus weevil (*Sigastus* sp.), fruitspotting bug, *Amblypelta nitida* Stål (Hemiptera: Coreidae), the banana spotting bug, *A. lutescens lutescens* Distant, lace bug, *Ulonemia concava* Drake (Hemiptera: Tingidae), the macadamia nutborer, *Cryptophlebia ombrodelta* Lower (Lepidoptera: Tortricidae), macadamia leafminer, *Acrocercops chionosema* Turner (Lepidoptera: Gracillariidae), macadamia felted coccid, *Eriococcus ironsidei* Williams (Hemiptera: Eriococcidae), macadamia flower caterpillar (*Cryptoblabes hemigypsa*), mites and thrips species, kernel grub (*Assaria seminivale*) and bark beetles (*Cryphalus subcompactus*) or *Xyleborus* sp.). [1-7]

Strategies to curb the activity of these pests have been assessed for integrated pest management (IPM), conventional farming, and organic farming systems. [8-10] There have been a number of successes, particularly with bio-control and insecticides.[3,11-13] This has provided some solutions but has not kept pace with chemical resistance and the ongoing emergence of new arthropod pests.[3,14-16] This difficult situation is compounded by the likelihood that some pesticides, most notably endosulfan, have been or are soon to be withdrawn from use while alternatives are non-selective and/or expensive.[2,13,17] Finally, there are community and environmental objections to pesticide use in a number of growing districts.[2]

It is against this background that this literature review assesses the potential for including an inter-row insectary in the macadamia orchard. The review considers propositions that insectaries provide vegetational diversity, which can encourage the activity of beneficial predators and parasitoids. If this is the case, insectaries provide an important new strategy for arthropod pest management.[18-21]

This review provides the first opportunity for the consideration of these issues within the specific context of macadamia orchards. In macadamia orchards, a range of inter-row practices are standardised including heavy regular mowing and heavy control of “naturalised weeds”, which inhibit vegetational diversity. These practices have not been assessed in terms of their impact on insect ecology, and particularly beneficial insects.

This literature review is part of the larger IPM Program for the Australian Macadamia Industry [Horticulture Innovation Australia (Hort Innovation) MC16003-8].

Review

Principles and propositions for in-crop insectaries

A well-established body of literature proposes that agricultural and horticultural landscapes are excessively simplified.[19,22] This simplification, brought about by human activity, shifts the landscape away from one of relative complexity and can be quantified in terms of reduced biodiversity.[23,24] This reduction in biodiversity is the result of two inter-related trends. First, at a landscape level, an ever-increasing land area is being brought into intensive crop production, converting large areas exclusively into crop lands of a limited range of plant species.[18,25-28] Second, at the field level, contemporary farming practices include the constant and permanent removal of non-crop vegetation, elimination of year-round flowering plants, and high pesticide use.[29] These trends are adversely disrupting a number of key ecosystem services, including pollination and nutrient cycling, amongst others.[i] [30,31] Of particular interest to this review is how these trends are associated with the extensively documented disappearance of beneficial arthropods, notably pollinators, from farming systems.[20,29,32,33]

The disappearance of beneficials is occurring alongside emerging problems with arthropod pests, indicating an apparent diminution of biological control services.[34] This is especially strongly associated with low vegetation diversity and complexity.[27,35-38] Vegetational diversity, by contrast, is associated with the presence of diverse arthropods (insects, spiders, mites), including diverse beneficial predators (eg., spiders, lacewings, ladybugs, predatory mites, and so on) and parasitoids (eg., parasitoid fly and wasp species). The absence of these beneficials leaves specialised crop pests unchecked.

By contrast, the maintenance and restoration of diverse and complex plant communities in inter-rows and field margins will also encourage beneficial populations.[39] Natural enemy interactions are strongest in complex agricultural landscapes.[40] This complexity confers a systemic resilience and tends to reduce outbreaks of phytophagous insects.[41,42] For example, recent work on spiders demonstrates a much under-appreciated generalist predator, capable of removing large volumes of prey from an ecosystem and travelling during key periods in the season to do so.[43-47] With this in mind, it is of considerable concern that this project has recently received anecdotal reports from macadamia growers in Bundaberg, northern NSW and Nambucca Heads of an appreciable drop in spider activity in orchards over the past 10 years.

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[i] It is noted here that entomological studies consider scale at either the landscape or paddock level, with different interactions, causal factors and so on as their principal focus. Further elucidation of these differing theoretical and methodological perspectives is beyond the scope of this study.

