Final Report

Field and landscape management to support beneficial arthropods for IPM on vegetable farms

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Project code:

VG16062

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Funding statement:

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

Publishing details:

ISBN 978 0 7341 4679 3

Published and distributed by: Hort Innovation

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North Sydney NSW 2060

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www.horticulture.com.au

Content

Public Summary

Much international research, and growing amounts of work in Australia, shows that vegetation on farms can be managed in strategic ways to suppress pests. This project focused on vegetable farms to assess scope to develop practical approaches for growers. An initial survey of 491 fields of brassica vegetables, sweetcorn, carrot, lettuce, French bean and lettuce was important in establishing that numbers of pests and beneficial insects are not uniform within each crop field. Rather, they are strongly affected by the immediately adjacent land use. Pests were suppressed in crops adjacent to riparian (water course) vegetation, dams and road ways but elevated adjacent to crops and weedy areas. Beneficial insects that attack pests were more numerous in areas of crops adjacent to water course vegetation and roadways. From a practical perspective, this work is important in showing that growers can exert strong effects on pest management via crop placement in relation to existing land uses, control of weeds, and the preservation and rehabilitation of water course vegetation. Practical, evidence-based recommendations for growers that guide crop placement in relation to other land uses have been developed for brassica vegetables, sweetcorn, carrot, lettuce, French bean and lettuce.

The second phase of the project focused on developing additional options for growers, based on plants that can be rapidly establish within fields. Three annual plants (alyssum, buckwheat and cornflower) were selected based on a review of the international literature and an analysis of the potential benefits and risks of plant species. These were trialed on brassica vegetable and sweetcorn farms as nectar sources to support beneficial insects. One biennial plant (yellow rocket) was tested in additional trials as a trap crop that would reduce egg laying by diamondback moth on brassica vegetable crops.

Nectar plant strips in New South Wales, Victoria, Queensland and South Australia promoted abundance of beneficials for up to 20 m into the crop. Pest numbers, and damaged crop plants, were reduced and diamondback moth parasitism rate was doubled. Benefit: cost ratios of nectar plant strips were as high as 8:1 in cases where the strips were accommodated in uncultivated areas such as sprinkler rows. Yellow rocket strips proved to be highly attractive to diamondback moth so has potential as a trap crop, relieving the primary crop of pest pressure, but proved difficult to establish from seed, with the planting of seedlings recommended. Recommendations have been communicated in a series of industry–focused magazine and TV features, factsheets, workshop and farm walk activities and this has led to significant levels of interest by growers.

Technical Summary

Field and landscape management of crop pests, by biological control or by direct effects of vegetation on pests, offer great opportunities to vegetable growers. An initial survey of 491 fields of brassica vegetables, sweetcorn, carrot, lettuce, French bean and lettuce established that pest and beneficial arthropod densities are not uniform within each crop field. Rather, densities are strongly affected by the immediately adjacent land use. Robust effects were evident over the six crop species, multiple geographical regions and several seasons. Overall numbers of pests were suppressed in crops adjacent to riparian areas, roads and waterbodies but elevated adjacent to crops and weedy areas. Natural enemies ('beneficials') are likely to have been responsible for some of these effects because overall numbers were elevated in areas of crops adjacent to riparian areas whilst roads (lined by undisturbed vegetation and often with trees) significantly increased parasitic Hymenoptera, predatory beetles, spiders and brown lacewings. Pest suppression did not, however, consistently result from the elevated numbers of beneficials adjacent to weedy areas, crops and shelterbelts. Further, pest suppression was not necessarily dependent on beneficials since pests were suppressed adjacent to waterbodies despite that land use having only negative effects on beneficials, likely reflecting a barrier effect to movement of all insects into adjacent crops. Results suggest that within-field insect assemblages have strong spatial structure that is strongly affected by immediately adjacent land use. From a practical perspective, this work is important in showing that, irrespective of any underlying effect of the wider landscape, farmers can exert strong effects on pest management via crop placement in relation to existing land uses, control of weeds, and the preservation and rehabilitation of riparian areas. Partitioning this large data set according to each of the six crop types surveyed allowed the production of a series of practical, evidence-based recommendations for growers that guide crop placement in relation to other land uses on adjoining the farm and for weed control or promotion of riparian vegetation. From a research perspective, the results showed powerfully that there is scope to influence relative densities of pests and beneficials in vegetable crops under Australian conditions. Importantly, however, there is a need to develop approaches based on plants that growers can rapidly establish rather than be reliant on slower-to-establish woody vegetation features such as shelterbelts. This conclusion underpinned the second major phase of the project in which on-farm trials were undertaken. Three annual plants (alyssum, buckwheat and cornflower) and one biennial (yellow rocket) were selected based on a literature review and assessment of practicalities. Trials of in-crop flower strips in New South Wales, Victoria, Queensland and South Australia brassica crops showed that annual plant strips promoted abundance of beneficials such as parasitic wasps and predatory beetles with numbers elevated for up to 20 m into the crop. Pest numbers and numbers of pest-damaged crop plants were reduced, and parasitism of diamondback moth doubled. Benefit: cost ratios were as high as 8:1 in cases where the flower strips were accommodated in uncultivated areas such as sprinkler rows. The biennial plant, yellow rocket, proved to be highly attractive to diamondback moth so has potential as a trap crop, relieving the primary crop of pest pressure, but proved difficult to establish from seed, with the planting of seedlings recommended. In sweetcorn, drought conditions and low water allocations led to work being restricted to three sites in Queensland. Findings have been communicated in a series of industry–focused magazine and TV features, workshop and farm walk ('field day') activities and this has led to significant levels of interest by growers.

Fact sheets have been produced to guide farmers interested in adoption of these practices.

Keywords

Conservation biological control; natural enemy; beneficial insect; habitat management; brassica; sweetcorn; lettuce; capsicum; carrot; French bean; pest management; IPM

Introduction

All over the world there are calls from science, policy makers and the public for agricultural systems to redesign towards environmentally safe and sustainable practices (Bommarco et al. 2013; Garibaldi et al. 2019; Harvey et al. 2020; Pretty et al. 2018; Sánchez-Bayo & Wyckhuys 2019). Public concern is increasing in response to reports of declines in numbers and diversity of terrestrial vertebrates (Ceballos et al. 2020), arthropods (Sánchez-Bayo & Wyckhuys ; Seibold et al. 2019), plants (Humphreys et al. 2019) and the ecosystem services they provide (Harvey et al. 2020; Sánchez-Bayo & Wyckhuys 2019). The Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) 2019 media releases illustrated breaking points and stresses in the environment coupled with the challenge of feeding the world (IPBES 2019).

There is global recognition that ecosystem services, such as biological control of crop pests by beneficial arthropods offer great opportunities to growers. A considerable body of work supported by Hort Innovation has been carried out examining dynamics and movement of natural enemies ('beneficials') at the landscape scale from native and non-native vegetation, especially that planting and/or promoting native species is beneficial to populations of beneficials in the landscape. However, there is still much to be done on connecting the landscape scale dynamics within field management (Bianchi et al. 2017; Heimoana et al. 2017; Macfadyen et al. 2015; Schellhorn et al. 2015).

Insecticides remain a major component of Australian vegetable pest management, albeit within integrated pest management (IPM) programs (Zalucki et al. 2015), despite evidence of high levels of resistance in populations of major horticultural pests including diamondback moth, Plutella xylostella (Eziah et al. 2008; Rahman et al. 2010), Helicoverpa armigera (Downes et al. 2017), green peach aphid, Myzus persicae (de Little et al. 2017; Umina et al. 2014), onion thrips, Thrips tabaci (Herron et al. 2011) and western flower thrips, Frankliniella occidentalis (Thalavaisundaram et al. 2008). Some of the commonly used pesticides have already been banned in other countries and there is mounting pressure for similar restrictions in Australia (Hauxwell 2018).

The motivations for adoption of IPM programs in the past have often been related to crises such as spray failure, loss of market access and changes in pesticide availability. There is now a more gradual shift due to changing grower and consumer perceptions in the damage caused by pesticide overuse (Grasswitz 2019; Schellhorn et al. 2009). A recent Australia wide survey of public perceptions found there was a high level of public trust in vegetable growing, but perception of environmental responsibility was the major driver of that trust (Voconiq 2020). Notwithstanding this, over 65% of respondents felt that rural industries should be doing more to find a better way to control pests than just chemicals.

The vegetable industry in Australia has many farms with small field sizes and a high diversity of crops. This affords opportunities for IPM approaches such as intercropping, trap cropping, cultivar mixes and habitat management that are less available to broadacre agriculture where larger areas of simultaneously planted monocultures are the norm (Grasswitz 2019). Whilst some IPM tactics can be used at any scale of production, others are easier and more cost effective on smaller scale farms (Grasswitz 2019) that are typical for Australian vegetable production (Weragoda et al. 2017). Here for example, a given crop may be planted sequentially and with a mix of crop species or cultivars. This project aimed to investigate the scope for development of such methods for use in Australian horticultural crops.

The work extended over six major commodities: brassica vegetables *Brassica* spp.) (Brassicaceae), sweetcorn (*Zea mays* L.) (Poaceae), lettuce (*Lactuca sativa* L.) (Asteraceae), carrot (*Daucus carota* L.) (Apiaceae), French bean (*Phaseolus vulgaris* L.) (Fabaceae) and capsicum (*Capsicum annuum* L.) (Solanaceae). Initial work covered all these crops with a geographically wide survey of fields. That provided information on the response of pests and beneficials to adjacent land use which was integrated with a comprehensive literature review of international work. Together, those activities served to identify the greatest opportunities for particular strategies and crop types. The final phase of work experimentally tested these opportunities (in brassicas and sweetcorn) using on-farm trials.

Methodology

Note: The overview given in this section is complemented by a more detailed description provided in Appendix 1.

Literature Review

Potential habitat management strategies that had suitability for Australian vegetable production systems were identified through a comprehensive literature review. Due to the large volume of work that has been published on conservation biological control over the past two decades (over 3000 publications), the review focused on habitat management strategies that have field-proven benefits in vegetable production systems. Strategies that have potential to provide refuge and resources to beneficial insects or to directly suppress pests were identified. Key characteristics including planting and flowering times as well as their benefits to beneficials or direct suppressive effects on pests, of tested plant species were analysed against plants that are currently available in Australia and are not considered weeds or hosts of Australian pest insects.

Field Survey

The next stage in developing habitat management strategies best suited to Australian production systems was to conduct field surveys in a range of vegetable producing regions within NSW, QLD, VIC, SA, TAS and WA. The aim of the field surveys was to provide a detailed evidence base of current crop and non-crop vegetation structures in a variety of environments and the effects of crop-adjacent land uses, for example shelterbelts (Figure 1), on pest and beneficial abundance in crops. These surveys were carried out over 12 months to sample seasonal effects and cropping patterns and fluctuating insect abundance.

Figure 1. Left: Shelterbelt of native trees planted along the edge of a brassica field. Right: Farm walk near Kelso, NSW at the site of a trial of in-field flower strips.

Farmer Interviews

Associated with field survey phase of the project, interviews were conducted with growers to assess which components of IPM and habitat management are already being used on-farm and to identify strategies that would be most readily accepted by vegetable growers. This included qualitative information of vegetable grower perceptions of major pest species and their management.

Refinement of Intervention Types

Following the identification possible habitat management strategies, consultation with the project's Stakeholder Reference Group which consisted of representatives from Hort Innovation and AUSVEG and growers from NSW, QLD, SA, WA and TAS, helped narrow down the prospective strategies to three flowering plant species and one trap crop species to be tested in brassica and corn pest management.

Field trials

Trials in brassica fields were carried out over spring-summer 2019–20 at Bathurst, NSW; Mount Barker and Langhorne Creek, SA; Devon Meadows and Werribee South, Vic and the Lockyer Valley, Qld. Planned NSW trials in sweetcorn were cancelled due to the severe water shortage resulting in near zero water allocation for sweetcorn growers in spring-summer 2019–20. Three field trials in sweetcorn were held in QLD in autumn 2020.

The flowering/companion planting strips aimed to support a beneficial insect assemblage close to the field to encourage predation and parasitism of pests within the field. At each site, a flowering strip was hand sown in a 1.5 x 24 m strip parallel to crop rows. Another 1.5 x 24 m area was left unplanted as a control treatment against which the effects of the flowering strip could be compared. Flowering strips and control strips were separated linearly by at least 10 m. Accordingly, there was only one experimental replicate per field, but full replication was afforded by the use of multiple such fields across several states. Nested within each flowering strip, three plant species alyssum (*Lobularia maritima*), buckwheat (*Fagopyrum esculentum*), and cornflower (*Centaurea cyanus*)) were established as sub-plots, each replicated four times per field. The field trial aimed to test two hypotheses. Firstly, the effect of the within-field flowering strip on beneficials, pests and crop damage with measurements taken at spatial intervals ranging from immediately adjacent to the strip and at 5m intervals extending to 20m. This study aimed to determine the spatial extent of beneficial effects from the strip and indicate an optimal spacing of strips for later recommendations to growers. Second, the planting of each of the three flower species as discrete sub-plots within the overall flowering strip afforded the opportunity to test (in a manner that was replicated within every field) whether flower species differed in terms of visitation by beneficials and pests. This study aimed to identify if any of the flower species was strongly preferred by important types of beneficial (so to be favoured by growers when selecting flower species) or was visited and fed upon by any pests (so to be avoided by growers)). Assessments of pests and beneficials were conducted 2-3 times on each site, coinciding as closely as possible to peak flowering of the three species in the mixed-flowering strip.

A separate series of sites was used to evaluate the potential of yellow rocket (*Barbarea vulgaris*), a brassica species that has been shown to be attractive to diamondback moth for laying eggs but the larval stages are unable to reach maturity feeding on this plant (Idris & Grafius 1996). The aim of testing the trap crop was to determine if numbers of diamondback moth in the adjacent crop were reduced and the spatial extent of any such benefit. The assessments were conducted fortnightly, starting from 4-6 weeks after planting both trap and main crop.

The results of trials were used to perform a benefit: cost analysis to determine if the respective effects of the habitat management strategies were cost effective for farmers to implement given the extra costs associated with seed and planting.

Landscape Study

A research master student (funded by the Commonwealth Government) was recruited to the project team to undertake an additional component of study. That work involved geographic information systems (GIS) analyses of the composition of the landscape (e.g. proportion of crops or woody vegetation) surrounding each of the sites used in the studies described above.

Outreach

Regular communication with the vegetable industry was carried out using local and industry media channels to promote the concept of the potential to reduce pesticide use in a way that still provided effective pest management. In each state - with cooperation from the host farmers - a trial site was used to host a farm walk to allow growers from that region to have discussions with project team members and the farmers about practicalities and the science behind habitat management (Figure 1). The ABC television program Landline filmed a segment at the Victorian field sites as well as interviewing team members and growers. The episode was aired in May 2020 and repeated in February 2021.

Information from the literature review, field surveys, grower interviews, field trials and consultation with the Stakeholder Reference Group was condensed into a pair of fact sheets. These featured information on the concept of habitat management for pest suppression including lists of habitat management plant species by region that could be used in along with planting and flowering time periods. Suggestions of crop placements (in relation to adjacent land uses) that can increase or decrease pest abundance and of landscape level habitat features that influence pest management. The overall aim of this was to generate a resource practical, crop- and region-specific recommendations for growers interested in adopting this approach to pest management.

Outputs

Table 1. List of project external outputs

Output	Description	Comments
Literature review	"Prospects for habitat management approaches to suppress pests of selected vegetables in Australia: a review"	First draft submitted in milestone 102. Scientific paper version currently under review by *Austral Entomology*.
Field survey report	Report on arthropod abundance data in relation to adjacent vegetation from nearly 500 fields across NSW, VIC, QLD, SA, TAS, WA.	Technical report submitted under milestone 106 (Appendix 2).
Grower interviews report	Report on pest management practices of 75 vegetable growers and potential for incorporating habitat management.	Technical report submitted under milestone 103. Scientific paper currently in preparation. Key findings included in Results section.
Field trial report	Report on effects of flowering plants borders and trap crops beside brassica and sweet corn fields on arthropod abundance.	Preliminary data presented in milestone 104. Scientific paper currently in preparation. Key findings included in Results section.
Landscape-scale effects report	GIS analyses of the composition of the landscape by masters student	Scientific papers (x2) submitted for publication. Key findings included in Results section.
Cost benefit analysis	Tables of likely costs per hectare of habitat management interventions	Key findings included in Results section.
Industry communications	ABC TV Landline TV segment May 2020. https://www.abc.net.au/landline/beneficial-bugs:-good-bugs-keeping-pest-insects-at/12122402 Prime TV News. https://www.facebook.com/PRIME7NewsCentralWest/videos/1023414281354918/ 'Companion planting to control the pests' Central West Daily March 2018 'Boosting beneficial insects on vegetable farms' Vegetables Australia May 2018 'Boosting beneficial insects on vegetable farms' WA Vegetables Winter 2018 'Suppressing vegetable pests on your farm' WA vegetables, Spring 2018 'Working with growers to secure a cleaner, greener future' Vegetables Australia	

	August 2019 "Farmer trials attracting bugs to protect his vegetable crops rather than relying on pesticides" ABC, online and TV. 5 April 2020 "Flowers attract beneficials to veg crops" The Land Australia. 12/05/20. URL ct.moreover.com/?a=42089617041&p=1gw&v=1&x=IDHZX30qyjZRR_PA4yXlPg Flowers attract beneficials to veg crops. Good Fruit & Vegetables Magazine. 12/05/20. URL ct.moreover.com/?a=42089647244&p=1gw&v=1&x=raKTYk6X83rUSPuqTabQ8Q "Flowers attract beneficials to veg crops" Stock & Land. 12/05/20. URL ct.moreover.com/?a=42089736899&p=1gw&v=1&x=rinawjHl0tVKHh6YRvTZ5Q "Flowers attract beneficials to veg crops". Queensland Country Life. 12/05/20. URL ct.moreover.com/?a=42089767892&p=1gw&v=1&x=41Xw29h2fsiQi4fyFFIAdA "Flowers attract beneficials to veg crops". North Queensland Register. 12/05/20. URL ct.moreover.com/?a=42089621975&p=1gw&v=1&x=mG2pAyC4-8zOipLCqbDUzQ "Flowers attract beneficials to veg crops". Farm Weekly. 12/05/20. URL ct.moreover.com/?a=42089693189&p=1gw&v=1&x=5QagDQPxd1RQzR0PF1Wyfw "Flowering field trials bolster crop production". 4BC Country. 16/04/20. URL ct.moreover.com/?a=41886330838&p=1gw&v=1&x=gRylhlUaKbcJfOjcn-RFDQ "Flowering field trials bolster crop production". 2GB. 16/04/20. URL ct.moreover.com/?a=41886344280&p=1gw&v=1&x=Iatg1ZBUN4fFxw1ir-u6rQ "This farm is harnessing a bug army to protect vegetable crops". ABC Online. 04/04/20. URL ct.moreover.com/?a=41798277866&p=1gw&v=1&x=8_PgZfzksYfm8gFrIfpdmA "Farmer trials attracting bugs to protect his vegetable crops rather than relying on pesticides". ABC Premium News (Australia). 04/04/20. "This farm is harnessing a bug army to protect vegetable crops". Ahlain News. United Arab Emirates. 04/04/20. URL ct.moreover.com/?a=41798280608&p=1gw&v=1&x=1QAlzigiKntlxPN0RXsQyw "Instead of pesticides, trial looks at getting insects on side". Bathurst Western Advocate. 02/02/20. URL ct.moreover.com/?a=41278601749&p=1gw&v=1&x=qUjSa4A8Fu6zsqLBL7I2mQ "Natural habitat can help farmers control pests but not always a win-win". Get Farming. 01/08/18. URL getfarming.com.au/2018/08/01/natural-habitat-can-help-farmers-control-pests-but-not-always-a-win-win/ Stakeholder advisory group meeting minutes. 2018, 2019, 2020.	
Project update summary presentation.	VegNET R&D Field Day (SA) on 23-10-2019.	
Project update summary presentation.	VegNET Native Veg Insectarium Event (Vic) on 23-10-2019.	
Project update summary	"Field management to support beneficial	

presentation.	arthropods for IPM on vegetable farms". Webinar presentation for RMCG (Melbourne) 17-03-2020.	
Habitat management guidelines	Effects of adjacent vegetation on pests, habitats to encourage and avoid.	First presented in milestone 104. Refined as factsheets. Appendix 3.

Key results

Key results are presented in this section and set out in detail in the appendices.

Field survey

Key Points

- Preserve uncultivated areas on farm, including woody vegetation and shelter belts, as these can support beneficials and help suppress crop pests.
- Exercise effective control of weeds, especially those that are botanically related to your crop (e.g. brassica weeds close to brassica vegetables) and including weeds within areas of woody vegetation.
- Check the tables (below) for planting recommendations specific to sweetcorn, brassicas, lettuce, carrot, French bean and capsicum.

IN-CROP PESTS INCREASED BY: adjacent weedy areas and (to a lesser extent) the presence of vegetable crops especially beans, carrots, tomato and corn.	**IN-CROP PESTS** DECREASED BY: Dams, riparian areas and roadways (and their associated vegetation). Pests were also decreased by shelterbelts and pastures but the effects were not statistically significant.
IN-CROP NATURAL ENEMY INCREASED BY: vegetables crops, weeds and – especially – shelterbelts and riparian vegetation.	**IN-CROP NATURAL ENEMY** DECREASED BY: dams (but not to a statistically significant extend) and by pastures.

Figure 2. Summary of overall effects of adjacent land use on the numbers of pests and natural enemies in vegetable crops: desirable (green) and undesirable (red) effects. (See tables 2-7 below for crop-specific affects)

Figure 3. Image used in fact sheets on habitat management.

Four hundred and ninety-one fields were surveyed across multiple states and regions, comprising 69 sweet corn, 71 lettuce, 22 bean, 39 capsicum, 44 carrot, and 246 brassica vegetable crops (23 Brussels sprouts, 70 broccoli, 61 cabbage, and 91 cauliflower). Pests and beneficials (natural enemies) were counted in the crop margins close to each different type of land use and in each field centre. The density of arthropods in the field centre represented a baseline for comparisons. Pooled analysis tested whether the density of a taxon of arthropod in the edges of the crop differed significantly from the centre depending on the adjacent land use. An analysis of pooled data from 491 field with all arthropods sorted by type, showed important overall effects of adjacent land use types on densities (Figure 2).

Field centres tended to have relatively low densities of beneficials. Beneficial numbers were significantly greater on the crop edge adjacent to shelterbelts, riparian vegetation and other crops of corn, capsicum, and especially sorghum.

These results are remarkable in showing significant effects given that the pooled data set included all crop types, geographical regions and insecticide use types. These overall findings can be interpreted to provide general guidance to growers and land managers on the patterns of land use that represent either high- or low-risk for pest build-up. The data set also allows 'drilling-down' to provide more specific information for individual focal crops. These are shown in tables 2-7 that take the form of 'heart maps' with the colouring of cells showing the strength and desirability (or otherwise) of effects of each land use on each type of pest and beneficial for which there were adequate data to analyse. This allows a grower of a given crop type to address a given pest of particular concern (or focus management on a given type of beneficial; or to adopt a more holistic approach by adopting management that reflected the consistency of dark green colouration (showing beneficial effects) in the majority of the cells in a given column (representing an adjacent land use. Land uses associated with green cells are recommended for the placement of a crop, especially a vulnerable or high value crop. Those land uses can also be protected and enhanced, for example, by fencing-out livestock and by replanting.

Table 2. Sweetcorn results showing desirable effects (more beneficials, fewer pests) in green and undesirable effects (fewer beneficials and more pests) in red. Intensity of shading shows how strong the effect is whilst the characters in each cell show the level of confidence in the result from statistical analysis (0= no effect, *= 95% confidence, ** = 99% confidence, *** = 99.9% confidence).

Pests	Weeds	Shelterbelt	Road	Riparian veg	Pasture	Lettuce	Sweetcorn
Thrips	***	0	***	**	*	0	0
Rutherglen bug	0	***	***	0	0	0	***
Corn earworm	*	0	**	**	**	0	0
Jassid	0	*	0	0	*	0	0
Corn rootworm	**	0	0	**	*	0	0
Corn aphid	***	**	0	***	0	0	0

Beneficials	Weeds	Shelterbelt	Road	Riparian veg	Pasture	Lettuce	Sweetcorn
Ladybeetle	***	***	0	**	0	0	***
Red and blue beetle	***	***	**	***	0	0	0
Orius species	**	***	***	*	0	0	0
Green lacewing	0	0	***	0	0	0	***
Soldier beetles	0	*	0	0	***	0	**

In most districts, corn earworm is the pest of greatest concern. Crops adjacent to riparian vegetation tends to have low densities of this pest. Riparian vegetation also assists with thrips. Where possible, sweetcorn should be planted adjacent to riparian vegetation, specifically if corn earworm is the main concern but note that corn aphid may be promoted. Woody vegetation such as shelterbelts reduced the density of Rutherglen bug. These beneficial effects are associated with enhancement of beneficial insects such as ladybird beetles, red and blue beetles and Orius spp. In the longer term, efforts to protect riparian vegetation and expand woody vegetation are likely to bring dividends. Pasture (mainly lucerne) tends to promote thrips, jassids and corn rootworm so vigilance is recommended when planting sweetcorn adjacent to this land use. Roads, which are bordered by undisturbed vegetation and often with trees, significantly reduced the densities of thrips, Rutherglen bugs and corn earworm, likely reflecting the shelter and food resources provided by roadside vegetation. This reinforces the necessity of undisturbed habitats (e.g., trees). Where possible, protect and expand woody vegetation (e.g., shelterbelts).

Table 3. Brassica vegetable results showing desirable effects (more beneficials, fewer pests) in green and undesirable effects (fewer beneficials and more pests) in red. Intensity of shading shows how strong the effect is whilst the characters in each cell show the level of confidence in the result from statistical analysis (0= no effect, *= 95% confidence, ** = 99% confidence, * = 99.9% confidence).**

Pests	Weeds	Shelterbelt	Road	Riparian veg	Pasture	Dam	Brassicas
Cabbage aphid	0	***	0	*	0	***	**
Green peach aphids	0	0	***	0	0	0	0
Thrips	***	***	0	***	_***	***	***
Whitefly	***	***	**	0	***	0	0
Rutherglen bug	0	0	0	***	***	**	***
Diamondback moth	0	***	0	***	**	0	0
Cabbage white butterfly	0	0	0	**	0	0	*
Beneficials	**Weeds**	**Shelterbelt**	**Road**	**Riparian veg**	**Pasture**	**Dam**	**Brassicas**
Ladybeetle	0	***	0	0	***	0	***
Spider	*	*	***	0	0	0	0
Brown lacewing	*	***	***	**	***	0	0
Parasitic wasps	0	***	*	0	*	0	**
Aphid mummies	0	***	***	0	0	**	***

Diamondback moth is the pest of greatest concern. Densities of this pest are reduced in the crop adjacent to riparian vegetation and shelterbelts. Where possible, situate the most vulnerable or highest value plantings adjacent to such vegetation. This also assists with the other major caterpillar pests, cabbage white butterfly as well as Rutherglen bug, thrips and whitefly. In the longer term, efforts to protect and expand woody vegetation are likely to bring dividends. These beneficial effects are largely the result of enhancement of beneficial insects such as parasitic wasps, ladybird beetles and spiders. Weedy areas (including pastures with brassica weeds) tend to promote pests should be managed/avoided. Shelterbelt vegetation was found to be associated with higher numbers of cabbage aphid (which feeds only on brassica family plants) so, reinforces the necessity to control such weeds and – where possible – avoid siting crops close to areas with brassica weeds.

Table 4. Lettuce results showing desirable effects (more beneficials, fewer pests) in green and undesirable effects (fewer beneficials and more pests) in red. Intensity of shading shows how strong the effect is whilst the characters in each cell show the level of confidence in the result from statistical analysis (0= no effect, *= 95% confidence, ** = 99% confidence, *** = 99.9% confidence).

Pests	Weeds	Shelterbelt	Road	Riparian veg	Brassicas	Lettuce	
Thrips	***	***	0	***	***	***	
Whitefly	*	*	*	***	***	0	
Rutherglen bug	***	0	**	**	*	***	
Beneficials	**Weed**	**Shelterbelt**	**Road**	**Riparian veg**	**Pasture**	**Dam**	**Brassicas**
Ladybeetle	0	***	0	0	***	0	***
Spider	*	*	***	0	0	0	0
Brown lacewing	*	***	***	**	***	0	0
Parasitic wasps	0	***	*	0	*	0	**
Aphid mummies	0	***	***	0	0	**	***

Recommendations for lettuce strongly depend on which pest types are of primary concern in your district. Shelterbelt and riparian vegetation tend to give lower densities of whiteflies but promote thrips. Planting lettuce adjacent to other lettuce crops had neutral or positive effects on pests and beneficials.

Table 5. Carrot results showing desirable effects (more beneficials, fewer pests) in green and undesirable effects (fewer beneficials and more pests) in red. Intensity of shading shows how strong the effect is whilst the characters in each cell show the level of confidence in the result from statistical analysis (0= no effect, *= 95% confidence, ** = 99% confidence, *** = 99.9% confidence).

