Horticulture Innovation Australia

Final Report

Landscape diversity and field margin management

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Summary

Australian vegetable production is under increased pressure to achieve more profitable and sustainable production as input costs are increasing together with increasing vegetable production (2% per annum), the Australian population (1.7% over the same period, Australian vegetable industry Strategic Investment Plan 2012 - 2017) and environmental degradation. Thus, an integrated approach that achieves reduced inputs and sustains natural habitats as refuges and a resource base for beneficial organisms is required. The homogenous nature of agricultural landscapes reduces biodiversity of natural enemies and thereby biocontrol, but this can be partly offset by developing refuges at field margins and in the surrounding landscapes as shown in a large body of international research.

In this project, we review Australian and international literature related to the role of field margins and landscapes surrounding crop fields in providing resources to beneficial organisms and reducing arthropod pest pressure in vegetable and other crops. Using literature on bio-physical data, together with published literature on farmers' perceptions and adoptions, as well as expert (researcher) opinions from conducting interviews, we captured the current knowledge, identified knowledge gaps, and farmers' perceptions and barriers to adoption. These results were used to generate recommendations on how to manage off-production habitats at field margins and in surrounding landscapes for vegetable pest suppression, and what is needed for this to be implemented by farmers. Several trends are emerging that show support for on-farm and area-wide vegetation management that will contribute to pest reduction, yet knowledge gaps need to be filled before we can implement on-farm region specific management actions for the vegetable industry.

The general emerging trends include:

- Weeds generally support pest abundances and their reproduction;
- Native plant species generally support beneficials and do not support pests (with some exceptions), and there are options for native plants that can provide additional on-farm income (see Revegetation by Design);
- Lucerne can provide multiple benefits and low risk, such as high abundance of beneficials, low pests problems, and additional farm income;
- Beneficial arthropods need a certain habitat area and configuration in landscapes surrounding crop fields, but which habitat, how much and where remains to be investigated in Australia. It appears that >10% lucerne in a circular landscape of 1.5km diameter provides benefits in terms of biocontrol in vegetable crops. Adjacent woody vegetation (shelterbelts, remnant woodland) provides multiple benefits, including in-field biocontrol, and even narrow patches (25 m x 100 m) have been shown to support beneficials, that then move to the adjacent crop. However, the required amount at the landscape scale remains unknown; and
- Habitat condition such as complexity (plant diversity and structure including under- mid- and upperstory) and weediness (exotic grasses and broadleafs) should be taken into account and managed.

The benefits of perennial (non-crop and crop) habitat at field margins and in surrounding landscapes can be fully realized only together with in-field integrated pest management (IPM), in particular reduced pesticide application depending on the economic thresholds. Maintaining native vegetation and removing weeds from surrounding habitats appears to be an obvious low risk option that will enhance habitat condition and abundance of beneficials, but not pests. Weed-pest and native plant-beneficial associations have been determined and criteria for plant selection including risk estimates for plant families to be used in revegetation programs are available mainly from the Revegetation by Design program (Schellhorn et al. 2006, 2007, Taverner and Wood 2006, Schellhorn et al. 2010). The identified plants in these projects support beneficials, do not host pests, and some provide additional income on farm (native bush-tucker industry, native cut flower industry and seed for the revegetation industry). . Growers also identified these three criteria (high benefit, low risk, additional income) in our review as important for adoption.

More generally, adoption can only happen when there are on-farm vegetation options to implement; this is lacking. Therefore, to prepare for implementation we need to:

- Close the knowledge gap (clearly demonstrate benefits and risks of on-farm vegetation management option through research);
- Provide a 'menu' of options (farmers differ in their goals and management possibilities and should have a possibility to tailor their management decision based on the needs of their farm enterprise);
- Take a holistic approach (if field margin and landscape management programs have multiple objectives they will be more effective and more likely to be adopted);

To move from implementation to adoption we must:

- Address the financial aspects (financial incentives would largely increase adoption, but there are other forms of income, such as an increase in farm productivity and additional income from native plants);
- Disseminate this knowledge through ongoing extension; Establish knowledgeable, trustworthy and independent personnel on-the-ground that will work collaboratively with farmers to help them develop solutions;
- Increase simplicity (management recommendations should be practical and manageable for farmers);

As a priority to increase adoption by vegetable growers, we suggest three main areas:

1. Increase knowledge through research (in order of priority), and focus on:

- Assessing the appropriate management of lucerne (e.g. mowing time that push beneficials into the vegetable field) to maximize benefits to specific vegetable crops;

- Providing experimental evidence of weed/native vegetation management (e.g. removal, revegetation) on in-field pest suppression;
- Understanding the mechanisms of how perennial habitat benefits pest suppression, rather than only quantifying the impact. This is a crucial step if research findings should be well understood and broadly applied at the crop, farm and regional scale;
- Quantifying the benefits/risks of perennial vegetation for vegetable crops depending on habitat condition, distances from the crop field and amounts in the landscapes;
- Multiple benefits/risks need to be addressed simultaneously (including multiple ecosystem services, pest complexes)
- Combined effects of different management activities at local and landscape scales in relation to pest suppression

Taking steps to address the knowledge gaps identified in the report will contribute to helping the horticulture industry to develop guidelines on what, where and how much off-production habitat to integrate to achieve successful biocontrol.

2. Increase growers' knowledge through extension: Provide growers with information about benefits and threats of native vegetation as well as risks of not having any. This can be done through popular press articles, flowcharts, workshops, factsheets, newsletters and field days. Innovative growers who already have benefited from native vegetation and lucerne on their farms should be engaged to champion the benefits. Sharing this knowledge with trustworthy and independent personnel that are frequently in direct contact with farmers would ensure increased and ongoing adoption (after the lifetime of the project).

3. Finally, creating a region-specific decision-support tool, by building on the learnings from the Revegetation by Design projects. The current GRDC On-the-Ground NRM Action chart will help to link crop protection, weed and native vegetation management. This will allow growers to identify their region, then choose the low risk/high benefit plants for maintaining, revegetation and/or weeds to remove. Each relevant plant species should be cross-referenced to information on characteristics such as bio-region, growth habit, flowering times, fire retardancy, butterfly / bee habitat, the associations with vegetable pests and beneficials, where to source the tube-stock, management for establishment/removal, and additional benefits/risks. This would increase adoption because it increases knowledge of farmers about benefits/risks and possible additional income, provides a 'menu' of options and information about additional benefits (holistic approach), and therefore satisfies several of the above-mentioned adoption criteria.

Keywords

Perennial vegetation, crop margins; pests; beneficial insects; native vegetation; weeds; Integrated Pest Management; pest suppression; non-crop habitat; landscapes; natural enemies; biocontrol

Introduction

Agricultural expansion and intensification worldwide have led to environmental degradation and development of pesticide resistance, while demand for agricultural products is constantly increasing. This has raised concerns about reaching a yield plateau with current chemical inputs and intensive farm management. Thus, future agriculture in Australia and worldwide will need to intensify production while minimizing negative impacts on the environment. A sustainable way to do this is to utilize the benefits humans gain from ecosystems surrounding crop fields (ecosystem services), such as pest suppression by beneficial arthropods.

There is strong evidence in the international literature that semi-natural habitats in the surroundings of crop fields contain important resources that are important for the majority of beneficial arthropod species (see Appendix I and reviews by Bianchi et al. 2006, Chaplin-Kramer et al. 2011, Veres et al. 2013). These studies are primarily from the EU and the USA and have led to programs that provide incentives directly to farmers to protect and manage land for biodiversity and can contribute to ecosystem services, such as pollination and biocontrol (Batáry et al. 2015). Increasingly, similar information is being gathered in Australia in relation to pests and natural enemies across different production systems: vegetable (Stephens et al. 2006, Schellhorn et al, 2010, Costamanga et al. 2015), cotton (Perovic 2010, Bianchi et al 2015), grain (Nash et al 2008; Macfadyen et al 2015, Parry et al 2015) and viticulture (Thompson et al. 2013). This project provides a critical overview of this research in Australia. More specifically, the focus of this project is a review of the literature that considers the role of diverse off-production habitats at different scales, from field margins to landscapes surrounding crop fields for enhancing natural enemy abundance and pest suppression and can be applied to the Australian vegetable industry. Second, the literature review of growers' perceptions and adoption of natural vegetation management for ecosystem service provision in Australia is provided. The information from the review together with the results of the expert survey we conducted has generated a range of recommendations to Horticulture Innovation Australia (Hort Innovation) in the form of this project report and to researchers via the submission of a peer reviewed publication.

Glossary

Ecosystem services: ecological functions provided by nature that benefit humans, for example, pest control provided by entomophagous organisms (vertebrates, arthropods, fungi, nematodes etc) and pollination provided by flower-visiting arthropods that contribute to food production.

Landscape structure: type of use (composition), size, shape, and arrangement of vegetation patches and physical elements (e.g., water bodies, dwellings) in a landscape.

Semi-natural habitat: habitat area on a farm that is non-productive (no intentional inputs of agrochemicals). This term is commonly used in international literature for grasslands and woodlands that are not used for production (but are sometimes grazed). In Australia, the term **native vegetation** is more common for these habitats, although when defined so broadly, the term 'native vegetation' may incorporate weeds that are generally exotic.

Biological control: conservation of existing natural enemies in an environment as a method of controlling crop pests.

Methodology

To evaluate the evidence of the impact of field margins and diverse habitats in the landscapes surrounding crop fields, on pest and natural enemy abundances and pest suppression, we conducted a literature survey. Firstly, we critically evaluated peer-reviewed and grey literature from Australia on abundances of arthropod pests, and their natural enemies in field margins and diverse habitats in the landscape surrounding crop fields, their movement into a crop and in-field pest suppression (Appendix 1). We searched peer-reviewed literature in the Web of Science and Scopus using the key words: pest AND crop AND Australia AND landscape OR margin. Additionally, we searched for publications in the citations listed within relevant articles. We additionally identified relevant 'grey' (non peer-reviewed) literature. We searched for grey literature in Google, Trove, Pandora and government agencies Rural Industries Research and Development Corporation (RIRDC) and Hort Innovation and CSIRO library. As part of this process, we identified trends and knowledge gaps and compared the findings to the international literature. This helped to provide insight into areas that have yet to be investigated in Australia and therefore warrant further consideration.

Secondly, we used results from published research on Australian grower perception and behavior (adoption and barriers to adoption) towards managed field margins, and native vegetation associated with horticulture and agriculture from the grey and published literature (see Appendix 2). We used the same search engines as above using words: farmer OR grower AND Australia AND landscape OR field margin OR ecosystem service. More attention is given to the recent literature (published in the past 5-10 years), as farmers' perception and attitudes can substantially change over time.

Thirdly, we surveyed Australian researchers across states that are currently working or have published research related to the topic (Appendix 3). The researchers were identified based on our existing contacts, recommendations from the people interviewed and authors from the literature. They were included in the interview if they had experience in investigating the effects of field margins and/or landscapes on crop pest and beneficials in Australia. Thirty six researchers were approached by email and/or phone and a total of 26 responded. Experts were interviewed using telephone surveys during April-May 2016. The interviews contained 2 sections, first information about crop and region in Australia, as well as pests and beneficials that the participant has the most experience working with, and second, knowledge and attitudes about the effects of field margins and landscape complexity on pests and biocontrol, knowledge gaps and recommendations (see Appendix 3 for the list of questions and results). The purpose of this survey was not to conduct statistical analyses of the experts' opinions and attitudes, but rather to help identify knowledge gaps and recommendations for farmers, given the paucity of published literature on this topic. Thus, the questions were open-ended, and the answers were not influenced by offering solutions.

Outputs

- A draft literature review of the benefits of land diversity and field margin management practices in Horticulture and other crop industries suitable for publishing in a peer reviewed journal.
- Recommendations generated from reviewing literature and surveying the current opinions of the leaders in this area of research throughout Australia. The report was unable to make any regionally specific recommendations. This was due to the lack of regionally specific information.
- An overview of farmer attitudes and opinions on benefits and barriers to implementation of the recommended actions as identified by reviewing the literature.
- A list of knowledge gaps and recommendations about further data and studies needed to achieve the goal of better understanding how to use off-production habitat to achieve the goal of reduced inputs and successful biocontrol in vegetable crops.
- Recommendations on which management practices can benefit the vegetable industry and are likely to be implemented by farmers informed by the results of the survey.