A principal virtue of vegetational diversity is its correlation with an increase in insect community stability within the crop area.[22] Parasitoid and predator populations reliant on non-crop vegetation are present and can quickly capitalise on the activity of pests across seasonal variation.[48]

The underlying specific mechanism by which the ecosystem service of orchard pest control is provided by plant diversity are likely the result of one, many or all of the following factors:[39,41,49-52]

1. Provision of floral resources. Most species of beneficial adult predators and parasitoids require a diet of nectar and/or pollen for supplementing their energy requirements. Many species will have strategies for conditions where these are limited or unavailable. But overall, longevity and fecundity are advantaged where floral resources are guaranteed. Ramsden et. al.[51] establish that additional floral resources is the single most important factor in promoting the success of beneficials in the field, as compared against availability of additional prey or over-wintering sites. Tschumi et. al.[52] found that when it comes to providing biological services, perennial, species-rich wild-flower strips out-perform grassy flower strips and also species-limited flowering strips.
2. Presence of additional prey - non-economic or neutral insects. Biodiverse ecosystems will include non-economic or neutral insects alongside beneficials and pests.[49] These insects may play an important role as prey for beneficials across seasonal and other variations, ensuring a sustained beneficial population, irrespective of the presence or otherwise of target pests.[53] Ramsden et al[51] argue that additional prey is an important consideration where diversity of beneficials is key. The needs of different insect, mite and spider species vary considerably over time and additional prey is especially important when combined with additional floral resources. Grass et al[54] find that wildflower diversity is very strongly linked to the presence of so-called non-economic insects in the orchard.
3. Suitable overwintering sites. Provision of winter habitat for food and refuge has been identified as a potential factor in ensuring a beneficial population year-round in-crop.[51] The relative arrival of beneficial to pest populations, particularly early in the growing season, is especially important for pest suppression, and over-wintering sites can enable a close association.[55]
4. Modification of microclimate. Different species will have different preferences when it to comes to microclimate. A range of factors come together to influence microclimate, and vegetative diversity is especially important in this calculation. For example, plant height, herbage quality and density will affect temperature and humidity. [49]
5. Production of chemical stimulus. Altieri et al[49] demonstrate in a number of field trials and experiments that beans co-located with weeds are considerably less attractive to common pests. Likewise, Tahvanainen and Root[41] demonstrate that the presence of non-crop plants interferes with the pest insect's chemically reliant finding and feeding behaviour. The flip

side of this, as argued by Finch and Collier,[50] is that plant volatiles act as the first of three links in the success of pests establishing on monoculture crops. The second link is discussed below. The third link comes from non-volatile plant chemicals.

6. Alteration of colonisation background. A number of studies have found that pest insects are able to more readily establish in crops with a "clean" vegetative background, to the extent that they will preferentially colonise "large, pure stands of their host plants".[49] Plants set against bare soil provide an especially strong stimuli for insect phototactic and optomotor reactions. Visual stimuli is the second link in Finch and Collier's "appropriate/inappropriate landings" theory for pest success in monoculture.[50]
7. Physical barriers. Diverse vegetation located in the inter-row, hedge-row and field margin can form physical barriers, hiding the target plant from the pest arthropod.[49,50]

These factors are key areas for applied strategies for arthropod pest management.[19-21,39,56]

Research findings

International work

A number of research groups have conducted trials and significant syntheses of experimental data and/or literature reviews into vegetative diversity and its capacity for advantaging insect biocontrol.[20,26,57] Rusch et. al[37] undertook a synthesis of European and American data and found a consistent negative effect of landscape simplification on natural pest control, which was on average 46% lower in homogeneous landscapes dominated by cultivated land. Within those homogeneous landscapes, Letourneau et al[58] review 552 experiments from 45 articles (published 1998-2008) and conclude that diversified crops have more natural enemies, fewer pests, and less crop damage than comparable crops with no or fewer associated plant species. They include an important caveat that a significant negative impact on yield is observed relative to the proportion of landscape converted away from crop to insectary.[i]

Bianchi et. al[27] found that in the studies they reviewed, beneficial populations were higher and pest pressures lower in complex landscapes (74%) versus simple landscapes (45%). Simon et. al[56] reviewed the literature on apple, pear and peach orchard management and found that the effect of plant diversity on pest control was mostly positive (16 cases) or insignificant (9) or negative (5). Veres et. al[59] reviewed 72 case studies, and found 45 reporting an effect of landscape composition on pest suppression. Zandstra and Motooka[39] reviewed the literature on weed and insect interactions and

[i] This meta-analysis does not vote count (which is typically the case in meta-analysis) and thus statistical anomaly is avoided, providing a more definitive assessment.

identified many studies establishing a positive association between "weedy" vegetative diversity, the presence of beneficial insects and suppression of pests.