Pests	Weeds	Sweetcorn	Shelterbelt	Road	Pasture	Dam	Brassicas	Bean	Carrot
Thrips	0	0	0	*	**	0	***	0	0
Whitefly	0	0	***	0	*	0	0	0	*
Rutherglen bug	***	0	0	***	***	***	0	0	***
Jassid	0	0	0	0	*	0	0	0	*
Mirid bug	**	0	0	0	0	*	0	0	0
Beneficials	**Weeds**	**Sweetcorn**	**Shelterbelt**	**Road**	**Pasture**	**Dam**	**Brassicas**	**Bean**	**Carrot**
Ladybeetle	0	0	***	0	0	0	0	0	0
Spider	0	0	0	0	**	0	0	0	0
Parasitic wasps	*	0	0	0	**	0	0	0	0

Jassid, thrips and whitefly densities were reduced in carrot crops adjacent to pastures. Numbers of parasitic wasps were also enhanced by adjacent pasture. Shelterbelts were associated with higher numbers of ladybeetles. Shelterbelts support beneficials but also tend to increase whiteflies so care should be taken if these are of significant concern in your district.

Table 6. French been results showing desirable effects (more beneficials, fewer pests) in green and undesirable effects (fewer beneficials and more pests) in red. Intensity of shading shows how strong the effect is whilst the characters in each cell show the level of confidence in the result from statistical analysis (0= no effect, *= 95% confidence, ** = 99% confidence, *** = 99.9% confidence).

Pests	Weed	Shelterbelt	Road	Pasture	Bean
Thrips	*	0	***	**	0
Whitefly	0	0	*	0	**
Tobacco cutworm	0	0	***	0	**
Beneficials	**Weed**	**Shelterbelt**	**Road**	**Pasture**	**Bean**
Ladybeetle	0	0	0	**	0
Spider	0	0	0	**	0

Tobacco cutworm numbers are increased when bean fields are planted adjacent to each other. Beans fields adjacent to pasture had higher numbers of ladybeetles and spiders and fewer thrips. Roads, which are bordered by undisturbed vegetation and often with trees, significantly reduced the densities of thrips and tobacco cutworm, likely reflecting the natural enemy shelter and food resources provided by roadside vegetation though only pastures led to significant levels of enhancement of natural enemies.

Table 7. Capsicum results showing desirable effects (more beneficials, fewer pests) in green and undesirable effects (fewer beneficials and more pests) in red. Intensity of shading shows how strong the effect is whilst the characters in each cell show the level of confidence in the result from statistical analysis (0= no effect, *= 95% confidence, ** = 99% confidence, * = 99.9% confidence).**

Pests	Weed	Road	Sorghum	Capsicum
Rutherglen bug	0	0	0	**
Beneficials	**Weed**	**Road**	**Sorghum**	**Capsicum**
Green lacewing	0	***	***	*

Rutherglen bug is increased in crop areas adjacent to other capsicum crops so avoid contiguous planting. Sorghum was associated with higher numbers of green lacewings so recommended for suppression of soft-bodied pests such as aphids.

Farmer Interviews

Seventy-five interviews were held, accounting for approximately 3% of Australian vegetable growers (Figure 4). An Australian Bureau of Statistics survey reported 2470 growers of vegetables in Australia with an annual production value over $40 000 (Weragoda et al., 2017).

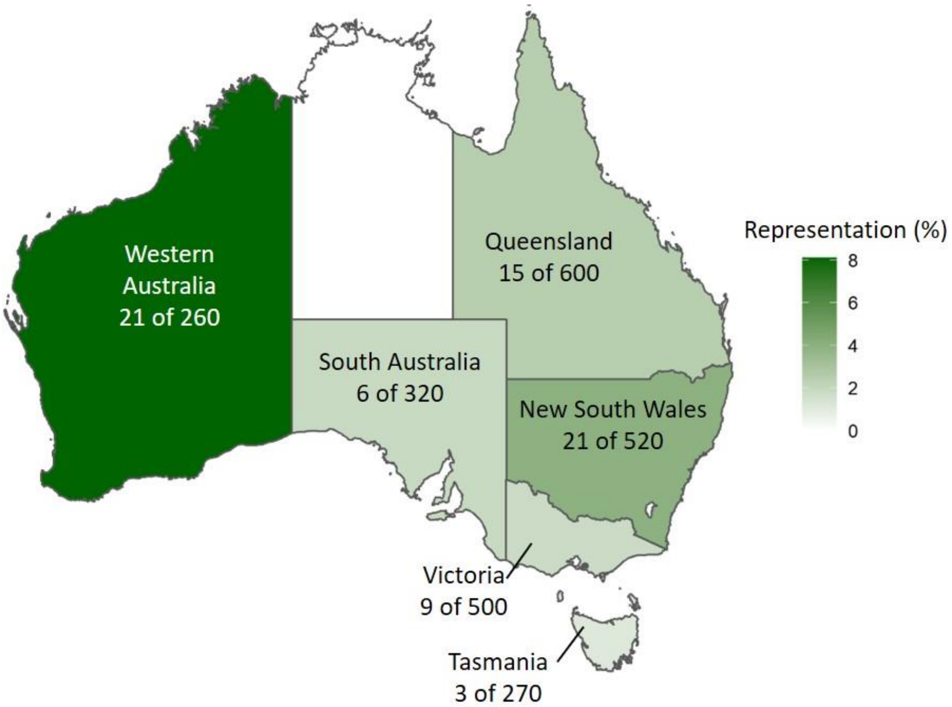


Figure 4. Numbers of growers interviewed in each state along with numbers of vegetable farms for each state according to Weragoda et al. (2017) survey.

Horticultural production was the main business of all participants; 49 (65%) only grew vegetables. The remainder had a variety of secondary enterprises, including perennial horticulture, pastures, grain or oilseed cropping. All except for six grew more than one type of vegetable with 2-4 crop types (63% growers) the most common production mix. Due to the wide range of crop types and varieties, crops were grouped by plant family or production type. The most common crops were broccoli, cauliflower and other Brassica oleracea L. (Brassicaceae) vegetables grown by 49 participants. This was followed by sweetcorn (25), lettuce (24), Fabaceae (21), Allium spp. (18), Apiaceae (17), potato (17), Cucurbitaceae (15) and Solanaceae (12). Less common crops grown by the participants were, spinach, sweetpotato, asparagus, ginger and basil.

Secondary enterprises included mango (*Mangifera indica*) (1), banana *Musa* sp. (3), lemon (*Citrus × limon*) (1) and fig (*Ficus carica*) (1) (all WA growers). Rotational grazing or cover crops included lucerne (*Medicago sativa* L.), barley (*Hordeum vulgare* L.) and oats (*Avena sativa* L.). Grain crops included sorghum (*Sorghum bicolor* L.), chickpea (*Cicer arietinum* L.) and wheat (*Triticum aestivum* L.).

Growers' perspectives on key vegetable pests and their management

The most important pest as indicated by growers was the specialist brassica herbivore diamondback moth (58 growers) but only 16 of the 49 brassica growers considered the other specialist brassica herbivore, cabbage white butterfly (*Pieris rapae*) a pest. The growers who nominated diamondback moth as the major pest had either grown brassicas in the past or were growing field brassica crops. Aphids (44 growers) was the second most problematic pest type. Reflecting the range of species grouped into this category, the growers who nominated aphids as a pest grew a variety of crops with no crop having a greater problem than other crops. *Helicoverpa* spp. was mentioned by 34 growers which comprised corn, lettuce, peas and bean growers. Responses from a small number of growers included greenhouse and silverleaf whitefly ((*Trialeurodes vaporariorum* and *Bemisia tabaci,* respectively) and Rutherglen bug (*Nysius vinitor*), the latter chiefly a harvest contaminant and cause of quality issues rather than direct yield loss.

Pest management practices and their impact on pest perception

Most growers interviewed (65) stated that they used synthetic pesticides. Just over half, 40 growers, said that they use broad-spectrum synthetic pesticides at times whilst 25 stated that synthetic insecticide use was confined to selective products (Cole et al., 2011). Growers that indicated that they used only biological pesticides (Campos et al., 2019) such as Bacillus thuringiensis (Bt) or nuclear polyhedrosis virus (NPV) (13.3%) were not necessarily certified organic (some still used synthetic fertilisers, a barrier for organic certification).

The incidence of perception of diamondback moth as a pest significantly differed based on pesticide selection. Of the brassica growers that mostly used synthetic insecticides to manage DBM, 90% identified diamondback moth as a problem pest whilst only 33% of growers that used only botanic pesticides identified it as a problem. Perception of this pest as a problem also differed according to the numbers of crops the grower grew. Farms with one or few crops species were associated with relatively high levels of growers considering this brassica-specialist pest to be a problem whilst this view was progressively less common among growers with gradually larger numbers of crops. The perception of cabbage white butterfly or aphids was not significantly affected by pesticide selection.

Perception of *Helicoverpa* spp. as a pest differed significantly among pesticide use categories. All growers who reported use of only botanical products did not consider Helicoverpa spp. a problem pest, whereas 54% of those using synthetic insecticides nominated *Helicoverpa* spp. as a pest. Strikingly, eight corn growers did not consider Helicoverpa spp. to be a major pest. When questioned, these growers did not consider these pests a ‘problem’ as their management practices kept populations under control and below damage levels. One grower considered that growing lucerne adjacent to corn was donor habitat for beneficial insects, a complement to use of NPV to protect the corn cobs over the susceptible period. None of the growers who used only botanical pesticides listed *Helicoverpa* spp. as a pest.

Various reasons were given for pesticide selection. Some indicated that they had moved to using only organic pesticides for ‘health reasons’ or that they felt they were able to manage pests sufficiently without synthetic products. However, for uses of broad-spectrum synthetic products, market was an important influence, particularly when produce was destined for export or a domestic buyer with a high rate of product rejection due to minor damage (see below).

Insecticide use

Over half the participants stated that they limit their use of synthetic pesticides to products that are marketed as being selective. One younger grower stated he was happy to use newer selective products but his ‘retired’ father was often disappointed with the non-instant impact when he visited fields. Another grower expressed that the same pest control strategies being applied have worked for a couple of generations. Broccoli growers were least concerned about pests as the florets (marketable portion) were attacked less often than was foliage. In some cases, growers reported not spraying broccoli at all after planting out seedlings.

Other management practices

Crop monitoring was carried out by 84% of growers whilst a third of growers (34%) had purchased beneficial insects such as Trichogramma spp. parasitoids. Only 5.3% of growers indicated that they had implemented some type of habitat management for pest management. Many growers had heard of field scale habitat management or were intrigued by the idea but stated that it had to be ‘affordable’, others expressed interest because it would fit in with their pivot irrigation systems whereas trees were too tall to do so. Shelterbelts were present on 53.5% of interviewees’ farms. A few considered no-crop vegetation a problematic source of pests or potential contaminants (e.g. leaves). A follow-up question on potentially hosting a habitat management field trial was meet with enthusiasm by many growers.

Crop rotation was practiced by 73.3% growers and 34.7% had selected crop varieties based on their pest tolerance or resistance properties. For example, in brassica growing areas in south-east Queensland, where resistance to diamondback moth is a problem, brassicas are now typically grown in rotation with non-host crops of pumpkin, melons, onions, potatoes and beans. Cover crops such as pulses, buckwheat or lucerne were used as part of a crop rotation by 33% of growers and 8% practiced intercropping (where a small number of rows of one crop would be interspaced by rows of another). The majority of growers (56.7%) limited their production to less than 4 crop types. The reasons given for number of crop types was mostly around markets and infrastructure requirements. However, there was a relatively high number of growers that grew up to 6 different crop types (34.7%) and a small number (10.7%) that grew over 6 different crops.

Field Trials and Benefit: cost analysis

Key Points

- For rapid benefit, growers can establish strips of plants within vegetable fields. Nectar plants check pests by promoting beneficials that kill the pests, whilst trap-crop strips can operate directly against pests.
- Trials in brassica vegetables and sweetcorn suggest that strips need to be no more than 30 m apart to provide benefit to the entire crop.
- Nectar plant strips appear especially effective if land within 1km of the field is dominated by cropland and has few woodland and pasture areas.
- Economic benefit of nectar plant strips within vegetable fields is greatest when these are accommodated in areas such as sprinkler rows, so no crop area is sacrificed.

Figure 5. For rapid benefit, growers can sow strips of annual plants such as cornflower in crop fields. (Photo: S. Munro)

Assessment of arthropod abundance

Spatial effects on arthropods in the crop

Reflecting the fact that trials took place on commercial farms and host growers needed to exercise effective pest suppression, numbers of pests were held at consistently low levels on all sites. Notwithstanding this, there was a detectable (and statistically significant) additional benefit of flower strips: a decrease in numbers of diamondback moth in areas of the crop immediately adjacent to or 5m from the flower strips (Figure 6).

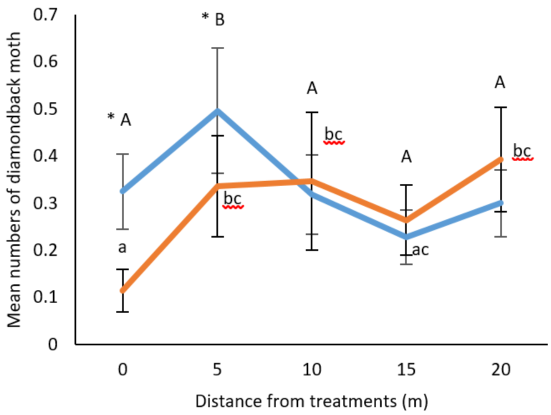


Figure 6. Mean numbers of diamondback moth in crop adjacent to flowering strips (yellow line) or control area with no flowers (blue line). 0 indicates first sampling point immediately adjacent to the flowering strips or control. All others sampling points were at 5 metre intervals up to 20 metres. * indicates where mean is significantly different between treatments within a distance. Small letters indicate significant difference among distances within a treatment. Capital letters indicate significant difference in the mean of pest arthropods at different sampling points in the control plot at a 5% level of probability.

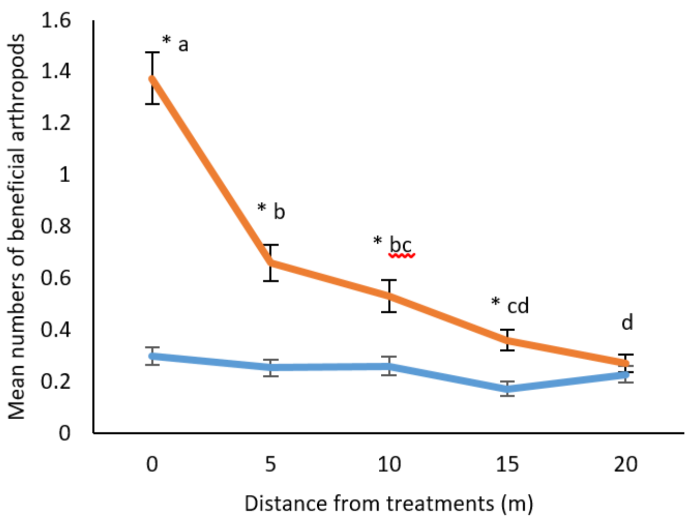


Figure 7. Mean numbers of natural enemies in crop adjacent to flowering strips (yellow line) or control area with no flowers (blue line). 0 indicates first sampling point immediately adjacent to the flowering strips or control. All others sampling points were at 5 metre intervals up to 20 metres. * indicates where mean is significantly different between treatments within a distance. Small letters indicate significant difference among distances within a treatment. Capital letters indicate significant difference in the mean of pest arthropods at different sampling points in the control plot at a 5% level of probability.

Number of natural enemies were very strongly and statistically significantly influenced by the flowering strips (Figure 7). Counts on crop plants were more than five-fold higher in areas of crop immediately adjacent to the flowering strips compared to the control areas and more than doubled even 15m from the flowers. Flowering strips significantly increased numbers of a wide range of natural enemy types including ladybeetles, spiders, parasitoids wasps, brown lacewings, damsel bugs, and carabid beetles. Present also were red and blue beetles, rove beetles, and haplothrips but their abundance and spatial distribution were not significantly influenced by the presence of the flowering strips.

The higher numbers of natural enemies are consistent with the observed effect on diamondback moth. This link is further supported by result from the use of sentinel baits of diamondback moth larvae exposed to 'wild' parasitoids in the field. Significantly higher numbers of larvae from sentinel plants placed in flowering plots (8.76%) were parasitised by wasps than that of in control plots (3.23%).

Relative attractivness of flowering plant species.

Numbers of pests captured on sticky traps positioned in sub-plots of each flowering plant species were approximately five-fold lower than the number so beneficial natural enemies captured (Figure 8). Numbers of pests caught did not differ significantly among plant species. Together, these two findings indicate that none of the flowering plant species were attractive to pests so do not represent a risk of inadvertently favouring pests when added as strips to brassica crops.

Large numbers of beneficials were captured on sticky traps positioned in sub-plots of each flowering plant species (Figure 8). Partitioning catches into the major types of beneficials revealed that cornflower was most attractive to parasitoid wasps whilst craneflies were trapped significantly more from alyssum than buckwheat and cornflower. Alyssum also attracted significantly more rove beetles, *Orius* spp., and red and blue beetles than buckwheat.

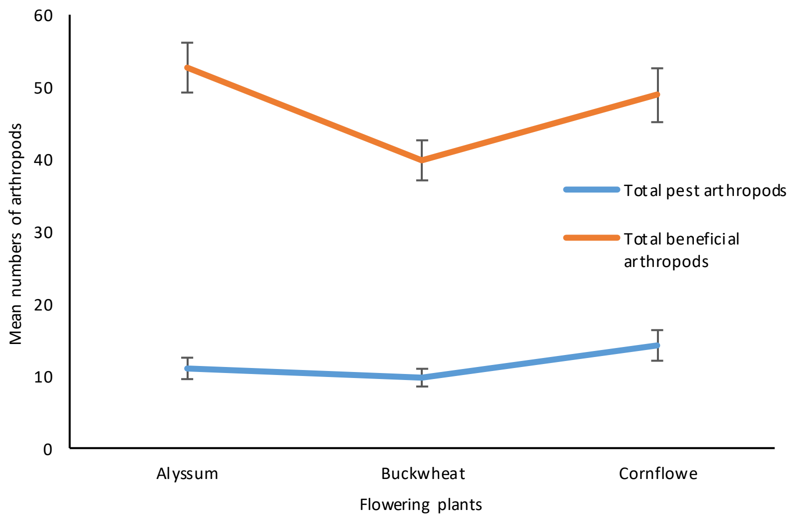


Figure 8. Mean numbers of pests and beneficials captured on sticky traps mounted on flowering strips.

Assessment of crop damage

Benefits of habitat manipulation ranged from $57 (cabbage) to $92 (Brussels sprouts) based on a 500 m^2 production unit (Table 8).

Two scenarios are modelled to reflect the costs for placement of flowering strips in differing areas. If these occupy land that otherwise would be used for brassica production, the foregone yield leads to negative economic impacts with benefit: cost ratios between 0.52: 1 and 0.77: 1 (Table 10). In cases where habitat manipulation strategies have proven popular overseas (e.g. African maize, Asian rice), the strips or equivalent features are placed in the borders of crops or established as a groundcover so do not lead to a reduction in primary crop production area. Under this more realistic scenario, benefit: cost ratios are highly favourable, ranging from 4.6: 1 to 7.9: 1 (Table 9).

Table 8: Yield and income comparison (per 500 m^2)

Plants	Price per unit	Habitat management			Control			Benefit
		Marketable plants harvested	Damaged plants	Income	Marketable plants harvested	Damaged plants	Income	Extra Income
Cabbage	$1.50	846 ± 5	54 ± 7	$1 269	808 ± 8	92 ± 9	$1 212	$57.00
Cauliflower	$1.70	864 ± 7	36 ± 5	$1 469	810 ± 7	90 ± 9	$1 377	$91.80
Chinese cabbage	$1.50	864 ± 8	36 ± 6	$1 269	808 ± 6	92 ± 7	$1 212	$84.00

Table 9: Economic impact of using flowering plants in sprinkler row, headland or other uncropped area. Numbers based on an area of 36m2. Numbers of (B) from table 8.

Crop	Land	Seed ($)	Labour ($)	Total cost ($) **(A)**	Difference in income ($) **(B)**	Benefit: cost **(B/A)**
Cabbage	-	1.60	10.00	11.60	54.00	4.65
Cauliflower	-	1.60	10.00	11.60	91.80	7.91
Chinese cabbage	-	1.60	10.00	11.60	81.00	6.98

Table 10: Economic impact of using flowering plants in area that otherwise would be cropped. Numbers based on an area of 36m^2. Numbers of (B) from table 8.

Crop	Land	Seed ($)	Labour ($)	Total cost ($) **(A)**	Difference in income ($) **(B)**	Benefit: cost **(B/A)**
Cabbage	97.50	1.60	10.00	109.10	57.00	0.52
Cauliflower	110.50	1.60	10.00	122.10	91.80	0.75
Chinese cabbage	97.50	1.60	10.00	109.10	84.00	0.77

Landscape scale study

Effect of landscape properties on pests and natural enemies in brassica vegetables

The landscapes in this study ranged from simple, highly disturbed in nature with strong representation of croplands to much more complex and less disturbed areas with more woodland and pasture. Over this range of landscape types there were significant direct effects on pests and natural enemies. Key findings are as follows.

PASTURE. At the largest spatial scale analysed, extending 5000 m from focal fields, increasing composition of pasture reduced overall pest numbers in the crop. This effect was evident also for diamondback moth, likely because of the availability of brassica weeds and volunteers (its host plants) in and around pastures was lower than in other land uses such as croplands.

WOODLAND. An increased abundance of natural enemies was observed for crops located in landscapes with increasing composition of woodlands in the landscape at the 1 km spatial scale. This likely reflects the availability of shelter and alternative foods (nectar, pollen, non-pest insect prey) provided by the complex, perennial vegetation.

Interaction between landscape properties and the use of flowering plant strips in brassica vegetable fields

Natural enemy abundance in crops was strongly elevated by establishing flowering strips in cases where crops were set in landscapes with high composition of cropland at the 1000 m scale. The benefit of flower strips reduced as cropland composition in the surrounding landscape declined (Figure 9). Natural enemy numbers were comparable to those in the control (no flower) treatment – that is, there was no benefit to the grower of establishing flower strips - when cropland composition was low.

In the control treatment, natural enemy numbers were consistently low across the full range of cropland compositions. This signals that if a crop is in a landscape with relatively low proportions of cropland, the other land uses (such as woodland, riparian areas, roadways and pastures) already provide beneficials with sufficient shelter and food resources. Accordingly, the addition of a flowering strip provides no extra benefit. Conversely, landscapes dominated by croplands are depauperate in resources for beneficial so the addition of a flowering strip to a brassica crop can have a large benefit to natural enemy numbers.

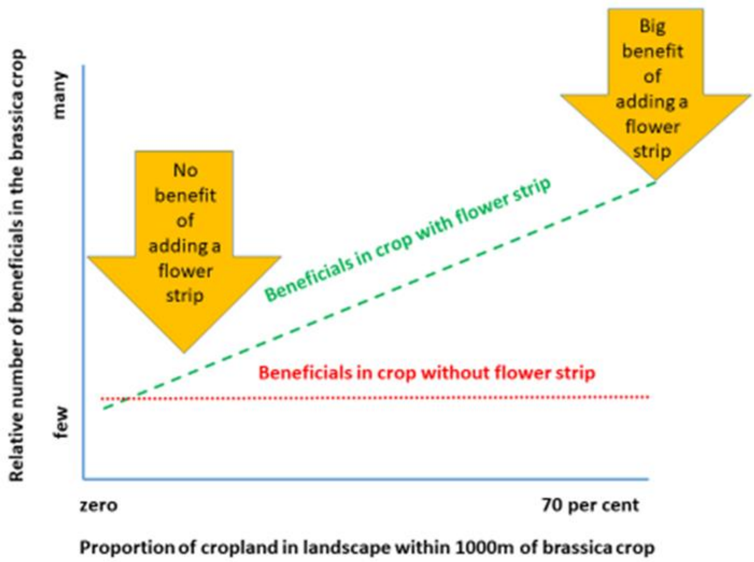


Figure 9. Stylized representation of the effect of composition of cropland in landscape area of 1000 m that significantly increased in-field natural enemy abundance in fields with flowering strips (dashed line) than without flowering strips or control treatment (dotted line).

Outcomes

The headline **'end-of-project outcome'** originally defined in the Logic Model for this project was **'suppression of targeted vegetable pests in key crops and regions'** (Figure 10). Achievement of this outcome is evident in two ways. First, in the series of on-farm field trials conducted in multiple states during the second major phase of the project, vegetable pests were suppressed. Statistically significant effects were evident for pest densities on brassica vegetables. Several of the growers associated with field trials have indicated an intention to continue and further develop the approaches developed in this project, potentially applying them to additional crop types.

The scope of the project did not include an end-of-project survey of levels of grower uptake and levels of pest suppression on a regional basis but interactions with growers and other stakeholders suggests significant levels of interest and adoption, consistent with the project's **intermediate outcome** of **'Aust vegetable growers have embraced evidence based vegetation management to suppress pests'** (Figure 10).

Accordingly, a second way in which the project is very likely to have achieved suppression of targeted vegetable pests in key crops and regions is by adoption beyond the growers that hosted research trials. One example is a farm in the Lockyer Valley which is planning to incorporate floral strips in brassica crops after several seasons facing complications with insecticide resistance. Other farms in this region have already been using alyssum floral strips for pest control in brassica fields.

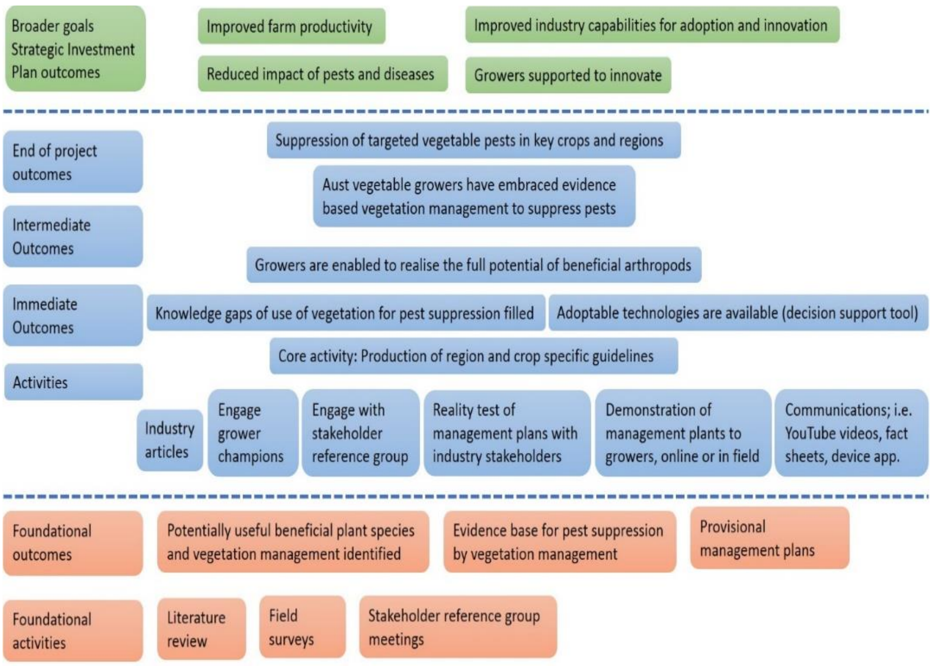


Figure 9**. Logic model for project VG16062.**

The preceding outcomes are founded on the second **intermediate outcome**, '**growers are enabled to realise the full potential of beneficial arthropod**s' (Figure 9). Whilst it is too early to say that the industry as a whole (nationwide) is already realising the full potential of beneficials, good numbers of individual growers are at this point. This position has been facilitated by comprehensive achievement of the **three immediate outcomes** that were initially defined for the project. The first of these, **'knowledge gaps of use of vegetation for pest suppression**' has been met comprehensively by the literature review, field survey and field trial. This project has provided a wider knowledge base for the use of habitat management on vegetable farms in Australia. The review of international literature of successful habitat management approaches used in vegetable crops in other countries provided a highly positive evidence base at the start of the project. For all of the crop species covered by this project, we were able to identify cases of overseas work that provided important leads. In several of the crops, such as brassica vegetables, there was an exceptionally strong evidence base including plant species that are likely to perform well under Australian production conditions. This information then allowed the agronomic literature to be identified for these plant and trap crop species to provide a more detailed understanding of their suitability. That in turn allowed production of calendars for planting, blooming periods etc, as well as an assessment of the potential risks (e.g. weedy potential) and the major pests and beneficials they might affect.

The new knowledge generated has been communicated by a suite of end-user communication activities (see Outputs) consistent with those originally identified in the project's logic model (Figure 9). Farm walks have been held in WA, SA, VIC and NSW, each hosted by a grower on whose property we had a field trial. No participant surveys were circulated at the field days but verbal feedback was positive. A participant at the South Australian event was especially interested in scope for field scale habitat management in additional crop types including vineyards. The host of the event in Bathurst was interviewed for TV and talked very positively about the approach including the fact that it had avoided the need to spray that crop. Similarly, the host of the Melbourne trial spoke very positively on ABC Landline TV about the specific work undertaken on his farm and its wider potential. Other communication forms used to generate outcomes were TV (ABC Landline, Prime News), radio, newspaper, magazine articles and web platforms.