Outcomes

Synthesised information for delivery to the vegetable industry on the:

- Current knowledge and knowledge gaps regarding the importance of land diversity and field margins for beneficial insects and pest avoidance.
- Opinions of leading scientists in the field about future management practices likely to benefit vegetable pest control.
- Attitudes of farmers about the opportunities and barriers to implementation of recommended management practices.

Evaluation and Discussion

It is evident from international peer reviewed literature and the few Australian studies that field margins and other perennial habitats in the landscapes surrounding crop fields contribute to pest suppression. While field margin and landscape level studies are still in their early stage in Australia, especially compared to the dozens of studies in northern hemisphere temperate region, some important results are emerging (see Appendices 1 and 3 for more details). These include:

1. Most **native plants** are not associated with pests and certain low risk options for revegetation or maintenance on farm are identified in the literature (Schellhorn et al. 2006 VG0514, 2007 VG0624, 2012 VG07040, Taverner and Wood 2006, Schellhorn et al. 2010). The management options include maintaining natural vegetation and purposeful revegetation. Williams and Gascoign (2003) suggested a cost-effective way to increase native vegetation on farms by identifying niches not suitable for cropping, but suited to shrubs and trees (e.g. hill slopes); cost-effective approaches that minimize financial risk are the most likely to be adopted by farmers. If weeds are to be replaced by native plants, there are several suggested criteria (Schellhorn et al. 2010), such as native plants are not hosts for pests and diseases, but support natural enemies and that they are compatible with agronomic practices and the farm enterprise (e.g. low growing robust plants that don't impede the movement of machinery). There are examples of native plants that meet these criteria, for example, species in the Myrtaceae family. These plant species were identified in 'Revegetation by Design' program and were shown to support beneficials, do not support pests and even provide additional farm income because they are suitable for the native bush-tucker industry, native cut flower industry or seeds for the revegetation industry (see Box 3).

2. **Weeds** are commonly associated with pests and diseases, but they may also benefit some predators of pests (see an example in Box 1). It is important to note that just because a plant harbors a species designated as a pest, such as an aphid, its presence on a farm is not necessarily harmful to a particular crop. This is because not all aphids are pests in all crops and their presence in nearby vegetation could be useful to support natural enemies that can disperse into the fields. Aniseed weed could be useful in brassica production areas, but not in celery production areas as it harbors celery mosaic virus (Horne et al. 2008 VG05008). St Johns, Stinging nettle, Melon weed, and Bridal creeper did not support grain pests in the study by Perry et al. (2005) across three regions in Australia, but also supported low predator abundances. Regarding management, Gurr et al. (1998) suggested that in cases when a weed harbors beneficials, but not pests, cutting the weed could encourage their movement into the crop (similar to lucerne). However, high abundances of weeds may affect neighboring farms and have consequences for area-wide pest management. The majority of the published research shows that weeds harbor pests and therefore their removal and/or prevention of their establishment is likely to present the lowest risk management option, both on farm and in a wider landscape. This is also likely to reduce multiple crop pests and diseases and reduce pest reproduction. However, not all exotic plants (ornamentals, weeds) are harmful and again exotic plants in the Myrtaceae family present low risk for vegetable crops. The control of weed species can be targeted based on the focal crop and region and its association with pests identified in the literature.

3. **Native vegetation** is important to provide sufficient shelter and resources for beneficials and there is evidence to show that they move from native vegetation to the crop. Benefits will vary with the

quantity, type and configuration of native vegetation (for example, individual paddock trees, retained strips or blocks). The condition of native vegetation (especially disturbance due to for example grazing and related weediness, and complexity of the habitat including the presence/absence of under, mid and overstory, needs to be taken into account, not just the amount and position (connectivity, distance from the crop field). The management options include a reduction in clearing native vegetation, improved management to stop further deterioration (e.g. adoption of alternative grazing strategies (see Lunt et al. 2007 for a decision tree to help predict the effects of livestock grazing and grazing exclusion), fencing). The management action can be chosen depending on the dominant natural enemy group. For example, parasitoids are often poor dispersers and this may require increased proximity of native vegetation to the crop and management at smaller spatial scales, compared with generalist natural enemies.

BOX 1 Case Study: Replacing weeds with native vegetation: A promising approach to discourage pest thrips.*

AIM: The interactions between weeds, insect herbivores (including pest species), crops and beneficial insects can be negative or positive. Previous studies have traditionally focused on weeds and pests associated with the crop. Limited research has been conducted to explore the interactions between exotic pests and Australian native plants and the impact this has on production. A model system was used as a first step to determine what native plant species are least likely to host pest thrips, and can be used to replace weeds that do host pest thrips.

METHOD: The study took place in Northern Adelaide Plains, an intensive horticultural region that includes field and covered crops. Crops include Solanaceae (tomato, capsicum, potato and aubergine), Brassicaceae (broccoli, cabbage and cauliflower) and Cucurbitaceae (cucumber and zucchini). The most serious thrips pest of these crops is western flower thrips *Frankliniella occidentalis* (WFT). The study investigated WFT and three other pest thrips species: tomato thrips, *F. schultzei,* onion thrips, *Thrips tabaci* and a native thrips, *T. imaginis.* Nineteen weed and 12 native plant species common to the area were tested from 13 and three families respectively. Native plants included species of Chenopodiaceae (saltbushes), Mimosaceae (including *Acacia* sp.) and Myrtaceae (including *Eucalypt* sp.). The abundance of thrips from these plants was measured for 12 months from 28 sites adjacent to, and 16 sites >100m from horticultural fields.

RESULTS: The abundance of thrips were influenced by season, proximity to crop and plants species. Compared to weeds, all native plants tested had less likelihood of hosting the exotic and the native pest thrips species. The major pest thrips in vegetable production *Frankliniella. occidentalis* was never found in native plants belonging to Mimosaceae or Myrtaceae. Although the pest thrips were recorded from species of Chenopodiaceae, the odds of finding them on salt bush species were extremely low.

Conclusion: The judicious choice of surrounding vegetation has potential to be an important component of integrated pest management while increasing biodiversity conservation.

* *Schellhorn* N.A., Glatz R.V. and Wood G.M. 2010 The risk of exotic and native plants as hosts for four pest thrips (Thysanoptera: Thripinae). Bulletin of Entomological Research. 100, 501-510.

4. **Lucerne** has been shown to provide a relatively low risk and easily managed habitat to enhance the abundance of natural enemies of pests, especially in spring (see examples in Box 2), as well as providing a source of income. Furthermore, in horticulture production systems there is evidence to show that >10% lucerne has a strong influence on pest suppression within a landscape of 1.5km radius surrounding crop field. The low-risk nature of this management action means that although it has not been widely tested it could be applied to production systems and destroyed relatively easily if any issue did develop. Movement of the beneficials from lucerne to the crop can be encouraged by applying attractant within crop or by cutting the lucerne (Gurr et al. 1998). However, the best planting/harvesting management cycle in relation to the target crop needs to be investigated. Additionally, harvesting lucerne for hay can partly offset the loss of land taken out of primary crop production. Although legumes are shown to provide multiple benefits for Australian agriculture, as well as worldwide (Jankovic et al. 2016), the profit from pasture legumes is well below that of annual crops which may remain an important barrier to their adoption (Williams and Gascoign 2003).

5. At the **landscape level**, native vegetation seems to be crucial for sustaining populations and diversity of natural enemies worldwide. However, the role of landscapes for biocontrol remains poorly known in Australia, due to both a low number of published research and poor replication at the landscape level in the majority of published research. Thus, the lack of strong evidence for landscape effects of semi-natural vegetation on biocontrol in Australia, especially compared to Europe, could be due to: lack of published literature, studies not appropriately designed to test landscape effects, inappropriate spatial scales investigated (possibly too large – see below), differences in field sizes (larger fields compared to Europe) and amount and characteristics of semi-natural habitats (more open forests, more disturbed, less complex, evergreen) and crops (continuous cropping throughout a year in areas with warmer climate), and pesticide drift to native vegetation due to different application methods (crop dusters in Australia). Hence, the off-target effect of agrochemicals (especially broad-spectrum insecticides) should be reduced and pest-management options should be considered in relationship to the broader landscape (at least 1km surrounding focal field), but more research is needed to quantify the benefits and risks. Additionally, the benefits of local interventions, e.g. maintaining field margins, will likely depend on the landscape composition and configuration, as demonstrated in international literature. The other benefits of native vegetation (see below) in the landscapes should be considered and managed for accordingly.

Several issues should be taken into account when considering management recommendations: 1. It should be emphasized that all above mentioned approaches will be valuable only to farmers that are judicious in their use of pesticides and practice of IPM, as insecticide applications can harm beneficials and override the benefits of perennial habitats. Thus, landscape level studies and management should be related to in-field pest control to achieve desirable outcomes. The best strategy is a combination of field margin/landscape options to reduce pest colonization and increase biocontrol, and if economic threshold is reached then spraying with selective insecticides; 2. Most of the abovementioned results come from observational and not experimental studies, meaning that the casual relationships and the effects of different management options still need to be demonstrated. 3. Although the benefits of semi-natural area on farm for abundances of natural enemies of pests is clearly demonstrated in Australia, the link with pest control and crop plant damage and yield still requires further investigation.

BOX 2. Lucerne: Piecing together the evidence for pest suppression

BACKGROUND: Beneficial and pest insects come from surrounding areas each season or every time a new crop is grown. Numerous studies show that non-crop perennial habitat such and native remnant vegetation can provide beneficial insects with shelter, alternative hosts, pollen and nectar food sources, and be important to maintain or increase their abundance. In addition increasing the diversity of habitat can increase insect abundance.

Study1: To compare which crops were more attractive to beneficials, cotton was inter-planted with strips of sunflower, safflower, sorghum, tomato and lucerne. The highest densities of beneficial insects were found in lucerne. Furthermore, the densities of predatory insects declined the further away from the strip. This initial study showed that lucerne was a good source of beneficial insects and was suggested as a way to manipulate predator abundance in crops. However, the movement of beneficials from the lucerne to the crop and the impact on pest populations was not measured.

Study 2: Another experimental study measured whether cutting lucerne would force beneficial insects to move into adjacent crops. Ten by one metre strips of lucerne were sown along the edges of soybean crops. Predatory insects were quantified in both crops before and after cutting the lucerne. Results showed that cutting reduced the numbers of predatory and pests insects in the lucerne but did not influence the numbers of insects in the crop.

Study 3: A comprehensive landscape scale empirical experiment was undertaken to test lucerne for the suppression of melon aphid *Aphis gossypii* in cucurbits in the Lockyer Valley QLD. The total proportions of land-use for the 19 study farms included mainly pasture, native vegetation, and fallow fields. Lucerne and cucurbits were the only crops and each contributed 3% and 1% to total land use respectively. This study experimentally demonstrated that: 1) the timing of predator arrival is important. Aphid suppression was significantly greater when they were exposed to predatory insects early and continuously; 2) significantly higher pest suppression was associated with an increasing amount of lucerne in the landscape at 1.5km. These results were similar for both areas of complex habitat (more native vegetation) compared to habitat that was less complex (less native vegetation); and 3) the large amount of native vegetation and pasture did not have a positive effect on pest suppression. Authors note that this could be due to relatively poor quality of the native vegetation. Although these parameters were not measured, pasture and native vegetation in the area was grazed, had been partially cleared and unlike crops was not irrigated.

CONCLUSIONS: Results from these three studies show that lucerne does attract beneficials, increases pest suppression of aphids and has influence at a landscape scale. However, the role and application of lucerne for the suppression of different pests in specific production systems still requires testing. These studies demonstrate how results from several studies can contribute to building our knowledge about how to test and how to use of a specific crop to suppress horticultural pests.