More specifically, Dassou and Tixier[60] conducted a meta-analysis that find that where there is vegetational diversity, biological control is more likely to occur for specialist than generalist herbivores. They also found that plant diversification through the planting of cover-crops and relaxed weed management can increase the control of specialist herbivores by generalist predators.

Wright et al[61] reviewed nine studies of natural regeneration of ground cover (weedy and no-till) under perennial crops and the associated impact on the presence of natural enemies in the trees, natural enemies in the ground cover, and pests and crop damage. They found five out of nine studies report a positive influence, the rest being neutral, and concluded that the treatment had an "unknown effectiveness" and that there was currently "limited evidence".

The results reported across all of these studies indicate that arthropod pest suppression through vegetative diversity is a promising avenue of investigation. This is backed up by the numerous recent and benchmark historic individual studies of various arthropod pests in a range of crops, providing general confirmation and specific insights into a positive association between vegetational diversity in agricultural landscapes and insect diversity and the presence of beneficials.[18,25,40,41,44,62-64]

Less well studied to date are specific contributions of beneficials to pest control, and in turn, their mitigation of negative impact on crop yield. But a growing body of work indicates considerable potential. Gurr et. al[57] conducted a multi-country field trial of insectaries adjacent to rice crops and found that populations of two key pests were significantly reduced, insecticide applications were reduced by 70%, grain yields increased by 5% and an economic advantage of 7.5% was gained.

In a related vein, Iverson et. al[65] conducted a meta-analysis of biocontrol and yield (26 studies; 301 observations) in polycultures. Interestingly, they did not find that biocontrol had an effect on yield, but rather both were independently affected by polycultural cropping. The implications of this are beyond the scope of this literature review other than to highlight the benefits associated with microbial activity, soil structure and fertility and so on that come with higher levels of soil organic matter, as linked to increased vegetative abundance and diversity.

Blaauw and Isaacs[66] evaluated biological control services provided by increased beneficials numbers as a result of wildflower plantings adjacent to blueberries. They found significantly higher levels of biological control, as assessed by removal of pest eggs in a control (26%) against a trial (36%) in the wildflower planting and crop adjacent to the planting. The effect was absent at interior sites in the crop. Gontijo et. al[62] trialled plantings of sweet alyssum in apple orchards with a view to attracting aphid predators. They reported an increase in a diverse group of generalist predators in the plantings and adjacent trees within a week of flowering and also a reduction in aphids as compared against the control. Tschumi et. al[52] found a positive association between the planting of wildflower strips with wheat in reduced pest presence (eggs 44%, larvae 66%), reduced crop damage (40%) and increased yield (10%).

A number of jurisdictions are trialling these propositions in the field, and in connection with this, industry bodies are promoting the approach. For example, Sustainable Agriculture Research and Education (SARE) in the USA have provided numerous small grants to farmers, graduate students and researchers for studies considering improvement of the activity of beneficials with the planting of cover crops and wildflowers in a range of crops.[67] A significant body of work is being done on the role of pollinators, an important factor in this review, although outside its specific scope. For example, in the USA, the National Watermelon Promotion Board, Clemson University's Coastal Research and Education Center and the U.S. Vegetable Laboratory are partnering in trialling the impact of wildflower strips in promoting pollinators in watermelon crops.[68]

It is also important to note that a number of industries have been long-standing adopters of these practices. For example, in citrus orchards in China it is now common practice to sow weed seeds to provide breeding grounds for predatory mites (Song, 2016, pers. comm., 14 October) amongst others.

Australian work

In the Australian context, a range of studies have reviewed the proposed benefits of field margin and/or inter-row vegetation. Smith et. al[69] provide guidelines for retaining native remnants and thereby ensuring insect biodiversity in cropping and grazing systems. In a survey of Queensland, New South Wales and Western Australia, Schellhorn et. al[55] found a strong presence of key beneficial predators in native remnant vegetation, while they found weedy pastures play a key role in year-round hosting of pest insects. Danne et. al[70] trialled three native grasses in vineyards in South Australia, finding a higher abundance of predators and parasitoids there as against rows sown with an oat control. Retallack developed guidelines for managing insectaries in vineyards in South Australia, arguing that settings with diverse plant and insect species produce a more stable ecology, capable of absorbing the population dynamics of pest species.[71] Ridland trialled a number of different cover crops for relative performance in apple and pear orchards, finding that buckwheat and chicory/yarrow treatments demonstrated a positive correlation with mitigation of yield loss and fruit damage.[72]

Again, as with international industry practice, many Australian growers are effectively utilising vegetation-insect interactions for bio-control. The technique has been employed in citrus since the 1990s.[73] Potato growers in South Australia are now planting barley alongside the potato crop to provide a refuge for non-pest aphids, specifically to allow aphid parasitoids a guaranteed host across the season and to keep them in the field after spraying for controlling potato aphids (James Altmann 2016 pers. comm., 14 October).