The second of the immediate outcomes, 'adoptable technologies are available' has been met by the team synthesizing information from the survey and trials and integrating this with the comprehensive literature review to formulate appropriate technologies that fall into the following three categories: nectar plants, trap plants, and crop placement to maximise benefits of adjacent land uses and the wider landscape. At a more granular level, these three technologies have met the third immediate outcome by allowing the development of 'region and crop specific guidelines (see Recommendations)'. The general form, of these is: (i) recommendations for the use of nectar plant strips in brassica crops, (ii) recommendations for the use of trap plant strips in brassica crops, (iii) recommendations for the use of nectar plant strips in sweetcorn crops, and (iv) recommendations for a wider range of crops (carrot, lettuce, French bean, capsicum, sweetcorn and brassica vegetables) on crop placement and management of adjacent land. Crop calendars have been developed to guide vegetable growers who are implementing habitat management strategies on farms. The crop calendars include a list of plants that can be used as nectar sources, trap crops, or intercrops (crop species sown with the main crop, for example as admixed rows or alleys) along with their planting, growing, flowering and times when they are most valuable e.g. when key crops are under attack. The crop calendars are categorised by temperate, arid and tropical regions (Recommendation 9).

Among the strongest effects evident from this work, woody vegetation such as in the form of shelterbelts, riparian areas and roadside vegetation appear to be a robust, widely applicable technology that (in addition to widely recognised benefits for shelter, on-farm biodiversity conservation and hydrology) promote beneficials and provide pest suppression in adjacent vegetable crops. This latter effect appeared to be a very generally applicable effect across regions and crop types. The finding that shelterbelts enhance densities of beneficial insects in nearby crops is in broad agreement with international evidence that a vegetation heterogeneity in cropping systems stabilizes food production levels (Renard & Tilman 2019; Parry et al. 2015).).

The guidelines for which this project has generated the most comprehensive evidence base are those relating to these of nectar plants to protect brassica vegetable crops. Pest suppression was strengthened in the field trials, where a significantly higher number of beneficial arthropods including ladybeetles, lacewings, parasitic wasps and damsel bugs were found in the crop close to the flowering strips which, in turn, significantly reduced pest numbers. Effects on arthropods were evident up to 15 -20 meters from the flowering plants into the crop. The economic benefits of these habitat management strategies varied depending on the placement of the flowering plants. In scenarios where the habitat manipulation plants are placed in the borders of crops or uncultivated areas such as sprinkler rows so not taking land out of production, benefit: cost ratios are highly favourable, ranging from 4.65:1 to 7.91:1.

The foregoing outcomes have been communicated to growers by an exceptionally strong communication effort that has addressed all **six of the relevant activities** (Figure 9) defined in the logic model for this project. Consistent with the project's logic model, this engagement has also involved submissions to Hort Innovation that seek to align relevant Strategic Investment Plans (SIPs) with the opportunities identified by the project.

In relation to the Broader Goals identified in the logic model, the work in this project is the subject of a case study for an Austrade 'agriculture tool kit' promotion of Australian products.

Monitoring and evaluation

A logic model and monitoring & evaluation plan including project key evaluation questions were developed at the project inception meeting in December 2017 and finalized at a second meeting at Hort Innovation in January 2018. That defined the following Key Evaluation Questions (KEQs).

Key Evaluation Questions

Effectiveness: How effective has the project been in contributing to the suppression of pests in key vegetable crops and vegetable growing regions?

The project has succeeded in engaging with growers and collecting data from major vegetable growing regions extending from Western Australia to South Australia, east to the coastal strip of New South Wales, north to sub-tropical Queensland and south to cool temperate Tasmania (Figure 11).

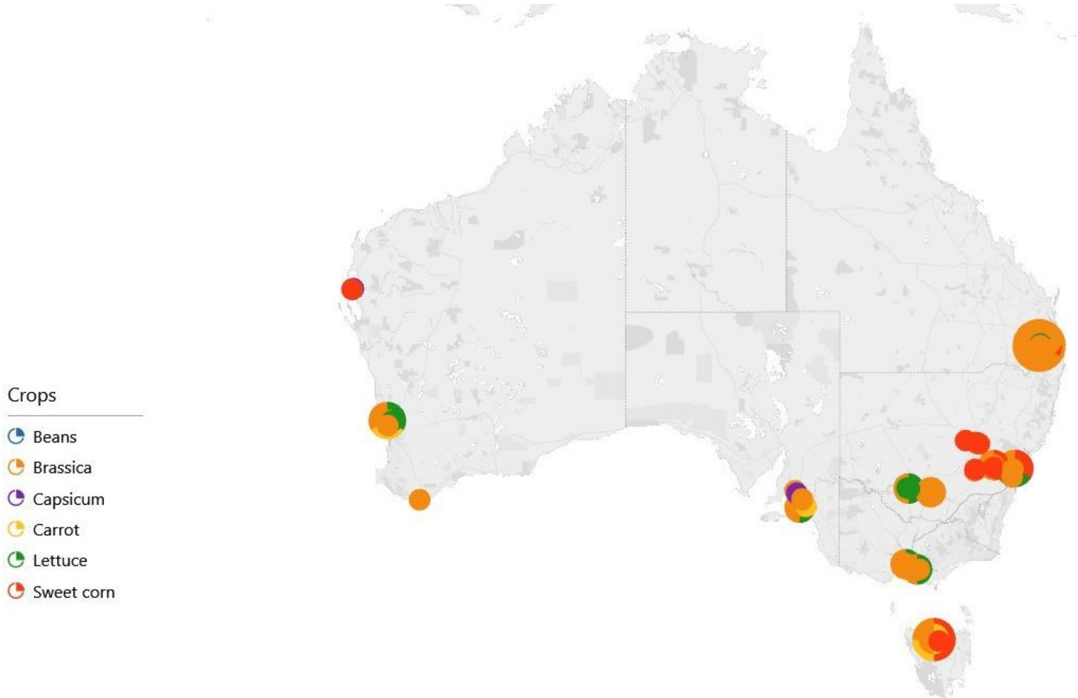


Figure 10. Locations of data collection sites. Colours represent the nature of the crop. Size of the colour indicates the sampling size.

For each of the six crop types covered by the project, tangible, evidence-based guidelines have been produced for growers in the arid, temperate and sub tropical regions (Recommendation 9). These were based, in part, on surveys of 491 crop fields in which the influence of adjacent land use on pests and beneficials was quantified. Aside from specific recommendations for each crop type, which take the form of "heat maps" (Tables 2-8), it is noteworthy that some land uses had robust effects across crop types, seasons and states. Overall numbers of pests were suppressed in crops adjacent to riparian areas, roads and waterbodies but strongly elevated adjacent to weedy areas (Figure 3). Beneficials are likely to have been responsible for some of these effects because they were more numerous in areas of crops adjacent to riparian areas as well as shelterbelts. Roads adjacent to crops and bordered by undisturbed vegetation and often with trees, significantly increased parasitic Hymenoptera, predatory beetles, spiders and brown lacewings in the crop, likely reflecting the shelter and alternative food resources provided by roadside vegetation.

In the second major phase of the project, in which the strongest opportunities for in-field management were to be pursued, the project concentrated on brassica vegetable and sweetcorn. Work in the latter crop was hampered by severe drought in eastern Australia so only a restricted number of trials was possible in QLD. In that work, and in the more ambitious, multi-state trials with brassicas, statistically significant benefits were evident. Flower strips led to significantly increased numbers of beneficials (ladybeetles, spiders, wasps, brown lacewings, damsel bugs, and carabid beetles) in adjacent brassica crops. Reflecting this result, reduced densities of diamondback moth were evident. Enhancement of beneficials tended to be greatest immediately adjacent to the flower strips and declined with distance but was evident up to 20m from the flower strips for some types of beneficial. Though diamondback moth counts on crop plants were significant only for the area within 5m of the flower strips, evidence for wider benefit was evident in a study of caterpillar parasitism by wasps. This was doubled in areas of the crop within 30 m of the flower strip compared with crop areas without a flower strip. In accordance with this, assessment of pest feeding activity on crop plants in areas 0-30 m from the flower strip revealed lower levels of damage than in corresponding areas with no flower strip. This translated into lower levels of crop damage and the benefit: cost analysis showed an economic advantage of up to 8:1. Detailed results are set out in **Field trials and benefit: cost analysis** section of the Results.

Relevance: How relevant are the region- and crop-specific vegetation management guidelines to the pest suppression needs of growers?

Vegetation management guidelines have been produced for each crop (brassica vegetables, sweetcorn, carrot, lettuce, French bean and lettuce). The guidelines also provide information related to region as reflected, for example, in the timing of flowering by potential nectar plant species. The relevance of the guidelines to the needs of growers was assured by (i) interviews of 75 growers across all states to determine their needs, and (ii) by engagement with the Stakeholder Reference Group. A key message from this was that there is a strong need for the development of adoptable technologies that would allow a grower to implement the relevant technique and be able to generate tangible benefits in the short term. This translates into a preference for technologies such as the use of annual plant species that will rapidly bloom and provide support to beneficial insect in the current production season. This contrasts with the scenario of exploiting the benefits provided by perennial vegetation such as shelterbelts that take many years to establish. In the survey of vegetable producers, 40 of the 75 interviewees had at least one shelterbelt on their property so would, potentially, have been able to exploit the effect we identified by positioning a crop adjacent to it. However, planting additional shelterbelts on those farms, as well as establishing them on other farms is a long-term strategy for pest suppression. Accordingly, the second phase of the project was focused on strategies to deliver immediate benefit.

Process appropriateness: How well has project engaged with growers?

An exceptionally high level of media interest and exposure has been generated by the project. Local and national media has included articles in local newspapers and radio stations, Prime TV and Channel 9 News. ABC TV Landline media team filmed the field trial in Devon Meadows (Vic) with Geoff Gurr, Olivia Reynolds and Syed Rizvi on 18-02-2020, with laboratory vision and further interviews conducted at **cesar**, Melbourne with Olivia Reynolds on 21-02-2020. The story was screened on 03-05-2020 which generated a number of following enquiries from industry to both CSU and Hort Innovation. The segment was aired a second time in a Landline re-run in February 2021.

Grower demonstration days were held in Bathurst, NSW (28-01-2020) (six attendees), in Hay Valley, SA (13-02-2020) (13 attendees) and in Werribee, Vic (17-03-2020) (seven attendees, despite COVID-19 pandemic restrictions applying at this time). These events were covered by the respective local media. Project updates presentations were given at the VegNET R&D Field Day, SA (23-10-2019), VegNET Native Veg Insectarium Event, Vic (23-10-2019) and the VegNET Bundaberg Fruit & Vegetable Growers Workshop on 'Biosecurity and Beneficials' (O. Reynolds; 18-02-2020). In Queensland, project updates have been presented to the Lockyer Valley Growers Association (03-02-20) and an expanded presentation (18-03-20).

Discussion with growers during farm walks showed that there was a high level of interest in experimenting with habitat management, especially with the growers hosting the trials. Questions often revolved around practical implementation of how to obtain seed and planting and management recommendations which indicated genuine interest in taking steps to develop this on their own farms.

Efficiency: How well was the project managed, given the dispersed team?

Meetings were held in December 2017 and January 2018, where most of the senior team met in person. A weekly team meeting was established in 2018 and ran until the project's end in 2020. This used video and telephone conferencing technology so minimized the adverse effects of Covid-19 in the final phase of the project though the pandemic did restrict the level of Victorian extension. All team members were invited and regularly engaged in the weekly video conference. The level of engagement was made flexible for various team members depending on commitments (both within and external to the project) for each stage. Regular discussions between the technical project staff also took place particularly during the trial design, set up and data gathering phases to ensure consistency of protocols across different trial locations.

All team members participated in the design of protocols for the survey and field trials. All team members contributed to milestone report and manuscript development.

Sustainability: What is in place to allow the project outcomes to endure?

Many of the communication materials produced during the project will remain accessible online. This is complemented by the project fact sheets for which content was developed in consultation with the Stakeholder Reference Group and will be hosted by Horticulture Innovation. All components of the project (literature review, field survey, farmer interviews, and on-farm field trials) will be formally published in journals making them available to stakeholders including other researchers so that momentum can be maintained to deliver progressively more benefits to Australian horticulture. The project team has also been engaging with Horticulture Innovation and other rural research and development corporations to conduct work in a greater range of crop systems.

Recommendations

Headlines

- **Preserve uncultivated areas on farm, including woody vegetation/shelter belts, as these can benefit vegetable growers by helping suppress crop pests especially if weeds are controlled within them.**
- **Establishing strips of nectar plants within vegetable fields to promote beneficials is an additional way to suppress crop pests and is especially effective if land within 1,000m of the field is dominated (more than 40 per cent) by other crops and has few woodland and pasture areas.**
- **Economic benefit of nectar plant strips within vegetable fields is greatest when these are accommodated in unused areas such as sprinkler rows so no crop area is sacrificed.**
- **Consider the many opportunities for future research to build on these new results to deliver benefit in a wider range of crop types.**

Specific Recommendations

1) **Effects of adjacent land use**: It is recommended that vegetable growers adopt the following practices to increase beneficials and decrease pests in crops.

(a) Brassica

Diamondback moth is the pest of greatest concern. Densities of this pest are reduced in the crop adjacent to riparian vegetation and shelterbelts. Where possible, situate the most vulnerable or highest value plantings adjacent to such vegetation. This also assists with the other major caterpillar pests, cabbage white butterfly as well as Rutherglen bug, thrips and whitefly. In the longer term, efforts to protect and expand woody vegetation are likely to bring dividends. These beneficial effects are largely the result of enhancement of beneficial insects such as parasitic wasps, ladybird beetles and spiders. Weedy areas (including pastures with brassica weeds) tend to promote pests should be managed/avoided. Shelterbelt vegetation was found to be associated with higher numbers of cabbage aphid (which feeds only on brassica family plants) so, reinforces the necessity to control such weeds and – where possible – avoid siting crops close to areas with brassica weeds.

(b) Sweetcorn

In most districts, corn earworm is the pest of greatest concern. Crops adjacent to riparian vegetation tends to have low densities of this pest. Riparian vegetation also assists with thrips. Where possible, sweetcorn should be planted adjacent to riparian vegetation, specifically if corn earworm is the main concern but note that corn aphid may be promoted. Woody vegetation such as shelterbelt reduced the density of Rutherglen bug. These beneficial effects are associated with enhancement of beneficial insects such as ladybird beetles, red and blue beetles and *Orius* spp. In the longer term, efforts to protect riparian vegetation and expand woody vegetation are likely to bring dividends. Pasture tends to promote pest thrips, jassids and corn rootworm so vigilance is recommended when planting sweetcorn field adjacent to this land use. Roads, which are bordered by undisturbed vegetation and often with trees, significantly reduced the densities of pest thrips, Rutherglen bugs and corn earworm, likely reflecting the shelter and food resources provided by roadside vegetation. This reinforces the necessity of undisturbed habitats (e.g., trees). Where possible, protect and expand woody vegetation (e.g., shelterbelts).

(c) Carrot

Jassid, thrips and whitefly densities were reduced in the crop adjacent to pastures. Numbers of parasitic wasps were also enhanced by adjacent pasture. Shelterbelts were associated with higher numbers of ladybeetles. Shelterbelts support beneficials but also tend to increase whiteflies so care should be taken if these are of significant concern in your district.

(d) Lettuce

Recommendations for lettuce strongly depend on which pest types are of primary concern in your district. Shelterbelt and riparian vegetation tend to give lower densities of whiteflies but promote pest thrips. Planting lettuce adjacent to other lettuce crops had neutral or positive effects on pests.

(e) French bean

Tobacco cutworm numbers are increased when bean fields are planted adjacent to each other. Beans fields adjacent to pasture had higher numbers of ladybeetles and spiders and fewer pest thrips. Roads, which are bordered by undisturbed vegetation and often with trees, significantly reduced the densities of thrips and tobacco cutworm, likely reflecting the shelter and food resources provided by roadside vegetation.

(f) Capsicum

Rutherglen bug is increased in crop areas adjacent to other capsicum crops so avoid contiguous planting. Sorghum was associated with higher numbers of green lacewings so recommended for suppression of soft-bodied pests.

Consistent with the foregoing trends, equivalent work is recommended across a wider range of horticultural and non-horticultural crop species including cross agency (RDC) investment.

2) Landscape scale interactions with adjacent land use effects

The inclusion in the project of a separately funded Master student allowed work on the interaction of landscape-scale effects with the effects caused by adjacent land use (see 1 above). This aspect of the project focused on brassica vegetables and allows a refinement to the recommendations possible for this commodity. It is recommended that when growers have flexibility in relation to siting a given crop, they adopt practices consistent with the following trends.

- **a)** Plant brassica crops adjacent to shelterbelts to suppress diamondback moth populations; this is most pronounced when the wider landscape (up to 5 km distant) contains a high proportions of woodland.
- **b)** Plant brassica crops adjacent to pastures to suppress diamondback moth populations; this is most pronounced when the nearby landscape (0.5 -1.0 km distant) contains high proportions of non-crop uses including dams, woodland and pasture.
- **c)** Plant brassica crops adjacent to non-brassica crops for suppression of diamondback moth and cabbage aphid; this is most pronounced when the nearby landscape (1.0 km distant) contains high proportions of non-crop uses including dams, woodland and pasture and if crop areas are present in patches rather than contiguous.
- **d)** Plant brassica crops adjacent to woody vegetation to enhance predatory ladybird numbers in brassica crops; this is especially marked in landscapes where crop areas are present in patches rather than contiguous whilst woodland is contiguous rather than patchy, and where dams are present.

3) Landscape scale effects and how these interact with nectar plant strips

Independent of the interactive effects on suppression of diamondback moth and cabbage aphid and enhancement of predatory ladybirds, the work also uncovered an independent effect of landscape structure on green peach and cabbage aphids. Brassica vegetables may be subject to higher rates of aphid colonization when the landscape (0.5 - 1km from the crop) contains high proportions of woody vegetation (likely reflecting the presence of uncontrolled weeds). Importantly, this findings does not imply the need to remove woody vegetation.

a) Vigilance should be exercised to avoid the establishment of weeds in uncultivated areas in relatively proximity to cropland. This can be accomplished by fencing to control stock access, maintaining weed suppression on the farm to reduce seed production and dispersal into uncultivated areas, and control of volunteer brassicas.

Landscape structure affected the strength of benefit obtained from establishing nectar plants in brassica crops. Strips were most effective in landscapes where crops dominated land use within 1,000 of the field in which nectar plants were sown. If, in contrast, the landscape had less than 40 per cent of its area cropped, with woodland and pastures dominating, nectar plant strips have little effect. This is because these landscapes already have plenty of habitat and resources for beneficials.

4) Survey of vegetable production management practices

This phase of the work provided a 'snapshot' of vegetable producers including pests that had the most impact on their decisions and management strategies employed for insect pest management. Many growers currently use a variety of tools that are compatible with habitat management including selective insecticides or biological products, green manures or cover crops and had on-farm features (e.g. shelterbelts) that are potentially positive for beneficials. Whilst this indicates overall potential to reduce industry dependence on insecticides, working towards this is challenging for growers servicing certain markets. Taken in conjunction with wider engagement with industry stakeholders, two main recommendations emerged.

a) Reducing dependence on insecticides demands strategies that are not dependent upon vegetation manipulation that is slow to establish (e.g. shelterbelts) or that operates at large (landscape) scales that extend beyond property boundaries. Rather, there is a need for in-field vegetation manipulation strategies that are based on annual (and possibly biennial) plants that provide rapid pay-back to growers. This was pursued and developed within the present project (see 6 below).

b) In the longer term there is a need to promote attitudes across the entire producer-to-consumer value chain that will recognise objects such as flower petals, gum tree leaves and ladybirds as indicators of a "clean" production system rather than a noxious contaminant that may lead to the rejection of a consignment. This will require further work to develop a more detailed understanding of attitudes and practices across Australia's horticulture industries and markets in order to develop appropriate marketing and communication materials.

5) Literature analysis

The global literature on conservation biological control in horticultural crops that was reviewed in this project established that there are successful overseas cases of habitat management in vegetable crops of importance to Australia. Crucially, many of these cases involved strategies that are consistent with the need identified above (point 4a). These rapidly established, in-field strategies were analysed for suitability under Australian conditions and then adapted and tested in this project, leading to practical recommendations for on-farm use (point 6 below). It was, however, not possible to pursue all of the opportunities presented by the review exercise. Only the most immediately promising lines of research were explored. It is recommended that further R&D investment be made to fully exploit the availability of information from overseas and fast track equivalent work in Australia across multiple crops, focusing especially on the opportunities listed below.

a) Alyssum, buckwheat and cornflower were identified as potential floral resources to attract and support beneficials against pests of brassica, lettuce, capsicum and sweetcorn.

b) Yellow rocket, Chinese cabbage (*Brassica rapa* var. chinensis), and green collard (*Brassica rapa* L. var. Acephala) (Brassicaceae) were identified as potential trap crops for diamondback moth.

c) Intercropping brassica with onion (*Allium cepa* L.) (Amaryllidaceae), tomato (*Solanum lycopersicum* L.) (Solanaceae), barley (*Hordeum vulgare* L.) (Poaceae), and yellow clover (*Melilotus officinalis* L.) (Fabaceae) has potential against pests of brassica crops.

d) Sorghum as a potential banker plant and basil (*Ocimum basilicum* L.) (Lamiaceae) as an intercrop, were identified to promote beneficials for capsicum pests. Banker plants harbour herbivores (usually non-pest species) that in turn support beneficial insects that can check pests on arrival in the mail crop.

e) Sunn hemp (*Crotalaria juncea* L.) (Fabaceae) and cowpea (*Vigna unguiculata* L.) (Fabaceae) can be grown with sweetcorn to attract parasitic wasps.

f) Intercropping French bean (*Phaseolus vulgaris* L.) (Fabaceae) with sweetcorn or coriander (*Coriandrum sativum* L.) (Apiaceae) and carrot with onion can attract beneficials.

6) Field trials of annual nectar plants in brassica crops.

This on-farm work yielded compelling evidence that this approach promotes beneficials, suppresses pest and has strong benefit: cost. It is recommended that factsheets developed by this project be complemented by wider messaging from Hort Innovation and AUSVEG to encourage adoption. Brassica growers can implement the following strategies and growers of other crops can experiment with other, similar strategies.

a) Densities of beneficial parasitoid wasps and predatory insects, and spiders are significantly increased on brassica crop plants up to 20m from flower strips of buckwheat, alyssum and cornflower. Whilst densities of pests remained very low in trial sites, trends in pest numbers and a doubling of diamondback moth parasitism suggest that numbers of caterpillars (diamondback moth and cabbage white butterfly) can be suppressed by flower strips. Jassids may be favoured by the mixed species flower strips but these are minor pests. Accordingly, strips should be established no more than 40 m apart.

b) Plant flowering strips in uncultivated areas such as sprinkler rows rather than taking land out of production. Of the three flower species, buckwheat was the least expensive.

c) Plant cornflower to enhance of parasitoid wasps and some predator species. Cornflower was more frequently visited by adult cabbage white butterfly than were other plant species but this did not lead to elevated numbers of caterpillars in the adjacent crop

d) Plant buckwheat for a fast-to-flower plant that provides early season nectar. Buckwheat was, however, least optimal for parasitoid enhancement and is frost tender so care is required with planting date in temperate zones.

e) Plant alyssum if a self-sowing flowering plant that gives a perennial benefit is desired.

7) Field trials of annual nectar plants in sweetcorn crops

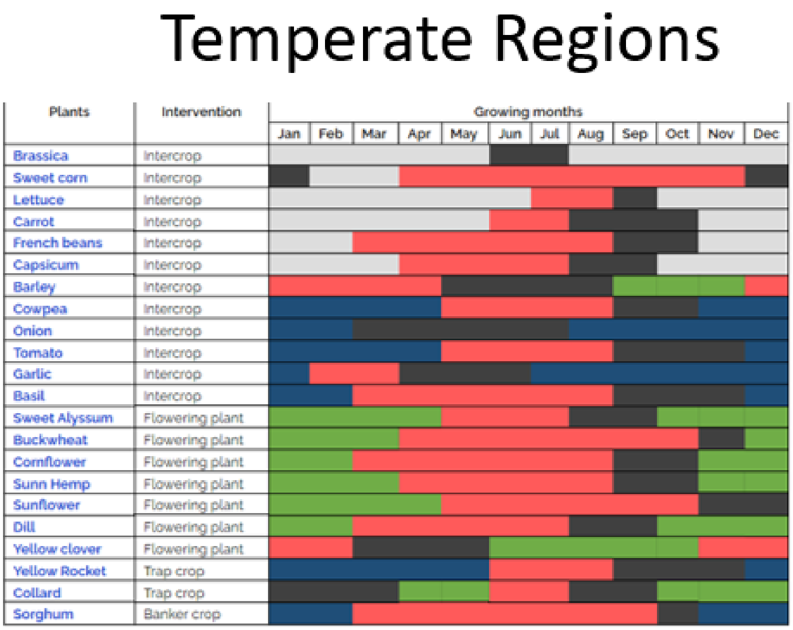
This on-farm work yielded encouraging results, but the scale of this work was constrained by drought and low water allocations to growers. It is recommended that flower strips be used by growers seeking to promote numbers of beneficials and that strips be planted approximately 30m apart. Only low numbers of pests were present on trial sites during the study, but the trends suggest that elevated numbers of beneficials had a suppressive effect on pest numbers. It is recommended that opportunities are identified to conduct more field trials to more completely test the potential of this approach.

8) Field trials of trap plants (yellow rocket) in brassica crops

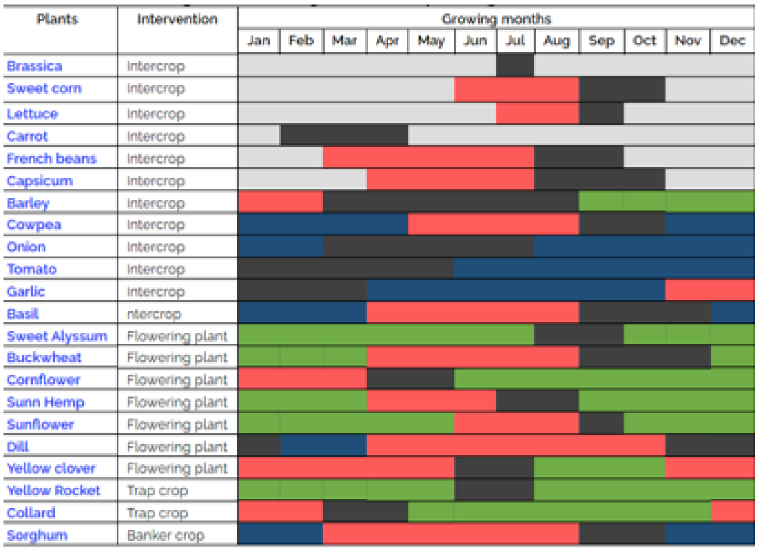
This on-farm work established that yellow rocket is difficult to establish from seed during drought years (that corresponded with this project). This method did, however, yield encouraging results on those sites where it was established with support from supplementary irrigation or by transplanting young plants rather than use of seed. It is recommended that opportunities are identified to conduct more field trials of this promising approach.

9) Region specific guidelines

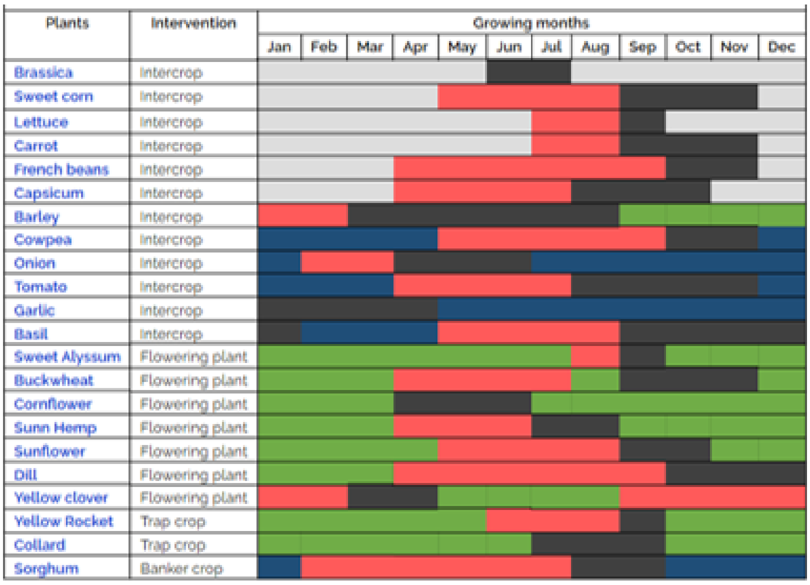
To assist growers in the selection and use of the various strategies mentioned in points 5 to 8 (above), a trio of charts has been compiled to cover arid, temperate and sub-tropical regions of Australia. Within each chart, the main phenological stages of key plant species are shown. Sowing period are shown for plants that have potential as flowering plant (nectar sources), as trap crops, and as banker or intercrops. Species selection for a given situation needs to be based on the growing period of each of these plant species in relation to the growing period of the vegetable crop.