References:
Study 1: Mensah, R 1999 Habitat diversity: Implications for the conservation and use of predatory insects of Helicoverpa spp. in cotton systems in Australia. International Journal of Pest Management 45:2, 91-100.

Study 2: Pearce, S.and Zalucki, M. 2005 Does the cutting of lucerne (Medicago sativa) encourage the movement of arthropod pests and predators into the adjacent crop? Australian Journal of Entomology 44, 219-225.

Study 3: Costamanga, A., Venables, W. and Schellhorn, N. 2015 Landscape-scale pest suppression is mediated by timing of predator arrival. Ecological Applications. 25(4) 1114-1130.

What is needed to increase adoption?

The most common cited benefits farmers perceive from semi-natural areas on farms that are relevant to the vegetable industry are: biodiversity (increased native species) and biocontrol, aesthetics, reduced wind damage to crops, shade and erosion prevention. The most common drawbacks cited were: increased pests, weeds, fire risk and reduced farm productivity and related room, water, time and money it requires to maintain. Farmers also perceive most of the ecosystem services to be moderately manageable and themselves moderately vulnerable to the potential loss of ecosystem services (Smith and Sullivan 2014).

To increase adoption by growers several main points emerged (see Appendix 2 for more details). First, adoption can only happen when there are on-farm vegetation options to implement; this is lacking. Therefore, to prepare for implementation we need to:

1. Close the knowledge gap (clearly demonstrate the benefits and risks of on-farm vegetation management through research);

2. Provide a 'menu' of options (farmers differ in their goals and management possibilities and should have a possibility to tailor their management decision based on the needs of their farm enterprise); and

3. Take a holistic approach (if field margin and landscape management programs have multiple objectives they will be effective and will more likely be adopted).

To move from implementation to adoption we must:

1. Address financial aspects (financial incentives would largely increase adoption, but there are other forms of income, such as e.g. increase in farm productivity, additional income from native plants, see e.g. Jellinek et al. 2013). Additionally, it is likely that in future producers will be restricted or unable to sell their products in certain markets if they don't manage vegetation sustainably. Thus, perceived public benefit may change to be a private benefit and therefore increase adoption;

2. Disseminate this knowledge through ongoing extension; Establish knowledgeable, trustworthy and independent personnel on ground that will work collaboratively with farmers to help them develop solutions; and

3. Increase simplicity (management recommendations should be practical and manageable for farmers).

Farmers choose pragmatic, effective low-cost options to achieve their goals (Reid et al. 2003). They are reluctant to consider natural enemies as a pest management option due to the high variability and uncertainty of the timing, number and frequency of natural enemy arrival in crop and their impact on pests. Thus, increased research effort is needed to demonstrate benefits/risks of different habitats and management actions, particularly which management actions will increase pest suppression in vegetable crop fields, but will not increase pest and weed abundances. These management actions need to be practical for farmers, i.e. they should not require large amount of water, time, money and room, especially in the absence of financial incentives.

Although we have some understanding of the key factors that will lead to adoption, we still need more options for implementation, demonstration and guidelines. Implementation options given to farmers should include all benefits/risks of different management actions, not only for in-field pest suppression, including different financial aspects (information about ways to increase farm income and about available incentives). While cost/benefit ratio is important for farmers, some of them might give environmental reasons a high priority (Schellhorn et al. 2007 VG06024) and therefore information about the benefits should include direct, private benefits to farmers (pest suppression and other ecosystem services, biosecurity, resilience), but also public benefits such as biodiversity conservation (see below). Finally, If there is knowledgeable, trustworthy and independent (not related to a chemical reseller) personel on ground that will help inform and support farmers to develop management option tailored to their farm enterprise, the rates of adoption are likely to increase. In the future, programs that consider actions at the landscape scale might be essential due to changes in markets, increased management costs, environmental degradation and pest resistance.

What are other benefits/risks that should be considered in holistic approach?

Native vegetation appears to provide multiple **benefits**, while presenting low risk for pest management. Some of these benefits are:

1. Pest suppression (supports beneficials, but less pests);

2. Biosecurity (a buffer against novel species, supports natural enemies of potential pests – this is especially important in the context of global changes such as climate change);

3. Supports other services provided by mobile animals (e.g. pollination, predation by bats and birds);

4. Other services provided by vegetation directly (e.g. mitigate salinity, increases water quality and balance, erosion control, wind-breaks/shade lines, shelter-belt, fire breaks);

5. Resilience (capacity to maintain and provide ecosystem services under changing conditions. Increasing diversity of plants should increase natural enemy diversity as well as their functional redundancy that may act as a buffer against loss of some species due to global change drivers and provide insurance against change);

6. Conservation (increase in biodiversity, provides habitats for endangered/declining species);

7. Other (aesthetics, mental health, property value, C-sequestration and carbon credits, monetary value due to payments for ecosystem services, timber production or any other additional income to the farm).

As a result, there are certain **risks** associated with decreasing area or clearing semi-natural vegetation on farm and in the surrounding landscapes and/or maintaining weeds:

1. Pesticide resistance (due to more spraying required);

2. Vulnerability to pest outbreaks (due to the lower predator: pray ratio);

3. Vulnerability to change (reduced resilience);

4. Changes in hydrology, fire regimes, and nutrient cycling due to weed infestation and lack of natives (currently there are 160 weeds considered threats to Australian biodiversity); and

5. The loss in biodiversity and other ecosystem services.

Thus, maintaining and managing native vegetation can have multiple benefits to farmers and the broader community and clearing native vegetation increases several risks. However, it should be noted that there are possible **threats** in some cases. For example, certain native plants may support some pest species. Monospecific stands of a single native plant with dense understory can harbor feral animals such as pigs and goats. Thus, it is important to develop a region and crop specific decision support tool that would list all known risks and benefits of certain management actions within semi-natural area.

Interviews with researchers

The results from the interviews with researchers largely agree with the literature review. Majority of interviewed researchers had experience in Queensland, particularly South Eastern Queensland (38%), while no respondents had experience in Tasmania or Northern Territory. Cotton was the most investigated crop, followed by beans (mainly chickpea), canola and cereals (wheat and barley), and less so pasture, sorghum and viticulture. One or two respondents had experience in one of the other vegetable crops (pumpkin, melon, sweet corn, tomatoes, capsicum, potato, lettuce, cabbage), or nuts (peanuts, macadamia, almond and hazelnut). *Helicoverpa* spp., aphids and mites were identified as the top three pests across crops, while lady beetles, Hymenopteran parasitoids (particularly *Trichogramma sp*.), lacewings, red and blue beetle and spiders were regarded as the most beneficial natural enemies.

Majority of respondents that had experience with landscape scale research showed that landscape complexity and semi-natural vegetation has a positive effect on beneficials. However, the landscape scale considered varied from areas that are within a 5km radius of a farm field (50% respondents) up to 100s of kilometers and only a few respondents defined landscapes from the focal organism's perspective. This is in a large contrast with international research that considers landscape scales affects on biocontrol mainly within the area up to 3km radius, but the scale depends on the organism group and, contrary to Australia, it was tested multiple times for the main pests and beneficials. Only 15% respondents had experience with field margins (although some considered field margins as a landscape scale research) and in all cases, they found positive effects of field margins on beneficials.

Better management, restoration and maintenance of native vegetation were considered as the key factors related to semi-natural habitats that would suppress pests in the crop. Management activities that would help achieve these objectives included weed removal, increase in diversity and patch connectivity. Twenty eight percent of respondents thought that reduced management activities that have negative effect on beneficials (reduced insecticides, grazing) would also have positive effect on pest suppression within crop. No respondent gave region specific management recommendations.

The major identified knowledge gaps in our interviews are related to arthropod ecology (85% respondents): dispersal of pests and beneficials, amount and position of native vegetation required for pest suppression, population dynamics including sources and sinks of different organisms over time and space, mechanisms and quantification of biocontrol. Fifty percent respondents thought that we need better understanding of management activities in relation to pest suppression, i.e. which management activities to priorities at different scales, from within crop fields to field margins and landscapes.

The cotton industry appears to be regarded among respondents as a leader in proving guidelines and recommendations for IPM, including protecting on farm native vegetation. Respondents generally regarded lack of knowledge, convincing demonstration (simplicity, cost/benefit ratio), guidelines and incentives as major obstacles to implementation.

BOX 3: Integrating native vegetation into horticultural production regions

Several projects have evaluated what native plant and grass species would be suitable to replace weeds adjacent or near horticultural crops. These projects include VG07040, VG06024, VG05014 and RIRDC No SAR- 49A and are often referred to as *Revegetation by Design: Informed and deliberate choice of native plant species*. Projects were undertaken in Lockyer Valley, including Gatton and Mulgowie Queensland, Adelaide Plains and Murray Mallee, South Australia. While each project had a different emphasis, a unifying aim was to provide information for growers to increase their confidence to choose the right native plant species for a given situation or benefits.

Native Vegetation: Selection Criteria

- Compatible with regional and community native vegetation strategies
- Have appropriate agronomic characteristics and are climatically suited to the area
- Relatively easy to establish and manage for example drought tolerance and availability of tube stock
- Maintain populations of beneficial insects
- Least likely to harbor insect pests
- Profit: Perennial natives that generate profit are most likely to engage growers, so the potential value of native plants for the cut flower industry, native bush tucker, and the revegetation industry were also considered.

Evaluation Methods: Evaluation of native plants included setting up demonstration plots of native plants alongside vegetable production facilities. Plant species was regularly sampled for invertebrate predators and pests. In addition to adults the immature stages of key insects, which is an indication that plants are growing populations of insects, were also quantified. Malaise traps and pollen identification were two methods used to confirm the movement of pests between habitats and which native plant species beneficials and pests were visiting. Evidence collected from these research experiments was used to evaluate relative risks and benefits of various native vegetation species specific to the regional location.

Native Vegetation: Examples *Eucalyptus tetragona and E. gillii* are considered low pest risk species are drought tolerant and are suitable for the cut flower market. Beneficial insects brown lace wings *Micromus tasmaniae* were found frequently on a range of native plants including. Eucalypt species. Pest insects are found on salt bush species however compared to exotic plants they are never in high abundance. Salt bush species such as *Enchylaena tomentose* also support many beneficial insects and on balance are considered low risk species and good alternatives for replacing weeds. *Chloris truncata* and *Enneapogon nigricans* are a summer growing drought tolerant native species that commonly occur on the Adelaide plains. They support beneficial insects, have some tolerance to glyphosate and are often found growing on road shoulders. They are less likely to harbor pest insects, have a prostrate habit, minimal fire risk, will out-compete weeds, and not shade crops. A limitation of native grass species was they difficult to establish and direct seed drill method had the best results. Other result show presence of remnant habitat (with and without weeds) near vegetable crops may allow for faster arrival to crops, earlier suppression of pests and fewer pest outbreaks.

Growers Attitudes to Native Vegetation: The feedback from presentation of results, questionnaires and surveys showed many growers were keen to trial native plants. However many said that they need to know where to locate the planting, how many metres apart and how to manage the refuge to get the most out of the pest control services, and other co-benefits such as income from hay or in the case of environmental plantings, income from carbon capture.

Recommendations: Two conservative general recommendations for choosing native plants include 1) avoid using any plants from the same plant family as the horticultural crop 2) comparing species to the results support choosing plant species belonging to the native plant family Myrtaceae would provide a 'best bet'. Results from these projects have a distinct regional focus. However it is easy to see how using similar criteria and methods of evaluation, revegetation by design could be extended to other regions.

References:

2012 HAL VG07040 Revegetation by design, Queensland: Natural resource management and IPM.
2007 HAL VG06024 Phase II: Native Vegetation to enhance biodiversity, beneficial insects and pest control in horticulture systems.
2006 HAL VG05014 Native Vegetation to enhance biodiversity, beneficial insects and pest control in horticulture systems.
2006 RIRDC No SAR- 49A Native Vegetation and Profitable Perennials to Ameliorate Salinity, and Enhance Biodiversity, Beneficial Insects an Pest Control.

Recommendations

General findings from the literature and the researchers surveyed agree that there are from conserving native vegetation at field margins and within landscapes for pest suppression.