Plant species suitable for orchard inter-rows

Knight and Gurr argue for "directed" approaches to the management of vegetative diversity - something that they define as "ecological engineering".[9] In this vein, Ridland favours "selective vegetational diversity" and "selective food plants" for the inter-row, which will support the lifecycle of beneficial and non-economic arthropods.[72] In this connection, Gurr et. al., argue that pesticide reduction is also factored into the system, with better use of existing agents via habitat management or "conservation biological control".[74]

The specifics of preferred plant species to be included in an inter-row must thus be considered. They can be distinguished by the following 6 characteristics.

1. <u>The plant is a suitable nectar or pollen source for beneficials and/or non-economic insects</u>. The effects of planting size and bloom richness are important considerations, with evidence suggesting that year-round, larger, more diverse plantings encourage a stronger presence from beneficials.[72] [51,52,75] The provision of nectar resource subsidies for parasitoids within and around crops has been shown to improve a range of related ecosystem services.[76]
2. <u>The plant accommodates alternative prey (non-economic insects) for beneficial predators and parasitoids.</u>[72] The pest arthropod population will cycle through seasonal and life-cycle fluctuations, and this can have a considerable impact on predators and parasitoids if they are entirely dependent on that single species. Beneficials will vacate the crop area if there is insufficient food, so alternative prey insects are essential.[76] These alternative prey insects include:
    a. Non-pest aphids, which are an important building block for sustaining populations of generalist predators.
    b. Non-pest Lepidoptera, which are especially important for spiders.
    c. A range of hosts for parasitic Diptera (flies).
3. <u>The plant provides shelter and/or overwintering sites</u>. It is important that a diverse and flourishing insect community of beneficials and non-economics is kept in the field year-round and across seasonal variation. As Schellhorn, Ramsden et al, Coombs and others argue, the relative timing of the arrival of pests and the beneficials that target them is crucial for pest suppression.[51,55,72,77] Early spring colonisation of crops by beneficials is crucial for keeping pest densities low.
4. <u>The plant does not host pests or diseases of the crop</u>. This is likely the single greatest reason for many commentators rejecting the idea of vegetational diversity.[72] The potential for weeds,

in particular, to host pest arthropods has a long record of documentation and is the principal rationale for the management of orchards as "clean".[39]

5. The plant is tolerant of seasonal variation. Variations in temperature, precipitation, light and so on, are considerable across seasons and also in the event of unseasonal conditions such as drought. Individual plants and plant communities must be able to tolerate these conditions.[72]
6. The plant has suitable floral architecture for feeding adult beneficials and non-economics. Patt et. al., established that there is an interplay between floral architecture, insect morphology and the searching behaviour of parasitoid wasps.[78] Foraging success is dependent on the availability of appropriate flowers; the success of the beneficial adult parasitoid itself being in turn dependent on its ability to forage for critical nutrients.[72]
7. The plant has an ability to withstand mowing and trampling. A lot of work has been done in providing recommendations on cover crops for erosion control in macadamia orchards, which can specifically withstand heavy trampling and mowing, as discussed below.[72,79,80]

Incorporating selective vegetational diversity into the macadamia inter-row

To date, the general principles of vegetative diversity - utilizing interactions amongst vegetation, pests and beneficials - have received very limited attention in Australian macadamia orchard management.[2] This review provides the first opportunity for the consideration of these issues within the specific context of macadamia orchards. It turns now to consider some ways in which vegetational diversity can be incorporated in the macadamia inter-row.

Grasses and legumes already growing as cover-crops in macadamia orchards

One source of inter-row vegetational diversity in macadamias is existing cover crop grasses and legumes. "Living groundcover" is current industry standard practice, principally for the purposes of soil management, weed suppression and improved micro-environment, but it is typically heavily mowed, which limits vegetational abundance and diversity. [79] [81]

Changes to mowing practices and herbicide use – less all round – will change the mix of plant species across the season and the general pattern of dominant species represented in the inter-row. This in turn will influence insect populations. For example, in pecan orchards in NSW, conversion to alternate row mowing was linked to a reduction in leaf hoppers and an increase in the presence of beneficials.[82] A range of selective mowing options – alternate row, Mohawk, half-row - are available as per the requirements of seasonal activity in the inter-row, available machinery, row width and so on.[81]

For macadamia orchards a key species to review in this context is smother grass. It has become widely recommended and used.[83,84] Smother grass has a strong ability for establishing in shady and heavily trafficked areas – conditions typical of conventionally managed macadamia orchards.