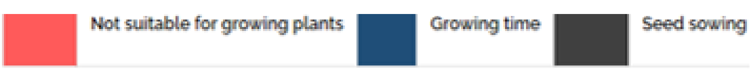


Sub-tropical regions



Arid Regions





Refereed scientific publications

Akter, S., Rizvi, S., Reynolds, O., Furlong, M., Melo, M.C., Mo, J., Munro, S., McDonald, S., Johnson, A.C., Gurr, G.M. Landscape context affects the scope for local-scale habitat management to mediate in-field pest and natural enemy densities. *Agronomy for Sustainable Development.* Submitted.

Akter, S., Rizvi, S., Haque, A., Reynolds, O., Furlong, M., Osborne, T., Melo, M.C., Mo, J., Munro, S., McDonald, S., Johnson, A.C., Gurr, G.M. Landscape context mediates the effects of local vegetation on in-field abundance of pests and natural enemies. *Journal of Applied Ecology* Submitted.

Johnson, AC, Liu, J., Reynolds, O.L., Furlong, M.J., Mo, J., Rizvi, S. and Gurr, G.M. Conservation biological control research is strongly uneven across trophic levels and economic measures. *Pest Management Science* Published: 06 November 2020 https://doi.org/10.1002/ps.6162.

Rizvi, S., Reynolds, O.L., Johnson, A.C., Haque, A., Furlong, M.J., Mo, J., Melo, M., Akter, S., Sandoval V. and Gurr, G.M. (2020) Prospects for habitat management to suppress vegetable pests in Australia. *Austral Entomology* (submitted).

References

Bianchi, FJJA, Walters, BJ, Cunningham, SA, Hemerik, L & Schellhorn, NA. 2017. Landscape-scale mass-action of spiders explains early-season immigration rates in crops. *Landscape Ecology* **32**, 1257-1267.

Bommarco, R, Kleijn, D & Potts, SG. 2013. Ecological intensification: harnessing ecosystem services for food security. *Trends in Ecology & Evolution* **28**, 230-238.

Ceballos, G, Ehrlich, PR & Raven, PH. 2020. Vertebrates on the brink as indicators of biological annihilation and the sixth mass extinction. *Proceedings of the National Academy of Sciences, USA* **117**, 201922686.

de Little, SC, Edwards, O, van Rooyen, AR, Weeks, A & Umina, PA. 2017. Discovery of metabolic resistance to neonicotinoids in green peach aphids (*Myzus persicae*) in Australia. *Pest Management Science* **73**, 1611-1617.

Downes, S, Kriticos, D, Parry, H, Paull, C, Schellhorn, N & Zalucki, MP. 2017. A perspective on management of *Helicoverpa armigera*: transgenic Bt cotton, IPM, and landscapes. *Pest Management Science* **73**, 485-492.

Eziah, VY, Rose, HA, Clift, AD & Mansfield, S. 2008. Susceptibility of four field populations of the diamondback moth *Plutella xylostella* L. (Lepidoptera: Yponomeutidae) to six insecticides in the Sydney region, New South Wales, Australia. *Australian Journal of Entomology* **47**, 355-360.

Garibaldi, LA, Perez-Mendez, N, Garratt, MPD, Gemmill-Herren, B, Miguez, FE & Dicks, LV. 2019. Policies for Ecological Intensification of Crop Production. *Trends in Ecology & Evolution* **34**, 282-286.

Grasswitz, TR. 2019. Integrated Pest Management (IPM) for Small-Scale Farms in Developed Economies: Challenges and Opportunities. *Insects* **10**.

Harvey, JA, Heinen, R, Armbrecht, I, et al. 2020. International scientists formulate a roadmap for insect conservation and recovery. *Nature Ecology & Evolution*.

Hauxwell, C. 2018. Pesticide bans might give us a buzz, but they won't necessarily save the bees. *The Conversation, February 6*.

Heimoana, V, Pilkington, LJ, Raman, A, et al. 2017. Integrating spatially explicit molecular and ecological methods to explore the significance of non-crop vegetation to predators of brassica pests. *Agriculture, Ecosystems & Environment* **239**, 12-19.

Herron, GA, Langfield, BJ, Tomlinson, TM & Mo, J. 2011. Dose-response testing of Australian populations of onion thrips *tabaci* Lindeman (Thysanoptera: Thripidae) further refines baseline data and detects methidathion and likely imidacloprid resistance. *Australian Journal of Entomology* **50**, 418-423.

Humphreys, AM, Govaerts, R, Ficinski, SZ, Nic Lughadha, E & Vorontsova, MS. 2019. Global dataset shows geography and life form predict modern plant extinction and rediscovery. *Nature Ecology & Evolution* **3**, 1043-1047.

Idris, AB & Grafius, E. 1996. Effects of Wild and Cultivated Host Plants on Oviposition, Survival, and Development of Diamondback Moth (Lepidoptera: Plutellidae) and Its Parasitoid *Diadegma insulare* (Hymenoptera: Ichneumonidae). *Environmental Entomology* **25**, 825-833.

IPBES. 2019. Nature's Dangerous Decline 'Unprecedented' Species Extinction Rates 'Accelerating'. Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services www.ipbes.net, Bonn, Germany.

Macfadyen, S, Hopkinson, J, Parry, H, et al. 2015. Early-season movement dynamics of phytophagous pest and natural enemies across a native vegetation-crop ecotone. *Agriculture, Ecosystems & Environment* **200**, 110-118.

Parry, HR, Macfadyen, S, Hopkinson, JE, et al. 2015. Plant composition modulates arthropod pest and predator abundance: Evidence for culling exotics and planting natives. *Basic and Applied Ecology* **16**, 531-543.

Pretty, J, Benton, TG, Bharucha, ZP, et al. 2018. Global assessment of agricultural system redesign for sustainable intensification. *Nature Sustainability* **1**, 441-446.

Rahman, MM, Baker, G, Powis, KJ, Roush, RT & Schmidt, O. 2010. Induction and Transmission of Tolerance to the Synthetic Pesticide Emamectin Benzoate in Field and Laboratory Populations of Diamondback Moth. *Journal of Economic Entomology* **103**, 1347-1354.

Renard, D & Tilman, D. 2019. National food production stabilized by crop diversity. *Nature* **571**, 257-260.

Sánchez-Bayo, F & Wyckhuys, KAG. 2019. Worldwide decline of the entomofauna: A review of its drivers. *Biological Conservation* **232**, 8-27.

Schellhorn, NA, Nyoike, TW & Liburd, OE. 2009. IPM programs in vegetable crops in Australia and USA: Current status and emerging trends. In: *Integrated Pest Management: Innovation-Development Process: Volume 1* (eds R Peshin & AK Dhawan) 575-597. Springer Dordrecht, Netherlands.

Schellhorn, NA, Parry, HR, Macfadyen, S, Wang, YM & Zalucki, MP. 2015. Connecting scales: Achieving in-field pest control from areawide and landscape ecology studies. *Insect Science* **22**, 35-51.

Seibold, S, Gossner, MM, Simons, NK, et al. 2019. Arthropod decline in grasslands and forests is associated with landscape-level drivers. *Nature* **574**, 671-674.

Thalavaisundaram, S, Herron, GA, Clift, AD & Rose, H. 2008. Pyrethroid resistance in *Frankliniella occidentalis* (Pergande) (Thysanoptera: Thripidae) and implications for its management in Australia. *Australian Journal of Entomology* **47**, 64-69.

Umina, PA, Edwards, O, Carson, P, Van Rooyen, A & Anderson, A. 2014. High levels of resistance to carbamate and pyrethroid chemicals widespread in Australian *Myzus persicae* (Hemiptera: Aphididae) populations. *Journal of Economic Entomology* **107**, 1626-1638.

Voconiq. 2020. Community trust in rural industries. A national survey. pp.27. Voconiq, Australia.

Weragoda, A, Frilay, J & Ashton, D. 2017. Australia vegetable-growing farms: An economic survey, 2015-16 and 2016-17. pp.51. Department of Agriculture and Water Resources, ABARES, Canberra.

Zalucki, MP, Furlong, MJ, Schellhorn, NA, Macfadyen, S & Davies, AP. 2015. Assessing the impact of natural enemies in agroecosystems: toward "real" IPM or in quest of the Holy Grail? *Insect Science* **22**, 1-5.

Intellectual property, commercialisation and confidentiality

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

Acknowledgements

This Charles Sturt University-led project would not have been possible but for the collaboration of Dr Olivia Reynolds (cesar), Associate Professor Mike Furlong (UQ), Jessica Page (IPM Technologies), and Dr Jianhua Mo, Mr Terry Osborne and Mr Scott Munro (NSWDPI). The landscape scale work was conducted by Mrs Salam Akter who was supported by Commonwealth Government scholarship. Her analyses were supported by Mr John Xie of CSU and the Spatial Analysis Network. We thank the members of the stakeholder reference group Brenda Kranz (Hort Innovation), Ashley Zamek (Hort Innovation), Callum Fletcher (AUSVEG), Jeff McSpedden (Bathurst NSW), Graeme Pitchford (Pitchford Produce, South Australia), Deon Gibson (Premium Fresh, Tasmania), Lynda Harding (Gingin Organics, Western Australia), Ant McConville (Queensland Fresh Exports Agronomy Services, Qld), Andrew Shaw (formally AUSVEG) and Lisa Brassington (formally AUSVEG) for guiding this project. We thank also the very many growers who participated in interviews, field surveys and field trials.

Appendix 1

1. Survey of vegetable fields and effects of adjacent land uses

Study Sites:

A total of 491 vegetable fields of six vegetable crops were surveyed from 115 commercial farms of *Brassica* spp. (Brassicaceae), sweetcorn (*Zea mays* L.) (Poaceae), lettuce (*Lactuca sativa* L.) (Asteraceae), carrot (*Daucus carota* L.) (Apiaceae), French bean (*Phaseolus vulgaris* L.) (Fabaceae) and capsicum (*Capsicum annuum* L.) (Solanaceae) (Table 1). Farms were selected from the vegetable growing regions in all states of Australia and field surveys were conducted from February 2018 to February 2019 (Fig. 1). The field survey involved farms growing at least one of our focal crops in the study area. The names of farms and their contacts were obtained from the local grower's agencies/associations, located in each region. The selection of the farms was irrespective of their applied pest management strategies, but the information of their pest management was noted and applied in the analyses. All farmers were first contacted on the phone. Farmers interested in further discussion were selected for an on-farm meeting and general information on the farm management methods, pest management techniques, habitat management approaches, number of cultivated crops, soil fertilizers, were noted. If farmer allowed, field survey was conducted.

Selection and classification of adjacent land-uses:

The land use adjacent to each field was visually identified and recorded. These were classified as cropland (with the name of the crop), woody vegetation (shelterbelts, riparian vegetation), pastures (often dominated by lucerne (*Medicago sativa*) but also including cultivated or uncultivated grasses), weed, and water bodies (dam) (Table 2). These classifications were to keep consistency throughout the study. The number of adjacent land-use types determined the number of sampling sites in each field. The length of the crop boundary adjacent to each land-use type was approximately determined and partitioned into 3 sections and only the centre section considered the sampling zone to avoid edge effects of other land-uses. On each sampling site, a total of 10 plants at 2 m away from the crop edge and at a roughly equidistant spacing were randomly selected. If a focal crop was adjacent to two similar types of land uses, then only one of that was counted. A total of 10 plants from the centre of each field were also selected, which served as a control (Fig. 2).

Data collection:

All surveys were non-destructive in nature and conducted on sunny days between 10.00 and 16.00 hours. All sides of leaves, stems, flowers and fruits of each plants were hand-searched for the presence of any arthropods (pests and beneficial). Arthropods were identified *in situ* based on visual observation up to the order/family/genus level, depending upon the type of arthropods.

All arthropods were counted visually in the field and recorded as a point count data except the population densities of aphids and aphid-mummies (parasitized aphids) which can be too numerous to count, were given a ranking as follows: aphids (0 = absent, 1 = a few scattered individuals, 2 = a few isolated small colonies, 3 = several small isolated colonies, 4 = large isolated colonies, 5 = large continuous colonies) and for aphid mummies (0 = absent; 1 = less than 10, 2 = less than 25, 3 = less than 50, 4 = more than 50). Most fields were only surveyed once, however some fields were revisited in next growing season.

Statistical analysis:

The Shapiro–Wilk test (Shapiro & Wilk, 1965; Razali & Yap, 2011), numerical approaches (skewness and kurtosis indices), and the normal Q-Q plot-based graphical method were used to check the normality of the data, and found that the distribution of arthropods are not following the normal distribution so data were analysed using generalized linear model (GLM) with a negative binomial distribution with log link function. Distribution of aphid and aphid-mummies were in ordinal numbers so analysed using ordinal regression. Pest management approach (conventional/biological), season of the sampling, climatic zones, and adjacent land-uses were used as a factors in the analyses.

The effects of adjacent land-uses on the abundance of arthropods were measured by comparing the arthropod abundance in the crop margin adjacent to each type land uses (sum of arthropod counted over 10 plants) with the abundance in the centre of the same field. The comparison between margins with the respective centre on the abundance of arthropods indicated the effect of land-uses adjacent that respective margin. This analysis was conducted for all vegetable fields and arthropod taxon to test the hypothesis that arthropods' numbers were influenced by the adjacent land-uses and should be inconsistent between field centres and edges adjacent to different land-uses. In order to strengthen the analysis, any adjacent land-use observed less than 5 times in any of the focal crop, was discarded from the analysis (Table 2). All statistical analyses were carried out with IBM SPSS Statistics v.25 (IBM, Armonk, NY, USA).

2. Farmer Interviews

Study areas

The study concentrated on the primary vegetable growing regions of New South Wales, Queensland, South Australia, Tasmania, Victoria and Western Australia. Accordingly, growers in the Sydney Basin, central- west and south-west of New South Wales; the south-western and north-western areas of Western Australia; Melbourne, Victoria, south-eastern Queensland, Adelaide basin, South Australia and Tasmania were interviewed between February 2018 and January 2019. Focal crops represented a wide range of the most economically important vegetable crops grown from cool temperate to sub-tropical regions and contrasting botanical families: Brassica spp. vegetables (Brassicaceae), sweetcorn (Zea mays L.) (Poaceae), lettuce (Lactuca sativa L.) (Asteraceae), beans (Phaseolus vulgaris L.) (Fabaceae), capsicum (Capsicum annuum L.) (Solanaceae) and carrot (Daucus carota L.) (Apiaceae).

Interviews

Initial participants identified via professional networks. The interviewers then used snowball sampling (Given, 2008) where contact information for other growers was provided by the participants. Interviews were carried out in the farm office or in the field. It was recognised that the timing to meeting in person on farm was not always convenient for growers, so if necessary, a time was arranged for interviews to be conducted by phone. The average time taken for an interview was 30 minutes. All interviews were voluntary, and participants were provided with written documentation which included the project objectives and ethics approval prior to the or during the initial farm visit.

The interviews were semi-structured, using a set of open response questions. The interview was not recorded but answers were noted by the interviewer on a prepared answer sheet which listed some of the anticipated answers such as crop types and common practices to speed up recording as well as open boxes to record additional responses and major points made in discussions. Answers by the growers including on pesticide use were taken at face value, we did not ask to examine grower records or sheds to verify responses. Whilst some specific products were named by growers, we also relied on their description of the pesticides they used as broad-spectrum or selective. Growers were asked about to use of 'habitat management' rather than the use of the more technical term 'conservation biological control'.

Analysis

Following the initial survey, due to the broad range of responses and sample size we categorised some responses by crop types, pest types, pesticide types and markets. Crops grown were grouped by plant family due to similarities in management and pest complexes, for example, cabbage and broccoli in Brassicaceae, peas (*Pisum sativum*) and bean for Fabaceae, carrot and celery in Apiaceae, eggplant, tomato and capsicum in Solanaceae (except for potato which was kept separate), onion, leek and garlic as Allium spp. and melons and pumpkin in Cucurbitaceae. Other crop types were kept separate due to their differences in management and pest complex.

Due to the grower tendency to refer to aphids without distinguishing species, aphids were also grouped as one taxon even though species present in Australia exhibit contrasting levels of host range and specificity. Major aphid pests of vegetable crops in Australia include green peach aphid (*Myzus. persicae*), cabbage aphid (*Brevicoryne brassicae* L.), corn aphid (*Rhopalosiphum maidis* F.), currant lettuce aphid (*Nasonovia ribisnigri* Mosley) and willow carrot aphid (*Cavariella aegopodii* Scop.).

3. Field trials of in-crop strips and associated cost: benefit analysis.

Flowering strips

Study sites

Work was conducted from November 2019 to February 2020 in twelve brassica fields from six commercial vegetable farms, located in multiple states of Australia representing a wide range of climatic zones (Figure A1.1). All farms were conventionally managed and characterized by clay soils and intensive farming practices.

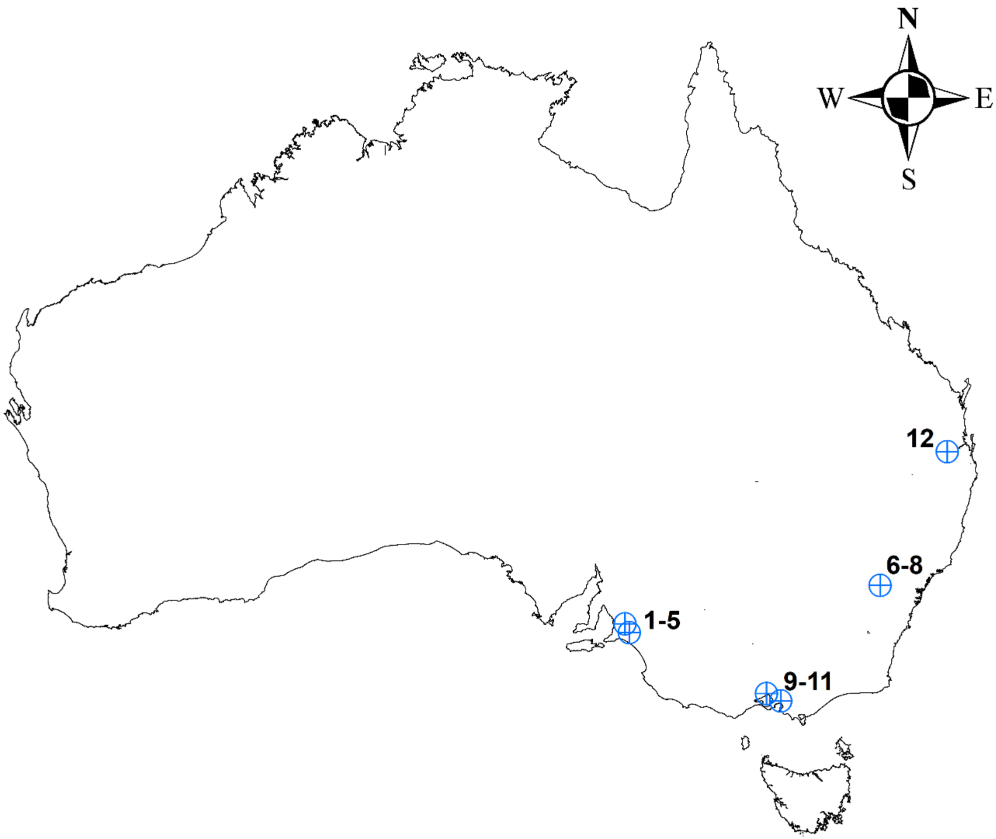


Figure A1.1. Location of the fields in four States in Australia. Numbers indicating the identity of individual sites. The map was created in ArcGIS 10.6 (ESRI, 2017).

Experimental design

Number of fields on each farm were depended upon the availability of the space and farmers' permission but each field was at least 500m away from other fields. Each site consisted of two plots: (1) a brassica area adjacent to a flowering strip (treatment plot), and (2) a brassica area adjacent to a fallow strip (control plot). Treatment and control plots were separated with a 15 m buffer zone. Treatment strips were a raised soil bed (1.3m x 24m x 0.3m; W x L x H) along the length of a randomly selected section of brassica field. The treatment plot was divided into 24 equal-sized subplots, each with one of one of the flowering plant species (sweet alyssum, buckwheat and cornflower) in a randomized fashion (Figure A1.2). Seeds of flowering plant species were sown manually, approximately 15 days earlier than planting of brassica crops. Control plots were left with a fallow raised soil bed (1.3m x 24m x 0.3m; W x L x H) along the length of the selected brassica field. The control of weeds was conducted manually.

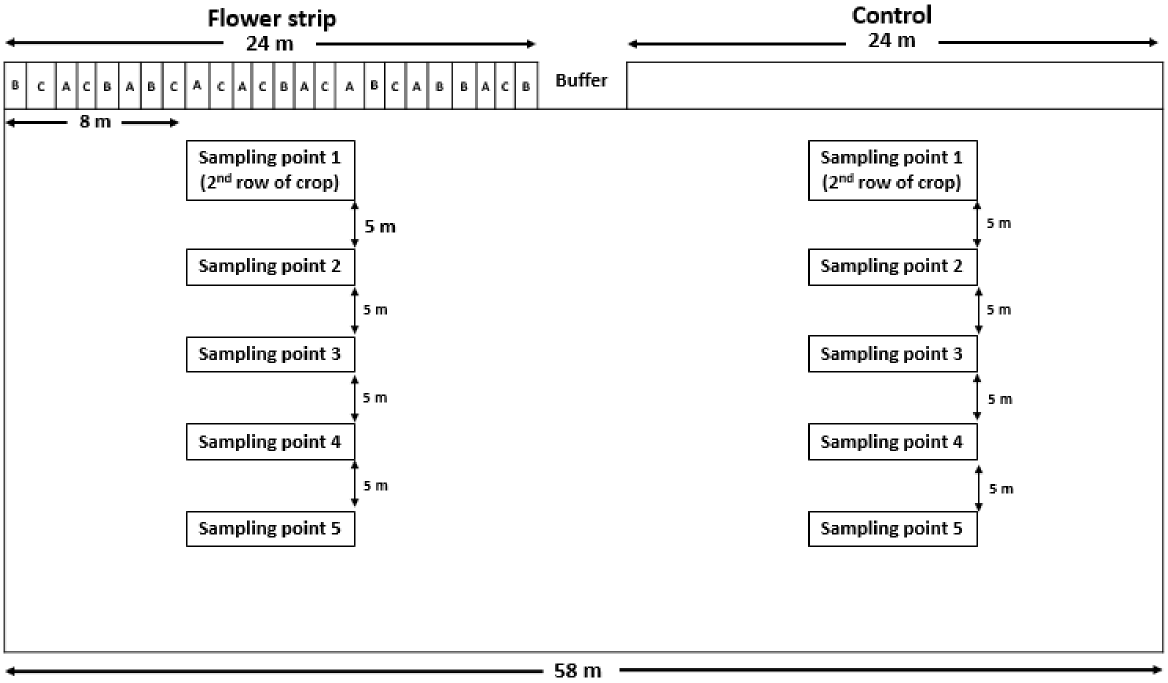


Figure A1.2. Layout of field trial used on each of the 12 sites. A = Alyssum, B = Buckwheat, C = Cornflower.

Assessment of arthropod abundance

Direct counts

Sampling started around 45 days after sowing seeds of flowering plant species when all flowering plants were blooming. To determine the spatial effect of flowering strips on arthropod density and plant damage, we assessed brassica plants at five sampling points along a transect running away from the centre of flower strips or control into the field. The first sampling point was in the centre of the first crop row of the treatment or control plot. An additional four sampling points were used at 5m intervals extending a total of 30m into the crop. At each sampling point, 10 brassica crop plants were randomly selected within the row and a visual search was carried out for arthropods (pests and natural enemies). The assessment was conducted fortnightly and repeated three times.

Assessment of parasitism

Larval parasitism of *P. xylostella* was assessed using infested sentinel potted plants arranged in similar fashion in both treatment and control plots. Three pots containing single Brussel sprout plants (1.5-month-old) infested with 30 settled 2nd-3rd instar P. xylostella larvae from the laboratory colony were placed in the same position where sampling points for direct counts were marked. Each potted plant was placed in a green bucket (9 L) half filled with water to keep the plant hydrated and to prevent the fallen larvae from moving into the field. We also confirmed that the farmer's insecticide schedule should not coincide with the duration of our sentinel plant experiment. After 3 days, larvae were recovered from the potted plants and reared separately in a plastic jar (D = 6.7 cm, H = 7.5cm), covered with fine net cloth for aeration. Brussel sprout leaves were provided twice a day during larval growth and monitored subsequently until the emergence of a parasitoid or adult *P. xylostella*.

Assessment of crop damage

Crop damage was assessed in both treatment and control plots by counting the feeding damaged (due to insect chewing and undamaged head of the brassica crop. The assessment was conducted after 60 days after transplanting the brassica crops when the edible part of the brassica crop (head) was formed and developed. At each assessment, 10 plants were randomly selected from each sampling point and checked for any insect damage/hole by visual observation. Any hole or feeding damage on the head (edible part) led the plant to being categorised as non-marketable. Damage to the outer leaves of cabbages and cauliflowers, which are routinely trimmed and discarded, were not considered grounds for non-marketability. Equivalent assessment was conducted for the control plot sampling positions. These data were used in the benefit: cost analysis (see below).

Attractiveness of individual flower species

Arthropod assemblage on flowering strips were assessed for by mounting non-attractive (transparent) sticky traps in the middle of flowering strip sub plots. Clear sticky traps (measuring 21.0cm x 29.7cm) were prepared in the laboratory using clear 200 Micron lamination paper and coated with Tanglefoot (Brushable Tanglefoot Company®, Grand Rapids, MI 49504, USA). The traps were stapled vertically on one end of 1m long wooden stakes using staple gun or using transparent push pins. The mounted sticky traps were placed in each of the 24 subplots of flowering strips. Traps were in place for 72 h prior to retrieval and then placed in resealable sandwich bags (33cm x 38cm). The sealed bags with sticky traps were labelled and carried to the laboratory for counting and identification of arthropods. New traps were deployed every fortnightly and repeated three times. Each sticky trap was inspected in its entirety and if a trap was heavily covered arthropods then traps were divided into four grids and arthropods from a randomly selected grid were identified and counted. All arthropods (pests and beneficials), except bush flies and mosquitos, were identified and counted.

Data analysis

The Shapiro–Wilk test (Shapiro & Wilk, 1965; Razali & Yap, 2011), numerical approaches (skewness and kurtosis indices), and the normal Q-Q plot-based graphical method were used to check the normality of the data, and found that arthropod abundance data did not follow a normal distribution so data were analysed using generalized linear mix model (GLMM) with a negative binomial distribution with log link function. A Kruskall–Wallis ANOVA was used to analyse the arthropod assemblage on flowering plants. All statistical analyses were carried out with IBM SPSS Statistics v.24 (IBM, Armonk, NY, USA). An a priori a = 0.05 was employed for each statistical test.

Benefit: cost analysis

The benefit-cost analysis was performed using crop damage assessment data captured from the both treatment and control plots. The benefit: cost analysis considered the seed costs that applied during purchase of seeds for the establishment of flowering plants in the intervention. The analysis also reflected a labour cost for establishing the flowering plant borders. Other inputs such as, insecticide spray and the labour costs for spraying insecticides were not included as these were consistent across treatment and control plots. As in most other economic studies of pesticide use, externalities such as the potential impact of insecticides on the environment and human health were not included. Cost of brassica head was valued at farm gate prices. All values are estimated and represented in Australian dollar. No reduction in costs has been included for reduced need for insecticide purchase and associated labour. It is likely that such reductions would apply in practice because habitat management did lead to measurable benefits in terms of (i) increased natural enemies (ii) reduced pests and (iii) reduced crop loss. Only direct costs and benefits are modelled whereas, the wider effects, such as reduced resistance in pest populations, environmental impact, and human health and safety are not costed but are likely to be significant in the medium to long term.

Important assumptions made in the analysis were:

1) Seed costs are those that applied during purchase of seeds for the establishment of the trials. Under possible future wide use of these plants for habitat manipulation in Australia, costs would be substantially lower for bulk purchases and if increased demand led to more production of alyssum and cornflower which are currently ornamental plants.

2) No reduction in costs has been included for reduced need for insecticide purchase and associated labour. It is likely that such reductions would apply in practice because habitat management did lead to measurable benefits in terms of (i) increased natural enemies (ii) reduced pests and (iii) reduced crop loss.

3) Only direct costs and benefits are modelled. Wider effects, such as reduced resistance in pest populations, environmental impact, and human health and safety are not costed but are likely to be significant in the medium to long term.

Benefits of habitat manipulation ranged from $54 (cabbage) to $91 (Brussels sprouts) based on a 500 m2 production unit (Table 1).

4. Analysis of the influence of landscape.

This work used data from the trials of flowering strips in brassica fields (described above).