In general, there is evidence to recommend:

- Revegetate by Design, and select regionally suitable species of perennial native plants that don't support pests of vegetable crops, provide habitat for beneficials, and possibly provide additional farm income such as plants for the native cut flower industry, native bush tucker and seed for the native revegetation industry (see Box 3 for examples and a list of suggested selection criteria)
- Maintain native vegetation on farm, particularly woody vegetation at field margins
- Remove weeds from semi-natural area. Although in certain circumstances weeds can support beneficials, they are likely to support multiple pests and diseases and often present high risk (see an example in Box 1)
- Improve habitat quality (maintain vegetation strata, reduce weediness and avoid overgrazing)
- Consider planting lucerne at field margins and in broader landscapes (1.5km) (see Box 2 for several examples)
- Consider in-field IPM together with field margin and landscape management

Where to go from here?

To develop specific recommendations for particular vegetable crops, pests and regions, we identified several steps:

1. Developing a decision-support tool for growers by building on the learnings from the Revegetation by Design projects. The tool should allow growers to indetify their crop, region and dominant pest species, and be given several management options, such as particular weeds to control or native plant species to plant. Each relevant plant species should be cross-referenced to information on characteristics such as growth region and habitat requirements, flowering times, the associations with vegetable pests and beneficials, the associations with pollinators, fire retardancy, management for establishment/removal (if available). This would simplify the decision making process of a grower/advisor, by narrowing a range of possible species present in that region, helping their identification and determining if these species are present on the farm and what are appropriate management actions. Advances in technology will allow this process to be easier in the future with for example phone applications that can help on farm plant identification (see e.g. the app "Pl@ntNet" launched in 2013, that helps to identify plants from a picture taken by a phone). The farmers should also be given a list of additional benefits/risks related to a particular management option. Finally, when relevant information is gathered, moving from species lists to an interactive online decision support tool would ensure that the information is easily and continuously accessible.

2. Increasing knowledge of growers through extension: Provide growers with knowledge about benefits and threats of native vegetation as well as risks of not having any. This can be done

through popular press articles, seminars, flowcharts, workshops, factsheets, newsletters, field days (see for example factsheets with lists of weeds and associated pests and native plants and associated beneficials developed in conjunction with the GRDC). Innovative growers who already have and benefit from native vegetation on their farms should be engaged to champion the benefits. Sharing this knowledge with trustworthy and independent personnel that are frequently in direct contact with farmers would ensure increased and ongoing adoption (after the lifetime of the project).

3. Facilitate research to fill the knowledge gaps. The research should test how findings from other industries and international literature. apply to horticulture in Australia as well as develop and test novel approaches.

Knowledge gaps

Results from our survey and literature review identified many gaps in our knowledge that create a barrier to adoption - most of these relate to the broad areas of pest and beneficial ecology. Future research in the vegetable industry should focus on (in order of priority):

- Assessing the appropriate management of lucerne. Although lucerne is demonstrated to provide multiple benefits, the appropriate management (e.g. mowing time) still needs to be tested in relationship to specific vegetable crops.
- Providing experimental evidence of weed/native vegetation management (e.g. removal, revegetation) on in-field pest suppression (below economic injury level)
- Understanding the mechanisms how semi-natural area benefits pest suppression, rather than only quantifying the impact is a crucial step if research findings should be well understood and broadly applied and at the crop, farm or regional scale.
- Quantifying the benefits/risks of perennial vegetation for vegetable crops depending on habitat condition, distances from the crop field and amounts in the landscapes. Field margins and landscapes appear to be important in vegetables in Australia (Schellhorn et al. 2012, VG07040), but further research is needed to quantify the benefits/risks and assess which habitat, where and how much of it should be retained in the landscapes.
- Multiple benefits/risks need to be addressed simultaneously (including multiple ecosystem services, pest complexes)
- Combined (additive or interactive) effect of different management activities at local and landscape scales in relation to pest suppression

In conclusion, targeted management of field margins and perennial on-farm habitat can be implemented as part of an integrated pest management strategy. These are preventative approaches, and should be seen as part of the pest management tool kit (not as a replacement for insecticides, which will always need to play a role) that have multiple additional environmental and production benefits.

Scientific Refereed Publications

Journal article

Gagic, V., Schellhorn, N.A., Paull, C.A., 2016. Landscape diversity and field margin management in Australian horticultural systems (In preparation).

IP/Commercialisation

N/A

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Appendices

Appendix I

Literature review: The effects of field margins and land diversity on pest biocontrol in Australia

Simplification of agricultural landscapes due to agricultural intensification has raised concerns about deterioration of biodiversity and related ecosystem services, such as biological pest control (Foley et al. 2005, 2011). However, this can be partly offset by developing refuges at field margins (Thomas and Marshall 1999, Landis et al. 2000, Marshall and Moonen 2002, Olson and Wäckers, 2007) and in the surrounding landscapes (Tscharntke et al. 2005, Bianchi et al. 2006, Chaplin-Kramer et al. 2011, Veres et al. 2013). The majority of herbivores never become pests because they are suppressed by the activity of their natural enemies. Biocontrol is estimated to provide 5-10 times higher pest control compared to synthetic pesticides (Pimentel et al. 1992) and can save billions of dollars per year (Costanza et al. 1997, Losey and Vaughan 2006). The importance of biocontrol is likely to increase in the face of increasing human population together with increased insect pesticide resistance, input costs and environmental concerns. Thus, an integrated approach that achieves reduced inputs and sustains natural habitats as refuges and resource base for beneficial organisms is required.

Mobile beneficial arthropods are regulated by factors operating at multiple spatial scales (Thies and Tscharntke 1999, Tscharntke et al. 2005, Chaplin-Kramer and Kremen 2012). They recolonise crop fields from surrounding habitats that provide alternative resources such as food, hibernation/over-wintering sites and shelter (Landis et al. 2000, Tscharntke et al. 2005, Rusch et al. 2010). The non-crop vegetation in the landscape may also disrupt connectivity of crops, delay pest incursion and enhance predator arrival into crops (Chaplin-Kramer and Kremen 2012). Numerous studies worldwide have shown that abundance and richness of pest natural enemies (reviewed in Bianchi et al. 2006, Chaplin-Kramer et al. 2011, Veres et al., 2013) and biocontrol (Thies and Tscharntke 1999, Gardiner et al. 2009, Gagic et al. 2011, Thies et al. 2011, Chaplin-Kramer and Kremen, 2012) increase with landscape complexity (generally calculated as a percentage semi-natural area). However, this is not the case for all natural enemy taxa (e.g. aphid parasitoid diversity does not change with landscape complexity, Gagic et al. 2011). Furthermore, the landscape scale to which they respond may differ between specialist and generalist natural enemies (Chaplin-Kramer and Kremen, 2012) and importance of different taxa for biocontrol of the same pest may differ among regions (Thies et al. 2011). The evidence for the effect of landscape complexity on the pests is less compelling (Chaplin-Kramer et al. 2011, Veres et al. 2013), although semi-natural habitats are commonly perceived as a source of both pests and their natural enemies (Thies et al. 2005, Gagic et al. 2011, Rusch et al. 2011a, 2011b, Plecas et al. 2014, Jankovic et al. 2016)

The majority of studies investigating effects of semi-natural habitats (grasslands, woodlands) on pests and beneficials are conducted in the EU and USA (Veres et al., 2013), and have led to programs that provide incentives directly to farmers (e.g. agri-environment schemes) to protect and manage land for biodiversity (Pattanayak et al. 2010, Batáry et al. 2015). Increasingly, information is being gathered in Australia related to different production systems: vegetable (Stephens et al 2006, Schellhorn et al 2010, Costamanga et al. 2015), cotton/grain (Nash et al 2008, Perovic 2009, Bianchi et al 2013, Bianchi et al 2015, Macfadyen et al 2015a, Macfadyen et al 2015b, Parry et al 2015) and viticulture (Thompson et al. 2009, 2010a, 2010b). This review focuses on the effects of habitats adjacent to the crop field and in the surrounding landscapes on arthropod pests, beneficials and biocontrol in Australia. We first give an overview of the history of agricultural landscape development in Australia and similarities and differences with the Northern Hemisphere. This is important if findings from international literature are to be considered within an Australian context. Second, semi-natural habitats can provide benefit to farmers if they increase populations and diversity of natural enemies and if natural enemies substantially colonise fields, reduce pest densities and crop damage thereby increasing yield (Binachi et al. 2006). Thus, we review studies in Australia that measured 1. arthropod abundance and richness within semi-natural habitats, 2. movement and spill-over effects from, and out of, the crop habitat, 3. effects of semi-natural habitats on pests, beneficials and biocontrol within crop fields and how this relates to plant damage and yield.

History of agricultural landscape changes in Australia

In Australia 0.02% of the world's population uses 3% of the world's farmland area (Hamblin 2009). The landscapes started to be cleared for agriculture in 1800s (Lunt and Spooner, 2005), but the majority of native vegetation clearing in Australia predates the 1940s, prior to the Second World War. Since then, landscape fragmentation and homogenisation increased and local management practices intensified (The State of the Environment Report 2001, Reid 2003, Maron and Fitzsimons, 2007), as they did all over the world (Tscharntke et al. 2005). Semi-arid clay plains were converted to croplands, tropical rainforest to sugarcane monoculture, temperate forest to perennial pastures, heathlands on sand plains to wheat, canola and lupin fields. Sixty seven percent of Australia's native vegetation mainly in agricultural and urban areas has been cleared or substantially modified and 42 subregions (out of 355) have less than 30% native vegetation remaining (The Australian Native Vegetation Assessment 2001). Remnant native vegetation is often not representative of natural habitats as it is fragmented and on the least productive land. Historically, economic activities in Australia have focused on wheat and pastoral livestock production, while more recently mining and mineral processing increased, altogether resulting in a loss of biodiversity, soil degradation, dryland salinity, and erratic weather conditions, changed seasonal patterns in hydrological and nutrient cycles of the native ecosystems (Tibbett et al. 2012).

Australian landscapes are different from European and probably more similar to arable landscapes in the US (Thomson and Hoffmann, 2010b). Thomson and Hoffmann (2010b) argue that unlike in Europe, the woody habitat area at the landscape level is not necessarily strongly correlated with the woody area at the local level (in Europe, percentage semi-natural area is correlated at different spatial scales). Similarly to Australia, in the US landscapes have less variability in complexity, connectivity and land-use intensity, compared to Europe. Farming in Australia is also somewhat different from Northern Hemisphere. It is adjusted to old, flat, salty soils with a lack of deep, rich soils and mostly dry and variable climate. Australian fields are often larger in size, and differently managed compared to European. Although the same groups of natural enemies are important for biocontrol worldwide (*Hymenoptera* (ants and wasps), *Coleoptera* (carabid, coccinellid, and staphylinid beetles), *Heteroptera* (pirate, assassin, and ambush bugs), *Neuroptera* (lacewings), *Diptera* (syrphid and chamaemyiid flies), as well as mites and spiders, arthropod community structure and composition differs between Australia and Europe or the USA. For example, it appears that there are fewer species of carabids in Australia (Horne 2007). The pest complexes are different and where in Europe some native pests are controlled there is lack of natural enemies to control the pests that are exotic to Australia (see Canola example Gu et al. 2007). In temperate regions where majority of research is conducted, natural enemies need to go through overwintering period, mainly in woodlands. By contrast, in subtropical climate, natural enemies can switch among crop habitats year-round

(Schellhorn 2012 VG07040). Pests and beneficial in Australia need to deal with long hot and dry periods when they migrate, aestivate or enter diapause. For example, Diamondback Moth, a pest of *Brassicacea*, shows climate driven migratory patterns in Australia (Furlong et al. 2013). The prevalence of migratory pests is suggested to hamper the success of European pest control strategies. Finally, semi-natural woody vegetation in Australia is more open with less diverse understory and often under stronger grazing pressure, compared to temperate regions, indicating differences in disturbance regimes and in its role as a refuge (Schellhorn 2012 VG07040). Given the differences in climate, landscapes and farming practices between Australia and the rest of the world, patterns found in international literature cannot be easily translated to Australian conditions without testing.