Naturalised weeds – problems and promises

Naturalised weeds will appear where there is a relaxation in mowing and herbicide use and even more so where the soil is disturbed to break up grass dominance and allow germination of the existing seed bank. This is in fact one of the most controversial but potentially promising strategies under consideration. Numerous studies have established that so-called "weedy" orchards demonstrate superior parasitism rates of pests, when compared to clean orchards.[39]

A diverse range of naturalised weeds that are suitable for insectaries have established seed banks already present in the macadamia inter row. Importantly, for macadamias, most pests are unlikely to be hosted by this inter-row weed vegetation. The possible exceptions are *Nezara viridula* (green vegetable bug) and banana fruit caterpillar, which can be selectively found on some common weeds of the inter-row, including silverleaf nightshade, amaranthus, and ink weed.[85] Knight and Gurr argue that there is anecdotal evidence from macadamias that the density of *N. viridula* will increase, and in turn, crop damage in weedy plots, and that this is an important enough problem for "selective diversity" to be applied in an associated IPM strategy.[9]

Shearer considered four common inter-row plants in Hawaii as potential reservoirs of *Nezara viridula* in macadamias.[86] This is an important interaction because *Nezara viridula* populations eating macadamia alone cannot increase; other host plants are important. He found that *Desmodium tortuosum* (Sw.) and *Ricinus communis* L. were suitable host plant for immature *N. viridula*. The orchard ground cover, *Desmodium ovalifolium*, and a common weed, *Commelina diffusa* L., were found to be unsuitable.

By contrast, it is worth considering that so-called reservoir weeds can in some instances be considered a virtue. For example, the southern green stink bug (*Nezera viridula* L.) feeds on macadamia nuts in Hawaii, where tachinid fly *Trichopodapennipes* var. *pilipes* Fabr was introduced to manage the pest. This was especially effective when done in conjunction with the weed, rattlepod (*Crotalaria* sp.), which was planted along the edges of macadamia orchards. This approach reduced stink bug injury from 16% to less than 3%. Rattlepod blossoms were found to be highly attractive both to the pest and its parasitoid. Both species gather on the rattlepod plants: the stink bugs are parasitised and killed before entering the orchard and damaging the nuts.[39]

Seeding the macadamia inter-row – species selection

The complexities of cover crops should not be under-estimated. They harbour distinctive complexes of beneficials and pests, which have diverse trophic relationships.[87] Cover crops are effective to the extent to which they are well designed.[65] Little is currently known of plant species suitable for macadamia orchards for the purposes of insectaries and further review work is required for assessing proposed plant species for desirable characteristics in conjunction with screening their likelihood of providing a pest reservoir and weed potential. A suitable method may be borrowed from Ridland, who did similar work for the Australian pear and apple industry:[72]

1. Desktop study - This involves a review of the literature on beneficial parasitoids and predators known or proposed as likely to target pests in macadamia orchards. Furthermore, this review considers the food and habitat requirements, across the entire lifecycle, for these beneficials, and plants known to provide this. Finally this review considers any known problems with proposed plants as invasive weed species or reservoirs for pest arthropods.
2. Glasshouse and laboratory trials - This ranges from testing of plants in Petri dishes to potted plants in cages and is an efficient method of testing candidate plants for resistance to pests and diseases and for their ability to support beneficial arthropods
3. Field trials - Field trials can be implemented on several scales. Potted plants can be placed in cages. Other trials can involve small test plots in an effort to identify the insects they support and if the cover crops are vigorous. This includes small plots around target trees rows or plots of cover crops around vines or trees. They might involve multiple orchards (replication can be difficult at this scale).

Retallick provides an alternative approach, as specifically applied to development of insectaries for encouraging beneficial insects in vineyards in South Australia.[71] She bases her recommendations more in the ground of Participatory Action Research (PAR). She provides general recommendations on a broad list of plants known to attract beneficials, which the grower is encouraged to trial as per the characteristics of their specific vineyard. Retallick provides simple methods and tools in a growers' manual for observing and recording plant and insect interactions and associating these with possible suppression of arthropod pests in the vineyard.