A Dynamic Land Cover Dataset (DLCD) obtained from Lymburner et al. (2010) was used in ArcGIS 10.6 (ESRI, 2017) to measure the landscape properties at the spatial scales of 250 m, 500 m, 1000 m, 2500 m, and 5000 m radii from each field. Land uses were classified as cropland, woody vegetation (trees, shelterbelts, riparian regions, and shrubs), pastures, or water bodies. Landscape composition is the percentage of the land-use types at each spatial scale and assessed by using the spatially specific proportional area approach (Schmidt, Thies, Nentwig, & Tscharntke, 2008). Edge density is the ratio of the length of one land-use type and the total landscape area at a given spatial scale, and was assessed in metre per hectare (Bloomfield, McIntosh, & Lambin, 2020) for each land-use type at each spatial scale. Landscape connectivity of land-uses was measured using a cost-distance analysis similar to Perović et al. (2010). The cost-distance analysis involves assigning different costs or resistant values, which generated comparative cost-ratios (Chardon, Adriaensen, & Matthysen, 2003), to the land-uses within a spatial scale to measure the connectivity or hindrance that a species may face when assembling the destination (focal crop field) from a source within the spatial scale. Ten different sets of cost-ratios (Table A1.1) were used in the 'cost-distance' tool in ArcGIS 10.6. Two metrics of 'cost-distance' analysis were used for further statistical analysis. The summation of costs of all cells in the cost raster (digitized image layer) of a spatial scale represents the 'cost-area' metric. The cost-area for each spatial scale indicates the overall connectivity of that scale. Another metric was the cost-path, represents the path which taken the lowest cumulative cost to reach the crop field (destination) from the source within a spatial scale.

Table. A1.1 Assigned cost-ratios used in the cost-distance analysis. Favourable land-uses have the lowest cost (1) and unfavourable land-uses the highest cost (100) for a taxon to arrive at a focal field from a source in the landscape.

Land-use types	Cost-ratios									
	r1	r2	r3	r4	r5	r6	r7	r8	r9	r10
Water bodies	4	4	20	20	20	1	1	1	100	100
Croplands	2	4	10	20	10	1	1	1	1	100
Pastures	1	1	2	2	1	2	2	100	10	4
Woody vegetation	1	1	1	1	1	4	2	20	20	1

Statistical analyses:

The effects of landscape properties and two-way interactions between landscape properties and local habitat management with flowering strips and without flowering strips (control treatment) on arthropod abundance within focal crop fields were assessed. The number of arthropods recorded on the brassica plants within the field areas with flower strips compared to without flower strips was regressed with landscape variables at each of the five spatial scales using generalized linear mixed models (GLMM) with negative binomial distribution and field identity as a random factor in R version 3.5.2 and package 'lme4'. Arthropod data were square-root transformed to achieve normality before fitting in models (Baillod et al., 2017). Five different models were run for each arthropod taxon as well as for total pests and total natural enemies. The models were ranked based on the Akaike information criterion (AIC) to select the final model that generated the lowest AIC value. The level of significance and test statistics were calculated using type-III ANOVA of the final regression models. This statistical analysis was to investigate the hypothesis that the extent to which local habitat management with non-crop flowering plants influenced the in-field abundance of pests and natural enemies depend on the landscape properties.

Similarly, the abundance of arthropods at each sampling position (i.e. summation of abundance of arthropods counted on 20 plants at corresponding sampling points through the flowering half and control half) was regressed with landscape variables at each spatial scale and interaction of landscape variables with local interventions, using GLMM with negative binomial distribution and field identity as a random factor. This analysis was to examine the effect of landscape properties at each spatial scale on the distribution of pests and natural enemies at different sampling positions keeping the effect of local interventions aside. Furthermore, vertical sampling positions in figure 2 through flowering and control halves were analysed separately against landscape properties and interaction with local interventions following a similar analysis procedure. This statistical analysis was to investigate the distribution of pest and natural enemy arthropods within crop fields in relation to local and landscape properties. This analysis was performed using data captured from the brassica vegetable field trials conducted in 2020.

Appendix 2: Interim Project Report February 2020

Summary

Work in the final phase of the project has focused on trials of field management methods in brassica vegetables and sweetcorn, together with extension and communication activities. Brassica field trials have been conducted over the last six months in NSW (Bathurst), SA (Mount Barker and Langhorne Creek), Vic (Devon Meadows and Werribee South) and Qld (Lockyer Valley) (Table A2.1). Reflecting the seasonality of crop production, data capture from these trials has very recently been completed for 15 of the 16 trials. The final trial will run until March 2020. Preliminary analyses, of the effects on arthropods (pests and natural enemies) have been completed for the earliest trials and have yielded promising results (see below). A definitive analysis that combines all site data will be completed in coming weeks. Economic benefits of habitat manipulation involving flowering strips in a range of brassica vegetable crop species ranged from $54 (cabbage) to $91 (cauliflower) based on a 500 m^2 production unit. Three scenarios were modelled to reflect the costs for placement of flowering strips in differing areas. If these occupy land that otherwise would be used for brassica production, the foregone yield leads to negative economic impacts with benefit: cost ratios between 0.38:1 and 0.58:1.

In cases where habitat manipulation strategies have proven popular overseas (e.g. African maize, Asian rice), the strips or equivalent features are placed in the borders of crops or established as a groundcover so do not lead to a reduction in primary crop production area. Under this more realistic scenario, benefit: cost ratios are favourable, extending from 1: 2.7 to 1: 4.6 and are still more favourable under a scenario in which strips are within sprinkler rows (1: 3.6 – 1: 6.2). Field trials in sweetcorn were comprehensively planned but did not go ahead in NSW as the widespread drought led no water allocation, therefore growers were unable to plant sweetcorn crops. Reflecting the seasonality of crop production, planned sweetcorn trials in Queensland will commence in March, where growers have sufficient water. We anticipate being able to complete the program of work with this second crop by the end of the project, though it will be confined to Queensland sites as the next production season for NSW (summer 2020-21) is after project completion.

An exceptionally high level of media interest and exposure has been generated by the project. Preliminary results and a more general update on project progress have been reported in articles in the *Western Advocate* and *The Mount Barker Courier* (Appendix 1), Prime TV and Channel 9 News, and news releases. ABC TV Landline media team filmed the field trial in Devon Meadows (Vic) with Geoff Gurr, Olivia Reynolds and Syed Rizvi on 18-02-2020, with laboratory vision and further interviews conducted at **cesar**, Melbourne with Olivia Reynolds on 21-02-2020. The story is due to be screened on 03-05-2020). An ABC Rural interview was recorded with Tim Fookes with a broadcast date TBA.

Grower demonstration days have been held in Bathurst, NSW (28-01-2020) and in Hay Valley, SA (13-02-2020) both of which were covered by the respective local media. Project updates presentations were given at the VegNET R&D Field Day, SA (23-10-2019), VegNET Native Veg Insectarium Event, Vic (23-10-2019) and the VegNET Bundaberg Fruit & Vegetable Growers Workshop on 'Biosecurity and Beneficials' (O. Reynolds; 18-02-2020). In Queensland, project updates have been presented to the Lockyer Valley Growers Association (03-02-20) and an expanded presentation will be given at the group's next scheduled meeting (18-03-20).

Following feedback from the previous milestone report, field survey data (from the initial phase of the project) was reanalyzed using a different statistical approach (Bayesian Network analysis) and this provided a high level of verification of the findings from the original analysis (Generalised Linear Model analysis).

A research master student (funded by other sources; supervised by G. Gurr & O. Reynolds) recruited to join the project has undergone her research proposal defense and is now pursuing her plan to examine the extent to which landscape-scale effects such as the proportion of woody vegetation in the landscape affect the success of field-scale interventions.

Table A2.1. Completed and ongoing field trials.

Crop	Location	Treatments	Completed trials	Total trials
Brassica	Victoria	Flowering plants	3	4
	New South Wales	Flowering plants	3	3
	South Australia	Flowering plants	5	5
	Queensland	Flowering plants	1	1
	Queensland	Trap crop	1	1
	Victoria	Trap crop	2	2
Sweet corn	Queensland	Flowering plants	-	6

Public summary

Pressure is mounting to reduce reliance on insecticide spraying to control vegetable pests. Consumer preferences, changes in maximum residue limits in export markets, the reduced availability of insecticide products as a result of registration restrictions, and pests becoming resistant to frequently used compounds are all drivers for change. A project initiated by Hort Innovation aims to help vegetable growers rise to this challenge by developing ecological approaches to boost beneficial insects and check pest build-up. The team led by Prof Geoff Gurr of the Graham Centre for Agricultural Innovation at Charles Sturt University is determined to help growers by developing methods that are simple to implement and maintain, compatible with mainstream farming operations and can help drive down input costs.

During the first phase of the project the team found land use adjacent to the crop strongly influences the number of pests and beneficial insects in the crop. Features like shelterbelts and riparian vegetation enhanced the densities of beneficial insects in nearby areas of crops and tended to reduce pest numbers.

During the second phase, field trials in NSW, Vic, SA, and Qld are testing a range of habitat management strategies that can be adopted by farmers for field-scale interventions to suppress pests. In this way they provide the types of resources available in shelterbelts (e.g. nectar, pollen, shelter, alternative prey) but offer the advantages of taking up less space, ease of establishment, and immediacy of effect. The strategies being evaluated were selected based on the results from the initial field survey, farmer interviews, an extensive literature review, and availability and practicality of plants. The habitat management plants identified for trials were sweet alyssum, buckwheat and cornflower. These plants provide the floral resources to attract and support beneficial insects to control a diverse group of insect pests in brassica vegetable and sweet corn crops. Yellow rocket was identified as a potential trap crop for diamondback moth in brassica vegetable crops. At this stage, most of our brassica field trials have been completed and, as well as yielding promising preliminary results, have enabled the team to work closely with farmers to examine the practicalities of establishing habitat manipulation plants in commercial crops. Farm walks for growers, conducted on trial sites, generated a lot of interest and were covered by and reported in local media.

A preliminary analysis shows a significantly higher numbers of beneficial arthropods including ladybeetles, lacewings, red and blue beetles, parasitic wasps and damsel bugs on the flowering strips and in the brassica vegetable crops near the flowering plants which, in turn, significantly reduced the pests. This effect can be measured up to 15 meters from the flowering plants into the crop. Crop inspections revealed lower levels of crop damage, reflected in fewer heads rejected. Resulting benefits of habitat manipulation ranged from $54 (in cabbage) to $91 (in cauliflower) based on a 500 m^2 production unit. Assuming that habitat manipulation strips are placed in the borders of crops or sprinkler rows (so do not lead to a reduction in primary crop production area), benefit: cost ratios are highly favourable, extending from 4.6:1 to 7.9:1. Full analysis of the field trials and recommendations of potential habitat management strategies in the form of guidelines (to include benefit: cost analyses) will be completed by mid-2020.

Achievements

i) Conducted on-farm field trials in brassica vegetables NSW, Vic, SA, and Qld to test a set of habitat management strategies, i.e. flowering strips and trap crops. 15 of 16 trials completed.

ii) Sweetcorn trials planned in Queensland for Q1 and Q2 2020.

iii) A preliminary analysis on the field trials data completed and economic data captured.

iv) Grower demonstration days held in NSW and SA.

v) Print and electronic media output in NSW, Victoria and SA.

vi) Project updates have been presented in three VegNET grower-focused events.

vii) Field trials to be featured in an upcoming episode of Landline on ABC TV.

viii) Re-analysis of field survey data using Bayesian network methods completed, verifying earlier GLM analysis results.

Outputs

Diverse suite of **communication and dissemination materials** and events across a range of media platforms.

Western Advocate Online 2 Feb (https://www.westernadvocate.com.au/story/6603930/instead-of-pesticides-trial-looks-at-getting-insects-on-side)

Western Advocate Print 3 February (appended)

Mount Barker Courier 12 February (appended)

ABC Rural interview recorded with Tim Fookes- broadcast date TBA

Prime News Central West NSW (https://www.facebook.com/PRIME7NewsCentralWest/videos/1023414281354918)

9 News Central West NSW (https://www.facebook.com/9NewsCentralWest/videos/865708273866853)

ABC Landline Broadcast date TBA (probably 3 May).

VegNET grower workshop presentations by project staff in NSW, SA and Qld.

cesar DoorStep Science You Tube Video: https://www.youtube.com/watch?v=BgG42LKONno

Body of data of unmatched size generated on the effects of field-scale management options to suppress pests in brassica vegetables. When analyses are complete this will yield guidelines and management strategies for growers across wide parts of Australia.

Landscape-scale vegetation data integrated with field-scale arthropod data, providing a groundbreaking understanding of these important interactions.

Reanalysis of field survey data completed using Bayesian Network; providing verification of earlier conclusions. This will allow publication in a strong journal.

Outcomes

In accordance with the M&E Plan, we have completed our foundational activities. The key outcomes at this stage are (i) an enhanced level of understanding within industry of the scope for habitat manipulation approaches to be adopted in Australian vegetable systems and (ii) and enhanced evidence base and level of technical knowledge to serve as a platform for the development and promotion of habitat management methods to suppress pests and reduce reliance on insecticides.

Intellectual property

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

Issues and risks

The drought prevented sweetcorn trials planned for NSW but those planned for Queensland will go ahead.

List of Interim Project Report Appendices

A2.1. Two articles published in *Western Advocate* and *Mount Barker Courier*. (not reproduced because of copyright restrictions)

A2.2 Benefit: cost analysis report

A2.3 Information sheet for farmer field walks

A2.4 Posters for farmer field walks

A2.5 Reanalysis of field survey data.

Appendix 2.1

Two articles published in Western Advocate and Mount Barker Courier. (not reproduced because of copyright restrictions)

Appendix 2.2:

(not reproduced because of copyright restrictions)

Appendix 2.3: Information sheet for farmer field walks

Appendix 2.4: Information presented at farmer field walks

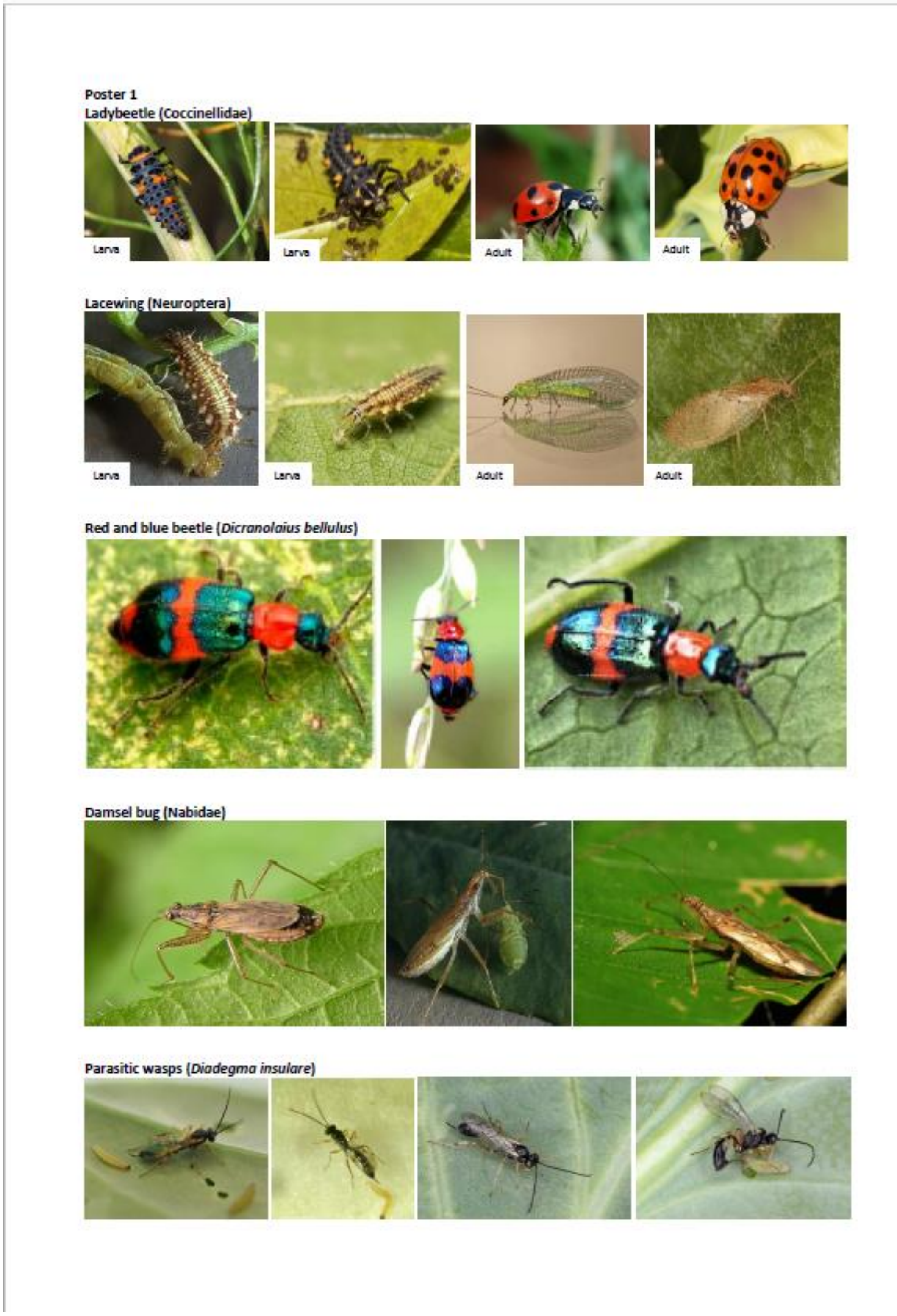


Figure A2.1 Insect identification poster.

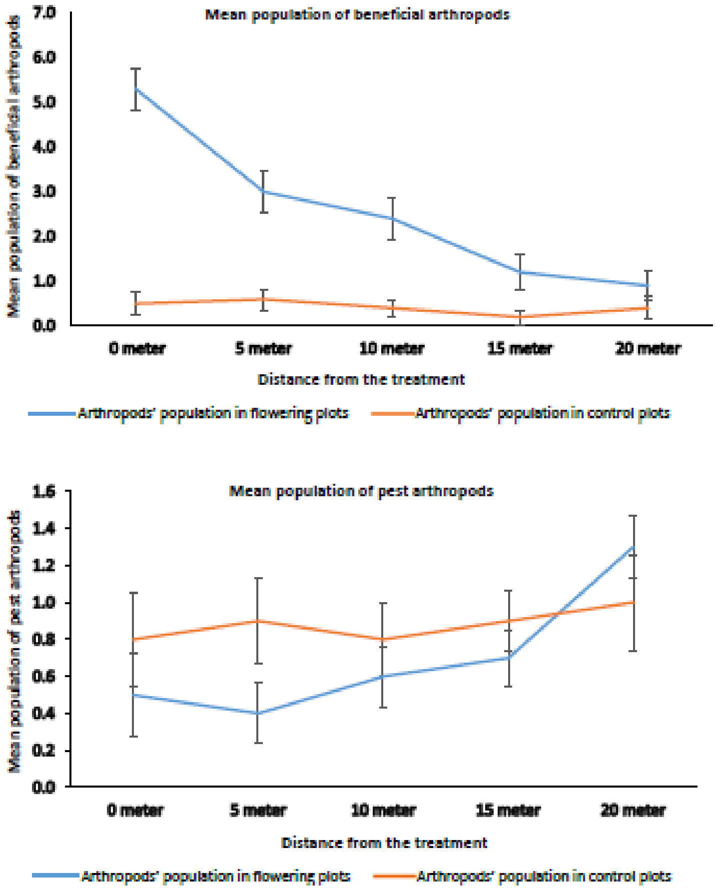


Figure A2.2 Preliminary results handout.

Height: 20-30 cm
Germination: 10-15 days, flowering: 4-5 weeks after germination
Sowing depth: Surface Sow
Blooming period: Year round in frost-free climates
Seeding rate: 1-1.5kg/hectare price: AU$ 500/kg
Cost of 1x8 meter² strips: AU$1.0
Very low maintenance and not known to attract any brassica pests

Height: 75-125 cm
Germination: 10-15 days, flowering: 4-5 weeks after germination
Sowing depth: 2-3 cm deep in soil
Blooming period: spring, summer, autumn
Seeding rate: 20-25 kg/hectare, price: AU$ 6/kg
Cost of 1x8 meter² strips: AU$ 0.20
Very low maintenance and not known to attract any brassica pests

Height: 50-75 cm
Germination: 10-15 days, flowering: 6-5 weeks after germination
Sowing depth: Surface Sow
Blooming period: spring, summer, autumn
Seeding rate: 2-3 kg/hectare price: AU$ 80/kg
Cost of 1x8 meter² strips: AU$ 0.40
Very low maintenance and not known to attract any brassica pests

Figure A2.3 Information on flowering plants

Appendix 2.5 Reanalysis of field survey data presented in interim final report

Field and landscape management to support beneficial arthropods for IPM on vegetable farms

Summary

Populations of beneficial arthropods in vegetable crops are strongly affected by what is growing around the crop. Numbers of pests and beneficials are noticeably varied within the crop; but the survey of 491 vegetable crops which compared pest and beneficial numbers with the composition and use of the area around the crop found distinct patterns. The survey covered six crop types, sweet corn, lettuce, bean, capsicum, carrot and brassica vegetables over 12 months from February 2018 to January 2019 depending on when the crops were growing. The farms surveyed were in New South Wales (NSW), Tasmania (Tas), Victoria (Vic), South Australia (SA) and Queensland (Qld) and included all management types such as, certified organic and integrated pest management that uses a mixture of biological and synthetic insecticides.

Two contrasting of statistical approaches, Bayesian Network (BN) analysis and a more traditional generalised linear model (GLM) analysis were in broad agreement for the key findings. Non-crop vegetation adjacent to crops in the form of riparian strips and shelterbelts tend to be associated with higher numbers of beneficial insects and spiders, and a lower numbers of pests, in the adjacent edges of vegetable fields. Field centres, in contrast, had more pests and fewer beneficials, suggesting that (i) riparian vegetation and shelterbelts are donor habitat for beneficials and that this was associated with natural pest suppression and (ii) the spatial scale at which vegetation affects in-crop pest and beneficial densities is small, at least for many key taxa.

Densities of pests and enemies were strongly affected by other variables including location, crop type and, especially, pesticide use. Notably, pests were no more numerous in fields where only biological insecticide types such as *Bacillus thuringiensis* (Bt) or Nuclear Polyhedrosis Virus (NPV) were used than in fields where synthetic insecticides were used. This suggests that beneficials can adequately check pest outbreaks if present in sufficiently large numbers by virtue of the presence of suitable non-crop vegetation.

Method

Field survey of pests and beneficials

Fields of sweet corn, capsicum, beans, lettuce, carrot and various brassica vegetables and were surveyed from February 2018 to January 2019 across vegetable producing areas in the Sydney Basin, Central West and South-west of New South Wales; the South-western and North-western areas of Western Australia; south-east and west Melbourne, Victoria, south-eastern Queensland, Adelaide basin, South Australia and north-eastern Tasmania. Fields selected were as minimum area of 20 m^2. For each field, additional data collected included cultivar, planting date and recent pest management practices. The number and types adjacent land-use to each field border was visually identified and categorised.

Sampling protocol

To determine the effects of adjacent land-uses on the arthropod community in vegetable crops, fields were surveyed along each edge adjoining each land-use type and also in the field centre. A common protocol was followed in all vegetable fields. A field typically has 2-6 adjacent land-use types; therefore the number of adjacent land-use types determined the number of sampling sites in each field. The length of the crop boundary adjacent to each land-use type was approximately determined and partitioned into 3 sections and only the centre section considered the sampling zone to avoid edge effects of other land-uses. Within each sampling zone a total of 10 plants between one and two metres from the crop edge and at a roughly equidistant spacing within the sampling zone were visually inspected for arthropods. The centre of the field was approximately determined and 10 plants with a similar spacing to the edge spacing were also inspected. Most pests were recorded as numbers per plant. Aphids and aphid mummies (parasitised aphids) which can be too numerous to count were given a ranking as follows: aphids (0 = absent, 1 = a few scattered individuals, 2 = a few isolated small colonies, 3 = several small isolated colonies, 4 = large isolated colonies, 5 = large continuous colonies) and for aphid mummies (0 = absent; 1 = less than 10, 2 = less than 25, 3 = less than 50, 4 = more than 50). Most fields were only surveyed once, however some fields were revisited during a different part of the year when the crop stage was different or a new crop had been planted.

Statistical analyses

All arthropods were counted visually in the field and recorded as a point count data except the density aphids and abundance of aphid-mummies (parasitised aphids) which were measured according to the predetermined scales. Fundamental research question of this field study was to determine the effects on the density and abundance of arthropods in the edges of each focal crop close to each type of adjacent land use. Examination of pest and natural enemy numbers showed many zeros, so the data were analysed using generalised linear model (GLM) with a negative binomial distribution using SPSS version 25. To complement the GLM analysis, three additional procedures were tested for suitability: structural equation modelling, multiple adaptive regression modelling, and Bayesian network approaches. The latter of these was proved most useful and was performed using Netica "6.07".

Brief description of Bayesian networks (BN)

A BN is probabilistic graphical representation, which consists of 'nodes', that represents a set of random variables, and 'links', that represent their conditional interdependencies (cause-effect relationship) via a directed acyclic graph (DAG) (Korb and Nicholson, 2004, Pearl, 1988). A BN model can include different types of nodes: 'nature' nodes, 'decision' nodes, and 'utility' nodes. Nodes which are influencing other nodes by causality links are called 'parent nodes', while influenced nodes are called 'child nodes'. Arrows between variables represent direct causal dependencies based on process understanding, statistical, or other types of associations. BNs exploit the distributional simplifications of a network structure by calculating how probable events are, and how these probabilities change given subsequent observations or external interventions (Düspohl et al., 2012; Korb and Nicholson, 2010). The graphical nature of BN facilitates ease in interpretation of the causal relationships among variables. BN models have been used extensively in ecology and environmental management to describe the influence of environmental variables on ecological response variables (Marcot et al., 2006). In agriculture, BN analysis has been used to model the effect of climate change in potato production (*Solanum tuberosum*) (Gu et al., 1994), predict yield response of winter wheat (*Triticum aestivum*) to fungicide application programs (Tari, 1996), and the development of a decision support system for growing malting barley (*Hordeum vulgare* L.) without the use of pesticides (Kristensen and Rasmussen, 2002). Bayesian Networks can be used in a top-down approach to analyse the impact the one or several parent nodes and analyse how states of nodes situated in lower parts of the network's hierarchy have their state's distribution changed (Düspohl et al., 2012).

We identified two major factors; 1) adjacent land use and 2) geographical region/climatic zones and parametrised the Bayesian Networks to explore the impact of those factors (parent nodes) on the population dynamics of arthropods (child nodes) in all focal crops. We also parametrized the Bayesian Networks with farm pest management strategies and explored its effects on densities of beneficials and pests.

Findings

Four hundred and ninety-one fields were surveyed across multiple States and regions, comprising 69 sweet corn, 71 lettuce, 22 bean, 39 capsicum, 44 carrot, and 246 brassica vegetable crops (23 Brussels sprouts, 70 broccoli, 61 cabbage, and 91 cauliflower) (Table 1). Fields were also categorised based on the types of insecticide products that had been used in that crop as 'biological' only or mixed. Biological fields were not necessarily organically certified, although some were, but only biological insecticidal products had been used in that crop. Mixed fields had used both biological and non-biological insecticidal products.

Table A2.2. Crop types and regions covered in the field survey. Field were also categorised by insecticide products used in that crop; as biological only or mixed for when biological and non-biological products were used.

Focal crops		Regions	Number of fields	Insecticide types used in crop	Total
Sweet corn	CW NSW	Kelso	11	biological = 69	69
		Canowindra	5		
		Dubbo	13		
	Sydney Basin	Richmond	4		
	Tasmania	Launceston	7		
	Western Australia	Carnarvon	17		
	Eastern Queensland	Lockyer Valley	2		
		Mulgowie	2		
		Wivenhoe Pocket	8		
Carrot	Western Australia	Gingin	10	biological = 11 mixed = 33	44
	Tasmania	Forth	25		
	Queensland	Lockyer Valley	7		
	South Australia	Langhorne Creek	2		
Lettuce	Western Australia	Gingin	12	biological = 5 mixed = 66	71
	W NSW	Riverina	8		
	Sydney Basin	Richmond	3		
	Victoria	near Melbourne	28		
	Eastern Queensland	Mount Sylvia	8		
		Lockyer Valley	12		
Bean	Western Australia	Carnarvon	9	biological = 1 mixed = 21	22
	Tasmania	Forth	10		
	Queensland	Wivenhoe Pocket	2		
		Mount Tarampa	1		
Capsicum	Western Australia	Carnarvon	31	biological = 0 mixed = 39	39
	South Australia	Virginia	8		

Table A2.3. Brassica types and regions covered in the field survey. Field were also categorised by insecticide products used in that crop; as biological only or mixed for when biological and non-biological products were used.

Focal crops		Regions	Number of fields	Insecticide types used in crop	Total	Focal crops
Brassica	**Broccoli**	Tasmania	Forth	21	biological = 10 mixed= 61	71
		Western Australia	Gingin	2		
			Albany	1		
		Victoria	near Melbourne	13		
		Queensland	Forest Hill	2		
			Lockyer Valley	18		
			Mount Sylvia	6		
			Mount Whitestone	1		
			Forth Tas	1		
			Mulgowie	6		
	Cauliflower	Victoria	near Melbourne	18	biological = 3 mixed = 89	92
		CW NSW	Kelso	27		
			Canowindra	24		
		Sydney Basin	Richmond	11		
		Tasmania	Forth	4		
		South Australia	Two well	1		
		Queensland	Lockyer Valley	5		
			Mount Sylvia	2		
	Brussels Sprouts	Tasmania	Forth	12	biological = 0 mixed = 23	23
		South Australia	Nairne	5		
			Mount Barker	4		
			Langhorne Creek,	2		
	Cabbage	Western Australia	Gingin	2	biological = 13 mixed = 47	60
		Sydney Basin	Camden	6		
		CW NSW	Kelso	3		
		W NSW	Riverina	7		
		Victoria	near Melbourne	16		
		Queensland	Lockyer Valley	16		
			Mount Sylvia	6		
			Mount Whitestone	2		
			Forest Hill	2		
Total number of sampled fields					**491**	

The density of arthropods in the field centre represented a baseline for comparisons. Pooled analysis tested whether the density of a taxon of arthropod in the edges of the crop differed significantly from the centre depending on the adjacent land use. An analysis of pooled data from 491 field with all arthropods sorted by guild, showed a significant ($p<0.001$) effect of adjacent land use types on densities by guild (Fig. A2.4-6). Crop fields adjacent to other crops of beans, carrots, tomato and corn showed a significantly higher number of pests at the focal crop edge compared with the centre. In contrast, crop field near other crops of capsicum, basil, lettuce or sorghum and shelterbelt vegetation had lower mean pest densities on the crop edge compared to the centre. For crops with basil and tomato adjacent, arthropod numbers in crop were so low only tentative conclusions can be drawn.