The large area of Australia, covering different climate and biogeographic regions, resulted in somewhat different region specific patterns in agricultural management and in arthropod communities. For example, some pests are unique in certain regions (19 unique pests out of 39 found in QLD and 10 out of 30 in SA in vegetable crops, Schellhorn 2007 VG06024). South-east Australia with the centre in Victoria is under particularly high environmental stress (NLWRA 2001). In southern Australia, large paddocks of crops in rotation with pasture, canola, cereals and legumes represent typical agricultural landscapes with little remnant woodland vegetation, non-crop vegetation along the road sides and windbreaks planted for stock protections, salinity control, farm forestry and as wildlife corridors (Bird et al. 1992). This region generates a substantial proportion of Australian grain production, but it is also one of the most ecologically degraded with less than 5% of the remnant vegetation cover with a quarter of remaining woody vegetation covering less than 5ha (NLWRA, 2001). Crops also replaced pastures that are now small, grazed, nutrient enriched and dominated by exotic annual species. Regeneration of ageing remnant eucalyptus remains feasible (up to 40% in Victoria), but the window of opportunity is decreasing quickly (Vesk and McNally 2006, Dorrough and Moxham 2005). The Australian government has committed to reversing decline in native vegetation (e.g. Victoria's Biodiversity Strategy 1997) with a target of 15-30% native vegetation cover, but this is often challenging. In Western Australia, most farmers don't commit more than 10% of farm area to remnants and revegetation (Smith 2008) and even 10% is suggested to be an ambitious target under current funding opportunities (Jellinek et al. 2013). However, there is increasing recognition in Australia that native vegetation is not something to be cleared, but also has intrinsic value and can help ecosystem resilience in the context of multiple uncertainties, such as climate change (Reid 2003). Biodiversity legislation and policies are increasing since 1992 when Australia ratified the United Nations Convention on Biological Diversity (see Reid 2003 and references therein). There is an initiative to revegetate some farming areas in Victoria for carbon capture and to maintain biodiversity in the face of climate change. Australian agencies and natural resource management organisations are conducting vegetation condition assessment and mapping (Pert et al. 2012), but the current approaches don't take landscape context into consideration and may not lead to the best biodiversity conservation decisions.

Some important differences between international and Australian terminology in the literature should be taking into account when comparing research findings. For example in Europe landscape level analyses in agroecology often considered circular area around focal filed with a radius of a few hundred meters up to 3km, while in Australia the landscape level analyses can be far greater. Understanding appropriate spatial scale dependant on the dispersive ability of the target organism is essential for sound landscape management recommendations. Second, while the term semi-natural area is commonly used worldwide (including mainly non-managed woodlands and grasslands), in Australian literature the term native vegetation is commonly used, thus emphasising plant origin. Finally, while weeds can be native and exotic species in temperate area, in Australia weeds are often exotic and therefore the distinction between weeds and native plants, rather than exotic and native plants is commonly used. Native vegetation is emphasised more in Australia, compared to Europe or the US, in relation to its benefit for pest suppression because pests are generally exotic species in

Australia, supported by exotic weeds, that are in turn related to exotic crop plants, while beneficial arthropods are mainly native and associated with native vegetation (Glatz 2015).

Abundance and diversity of pests and their natural enemies in non-crop habitats in Australia

Native plants in Australia are repeatedly shown to have low occurrence of pests and high occurrence of predators, while exotic weeds and crops harbour more pests. Schellhorn et al. (2010) found low occurrence of tree thrips species that are vectors of TSWV (tomato spotted wilt virus, which is known to cause huge economic loss of *Solanaceae* vegetables) on native plants. Tavener and Wood (2006) showed that brassica weeds harbour up to 300 times higher abundances of Western Flower Thrips compared to native plants and 160 times higher compared to native grasses. Latham and Jones, (1997) showed TSWV not to be common in native plants while 16 out of 45 exotic weeds harboured this disease. Wood et al. (2010) demonstrated a benefit of native saltbushes as reservoirs of agromyzid leafminer parasitoids on horticultural farms, while this native plant was less likely to support vegetable pests (Schellhorn et al. 2010). Contrary, Brassicaceous **weeds**, such as wild radish and wild turnip are hosts for pests, such as aphids and diamondback moth in canola and senescent weeds surrounding canola crop can harbour Rutherglen bugs (Gu et al. 2007, Furlong et al. 2008, Severtson et al. 2015). The presence of weeds, such as thistles in autumn is argued to affect an increase in slug population (Nash et al. 2007). Jassids that are pests in sweet corn, beans and other vegetable crops and vectors of maize wallaby ear were frequently found on exotic grass along roadsides (particularly green panic), but not on native plants sampled (Schellhorn 2006 VG 05014). Native plants had higher abundance of predators and lower abundance of pests compared to crops, with leafhoppers and Rutherglen bug, being dominant in crops and spiders and ants on native plants (Bianchi et al 2013). Perry et al. (2015) also found that native plants support lowest pest abundances and fewer pests than predators, while the majority of exotic weeds supported more pests than predators. Schellhorn (2007 VG06024) identified 37 native plant families that have low risk for pest management.

Native plants and exotic weeds can also differently affect reproduction of pests and predators. In the study across three Australian states, Perry et al. (2015) showed that pastures harbour pests, but also high proportion of juvenile predators. Crops and weeds are also shown to be more strongly associated with pest reproduction, compared to native plants (Bianchi et al 2013). Destruction of weeds in field margins, such as capeweed and thistle is argued to reduce redlegged earth mite abundances in canola because of the lack of pest breeding sites (Gu et al. 2007). Reproduction of the majority of predators (except for spiders) did not differ between native plants and crop (Bianchi et al 2013), although undisturbed areas are argued to be vital for immature predator stages, such as for red and blue beetle (Perovic et al. 2010).

However, not all studies found evidence for higher importance of native vegetation for natural enemy populations or weeds for pests. For example, in the study by (Schellhorn 2012 VG07040) native and riparian vegetation together with grasslands had the lowest natural enemy abundances, but this could be partly due to temporally restricted sampling period. Stephens et al. (2006) found that both native plants and weeds can be important parasitoid reservoirs, although the native saltbush *Atriplex semibaccata* attracted high numbers of parasitoids. The parasitoid assemblages they analysed consisted of *Trichogrammatidae, Scelionidae* and *Eulophidae*, which contain species important for biocontrol of *Lepidoptera, Hemiptera* and *Thysanoptera*. Schellhorn (2006 VG 05014) also found beneficial predators on both, weeds and native vegetation and high diversity of hoverflies and parasitoids in horticulture fields. The presence of weedy Yorkshire fog *(Holcus lanatus L.)* did not disrupt the beneficial effect of shelterbelt complex understory (Tsitsilas et al. 2006) and species composition of the remnant grassland, vegetation height and percentage cover did not affect carabid predator abundance (Nash et al. 2008). Horne et al. (2008 VG05008) found certain weed species to be useful in providing nectar and pollen to beneficial insects, especially hoverflies and wasps.

One of the major factors determining abundance and diversity of arthropods is the **complexity** and **quality** of semi-natural habitats. Semi-natural area in Australia varies from complex with understory (mainly grasses) and mid-story (small trees, shrubs) to simplified ecosystems without these two components. Tsitsilas et al. (2006) observed that numbers of pest mites and lucerne fleas are lower, while predatory mites and spiders were higher in shelterbelts compared to pastures, especially so when shelterbelts carried a groundcover with high grass. This is confirmed in experimental study with ground cover manipulation where reduced height and cover of vegetation decreased predatory mites, beetles and spiders within windbreaks (Tsitsilas et al. 2011, see also Ridsdill-Smith et al. 2008). Good quality ground cover is also shown to be important within orchards, as found in citrus, where dense ground cover enhanced predatory mites and had lower thrips damage (Smith & Papacek 1991, Colloff et al. 2013). High habitat complexity in shelterbelts (tree canopy, shrub and ground herb cover) were shown to support higher diversity of wasps (Lassau and Hochuli 2005), presumably owing to more potential microhabitat niches, shelters and hosts. Beneficial hymenoptera were found to increase with increased availability of floral resources, grass height and ground cover (Smith et al. 2015b). However, Smith et al. (2015a) found no effect of vegetation structure (number of trees and shrubs, canopy cover) on coccinellids in shelterbelts.

A common factor affecting these differences in habitat quality and its relationship with plant and animal biodiversity in Australia is **grazing**, recognised as a novel challenge to ecosystem services (Sherren et al. 2012). Grazing favours exotic annual plants and prevents regeneration by native species through frequent disturbance and raised availability of soul nutrients (Duncan and Dorrough 2009). Grazing intensity was shown to affect spider (Churchill and Ludwig 2004) and ant assemblages (Woinarski et al. 2002). Tree hedges and grass strips in field margins are argued to benefit Mesostigamtic mites (an arthropod order of mites that are primarily predatory), but grazing intensity can affect them through its effect on litter accumulation, soil organic matter and microclimate (Beaulieu and Weeks 2007).

Movement of pests and beneficials across the crop/non-crop boundary

To assess how richness and abundance of pests and predators in semi-natural area affect within-crop ecosystem services the species movement across the crop/non-crop boundary needs to be investigated (Rand et al. 2006, Schellhorn et al. 2014). Ultimately, the goal in agroecology is to design agricultural landscapes that reduce resources for pests and/or enhance natural enemy populations and their movement into the crop fields. Although natural enemies of pests may be abundant in semi-natural vegetation, the high contrast between crop fields and native vegetation may limit movement of some species into a crop or the movement may not be sufficient to affect pest suppression within crop (Pearce and Zalucki 2005, Macfadyen et al. 2015a). Hossain et al. (2002) showed that pests and their natural enemies move as a response to harvesting, from harvested lucerne to unharvested refuges. Macfadyen and Muller (2013) found greater parasitoid densities, especially aphid parasitoids, moving from native vegetation into the canola crop, while parasitoids of caterpillars moved more from cereals into canola. Later in the season both aphids and parasitiods, but not predators moved out of native vegetation. However, they found only a few instances of the same parasitoid species using hosts in both, canola and native vegetation. This was confirmed in the second study where predators were found to move more often from native vegetation into crops than vice versa irrespective of crop phenology, while pests and parasitoids showed similar movement patterns from native vegetation only at early stages, i.e. after crop emergence (Macfadyen et al. 2015a). Schellhorn (2008 VG06024) showed that that there is immigration of insect predators from native vegetation (particularly so riparian remnants) to crop, but also some pests, such as jassids that use exotic grasses common in remnant edges (Schellhorn et al. 2006 VG 05014). Furthermore, multiple studies demonstrated edge effect, i.e. higher abundances of pests and natural enemies at field edges (e.g. Thomson and Hoffmann, 2009), presumably due to their dispersal from surrounding vegetation and proximity to alternative resources (Rand et al. 2006). The field size and shape affects its edge-to-interior ratios and thus the importance of the edge effect. Larger field size in Australia together with edge effect described in many arthropods could mean different benefit of field margins and landscape complexity in Australia compared to Europe.

Evidence for the effect of non-crop habitats on in-field abundance and diversity of arthropods

Most arthropods in semi-natural areas do not disperse to crops (House et al. 2012). For biocontrol to be effective within crop field, natural enemies need to move from semi-natural area into crops and have a substantial impact on the pest species. High species abundance and richness in semi-natural vegetation in combination with evidence that the same species move into crop fields can provide circumstantial support that semi-natural habitats act as a source (Bianchi et al. 2015). More often, studies that demonstrate the role of semi-natural area as a source of beneficials in crops, investigate in-crop species abundance and diversity in fields with or without field margin or with low and high landscape complexity. Field margins in Australia are shown to enhance beneficial species abundances and/or richness within various crops and pastures: shelterbelts benefited pastures (Tsitsilas et al. 2006, 2011) and cotton fields (Perovic et al. 2009), remnant native grassland to canola (Nash et al. 2008), woody vegetation (but not pastures) to vineyards (Thomson and Hoffmann, 2009, 2010a, 2013), windbreaks to citrus (Smith and Papacek 1991).