Where should we start when it comes to introducing specific plant species into macadamia orchards? Obviously regional and localised climatic, soil, slope, and related factors are very important in the determination for a crop grown in regions as diverse as Nambucca Heads, northern NSW, Southeast Queensland, Bundaberg and the Atherton tablelands. Firth provides a good starting point for considering plant species (without a vigorous climbing habit) and suitable for macadamia orchards in northern NSW. (A more comprehensive list with sowing guide is included in the attachments).[79] Suitable species for pre-planting include:

- Summer-growing groundcovers: Caloona cowpeas, lablab, soybeans, silverleaf *Desmodium,* Siratro, mungbeans and pigeon peas
- Winter-growing groundcovers: lupins, Namoi woolly-pod vetch, oats, ryegrass

For the established orchard, Firth recommends: Amarillo peanut, hybrid peanut, smothergrass, *paspalum* sp., white clover, maku lotus, lotononis, joint vetch, and Namoi woolly-pod vetch.

As a point of difference for further consideration, for pomes in Victoria, Ridland trialled buckwheat, (Polygonaceae); white mustard, (Brassicaceae); chicory, yarrow, (Asteraceae); fennel, Queen Anne's lace, (Apiaceae); *Phacelia*, borage, (Hydrophyllaceae); perennial ryegrass, fescue, (Poaceae); fenugreek (Fabaceae). The species were selected to provide a spread of continuous flowering throughout the year. The buckwheat and the chicory/yarrow treatments were marginally the best performers based on yield and damage data.[72]

In the case of vineyards in South Australia, Retallick provides a fairly general list of flowering plants from the Umbelliferae, Compositae, Legume, Brassicaceae, and other families. She also considers natives, pointing to plants that produce abundant, nectar-rich, easily accessible inflorescences, including Angophora, Bursaria, Callistemon, Corymbia, Epacris, Eucalyptus, Grevillea, Kunzea, Leucopogon, Leptospermum, Melaleuca, Westringia, and Pimelea.[71]

Managing inter-row vegetation in macadamia orchards

As a final and critical consideration, it is important to review the issue of inter-row cover crop management.[72] If an IPM program includes inter-row vegetational diversity as a key recommendation, it must above all else have engaged with the practicalities of macadamia orchard operations, including:

1. The specific requirements of harvest, especially enough clear orchard floor for nut pickup.
2. The long harvest period – January-August – during which the inter-row will be heavily trafficked, compacting soil and damaging plants.
3. Row width, row orientation and tree height are critical pre-conditions because vegetational diversity is only possible where year-round sunlight is present in the inter-row. In many orchards this is not available and vegetational diversity in the inter-row is not feasible.

Given the heavy demands made particularly of the macadamia inter-row, a vegetational base of an easily established and hard wearing species such as smother grass, creeping vigna (David Forest 2017 pers.comm. 2 May) or prarie grass (Alan Coates 2017 pers.comm. 9 February) is a necessary but not sufficient starting condition – remembering that it is vegetational diversity that is the goal. Diversity comes especially with additional choices made as to how and when to mow and whether to rip and what seed.

It is preferable to avoid slashing in late summer to encourage seeding, ensure sufficient ground-cover, protect the soil during the wet season and reduce weeds in winter and early spring.[79] This can come into conflict with the need to maintain a clear orchard floor for harvest beginning in January and also managing bulk during this high growth period. With appropriate species selection, sufficient row width and appropriate machinery available, this is however easily resolved with scheduled reduced mowing practices. This would include decisions as to whether alternate row, half-row or mohawk is a most suitable mowing practice and whether and when ripping and seeding will occur.

Some weeds may need to be selectively removed from the inter-row if they seem invasive, harbour macadamia pests or in other ways are troublesome. Some grasses or groundcovers may need to be selectively managed as is already being done with some growers throwing grass clippings over smother grass to inhibit its tendency to dominate (Maurice Collin 2017 pers. comm. 2 February). Existing machinery may not be suitable for certain mowing activities; and future machinery purchases should consider insectary management. In the longer term, the width of rows and the layout of entire orchards may be rethought to allow for land allocated for vegetational diversity.

The kinds of changes to the inter-row associated with insectaries will mean that growers will need to make key operational decisions to be rolled-out over a number of years and thereafter maintained. These are best informed by careful planning and relevant advice.

Synthesis and recommendations

This review has brought together literature from a number of different areas. This final section provides a synthesis of this material, highlights areas for further elucidation, and provides some recommendations for next steps.

While there is extensive assessment of the diversity hypothesis across many crops, its application and implications for macadamias is not tested theoretically or empirically. But as with many crops, macadamia orchards and growing districts can be characterised as excessively simplified landscapes. This is the result of ever increasing hectares being brought into production, while non-crop flowering vegetation is constantly and permanently removed and pesticide use is high. The biodiversity of local plants and insects has been dramatically reduced - a loss of vegetational abundance and diversity and an associated loss of insect abundance and diversity.