Field centres tended to have relatively low densities of beneficials. Beneficial guild numbers were significantly greater on the crop edge adjacent to shelterbelts, riparian vegetation and other crops of corn, capsicum, and especially sorghum. Beneficial guild numbers on crop edges close to basil and banana were had elevated but were only represented by few sites.

These results are remarkable in showing so many statistically significant effects and with large effect sizes (i.e., multiple fold differences in means) given that the pooled data set included all crop types, geographical regions and insecticide use types. Setting aside the few cases where effects are statistically significantly different but based on small numbers of sites (viz. banana, bean, grapes, tomato), these global findings could be interpreted to provide broad-brush guidance to growers and land managers on the patterns of land use that represent either high- or low-risk for pest build-up. The data set does, however, allow 'drilling-down' to provide more specific information for individual focal crops.

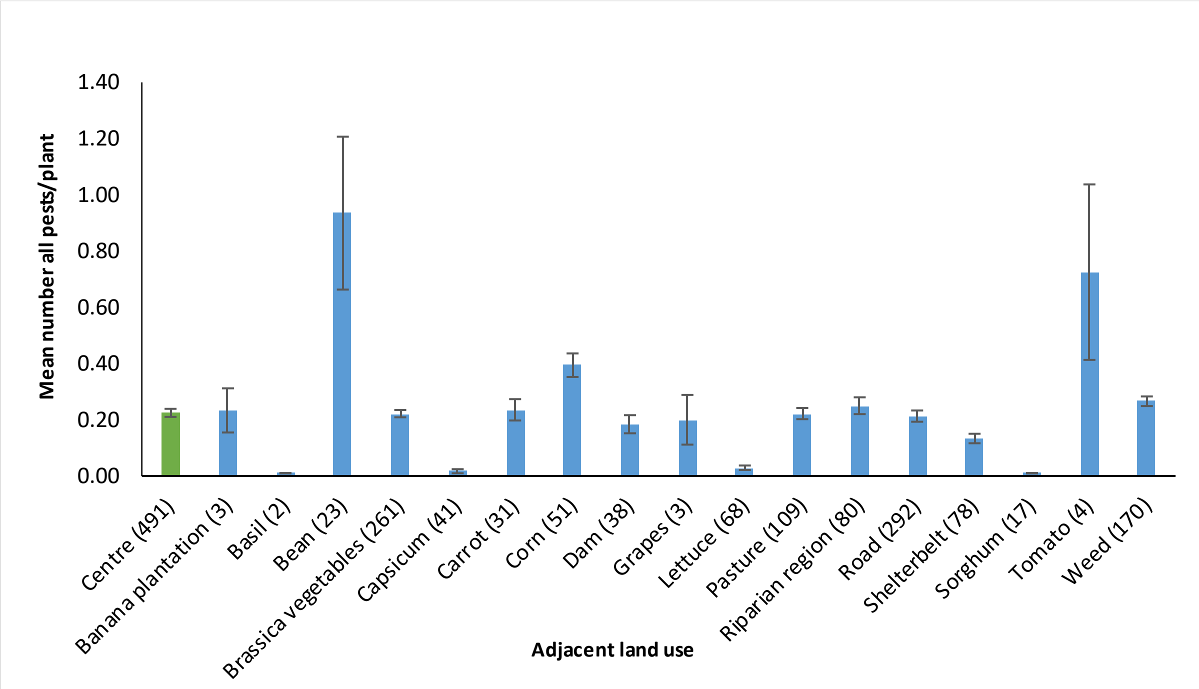
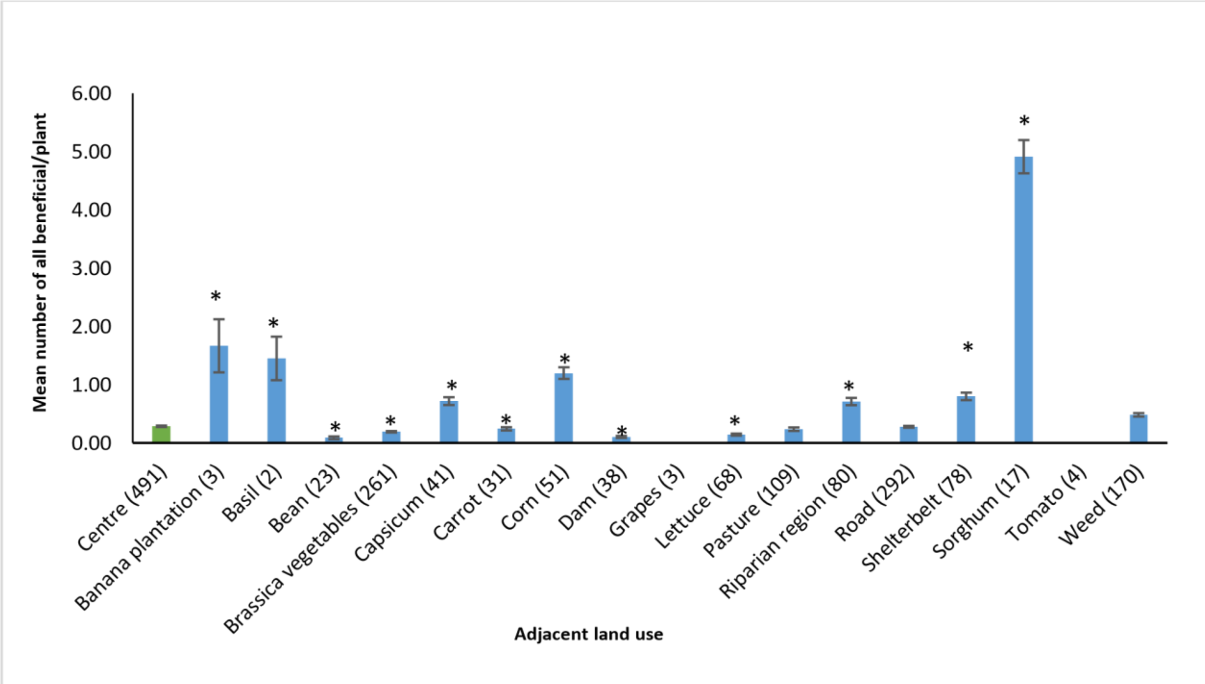


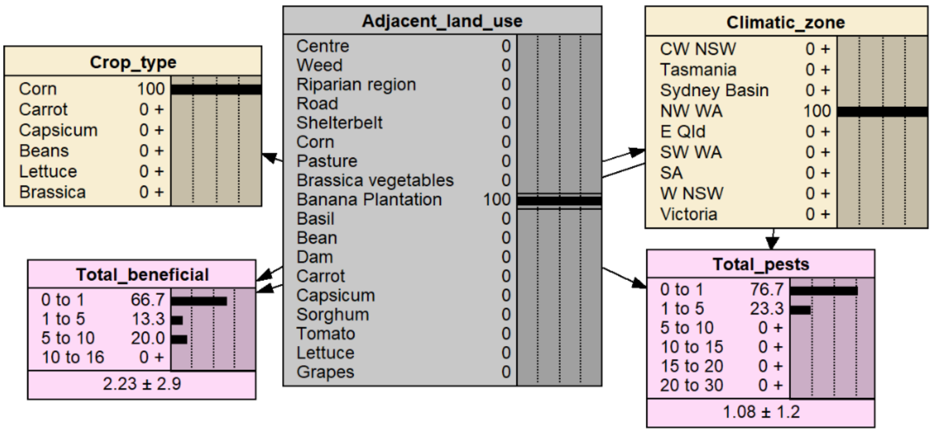
Figure A2.4 Mean number of pests counted in all vegetable fields. The 'Centre' (green) column shows the pests counted at the field centre. Other columns show the pests counted at the field edge adjacent to the land use labelled. * indicates where number of pests along the field edge is significantly different from the centre of the field at a 5% level of probability. Number in brackets shows the number of vegetable fields with each adjacent land use.



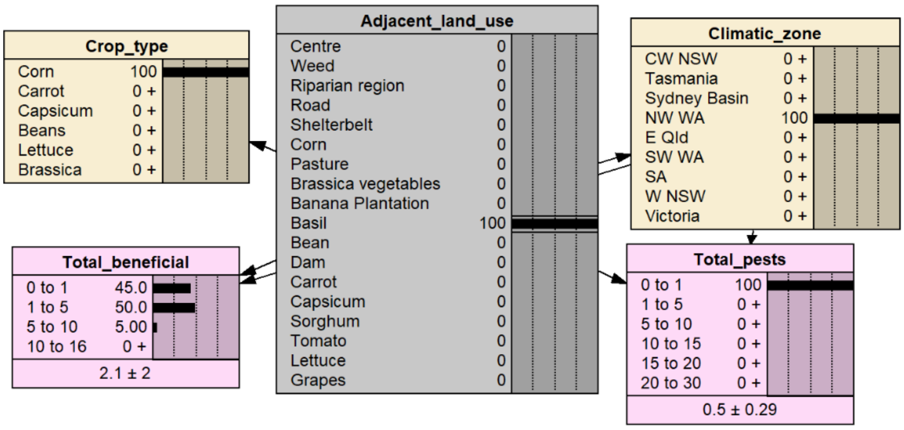
e A2.5. Mean number of beneficials counted in all vegetable fields. The 'Centre' (green) column shows the mean number of beneficial counted at the field centre. Other columns show the beneficials counted at the field edge adjacent to the land uses labelled. * indicates where number of beneficial along the field edge is significantly different from the centre of the field at a 5% level of probability. Number in brackets shows the number of vegetable fields with each adjacent land use.

Figure A2.6. Bayesian Network for the distribution of arthropods on the edge of vegetable fields adjacent to different land use types (A, banana plantation; B, basil; C, beans; D, brassica vegetables; E, capsicum; F, carrot; G, corn; H, dam; I, grapes; J, lettuce; K riparian region; L, shelterbelt,; M, sorghum; N, tomato).

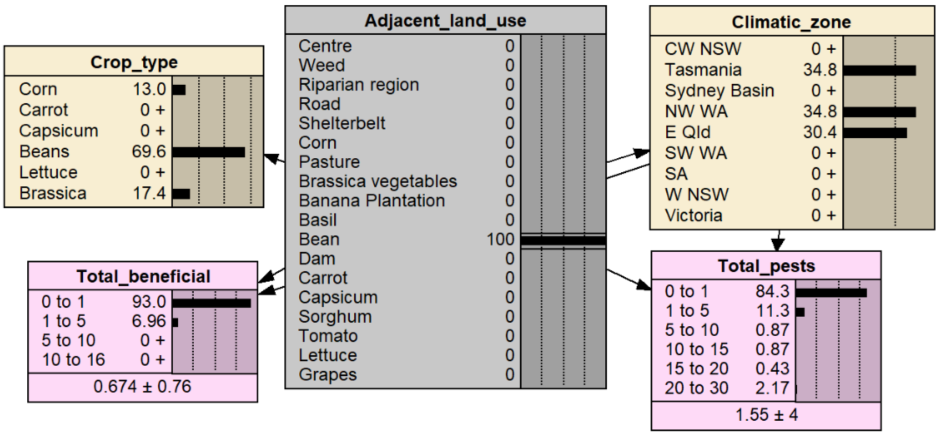
A. Banana



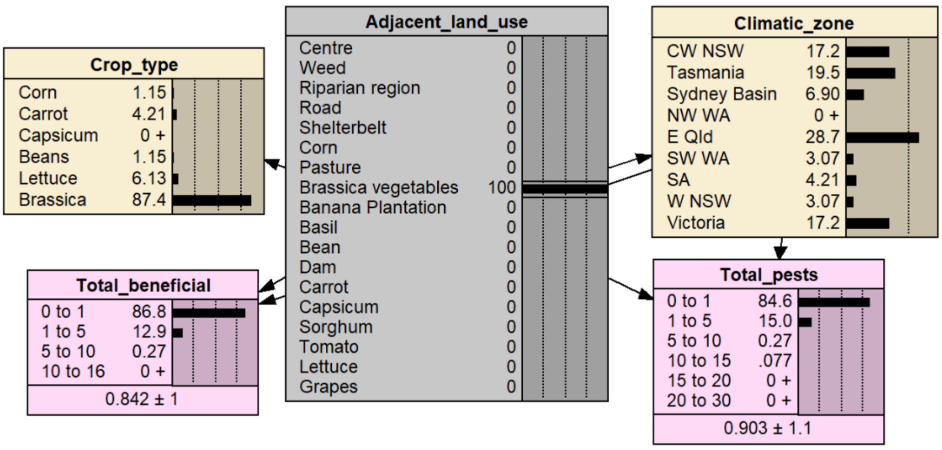
B. Basil



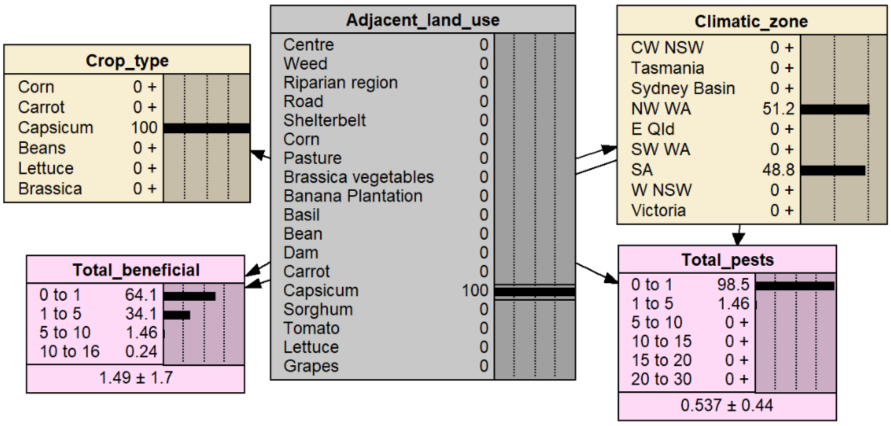
C. Beans



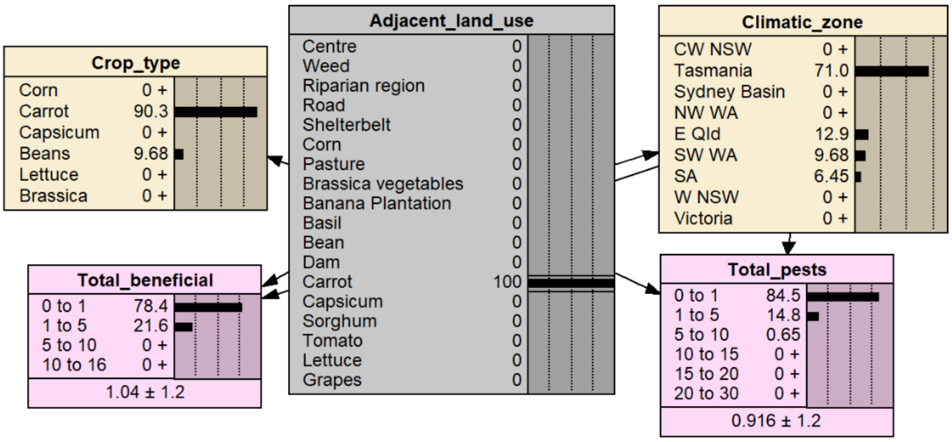
D. Brassica



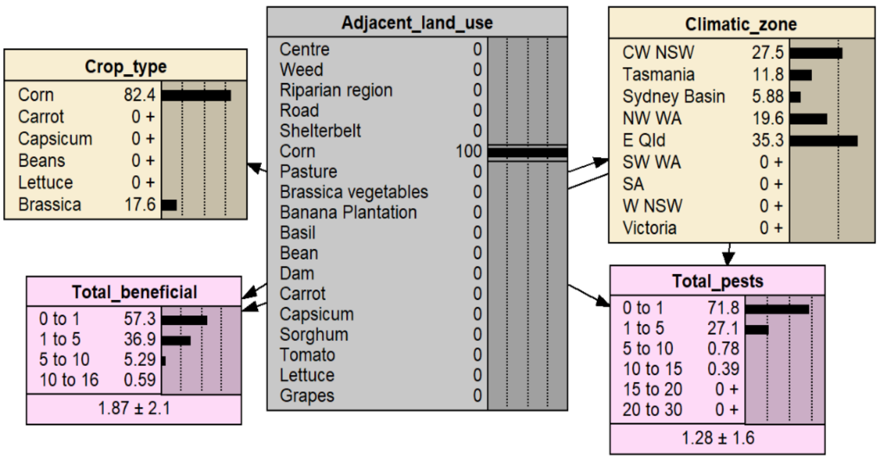
E. Capsicum



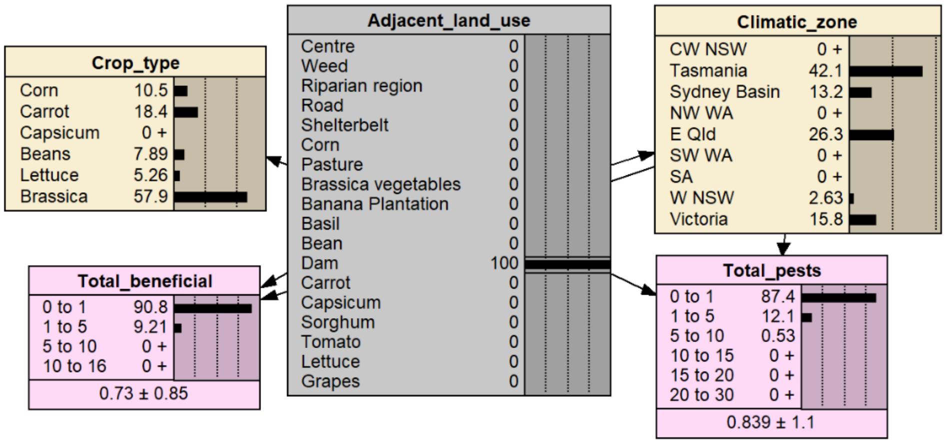
F. Carrot



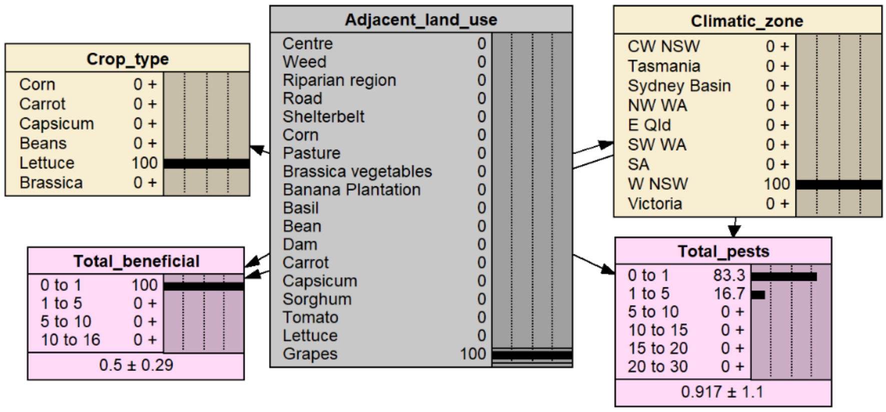
G. Corn



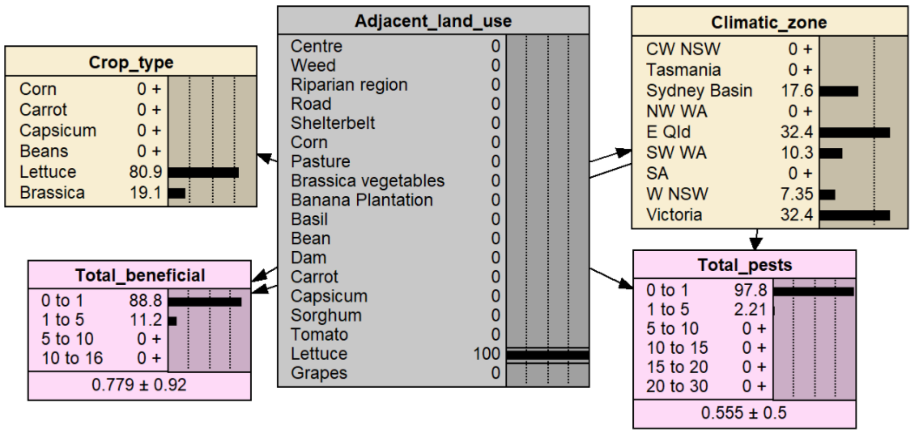
H. Dam



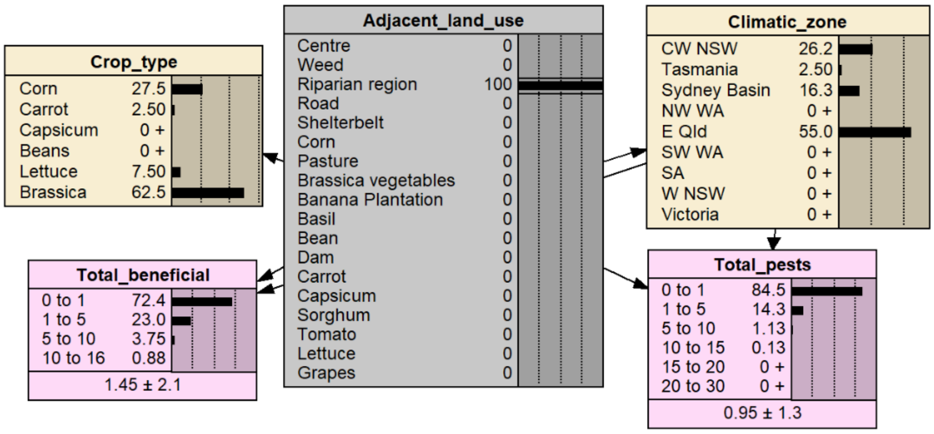
I. Grapes



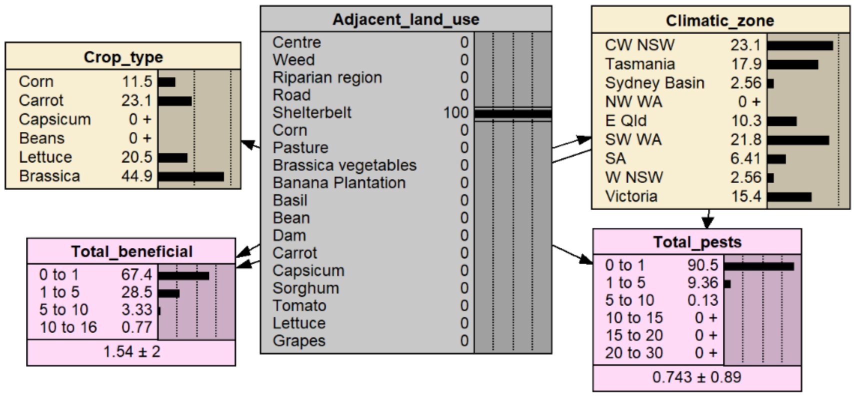
J. Lettuce



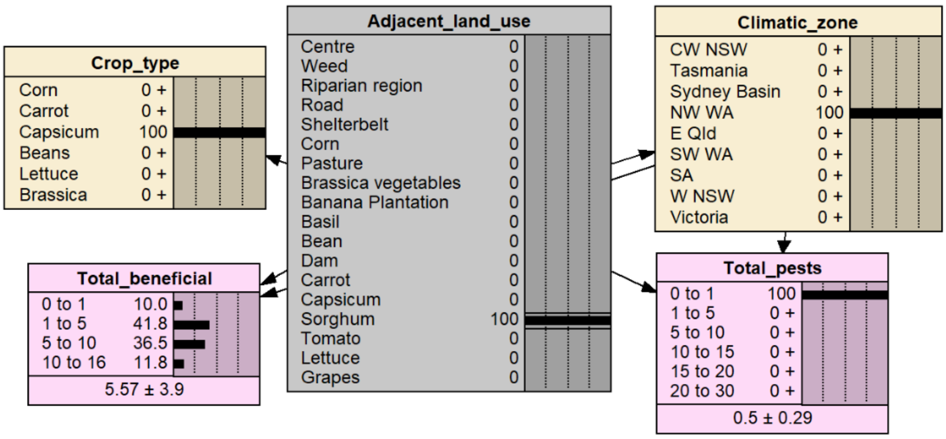
K. Riparian region



L. Shelterbelt



M. Sorghum



N. Tomato

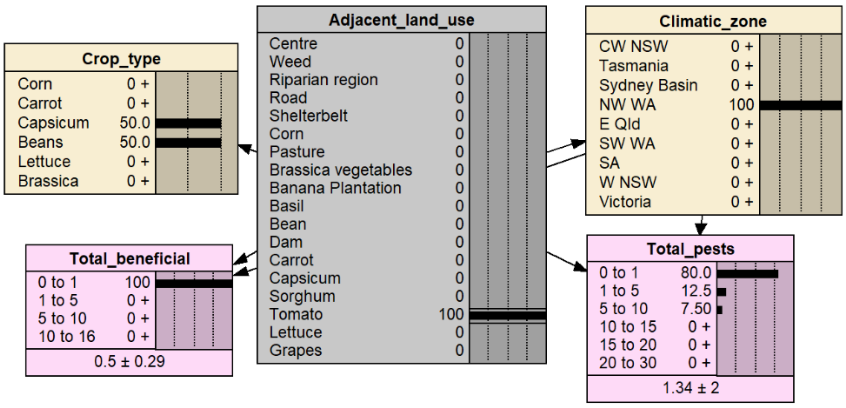


Figure A2.6. Bayesian Network for the distribution of arthropods on the edge of vegetable fields adjacent to different land use types (A, banana plantation; B, basil; C, beans; D, brassica vegetables; E, capsicum; F, carrot; G, corn; H, dam; I, grapes; J, lettuce; K riparian region; L, shelterbelt,; M, sorghum; N, tomato).

Sweet corn

Helicoverpa spp. (formally *Heliothis*), thrips (*Frankliniella williamsi*), jassids (*Austroasca viridigrisea*), Rutherglen bug (*Nysius vinitor*) and corn aphid (*Rhopalosiphum maidis*) were the major pests in sweet corn. The most common beneficials were ladybeetles (Coccinellidae), soldier beetle (*Cantharidae* sp.), red and blue beetle (*Dicranolaius bellulus*), Orius spp., and green lacewings (*Chrysoperla* spp). There was a significant variation within and among corn fields. Densities of pests and beneficials were affected by geographical region and adjacent land-use (Fig. A2.7-8). Higher pest densities were found in field edges adjacent to roads or pasture (Fig. A2.7). Both of these land uses (as well as dams, represented by just 4 sites) may represent barriers to pest ingress. Further work is necessary to identify the mechanism/s involved because often the roads that were immediately adjacent to focal crops were bordered on the far side by other vegetation (including trees and weeds) that may have had an effect on pests either directly or indirectly. Helicoverpa was predominant in Central West NSW (CW NSW) (Fig. A2.8) but was not found in the Sydney basin or Tasmania (Fig. A2.7). Jassids were found in the Sydney basin and Queensland and their density appeared to be elevated in crop edges adjacent to bean crops (Fig. A2.8-9). Thrips were predominant in south-east Queensland (E_Qld) and more abundant on the edges of corn fields bordered by brassicas or pasture (Fig. A2. 10-11). Aphids were more numerous in crop edges adjoining shelterbelts (Fig. A2.12). Reflecting this, densities of parasitised aphids (aphid mummies) were also higher along edge adjacent to shelterbelts, along with other beneficials (Fig. A2.13). Crop edges adjacent to corn, riparian vegetation and weeds as well as basil (with small sample size) had higher beneficial densities than in field centres. There were large differences among beneficial taxa, with predatory coleopterans promoted strongly by shelterbelts and riparian vegetation). In corn fields ladybeetle numbers were significantly higher on the edges adjacent to banana plantations, shelterbelts and weeds; soldier beetle numbers on the edges adjacent to dams, pasture, shelterbelts, and weedy areas; red and blue beetle on the edges adjacent to riparian regions, shelterbelts, and weeds; Orius spp numbers on the edges adjacent to shelterbelts and weeds; green lacewing numbers on the edges adjacent to banana plantations and basil when compared to the centre of the fields (Fig. A2.14-15).

BN models were employed to screen the impact of shelterbelt, riparian region, pasture and roads (Fig. A2.16-19) which matched with the findings of GLM.