Adjacent woody vegetation (shelterbelts and/or remnant woodland) can enhance pest natural enemies in crops and increase farmland biodiversity. In Australia, this is shown for abundance of smaller (such as *Trichogramma* and *Diomus sp*.), but not larger, more dispersive parasitoids and ladybirds in vineyards (Thomson and Hoffmann, 2009, 2010a, 2013). *Eucalyptus torelliana* windbreaks and Rhodes grass in inter-rows enhanced Australian phytoseiid mite, *Amblyseius victoriensis*, populations in citrus orchards (Smith and Papacek 1991). Remnant woodland and shelterbelts were also shown to provide a source of immigrants into cotton crops (Rencken 2007, Perovic et al. 2009). However, shelterbelts at field margins could harbor pests, such as *Australiodillo bifrons* (the flood bug) in addition to many beneficial natural enemies (Paoletti et al. 2007). Parasitoids in vineyards did not benefit from **adjacent pasture** (Thomson and Hoffmann, 2009), but remnant native grassland adjacent to crops was shown to harbour high densities of predatory beetle *Notonomus gravis*, a predator of slugs, and the effect decreased with distance in canola fields (Nash et al. 2008).

Adjacent crops can also benefit natural enemies within crop fields**. Lucernce** appears to harbour high abundances of natural enemies and have an important effect on their within crop abundances (Gurr et al. 1998 and references therein). Schellhorn and Silberbauer (2002) found higher abundance of beneficial predators within lucerne in spring and within sorghum in summer compared to other crop and non-crop habitats. Invertebrate predators are also shown to decline with distance from lucerne planted as strips in cotton (Mensah 1999). Pearce and Zalucki (2006) showed that wolf spiders were more abundant within lucerne and decreased with distance from the lucerne/soybean interface and Costamagna et al. (2015) found the highest predator abundance within 500m from lucerne. In some vegetable crops planting cereal strips could also be beneficial. When aphids are serious pests, such as in lettuce, planting **cereal strips** ahead of the crop may provide a source of predators and not pests for the vegetable crop, especially in the early crop stages (Horne et al. 2008 VG05008).

Several studies in Australia found stronger effect of field margins compared to non-crop vegetation at the **landscape** scale on a range of natural enemies (Thomson et al. 2010b, D'Alberto et al. 2012). The effect of field margins on beneficials is shown to be stronger when the landscape effect is low and particularly important for insects with low dispersal capacity (Schellhorn 2012 VG07040). Costamagna et al. (2015) did not find a positive effect of non-crop area in the landscapes on aphid natural enemies, but there was a positive relationship with aphids. Woody vegetation at the landscape scale had lower effect on parasitoids in vineyards compared to the effect of field margins (Thomson et al. 2009, 2010b). Individual trees (Alexander, Livistona, Coconut palms, Wattles, Eucalyptus) commonly found on growers' farm are argued to increase densities of white grabs in sugarcane when trees are at field margins (up to 150m away from the crop), possible having even larger effect than total vegetated area (Goebel et al. 2010, Zellner et al. 2014).

However, woody vegetation in the broader landscape was shown to benefit some natural enemies, such as *Eulophidae* parasitoids in vineyards (Thomson et al. 2010b) and natural enemies (*Oxyopes spp.* and D. *bellulus* - red and blue beetle), but not herbivores in cotton (Perovic et al. 2010). Contrary, grassland cover in the landscapes was shown to benefit pests, as found for the minor cotton pest *Austroasca viridigrisea* in cotton, but also generalist predators, such as red and blue beetle (although this species seems to prefer woodland) (Perovic et al. 2010). Importance of landscape heterogeneity together with stand structural complexity for enhancing biodiversity is highlighted in almost all work in Australian conifer and eucalypt plantations, but it may involve trade-offs with wood and pulp production, although some benefits for stand productivity and pest control are recognised (Lindenmayer et al. 2003, Elek and Wardlaw 2013). Macfadyen et al. (2015b) emphasised importance of analysing landscape connectivity of vegetation productivity in relationship to pests, as opposed to connectivity of habitat types or their configuration or composition (habitat area). In rare cases when pest is more sedentary, such as scarabaeid beetle *Heteronyx piceus* in peanuts (Ward and Rogers 2006), the surrounding landscapes could be managed only for supporting natural enemies. Finally diversity of crops surrounding focal field, not only diversity of semi-natural area, is likely to be important for biocontrol, but the right type of diversity should be chosen (Lawrence 2003). Schellhorn and Lawrence (2008) argued that the proportion of the new crop infested by silverleaf whitefly is determined by the number of host crops in landscapes of 3km radius surrounding crop in intensely cropped landscapes, and 0.5km radius in less intensely cropped landscapes, while the severity of infestation depends on sources within 100m in both landscape types.

Evidence for the effect of non-crop habitats on in-field biocontrol and crop damage and yield

Increased abundances and/or diversity of natural enemies of pests within field do not necessarily translate to higher biocontrol and yield. For example, Gagic et al (2011) showed that although parasitoid species richness did not change with landscape complexity, aphid parasitism rates increased in winter wheat in Germany. In Australia, the effects of field margins or surrounding landscapes on within crop biocontrol are rarely tested. However, shelterbelts are shown to have positive effect on biocontrol of earth mites (Tsitsilas et al. 2006). Adjacent remnant vegetation increased parasitism of light brown apple moth *Epiphyas postvittana* eggs in vineyards, while egg predation was either not affected (Thomson and Hoffmann 2009) or increased (Thomson and Hoffmann 2010a, 2013). Danne et al. (2010) found that egg predation of light brown apple moth was higher in the native cover crops, compared to the control (introduced annual cereal oats *Avena sativa*), but these native cover crops also increased abundance of some potential pests. Baggen and Gurr (1998) found that parasitism rates of *P. operculella* were higher when larvae were recovered from potato plants close to a flower strip, compared to 10m distant. However, proximity of flower strips also increased pest populations and crop damage. Costamagna et al. (2015) showed that aphid survival on melon decreased as the percentage of lucerne at 1.5 km increased. Peng et al. (1998) found that proximity of native vegetation enhances natural enemy abundance and diversity in cashews, especially the green ant abundances, and in turn increased yield.

Additionally, semi-natural area in field margins and in the surrounding landscapes can enhance other organisms, such as birds, bats and pollinators that can affect yield quantity and quality (e.g. Eadie and Stone 2012, Glatz 2015).

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Appendix II

Farmers’ perceptions and adoption

Awareness, adoption and potential impact of different integrated pest management strategies (IPM) has been assessed in several studies in Australia (Horne et al. 1997-PT437, 1999, 2008, 2009 - VG05007, Page and Horne 2007 VG06086., see also Schellhorn et al. 2009, Zalucki et al 2009, 2015). The majority of the research on IPM adoption by farmers focused on the value of in-field farm management in order to reduce pesticide application, although landscape-level changes are important for development of IPM strategies (Lawrence 2009, Schellhorn et al. 2015). The studies investigating IPM adoption indicate that the rate of adoption has been slow and is due to the failure of integrated pest control strategies, the lack of motivation and of IPM advisors (Barr and Cary 2000, Horne et al. 2008), especially in the absence of a crises. The farmers were reluctant to consider natural enemies as a pest management option due to the high variability and uncertainty of the timing, number and frequency of natural enemy arrival in crop and their impact on pests (Schellhorn et al. 2009, Zalucki et al. 2009, 2015). Security provided by chemicals (‘sample, spray and pray’ approach, Zalucki et al. 2009, 2015) is often chosen by farmers, over risky yield loss or delay, but growers often try to minimise use of pesticides without compromising yields, as shown for vegetable growers (Bleasing 2013 VG12048). However, the rate of IPM adoption can be exceptionally high if advice is given in person, by a crop advisor or someone with whom they have regular contact, such as trusted extension personnel (Horne et al. 1997 PT437, 1999, Norton et al. 1999, Brier et al. 2008, Page and Horne 2007, Schellhorn et al. 2009, Zalucki et al. 2009, Januchowski-Hartley et al. 2012). However, it should be kept in mind that an advisor may also be a chemical reseller who is more used to recommending pesticides for pest control (Page and Horne 2012).

In the past 30 years, there have been changes in farmer perceptions and practices (Zalucki et al. 2009). Emerging resistance issues, environmental awareness and public concerns are factors affecting adoption of IPM in the Australian cotton industry all of which have promoted regional cooperation among growers (Zalucki et al. 2009). These factors are likely to act in future to persuade growers in other industries, such as grain, to consider alternatives to high chemical inputs (Holloway et al. 2008, Lawrence 2009). However, for widespread adoption of IPM that relies on beneficial species it is important that benefits (from yield quality, quantity, stability, savings from reduced inputs), outweigh costs (Holloway et al. 2008). For example, although apple growers in Harcourt are aware of the potential pest outbreaks with the current management practices, the short-term economic gain overrides this rational thinking (Christensen and Gaire 2015). Since the price and efficacy of pest control are still some of the most important factors in many industries the crop value can strongly affect adoption of IPM (Zalucki et al. 2009, Nash and Hoffmann 2012). In the vegetable sector, the current rate of awareness and adoption of IPM varies across crops and regions (Horne et al. 1999, Schellhorn et al. 2009). Page and Horne (2007) found 28% of vegetable growers practice IPM. Growers that do not use IPM did not regard IPM to be too expensive or complicated, but rather argued that the current pesticide approach still works and so they were not going to change practice (Page and Horne 2007). In the future, market demand for IPM labelled products may be a strong driver of change (Schellhorn et al. 2009). For example, citrus growers from Queensland have access to more profitable international markets because they can combat fruit fly without insecticide use (Lloyd et al. 2007, Nash and Hoffmann 2012). However, more likely is that IPM may become standard practice. For example, IPM is now legislated in the EU directive (EU Directive 2009/128/EC) and there is a re-orientation of large retailers where they were previously purveyors of producer’s products, increasingly becoming the consumers. Walmart and Whole Foods now have ‘responsibly grown rating systems’ for chemical use and environmental stewardship that growers must abide by, and the information is communicated to consumers on packaging, e.g., good, better best. Labelling strategies that highlight producers who undertake remediation/conservation actions present an opportunity to maximising beneficial outcomes at a landscape level (Glatz 2015). If in future, producers are restricted or unable to sell their products if they don't manage vegetation sustainably, perceived public benefit may change to be a private benefit (Chudleigh et al. 2004).

Perceptions of landscapes and ecosystem services

Although agricultural policies influence farmers in various ways in Australia (e.g. export quality standards), farmers can still choose the specific management practices to meet policy requirements, and the choice they make will also depend on their perception of the landscapes (Sherren et al. 2012). Farmers balance monetary rewards with other benefits (aesthetics, stewardship, identity and lifestyle) (Januchowski-Hartley et al. 2012, Sherren et al. 2012). Farmers that adopt conservation measures realise the intrinsic value in biodiversity and see themselves as stewards of biodiversity and ecosystem services, both of which they regarded as important drivers of sustainability (Greiner and Gregg 2011, Januchowski-Hartley et al. 2012, Greiner 2015, Page and Bellotti 2015). In the study by Januchowski-Hartley et al. (2012) the landowners believed that invasive species management, riparian revegetation (ranked as their third priority) and maintaining native vegetation (ranked as their fourth priority) would benefit biodiversity and landscape aesthetics as well as provide private benefits. The value of the remnant and revegetated areas identified by landowners in the study by Jellinek et al. (2013) is that it can reduce wind damage to crops and livestock, increase native animals, aesthetic value and habitat connectivity. They also thought that it can increase pests, weeds and fire risk and reduce farm productivity and therefore require time for managing these areas by controlling weeds and pests. The majority of landholders in Victoria and NSW thought that they benefit from improved aesthetics, but also gained a net economic benefit from their remnant native vegetation mainly from firewood extraction, stock shelter, shade and grazing (Miles et al. 1998). The benefit of native vegetation for biocontrol was perceived to be offset by increased pest abundances (Miles et al. 1998). However, recent study found that biological control is still a highly valued ecosystem service on farms (Page and Bellotti 2015). Smith and Sullivan (2014) investigated 12 ecosystem services, including biocontrol, and found that farmers place a high value on all of them, but perceive most of them to be moderately manageable and themselves moderately vulnerable to the potential loss of ecosystem services. Average or high regard for native vegetation for erosion prevention, refuge for animals and windbreaks was also found in the study by Schellhorn et al. (2007 VG06024), although the drawbacks (it takes time to maintain, water and the areas) are also recognised. Graziers practicing holistic management (HM) perceived biodiversity conservation and crop production in an integrated way, demonstrated more adaptive behaviour (e.g. capacity to adapt management to align with new environmental conditions), systems thinking and considered the long-term challenges due to environmental degradation. Graziers not engaged with HM were more concerned with short-term weather events and considered only set-aside parcels for conservation activities (Sherren et al. 2012). HM farmers also often reported more consistent incomes and less need for high inputs (Sherren et al. 2012). Sherren et al. (2012) argues that this difference in perception of landscapes might be due to programs that started in the 1990s, such as Landcare that defined farm areas for either production or conservation and funded only projects on the later.