This review has provided the first opportunity for the consideration of these issues within the specific context of macadamia orchards. In macadamia orchards, a range of inter-row practices are standardised including heavy regular mowing and heavy control of “naturalised weeds”, which inhibit vegetational diversity. These practices have not been assessed in terms of their impact on insect ecology, and particularly beneficial insects.

Vegetational diversity in macadamia orchards can be established in the inter-row. Here, an insectary can be selectively cultivated, which encourages beneficials. It does so through the provision of additional year-round floral resources, the presence of additional year-round prey, the presence of over-wintering sites, some protection from insecticides, and modification of microclimate. At the same time it also discourages pests via chemical stimulation, alteration of the colonisation background, and physical barriers.

We have seen that in a range of crops this change in cultural practice will maximise natural enemy interactions. The extent to which this occurs in macadamias too may give orchards systemic resistance, reducing outbreaks of phytophageous insects and associated pest pressures. Furthermore, specialist herbivores may also be brought under control by generalist predators.

In this connection, we should consider recent work on spiders, revealing a hitherto much under-appreciated generalist predator. But their significance in Australian macadamia orchards is not currently well understood and there are worrying anecdotes of reduced activity. Likewise, there is currently limited understanding of the role of non-economic secondary prey insects including, non-pest aphids, Lepidoptera and Diptera, which may improve the overall fecundity, longevity and effectiveness of key predators and parasitoids.

Finally, there is the potential for biological control thus restored to reduce crop damage and improve crop yield, and in IPM systems, for a substantial reduction in insecticide application and cost.

Selective vegetational diversity in macadamia orchards must incorporate a number of considerations. A plant or combination of plants should aim to: provide year-round nectar or pollen suitable for beneficials; accommodate alternative prey year-round; provide shelter and over-wintering sites; not host pests or diseases of the crop; be tolerant to seasonal variation; have suitable floral architecture, and; withstand trampling and mowing, especially during harvest (January-August).

Selective vegetational diversity in macadamia orchards can be achieved through at least three general strategies. First, reduced mowing of grasses and legumes already present as cover-crops. Second, relaxed management and even encouragement of naturalised weeds. Third, seeding of the inter-row with new plant species.

Work to date on identifying and recommending plant species for the macadamia inter-row has taken soil management and erosion control as its principal focus. With this excellent work in place, living groundcover has been established as an industry standard. But it is time to revisit species recommendations with a view to establishing insectaries where the requirements of insects are factored into plant species selection. Also, where vegetative diversity and by association insect diversity are desired, the heavy reliance on swarded smother grass may be inadvertently contributing to conditions favourable for arthropod pests in macadamia orchards. Smother grass is a success in terms of establishment and erosion control, but it may be crowding out ecological diversity.

Furthermore, industry-specific guidance on plant species for growing regions in Nambucca Heads, Southeast Queensland, Bundaberg and the Atherton tablelands requires attention.

In so much as "weedy" macadamia orchards are concerned there is an equal mix of opportunity and threat. There is evidence that some weeds – blackberry nightshade, for example – can host pests of the macadamia. However, speculation as to the extent of the threat that this can pose for the Australian orchard is anecdotal and not well understood. A weed that attracts a pest may provide it with additional out of season opportunities for feeding and breeding. But it may also attract a pest's parasitoids or predators, ensuring the pest never enters the orchard or damages nuts.

Vegetational diversity in the macadamia inter-row can make a valuable contribution to IPM in the industry. In addition to an improved understanding of the issues raised above, growers and crop consultants would be well served by resources to help plan and roll out decisions. This includes advice on mowing, machinery, suitable plant species by locality and season and so on.

In the final analysis, this synthesis is built upon the propositions and principles of vegetational diversity as tested and applied in many crops, but not macadamias. If specific issues for macadamias are to be more completely understood, further work is required. The review has covered a number of methods including desktop study, glasshouse and laboratory trials, field trials, and PAR for advancing knowledge in this regard. When the matters highlighted above are more clearly understood, the implications for inter-row management for insectaries in terms of IPM monitoring, insecticide recommendations and so on, can be sketched out.