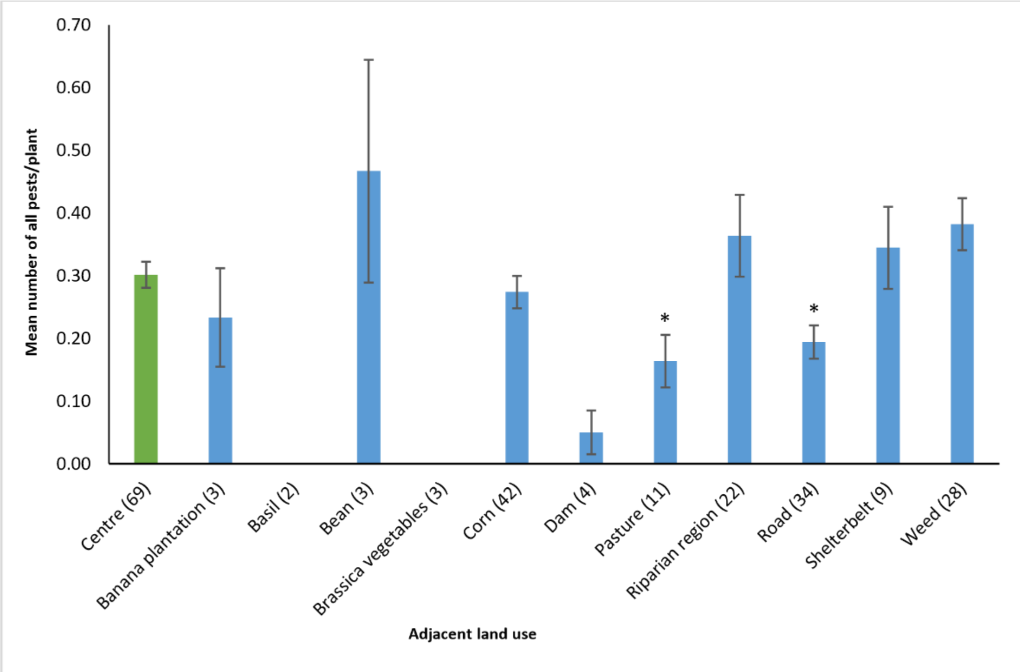


Figure A2.7. Mean number of pests in all corn fields. The 'Centre' (green) column shows the mean number of all pests counted at the field centre. Other columns show the pests counted at the field edges adjacent to the land use labelled. * indicates where number of pests along the edge is significantly different from the centre of the field at a 5% level of probability. Number in brackets shows the number of corn field with each adjacent land use. Thrips, whiteflies and Rutherglen bug data not included but are analysed separately.

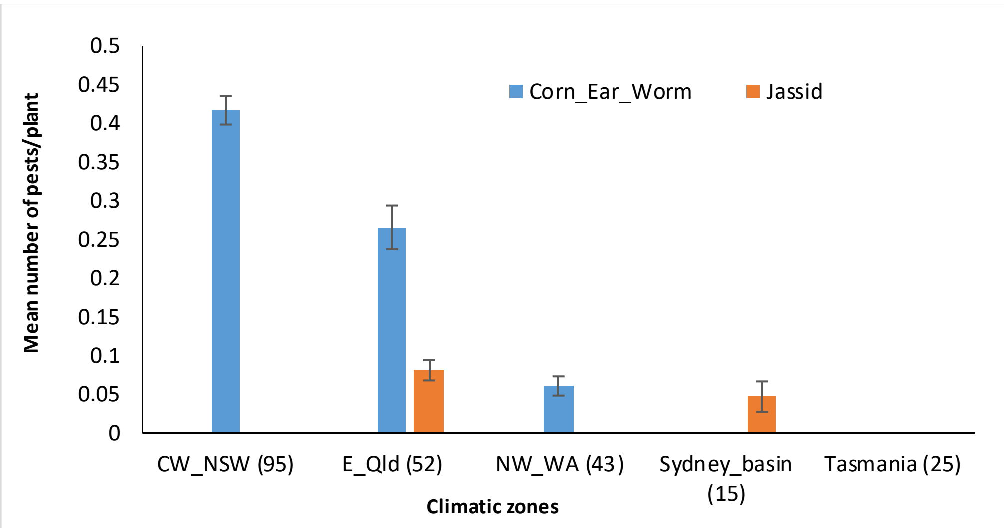


Figure A2.8. Major of pests in corn in different regions. Letters indicate significant difference at 5% level of probability. Number in brackets shows the numbers of fields.

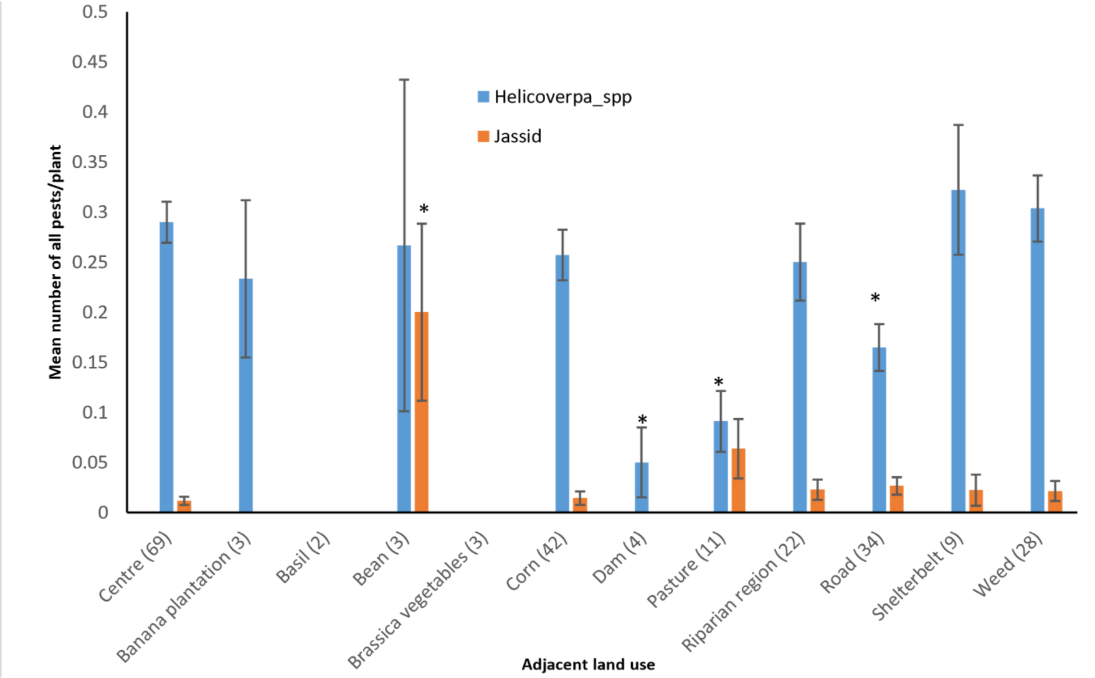


Figure A2.9. Mean number of *Helicoverpa* and jassids counted in corn fields. The 'Centre' (green) column shows the counts at the centre. Other columns show the counts at the field edge adjacent to land use labelled. * indicates where number of pests along the edge is significantly different from the centre of the field at a 5% level of probability. Number in brackets shows the number of fields with each adjacent land use.

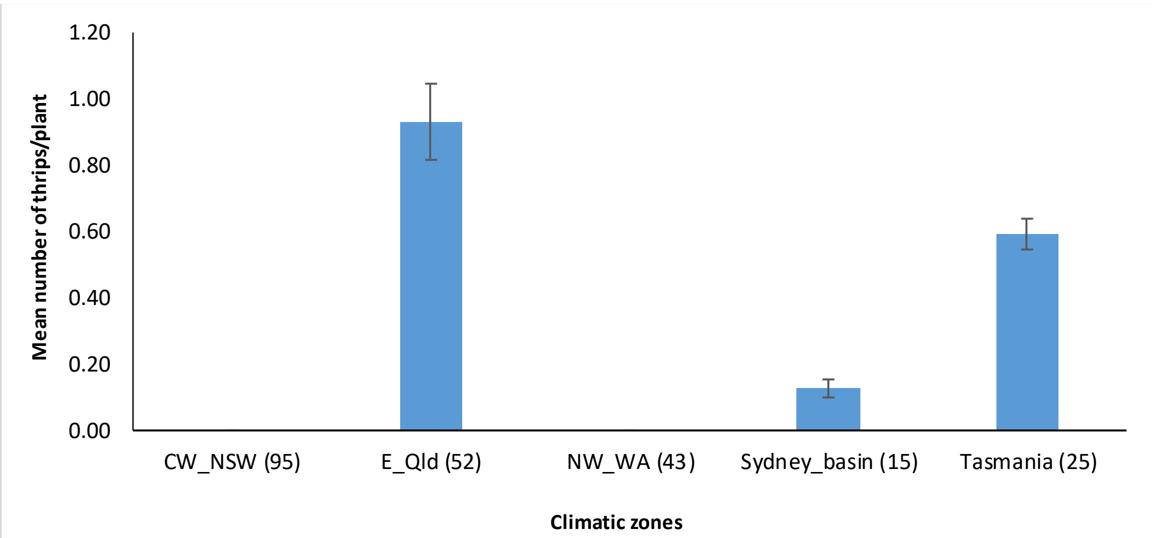


Figure A2.10. Number of thrips in corn fields in different regions. Letters indicate significant difference at 5% level of probability. Number in brackets shows the number of fields.

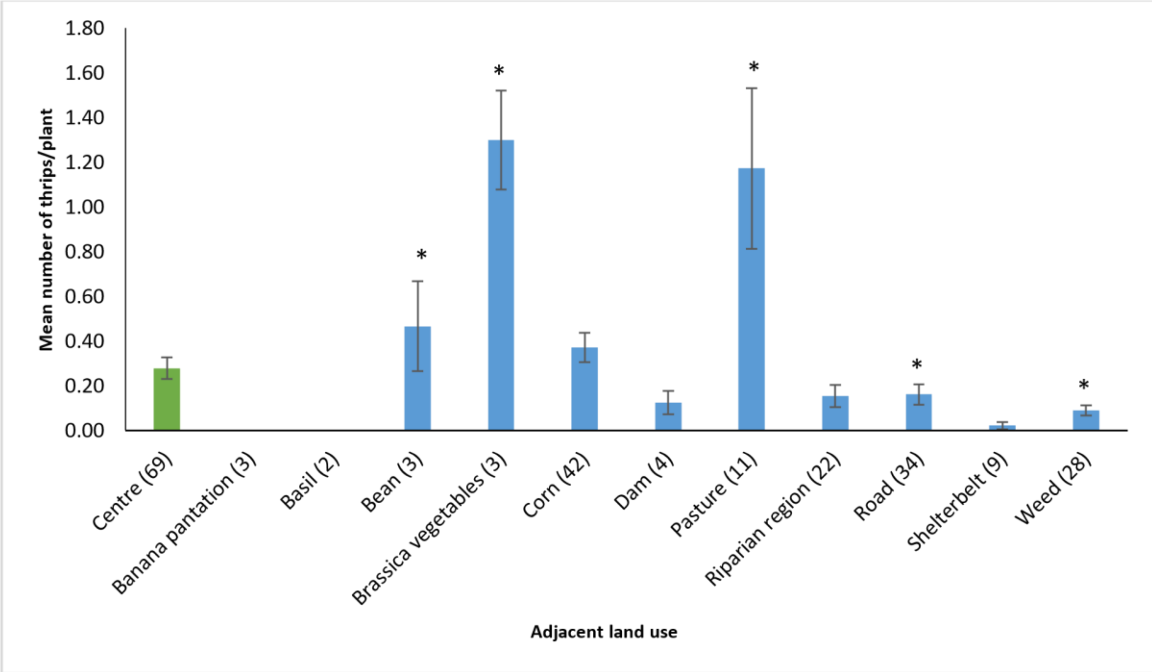


Figure A2.11. Mean number of thrips counted in corn fields. The 'Centre' (green) column shows the mean number of thrips at the field centre. Other columns show the counts at the field edges adjacent to land uses labelled. * indicates where number of thrips along the field edge is significantly different from the centre at a 5% level of probability. Number in brackets shows the number of field edges with each adjacent land use.

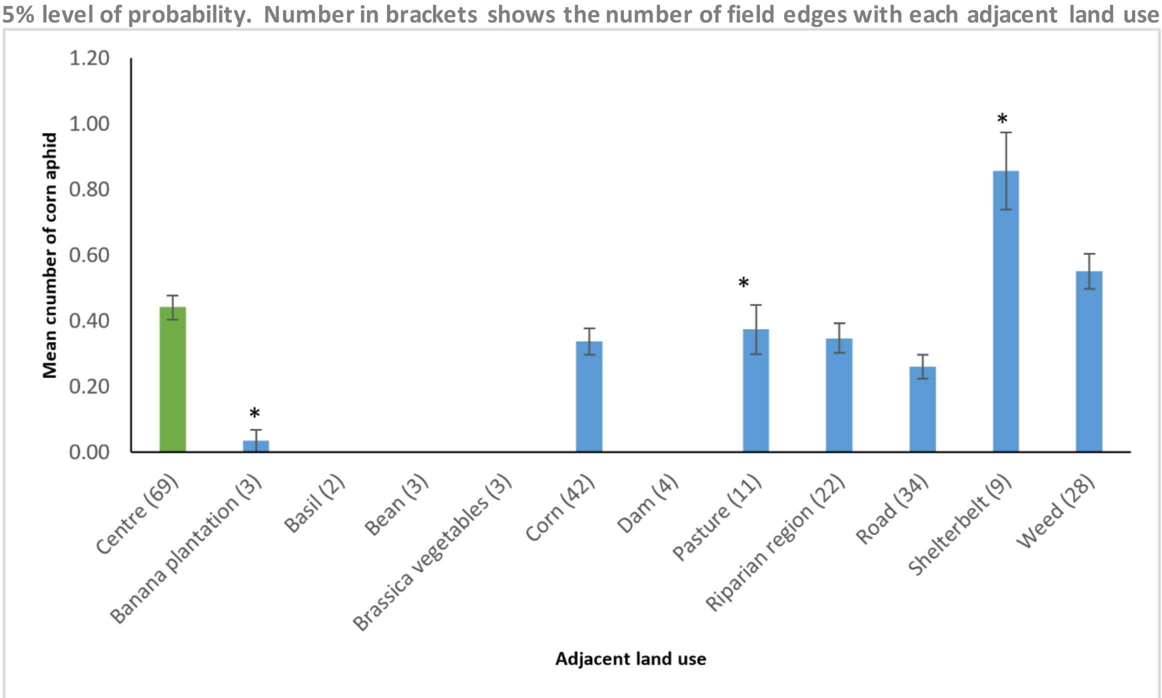


Figure A2.12. Mean number of aphids in all corn fields. The 'Centre' (green) column show the frequency of aphids in the field centre. Other columns show frequency in the edges of the corn field adjacent to land use labelled. * indicates where number of pests along the field edge is significantly different from the centre field at a 5% level of probability. Number in brackets shows the number of fields with each adjacent land use.

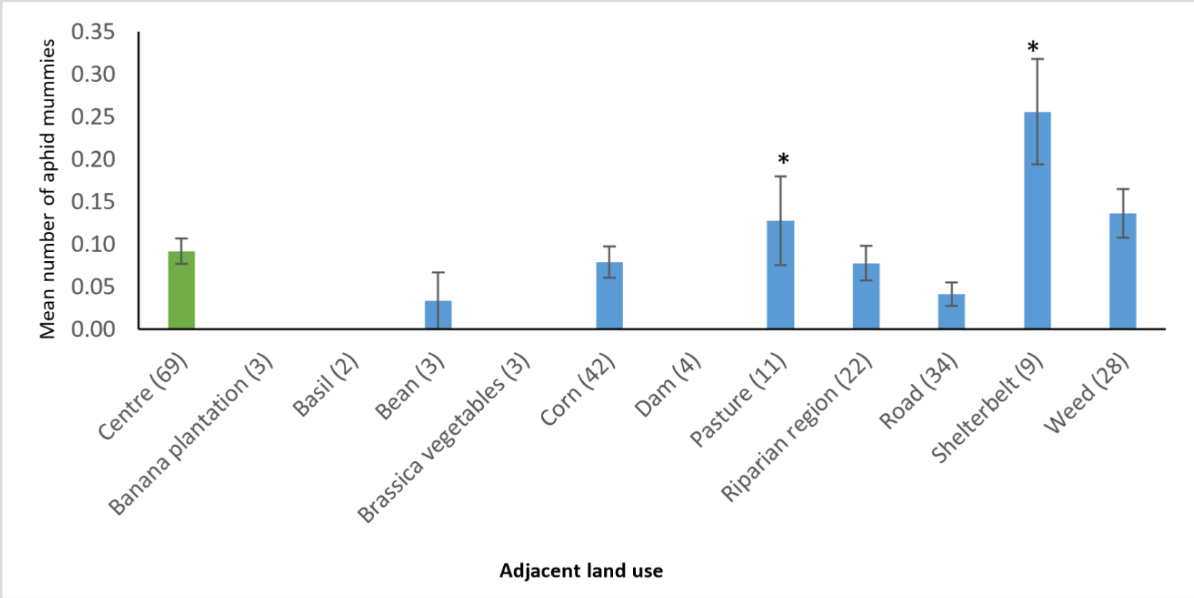


Figure A2.13. Mean number of aphid mummies (indicating aphid parasitoid activity) counted in corn fields. The 'Centre' (green) column shows the number counted at the field centre. Other columns show the shows the mean at the field edge adjacent to land use labelled. * indicates where number along the edge is significantly different from the centre of the field at a 5% level of probability. Number in brackets shows the number of fields with each adjacent land use.

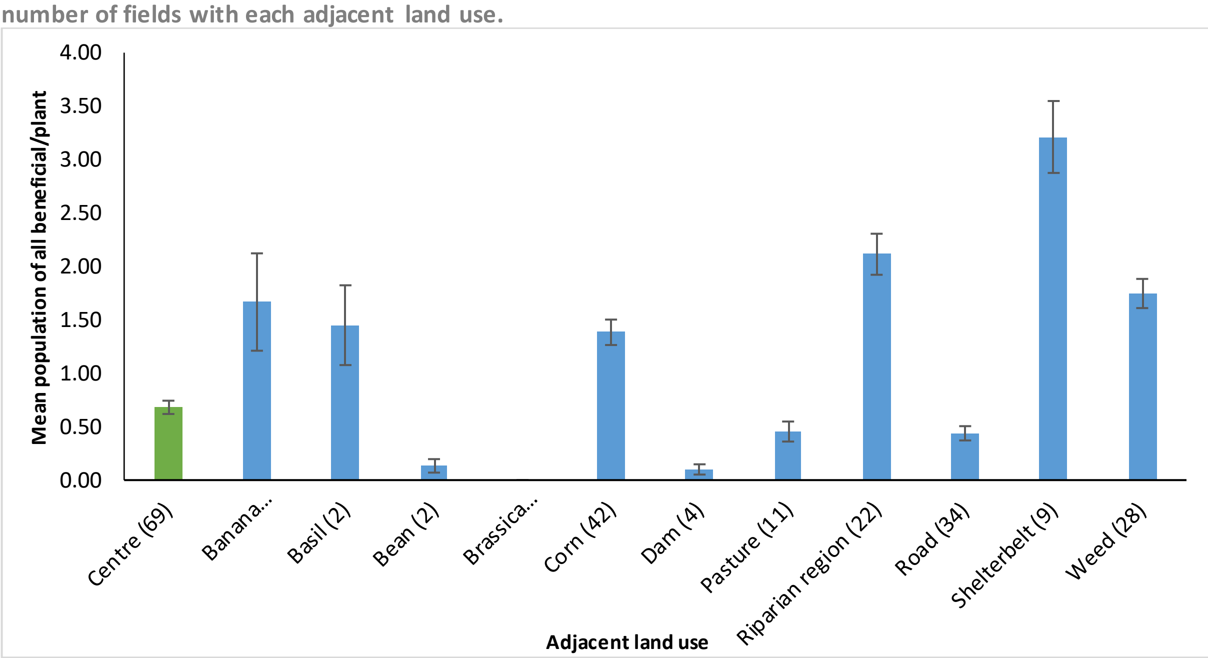


Figure A2.14. Mean number of beneficials in all corn fields. The 'Centre' (green) column shows the mean number of beneficials counted at the field centre. Other columns show beneficials counted at the field edge adjacent to the land use labelled. * indicates where number of beneficials along the field edge is significantly different from the centre of the field at a 5% level of probability. Number in brackets shows the number of fields with each adjacent land use.

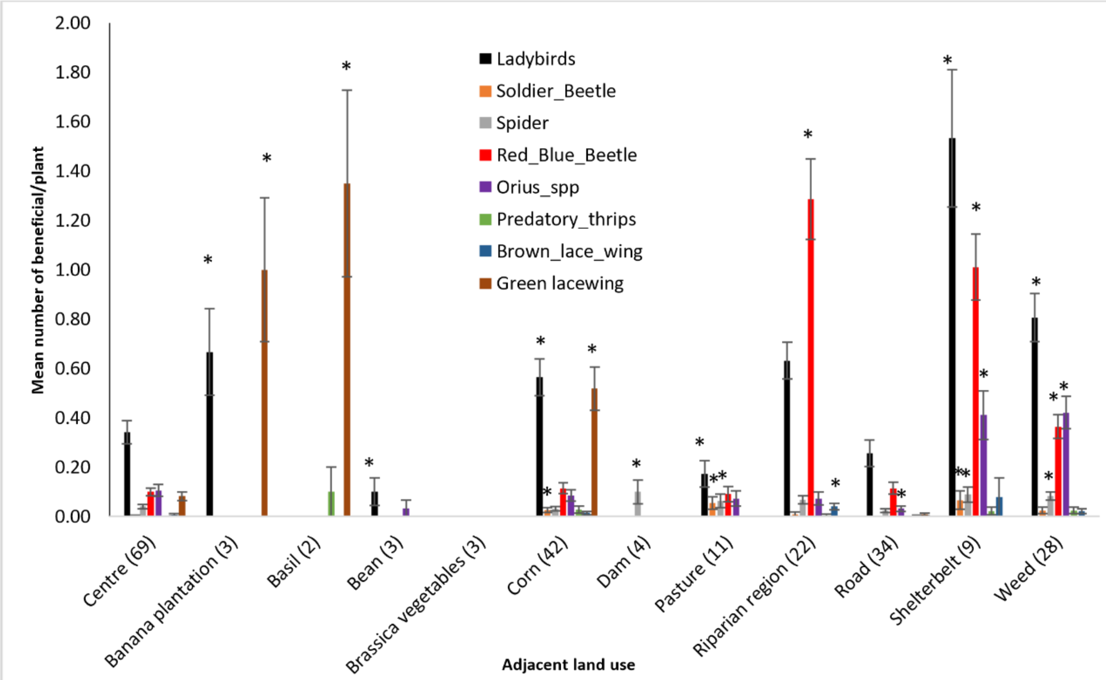


Figure A2.15. Mean number of beneficials by taxa all corn fields. The 'Centre' (green) column shows the number counted at the field centre. Other columns show the number counted at the field edge adjacent to land use labelled. * indicates where number along the edge is significantly different from the centre at a 5% level of probability. Number in brackets shows the number of fields with each adjacent land use.

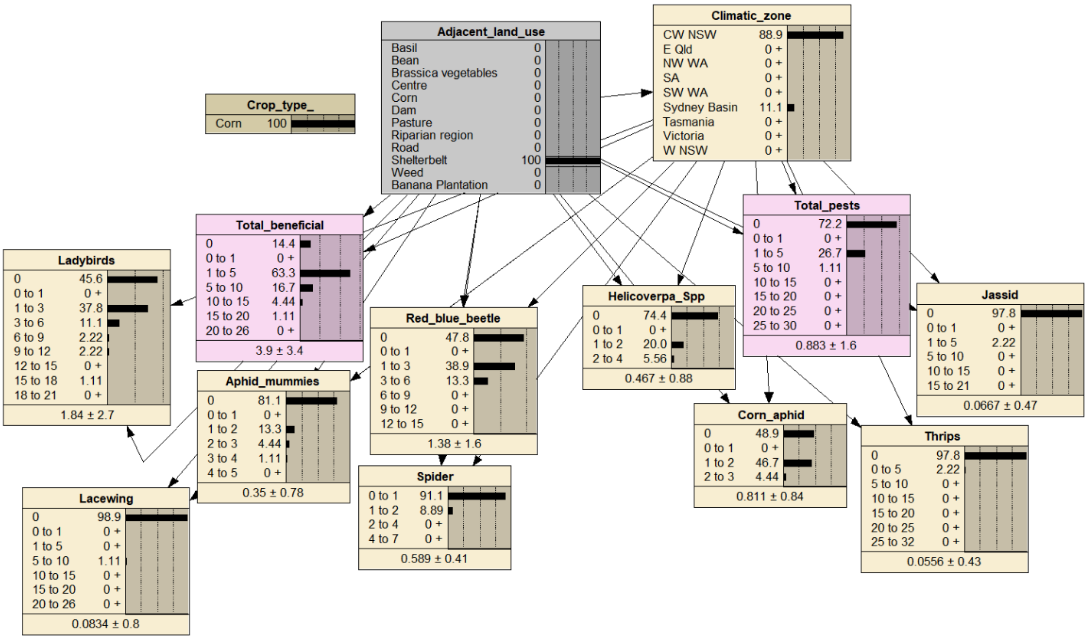


Figure A2.16. Bayesian network for the distribution of arthropods on the edge of corn fields adjacent to shelterbelt.

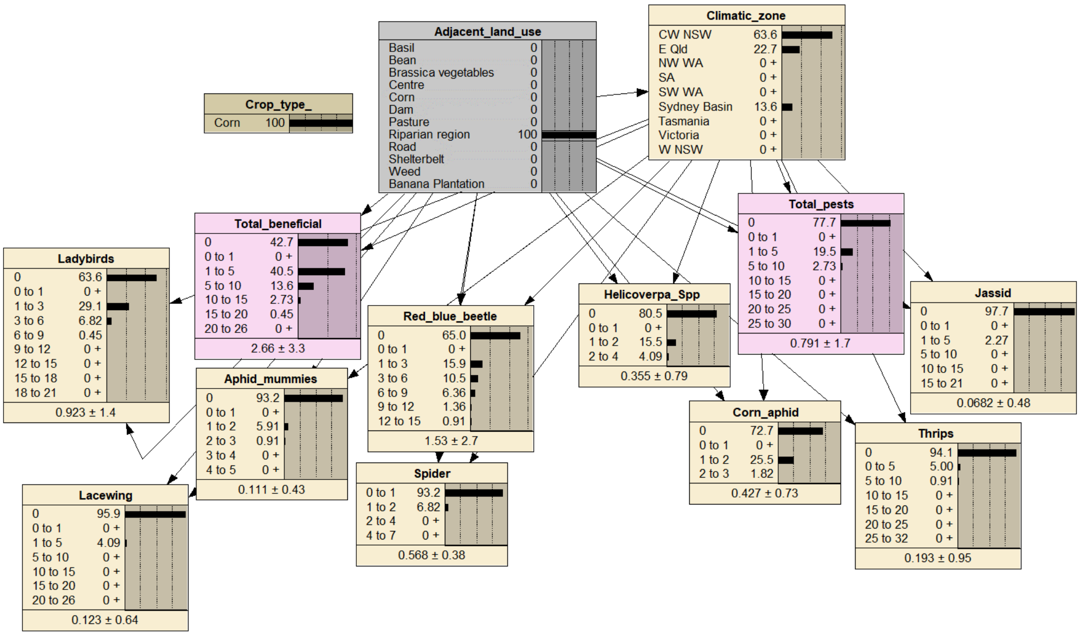


Figure A2.17. Bayesian network for the distribution of arthropods on the edge of corn fields adjacent to riparian region.

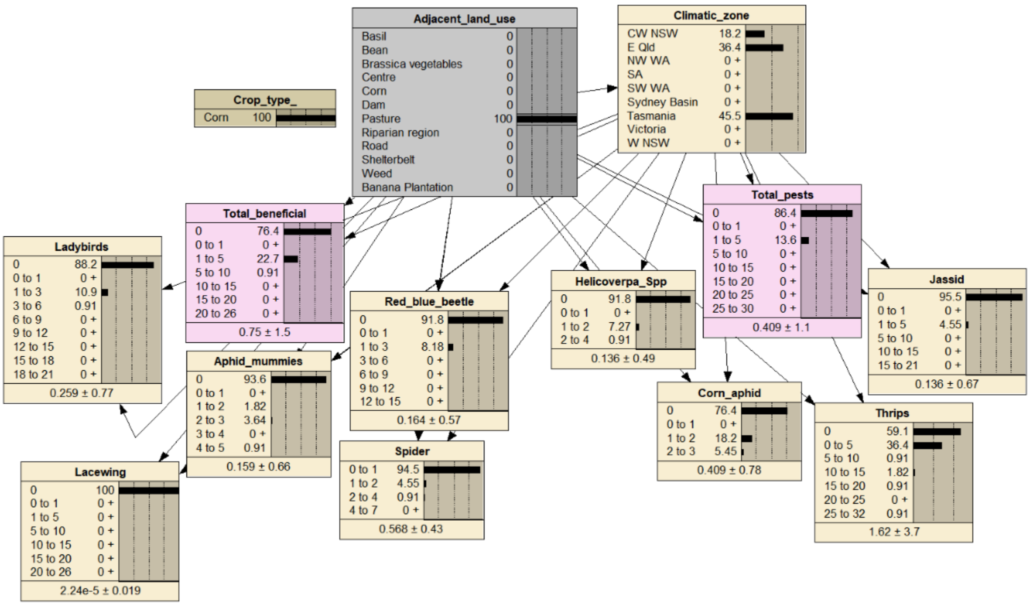


Figure A2.18. Bayesian network for the distribution of arthropods on the edge of corn fields adjacent to pasture.