Adoption

Australian farmers are motivated to conserve ecosystem services by financial, environmental and social factors (Pannell et al. 2006, Page and Bellotti 2015). Policy instruments that can promote adoption of holistic farm management are free materials, more accessible information and training (e.g. via internet, newsletters, social networks and extension mechanisms – field days, workshops, seminars) and short-term financial assistance (Schellhorn et al. 2007 VG06024, Schirmer et al., 2012, Sheeren et al. 2012). The majority of landowners would revegetate if there were payment for the loss of productive land or for carbon storage, although less than half thought that productive land loss or management requirements were impediments to revegetation (Jellinek et al. 2013). Thus, actions that provide public benefits (e.g. biodiversity, gully erosion control) with no perceived private benefits (improvement in production, such as planting of perennial pastures and trees for production) are not likely to be widely adopted. In these cases, appropriate incentives (cash for on ground works, extension and community recognition) might be required to offset private costs (Miles et al. 1998, Pannell et al. 2006, Cary and Roberts, 2011, Januchowski-Hartley et al. 2012). Furthermore, providing flexibility through offering multiple options or contract tailoring to fit the needs of the biodiversity goals as well as farmer's situation and preferences might be necessary due to significant heterogeneity of preferences (Schirmer et al. 2012, Greiner 2015). However, while cost/benefit ratio might be important for some farmers, some other might give environmental reasons a high priority (Schellhorn et al. 2007 VG06024).

Although non-financial factors such as personal and family well-being, care based ethics and stewardship ethics may be important for motivating Australian farmers to adopt conservation policies and practices, government uncertainty regarding conservation policies was identified by Page and Bellotti (2015) as the most important impediment, followed by financial constraints and lack of information. The major barriers to participating in riverine restoration reported by landholders were biases towards ecological as opposed to production outcomes, impractical programs and government mistrust (Januchowski-Hartley et al. 2012). However, majority of interviewed landholders (65%) would engage in riverine restoration to improve their land, be able to provide input into program design or receive some other benefits (Januchowski-Hartley et al. 2012). Jellinek et al. (2013) found that three quarters of landowners were planning or had undertaken restoration, and previous restoration activities and off-farm primary income source best predicted future revegetation actions. Perceived threats from weeds, pests or fire, rather than environmental outcomes, were more likely to affect a landowners' decision to manage restored or remnant areas, while lack of time and money were major impediments (Jellinek et al. 2013). Landholders not engaged in native vegetation planting on their farms had strong farming connections (more farming experience and farmed for more generations) (Raymond and Borown 2011). Previous revegetation activities were not influenced by region, primary source of income or enterprise type (Jellinek et al. 2013). Landowners that were Landcare group members were found to be most likely to have revegetated their land in the past, but were no more likely to revegetate in the future, compared to those that were not members (Jellinek et al. 2013).

Information is also identified as an important factor in adoption, especially demonstration and guidelines Schellhorn et al. (2007 VG06024). In a recent survey of farmers' willingness to participate in programs for conservation of ecosystem services in NSW, Page and Bellotti (2015) found that all farmers that have previously not participated in such programs (26%) were unaware of available programs. In grazing landscapes, the way farmers see and value landscape is influenced by training in holistic management principles, but it is possible that those who attend such training are also more receptive (Sherren et al. 2012). The growers need to know what beneficial insects they have, the impact their management activities have on them, as well as what is the role of native vegetation in their production system (Schellhorn et al. 2009). Although farmers are now more aware of the ecosystems and potential benefits of biocontrol (Zalucki et al. 2009), many farmers still lack a clear understanding of the impact of different practices on biodiversity and such knowledge can influence the decision to undertake biodiversity conservation (Greiner 2015).

It is likely that the benefit to some farmers comes from the holistic view of production as certain activities may have multiple benefits to farmers, but also multiple social and environmental benefits (Zalucki et al. 2009, Sheeren et al .2012, Nash and Hoffmann 2012). Economics of such interventions should be viewed in terms of overall farm revenue (Zalucki et al. 2009). Furthermore, selective implementation of IPM components may result in no effect, i.e. no increased biocontrol (Zalucki et al. 2009) and difficulties measuring the impact. For example, the benefit of field margins and landscapes cannot be fully assessed if the farms are sprayed with insecticides. Short time scales of measurements, and communication between growers and extension officers that last only during the lifetime of IPM projects are also argued to hinder objective measurements of success and the degree of implementation of various programs (Zalucki et al. 2009). In the future, to mitigate short-term financial stress, programs that consider actions at the landscape scale might be essential due to increased management costs, environmental degradation and pest resistance (Zalucki et al. 2009). However, for this to be implemented in IPM, landscape scale studies need to demonstrate the impact on pest complexes and the interaction with field level management, rather than to focus on single pest model systems (Schellhorn et al. 2015).

The uncertainty in the impact of landscapes and field margins on predators and thereby on pests is one of the major obstacles to adoption. Field studies reviewed here, together with modeling studies can help investigate the cost-benefit ratio of field margins and landscape manipulation to achieve increased biocontrol. However, it should be recognised that valuing environmental parameters in economic terms is difficult and argued to be fundamentally flawed (see Glatz 2015). A better alternative is demonstrating a clear link between different management options and in-field pest suppression below the economic injury level. This is essential if management recommendations are to be widely adopted, especially without financial incentives. In a long run, early preventive action can prove much cheaper, compared to restoring heavily degraded landscapes for farming (Eadie et al. 2012). Finally, maintaining native vegetation and, thus, the investment in biodiversity and ecosystem services research is important not only due to likely investment return, but also for an to environmental duty of care and Australia's international obligations to conserve biodiversity (Reid et al. 2003). By addressing the knowledge gaps identified in this report and coordinating the information already available, Australian horticulture could work towards fully integrating management actions to better realize the benefits of multiple ecosystem services including pest suppression and provide multiple benefits not only to farmers, but also to the broader community.

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Appendix III

Responses to Expert Survey:

This survey was conducted to understand the scientific community's perception and opinion about the benefits of non-crop habitat surrounding crop fields. Their views were gauged by asking a range of questions associated with these topics:

- Their research experience with landscape scale and field margin influence on pest and beneficial insects (e.g., natural enemies of pests, here after referred to as beneficials (abundance, diversity and biocontrol);
- Knowledge gaps that hinder management actions to achieve better pest suppression in their region

These survey results form part of the review being conducted by CSIRO on the effects of landscapes and field margins on pest control, and contribute to the crop and region specific recommendations to Horticulture Innovation Australia (Hort Innovation).

Methods:

Thirty six researchers from around the country were approached by email and or phone and a total of 26 responded. Researchers were given some background and times were prearranged for phone interview and or they responded by email.

The survey questions

Note: All the questions asked are in the context of landscape or field margin effect on pests and beneficials.

1. In what region of Australia do you have the most experience working in this landscape diversity and field margin management? Please also name towns.
2. In what crop do you have the most experience? Please rank them in order of most to least?
3. What is the main pest(s) in that crop and region?
4. What are the main beneficials in that crop and region?
5. How do you define landscape in your research? i.e. What is the scale of landscape?
6. Do you or have you conducted any research for this crop and region showing effects of **landscapes** on pests and beneficials (abundances, diversity, biocontrol)? If yes, please shortly describe the main findings.
7. Do you or have you conducted any research for this crop and region showing effects of **field margins** on pests and beneficials (abundances, diversity, biocontrol)? If yes, please shortly describe the main findings.
8. In the best case, what do you think needs to happen (at the landscape scale) in semi-natural habitats to suppress pests in the crop and region you are working with? Is it specific to this crop and region or is it general across different systems or regions in Australia?

9. What do you think we have a solid grasp on, and what do you suspect is true but don't have evidence for?
10. What are the knowledge gaps that hinder management practices from achieving better pest suppression for the crops that you work on in your region?
11. What are the current recommendations for your region? Are they being implemented? What do you think are the main obstacles to implementation of the current recommendations?
12. Do you have any other comments?
13. Can you recommend any other colleague suitable for this survey? If yes, please provide their contact details.

Question one: In what region of Australia do you have the most experience working in this landscape diversity and field margin management? Please also name towns.
Twenty six responses were received and respondents represented all states except Tasmania and Northern Territory. Due to the difference between sub-tropical and tropical climates, Queensland was divided in to Central – Northern QLD and South Eastern QLD. There were some cases where respondents had direct experience across more than one state (Table 1).

Table 1. Number of Survey Respondents by State and Territory

Central and Nth QLD	SE QLD	SE Aust	SA	NSW	VIC	WA	TAS	ACT	NT
4	10	4	4	7	3	3	0	1	0

Question two: In what crop do you have the most experience? Please rank them in order of most to least? The responses included all but two researchers having had experience in one or more of a total of 30 commodities including fruits, nut, vegetables, cotton and grain.

Question three: What is the main pest(s) in that crop and region?
Some respondents were specific to species for example *Nysius vinitor* Rutherglen bug (RGB) which had four responses, compared to other respondents who answered more generally for example "aphids". The top three pests identified were *Helicoverpa* spp., aphids and mites, which had 17, 15 and nine responses respectively.

Question four: What are the main beneficials in that crop and region?
Beneficial insects were not identified by species and instead respondents mentioned beneficials by general group. Fifteen groups of beneficials were mentioned including entomopathogenic (virus), bats and birds, which each had one response and bees (3 responses). The groups of beneficials most often identified in the responses were lady beetles, Hymenopteran parasitoids, lace wings and spiders which had 16, 13 responses respectively, spiders and lacewings each had 12 responses. Interestingly

respondents separated Hymenopteran parasitoids from *Trichogramma* sp. (7 responses). Those respondents who identified Helicoverpa spp., or other lepidopteran pests such as diamond backed moth (DBM) most often mentioned parasitoids including Trichogramma.

Question five: How do you define landscape in your research? i.e., what is the scale of landscape?
The definition of landscape from each of the respondents was different and was context dependant, determined primarily on the research question, the mobility of the focal pest and or beneficial. The responses ranged from landscapes being anything from individual fields to 100s of Km. Thirteen respondents considered landscapes were areas that were within a 5km radius of a farm field.

Answers to questions 6 – 11.These questions were often answered with a narrative. As a result information from the responses such as key words and concepts that were mentioned by more than one respondent for each of the questions were summarised for each of the questions. Often there was also an answer, which summarised a number of the key concepts expressed by other respondents. Where this occurred the response has been quoted directly.

Question six: Do you or have you conducted any research for this crop and region showing effects of landscapes on pests and beneficials (abundances, diversity, biocontrol)? If yes, please shortly describe the main findings.
All respondents accept for two had experience with landscape scale research involving beneficials, pests and crops (Table 2).

Table 2.

Experience with landscape scale research	Studies showed landscape influenced pests and or beneficials	Studies including semi-natural vegetation and showed results were positive for beneficials
24	18	12

There was one respondent who reported they had experience but the results of the effect had not been significant “*Yes. Type of non-crop vegetation (riparian/pasture/bush) had no significant effect on the numbers of marked predators or the total numbers of predators in adjacent crops*”

Question seven: Do you or have you conducted any research for this crop and region showing effects of field margins on pests and beneficials (abundances, diversity, biocontrol)? If yes, please shortly describe the main findings. Four of the 26 respondents had experience with field margins and their influence on beneficials. In all four cases the results on beneficials were positive. The most comprehensive results were from one respondent and quoted below.