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Attachments

Groundcovers for spring/summer (October to January) planting

what to sow	rate kg/ha	approximate seed cost 2003 $	fertiliser	remarks
High bulk species				
annual legumes				
Lablab	30-40	65-130	500kg/ha Mo super at sowing	Ideal before planting orchard. Disadvantage is tendency to climb over young trees when planted in orchards.
Caloona cowpeas	60	130	-	Ideal non-climbing summer legume
Soybean	60	65	500kg/ha Mo super at sowing	Can be harvested for grain. Diseases can be a problem when wet.
Glycine	8	110	500kg/ha Mo super at sowing	Perennial, adapted to frost-free red soils. Climbing plant also.
Siratro	5	110	500kg/ha Mo super at sowing	Less bulk, but more persistent than glycine. Climbing plant also.
Amer. Jointvetch cv Glenn	5	40	500lg/ha Mo super at sowing	Erect summer grower to 2m tall. Suit interrows in establishing orchard.
grasses				
Setaria (various varieties)	3-4	50-65	200kg/ha MAP at sowing	Perennial. Makes ideal mulch when slashed. Topdress with 100 kg/ha urea. Forms tussocks. Difficult to mow.
Hybrid forage sorghums	20	90	200kg/ha MAP at sowing	Early sowing preferred. Regrows after mowing. 50-100 kg/ha urea topdress after second mow.
Millett - Japanese	20	40	200kg/ha MAP at sowing	Sown earlier in spring than sorghums.
Broadleaf paspalum	5	40	200kg/ha MAP at sowing	Perenial shade tolerant. Year round grower. Summer dominant.
Lower growing species				
biennial/perennial legumes				
Amarillo peanut	20-25	400-500	500kg/ha MO super at sowing	Persistent perennial. Compatible with grasses. Shade-tolerant. Competes with bananas if grown near stems.
Shaw vigna	5	250	500kg/ha MO super at sowing	Compatible with grasses, slow to establish. Allow to reseed.
Bargoo jointvetch	3-4	120-150	300kg/ha MO super at sowing	Competitive summer grower suited to poor acid soils. Seed scarce.
Wynn cassia	5	90	500kg/ha MO super at sowing	Seed available Queensland. Dormant in winter. Allow to seed in autumn to regenerate in the following spring.
grasses				
Bahia grass cv Competidor	5	60	200kg/ha MAP super at sowing	Perennial. Persistent. Fairly shade-tolerant species. Slow to establish and spread.

What to sow	rate kg/ha	approximate seed cost 2003 $	fertiliser	remarks
Smothergrass	turf/runners	-	200kg/ha MAP at sowing	Persistent, shade-tolerant spreading perennial. May be competitive with young trees. Grown from runners.
Shadegro®	5	500	200kg/ha MAP at sowing	Perennial shade-tolerant. Less spreading than smothergrass and not as persistent. Seed
expensive.				
Microlaena cv wakefield	5	not available	200kg/ha MAP at sowing	Perennial shade-tolerant soft native. Less spreading than smothergrass.
other species				
Dichondra repens	5	275	200kg/ha MAP at sowing	Very low growing. Slow to establish. Moderate shade tolerance. Insufficient cover for steeper slopes.

Groundcovers for autumn/winter (March to June planting)

High-bulk species

legumes				
Sweet lupin or NZ blue lupin	60-90	50-80	500kg/ha Mo super at sowing	Slash/turn under at the end of flowering.
Namoi woolly-pod vetch	40-50	120-150	500kg/ha Mo super at sowing	Establishes quickly in autumn. Provides good cover to 50cm high. Dies off in summer.
grasses				
Oats	90-130	130-180	300kg/ha MAP Topdress with 100kg/ha urea	Establishes quickly. Use lower rates when sowing with a perennial legume. Regrows after mowing. Topdress with urea after for bulk.
mowing				
Rye - annual	30	100	300kg/ha MAP Topdress with 100kg/ha urea	Establishes quickly. Use lower rates when sowing with a perennial legume. Regrows after mowing. Topdress with urea after for bulk.
mowing				
Rye - perennial	30	200	300kg/ha MAP Topdress with 100kg/ha urea	Establishes quickly. Use lower rates when sowing with a perennial legume. Regrows after mowing. Topdress with urea after mowing for bulk.
low-growing perennial legumes				
White clover Haifa	4	50-100	500kg/ha Mo super at sowing	Can also be sown spring. May need periodic oversowing. Companion grasses must be kept short.
White clover Kenya	4	200	500kg/ha Mo super at sowing	Declines in winter. Slow to establish. Manage carefullly in the first year.
Maku lotus	4-5	120-150	500kg/ha Mo super at sowing	Slow to establish. Stays green in winter.
Lotononis	1	N/A	500kg/ha Mo super at sowing	Suits sandy soil

Mo super: molybdenised superphosphate
MAP: monoammonium phosphate

NOTE:
Generally, sowing rates are higher than those normally recommended for pasture.
Before buying seed, check its quality and that it is certified.
Inoculate all legume seed with the correct inoculum.
Consult your local seed merchant for the best varieties for your area.