“Vineyards – shelter belts have an impact on increased numbers of lacewings and predatory beetles. Haven’t seen an effect from the broader landscape, or from an increase in percent of other vegetation

in landscape. However, there are good effects at the small scale of 10s of meters but beyond that no additional effect. Shelter belts have a strong positive effect on the abundance of beetles, parasitoids, predatory mites and thrips. We have also shown the effect of increased predation on light brown apple moth adjacent to shelter belts.

Grains – there is an increase in predatory beetles which also impacts on reducing slug numbers into crop to a distance of 10s of meters when there is grassland adjacent to a field. Vegetation (with good understory) in shelter belts is important for predatory mites and for predation on mites into crop at a distance of 10s of meters. However, there is not much of an impact of shelter belts in the middle of large fields of canola. *We have shown an increase in biodiversity in crops with good field margins. There is a key benefit (in viticulture and grains) of having adjacent vegetation but you need a good understory (and it doesn't matter if understory is weedy or native)."*

Question eight: In the best case, what do you think needs to happen (at the landscape scale) in semi-natural habitats to suppress pests in the crop and region you are working? Is it specific to this crop and region or is it generalizable across different systems or regions in Australia? Many respondents mentioned a range of activities that could be undertaken in semi- natural habitats and most of these could be divided into two key objectives and associated activities to achieve these (Table 3).

Table 3. Q 8. In the best case, what do you think needs to happen (at the landscape scale) in semi-natural habitats to suppress pests in the crop and region you are working with. Proportion of responses for each of the two activities.

Key Objective	Related management activities For achieving objective	% responses
Better manage, restore and maintain native vegetation	Remove weeds; Increase functional diversity (specific plants that are specific to pest and beneficials); Increase diversity; Patch connectivity	76% #
Reduce management activities that have – ve effect on beneficials i.e. harvest	Reduce insecticides pesticides; Reduce grazing; Provide refuges for recolonization	28 % #

Total of 25 respondents; # means no answer from one respondent

Question 9: What do you think we have a solid grasp on, and what do you suspect is true but don't have evidence for?

There were two non-respondents but in general people thought there was a solid grasp on, or we know

- Native non crop vegetation has a positive influence on beneficials i.e. "*We can maintain greater diversity of beneficials in landscape with NV than without*";
- Native vegetation is "good";
- About the associations between species of plant, beneficial and pest insects;
- Beneficials have positive impacts on pests;
- Native vegetation is good for biodiversity;
- What applies to one species doesn't apply to another especially based on mobility.

The second part of question 9, what you suspect is true but don't have evidence for. The majority of respondents answered this as "what we don't know". Many responses mentioned the same points and many mentioned more than one point. Answers were summarised under key points and ranked by the number of times the points related to a key point were mentioned (Table 4).

Table. 4 Question 9 part 2 what we suspect is true but don't have evidence for ranked by the frequency a concept was mentioned in response to question 9. Rank = from 1, concept mentioned most times to 10 least.

Key Point	Related Points	Rank
Movement of pest and beneficials	- How often, when and how far; - Would help determine distance between crop and non-crop vegetation	**1**
Area of native veg required	- Do we have enough NV to measure a response; - Quantify how much non-crop for a positive impact	**2**
Quantify impact of beneficials	- How many do we need? - Without evidence we can't make recommendations	**3**
How to ensure continuity of effectiveness over time?		**4**
Don't know enough about the ecology of some pests and beneficials	- Where are they when there are no crops? - Sources	**5**
Don't know the real effect of	- Harvest; - Pesticides	**6**

beneficials due to disruptions		
Economics	- Financial viability for growers of using beneficials	**7**
How to manage for more than one pest		**8**
How to implement		**9**
If the positive effects of non-crop veg for beneficial of one pest will have a negative effect for other pests		**10**

Question 10: What are the knowledge gaps that hinder management practices from achieving better pest suppression for the crops that you work on in your region?
Most responses identified more than one gap and many gaps were similar across all of the responses. To summarise these related responses, they were divided into one of the following five categories. The dot points listed under the categories are paraphrased from the actual responses and provide examples of the gaps related to each of the categories.

The gaps identified by respondents in the broad category of **Ecology of pests, beneficials and non-crop plant species (mentioned 22 times)**

- Movement: How far does non crop habitat have to be from crop?
- Ability to identify the sources and sinks of pests and beneficials.
- Greater understanding of what drives populations.
- What area of non-crop is needed for effective pest suppression?

"Obviously our lack of knowledge of the nature and dynamic of ecosystem services. Don't know when or where the beneficials will turn up. Don't know their populations outside of the crop. Can't predict the population size of beneficials each season. For example, don't know when or how mealy bugs will turn up in a crop. Don't know how did they overwintered? Maybe if we had unlimited resources we could answer some of these questions. Because we still don't understand beneficial insect dynamics, we can't put a value on ecosystem services. If you could come up with a clear cost benefit for non-crop vegetation and substantial, quantifiable and predictable outcome it would be adopted."

The gaps identified by respondents in the broad category of **Management Activities (mentioned 13)**

- How do we prioritise management activities for pests and beneficials? Is it better to stop no till and plant native vegetation?
- Impact of chemical cocktails and the interactions of fungicides, miticides and insecticides on beneficials.
- How do we ensure the arrival of key beneficials at key points of crop development?
- Quantify, demonstrate and evaluate the impact of beneficials

"*Management practices are still heavily insecticide-based, and pest suppression appears to be working well enough to continue to justify it. We can all see the writing on the wall though*."

The gaps identified by respondents in the broad category of **Extension information and technology transfer (mentioned 6 times)**

- Develop simple steps for growers, rules of thumb, specific to regions, pests and commodities.
- Extend the information we already have develop in to practical applications for growers.
- Growers need independent information need to change the relationship between grower, pest management advice and chemical resellers.
- Pest management is just one of the many priorities for growers. Solutions should focus on multiple ecosystem services.

"The major knowledge gap is how available technology is communicated to farmers to facilitate its long-term adoption. A fundamental issue is that incentives for adoption of IPM/ harnessing of natural enemies through reduced insecticide use have frequently focused on the cost benefits of reduced insecticide use. Perhaps a more holistic communication/ education approach in which the broader environmental threats posed by broad spectrum insecticide/ pesticide use are emphasized might have greater penetration and impact".

The gaps identified by respondents in the broad category of **Economic Evaluation (3 times)**

"*Impact of groundwater on vegetation is a big unknown Impact of pollinators and short-lived flowering plants in riparian zones is a big unknown .Knowing where vegetation is most functional in a landscape and where to prioritise management efforts How much does it cost a grower to keep a single tree in a field? What benefit does that single tree provide?"*

Question 11: What are the current recommendations for your region? Are they being implemented? What do you think are the main obstacles to implementation of the current recommendations? Seven respondents were either not sure, didn't know or were not familiar with the current recommendations. Recommendations and responses addressing implementation were either non-existent or could be divided by production commodities for example cotton, grain and wine grapes.

Responses to question 11 by commodity:

Grains: Respondents said there was currently not enough information for the Grains industry to have recommendations and therefore there was no adoption.

Wine: The wine industry recommends shelterbelts and some have taken the recommendations on board.

Cotton: The cotton industry Cotton has comprehensive guides including myBMP (best management practice) and as part of that there is a module on protecting the farms natural assets. In addition, in the centre of the Pest and Beneficial Guide there are Six Principles to Sustainable Cotton Landscapes including protecting on farm remnants of native vegetation. As part of myBMP there are guidelines on spray windows and chemical rotation, and choice of insecticide that will be "soft" on beneficials. Spray thresholds don't include number of beneficials.

Brassica: According to one response related to brassica production "*we know all but have failed to* *implement it*" there are recommendations but they are not implemented for the brassica industry However the respondent didn't elaborate on what they were. The same respondent also identified the obstacles to the recommendations being implemented as *"In Brassica crops I think that the necessary technology for adoption of effective IPM has long existed. The major issue is that the research/extension community has singularly failed to achieve long term adoption of these technologies by the farming community (this is a worldwide issue for Brassica pest management)"*

General: Obstacles to implementation:

- Robust guidelines for example *x* % remnant vegetation you will get *y* result.
- No convincing demonstration. Perceived as being too complex, too time consuming costly.
- Lack of incentives by market, government and or industry.
- Provide growers with cost benefit analysis.
- Provide guidelines on understory plants to grow for beneficials.
- Policy drivers (financial incentives) that link areas of conservation to better farm practice.
- Growers slow to change unless there is good proof otherwise they will use the simple quick approach and spray.
- Weed control is expensive.

"Commissions from chemical companies for agronomists who sell their product, is the biggest problem. The number of times I have heard a grower admit that they have sprayed before threshold levels were reached because their agronomist advised them to, makes me suspicious that there agronomists are either making money out of getting growers to spray early, or they are nervous about or don't trust the thresholds".

In summary the responses to Question 11 were largely related to commodity and were not region specific. While some commodities had some general recommendations for native vegetation others according to respondents had none. Despite this many respondents mentioned they know that it is important to remove weeds, not spray unless pests had exceeded threshold and use a chemical least likely to have negative impact on beneficials. When it came to implementing any of the recommendations that were available, responses indicated that it was unclear to what degree there was implementation or adoption. Obstacles identified as barriers to implementation could largely be linked back to the gaps reported (above) in Question 10 and the points made in Question 9. These included the lack of specific knowledge around: (1) pest, beneficials ecology and their interactions with native vegetation; (2) lack of information to help develop guide management activities; (3) extension developing what we already know; and (4) the need to develop an economic case. To a large extent overcoming the obstacles identified as barriers, are directly related to and dependent on addressing the major categories of gaps.

OTHER COMMENTS Question 12

At the end of the survey the respondents were given an opportunity to add comments. Most respondents did not provide additional comment, but a few did, and they are provided here.

"Researchers need to think about how feasible is it for growers to implement the suggestions made by

researchers. There are lots of difficulties for growers to implement suggestions. For example, what if the semi-natural landscape creates another pest problem for growers? This is why there is often not good uptake of advice from researchers. We need to show good proof for growers to make changes also."

"*Australia is not Europe. We have a very different environment: the climate is not as stable, we have more pest problems and we have massive periods of dry unfavourable conditions*"

*"I strongly support researchers who are interested in understanding and utilising natural enemies to manage pests. This is pest MANAGEMENT. Most pest control typically attempts to exterminate pests from a crop (the use of broad-spectrum toxins), and in doing so exterminates natural enemies. True management involves tolerating some pests to support beneficials – it is a simple concept, but one that many people seem to have trouble accepting"***.**

"Point worth making/ because farmers are busy they will only change practice very slowly unless there is a crisis. The challenges is to encourage adoption in the absence of a crisis."

CONCLUSION

The majority of researchers contacted for this survey have conducted research on the role of non-crop habitat for pest suppression. Responses to this survey provide support that these landscape effects can extend up to 5km from field. The most immediate gap is the lack of recommendations for grains, and the lack of implementation of management actions. While there are some recommendations for some horticultural commodities it is clear that some recommendations for management actions and implementation are more developed for some compared to other industries such as grains, where there are none. Results from the survey also identified many gaps in our knowledge, which create a barrier to implementation - most of these were related to the broad areas pest and beneficial ecology. The main gap referred to by respondents was the need to understand movement of key pests and beneficials. Providing evidence of insect movement between non-crop habitat and crops, and subsequent pest suppression is a key gap identified from the survey. In addition, there is a need to understand how much semi-natural vegetation and how close to the crop is needed to capture this service, and the economics involved. A general trend from the survey is that there is consistent thinking about the basic concepts related to managing non-crop habitat to support beneficial insects. For example increasing habitat diversity and reducing and eliminating broad-spectrum insecticide use is key to supporting beneficial activity and IPM.