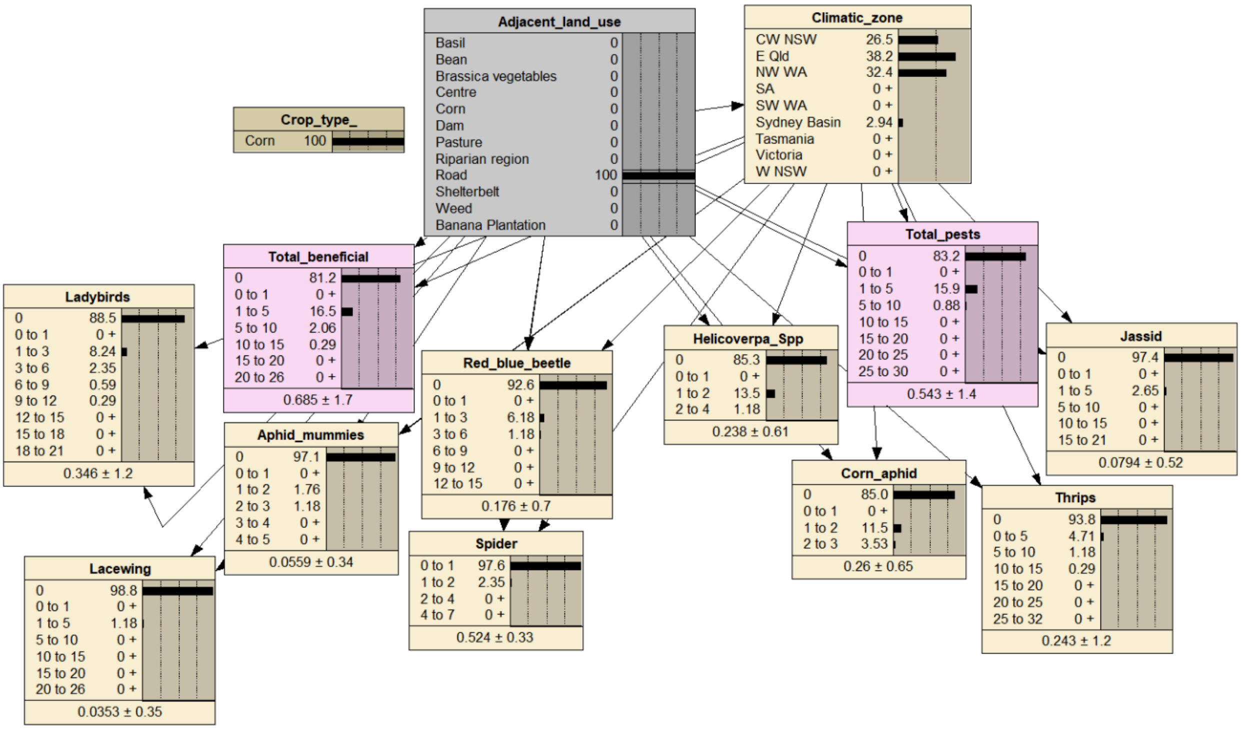


Figure A2.19. Bayesian network for the distribution of arthropods on the edge of corn fields adjacent to road.

Carrot

Jassids (*Austroasca viridigrisea*), thrips, whiteflies, mirids and Rutherglen bugs were the most common pests found in carrot fields. Adjacent land use and geographic location had a significant effect on the pest populations in carrot (Fig. A2.20-21). Fewer jassids were recorded at the field edge of the carrot fields adjacent to pasture (mostly lucerne) (Fig. A2.22) and riparian areas (Fig. A2.20, 23). Jassids were predominantly present in Queensland and southwestern Western Australia (Fig. A2.21) and the lowest pest incidence of jassids in South Australia.

Thrips were significantly higher in at the field edge adjacent to riparian vegetation, dams and brassica fields when compared with the centre of carrot fields (Fig. A2.24). Rutherglen bugs were significantly fewer in number in the field edge of carrot fields irrespective of the adjacent land use compared with the centre of the carrot field (Fig. A2.25).

Pooled analysis of total beneficials numbers at the field edge did not show any significant differences from the centre of the carrot field when compared to adjacent land-use. Partitioning beneficial by taxon, ladybeetles - the most abundant beneficials - were more numerous in margins of the carrot fields adjacent to shelterbelts when compared with the centre of the carrot field (Fig. A2.26). Parasitoids were more numerous in the margins adjacent to dams, pastures, shelterbelts and weedy areas (Fig. A2.27, A2.26, A2.28, A2.22). The abundance of other taxa was varied along the field edges compared to the centre of the field (Table A2.4 & A2.5).

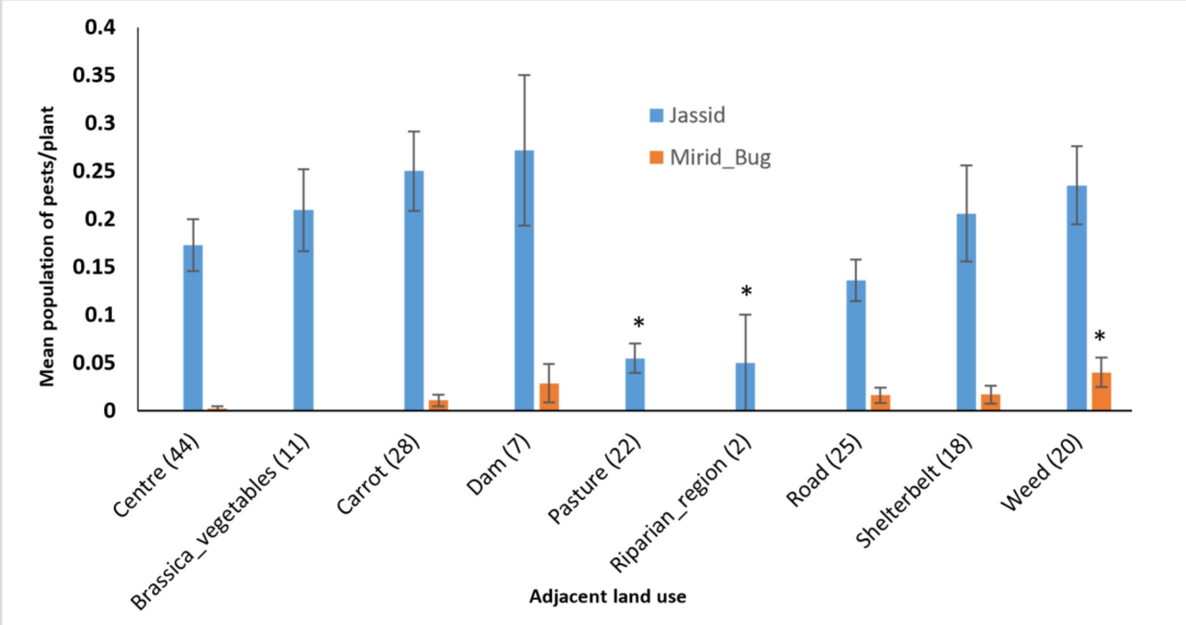


Figure A2.20. Mean number of jassids and mirid bugs in carrot fields. The 'Centre' column shows count at the field centre and other columns show the count at the field edge adjacent to the land use labelled. * indicates where number along the field edge is significantly different from the centre of the field at a 5% level of probability. Number in brackets shows the number of fields with each adjacent land use.

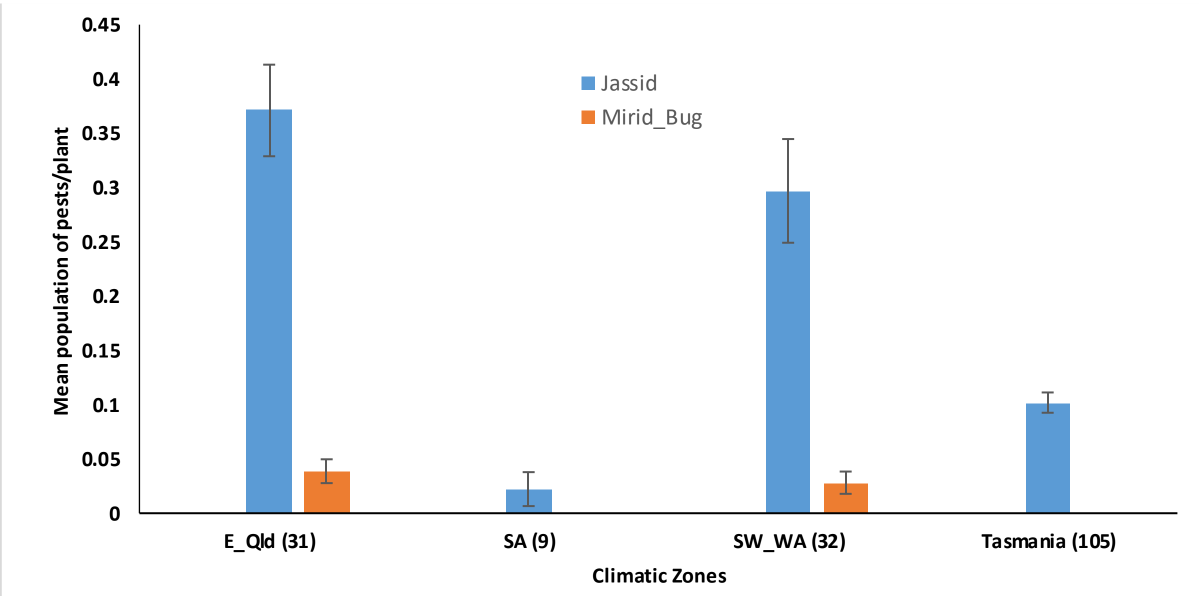


Figure A2.21. Number of jassids and mirid bugs in carrot fields in different geographic locations. Letters indicate significant difference between locations at 5% level of probability. Number in brackets shows the number of fields.

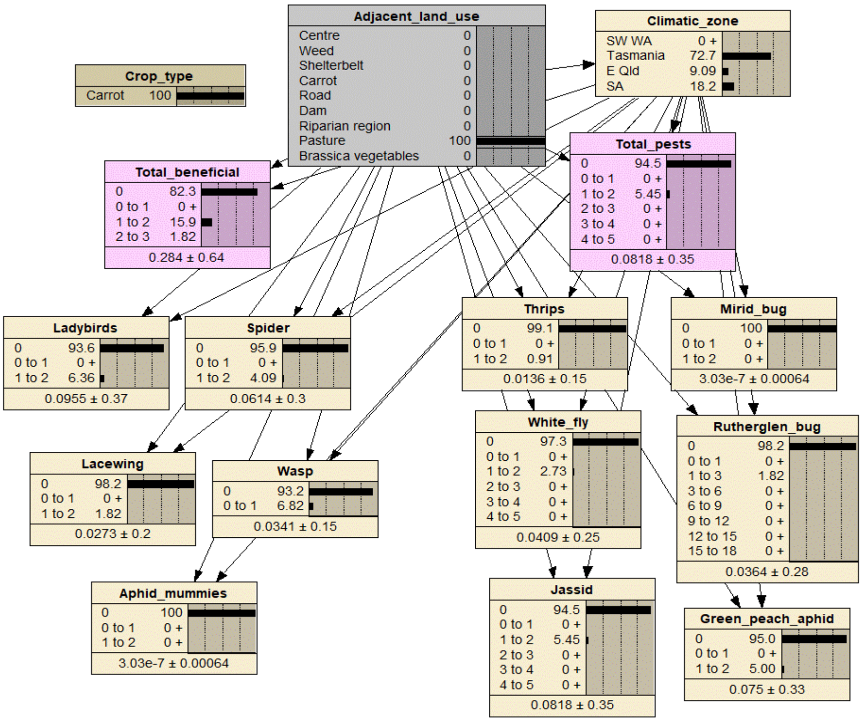


Figure A2.22. Bayesian network for the distribution of arthropods on the edge of carrot fields adjacent to pasture fields.

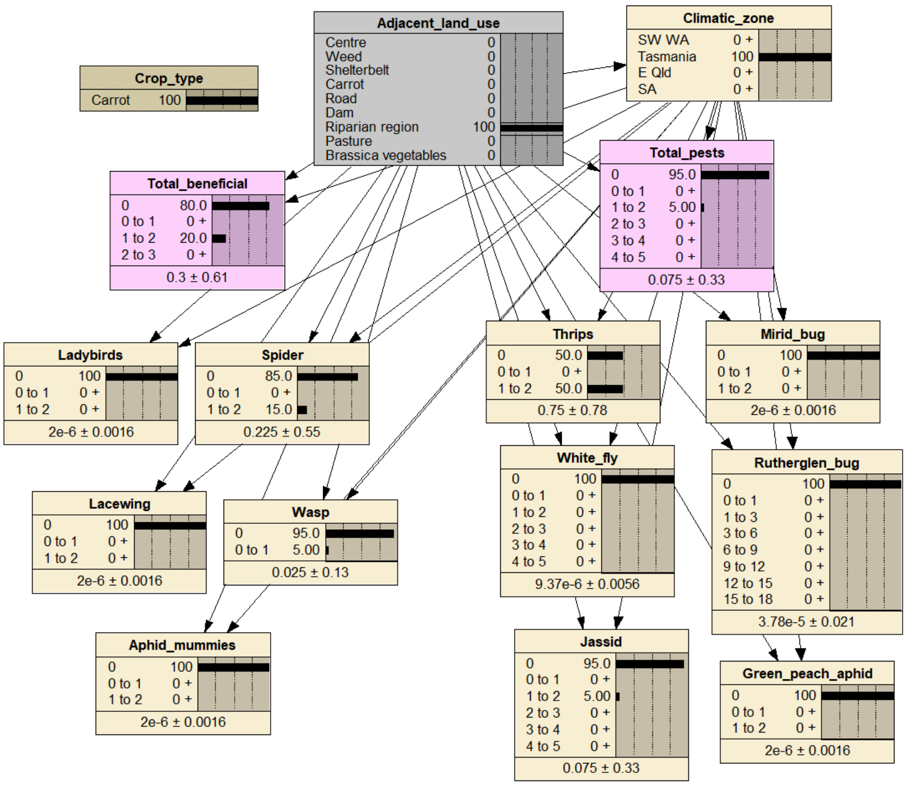


Figure A2.23. Bayesian network for the distribution of arthropods on the edge of carrot fields adjacent to a riparian region.

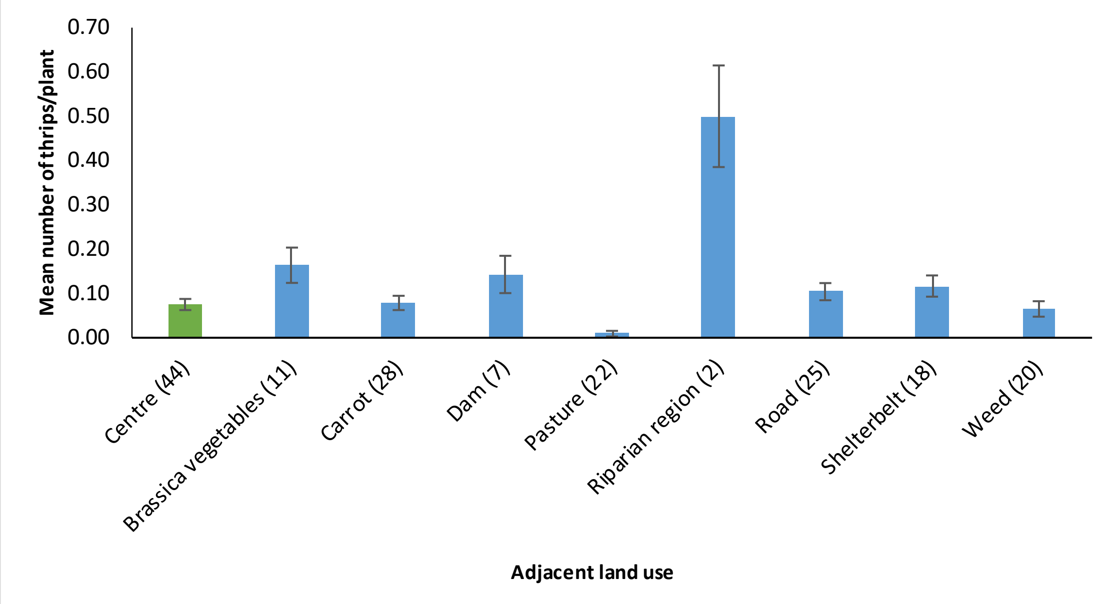


Figure A2.24. Mean number of thrips in carrot fields. The 'Centre' (green) column shows count at the field centre and other columns show the count at the field edge adjacent to the land use labelled. * indicates where number along the field edge is significantly different to the centre of the field at a 5% level of probability. Number in brackets show the numbers of fields with each adjacent land use.

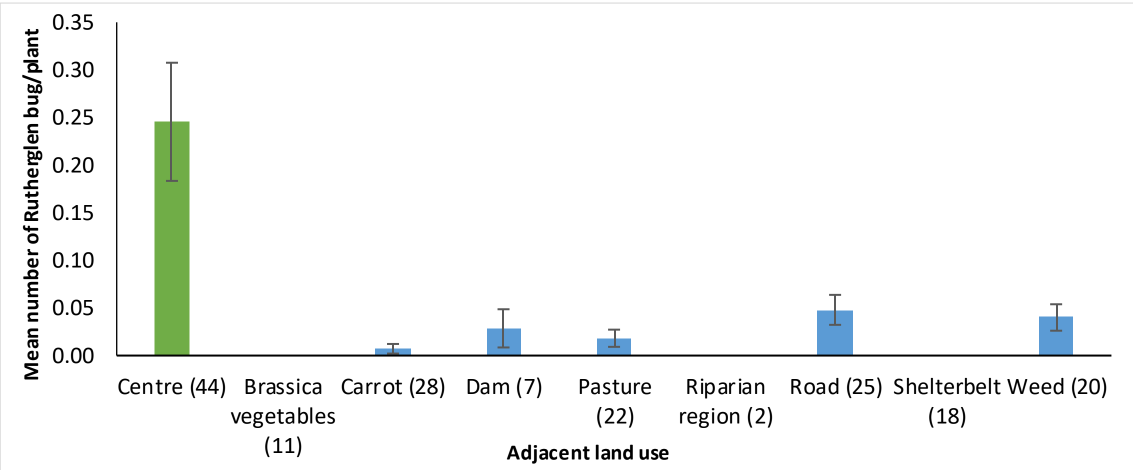
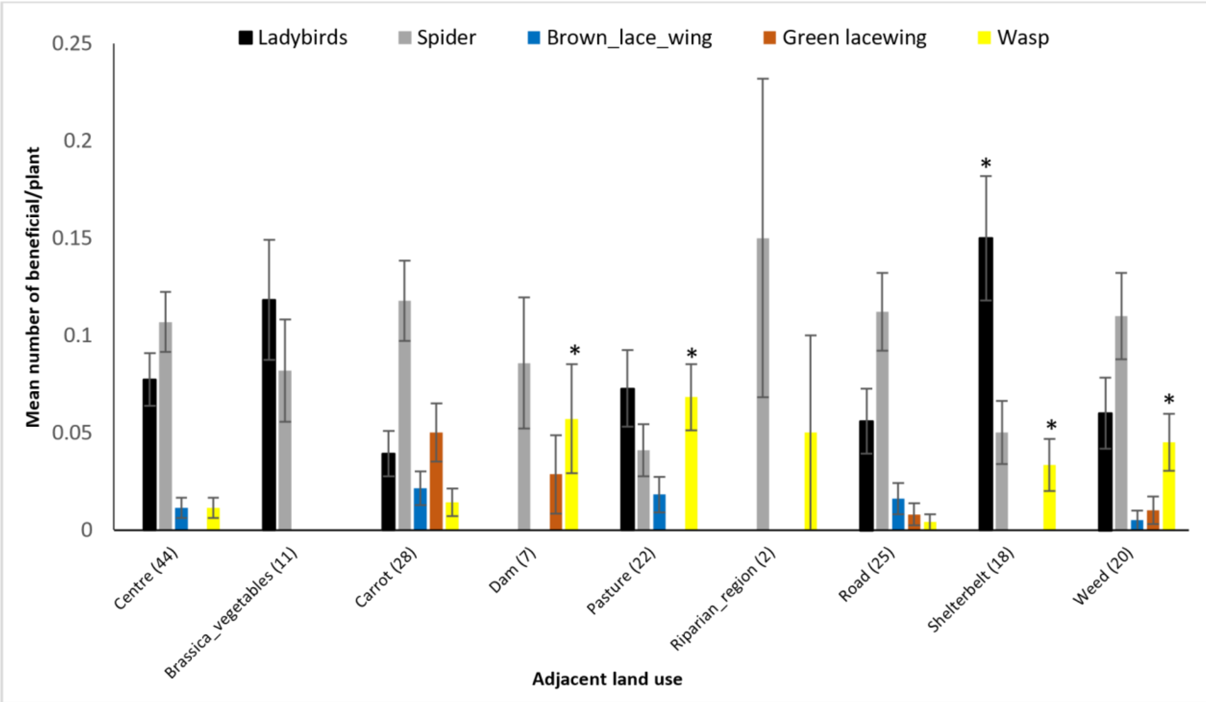


Figure A2.25. Mean number of Rutherglen bugs in carrot fields. The 'Centre' (green) column shows count at the field centre and other columns show the count at the field edge adjacent to the land use labelled. * indicates where number along the field edge is significantly different to the centre of the field at a 5% level of probability. Number in brackets show the numbers of fields with each adjacent land use.



FigureA2.26. Mean number of beneficials by taxa in carrot fields. The 'Centre' column shows count at the field centre and other columns show the count at the field edge adjacent to the land use labelled. * indicates where number along the field edge is significantly different to the centre of the field at a 5% level of probability. Number in brackets show the numbers of fields with each adjacent land use.

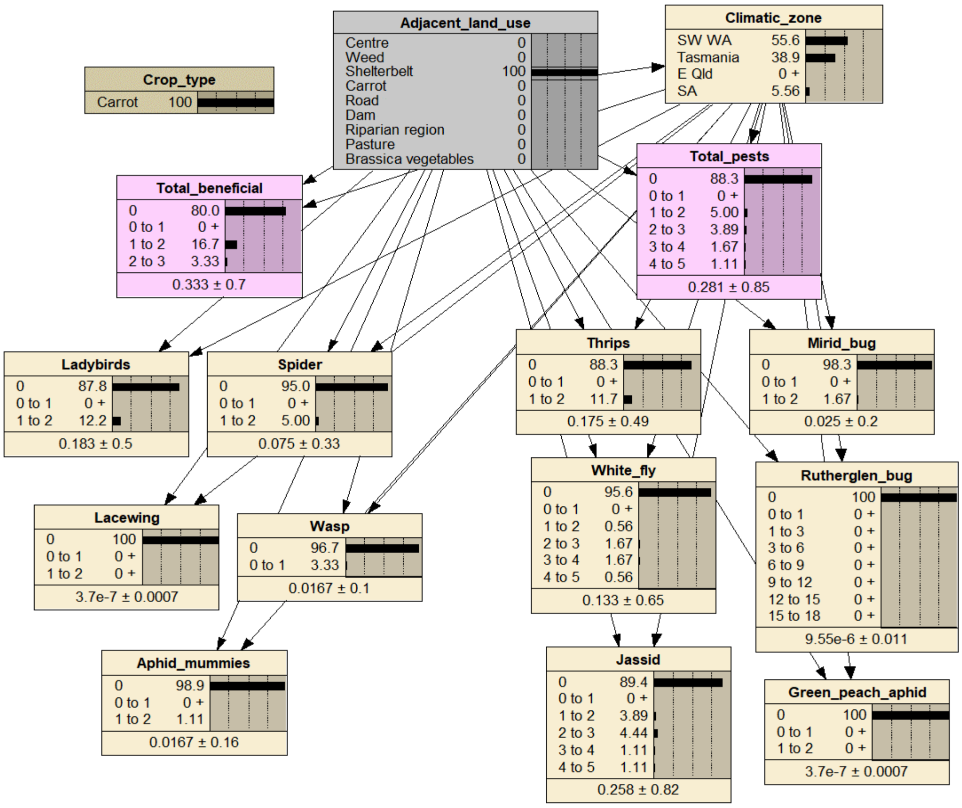


Figure A2.27. Bayesian network for the distribution of arthropods on the edge of carrot fields adjacent to shelterbelts.

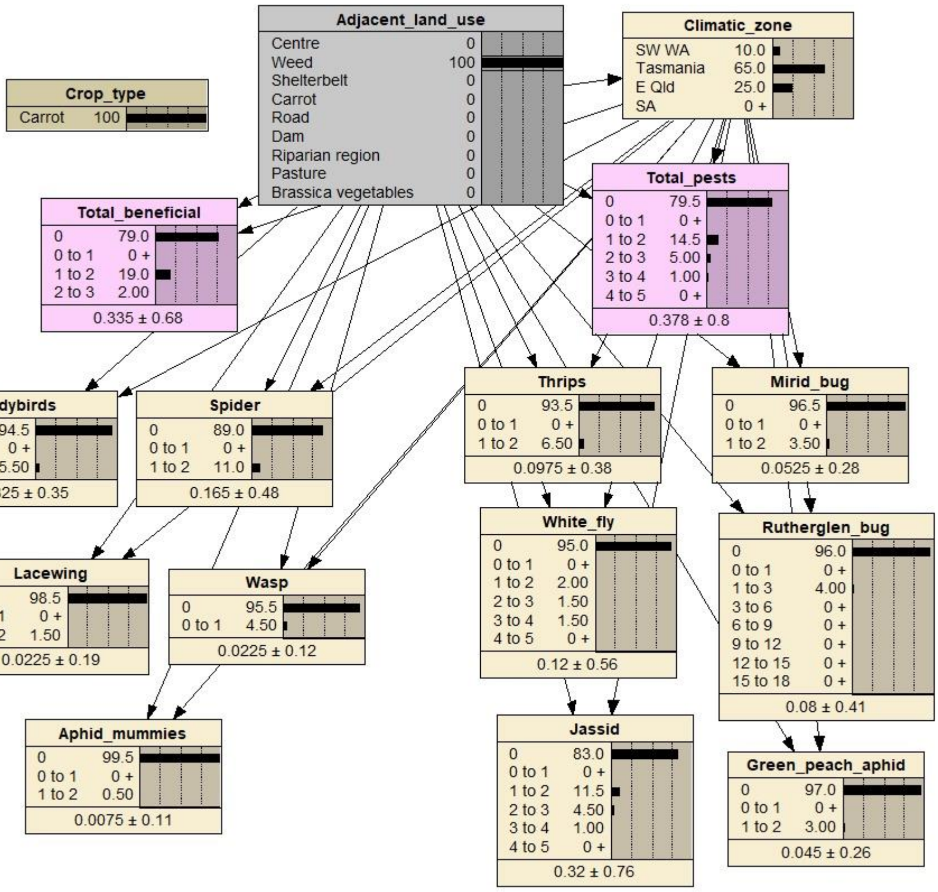


Figure A2.28. Bayesian network for the distribution of arthropods on the edge of carrot fields adjacent to weeds.

Table A2.4. Major pests of vegetable crops and the adjacent land types which significantly affect their population compared with the centre of the respective field. All findings were also verified by the BN modelling.

Major pests	Focal crops											
	Bean		Brassica		Capsicum		Carrot		Corn		Lettuce	
	Promote	Suppress	Promote	Suppress	Promote	Suppress	Promote	Suppress	Promote	Suppress	Promote	Suppress
Cabbage aphid	-	-	Shelterbelt	Weed	-	-	-	-	-	-	-	-
Green peach aphids	-	-	-	Bean, corn, and lettuce	-	-	-	-	-	-	-	-
Lettuce aphid	-	-	-	-	-	-	-	--	-	-	-	Lettuce, riparian, weed
Corn aphids	-	-	-	-	-	-	-	-	Shelterbelt	Banana plantation, riparian	-	-
Thrips	Tomato	Brassica, pasture, Road, weed	Corn and dam	-	-	-	Brassica, dam and riparian	-	Bean, brassica pasture	Road and weed	Brassica, grapes, riparian, shelterbelt weed	-
Whitefly	Road	Bean	Weed	Bean, riparian and shelterbelt	-	-	-	-	-	-	Brassica and grapes	Pasture, riparian, and shelterbelt
Rutherglen bug	Bean	-	Brassica and weed	Bean and riparian	Capsicum	-	-	Carrot, dam, pasture, road weed	-	Banana, riparian weed	Riparian, weed	Grapes, , pasture shelterbelt
Helicoverpa	-	-	-	Dam, pasture and road	-	-	-	-	-	Pasture, road and dam	-	-
Jassids	-	-	-	-	-	-	-	Pasture and riparian	Bean	-	Grapes	-
Mirids	-	-	-	-	-	-	Weed	-	-	-	-	-
Diamondback moth	-	-	Corn and pasture	Brassica and shelterbelt	-	-	-	-	-	-	-	-
Cabbage white butterfly	-	-	-	Shelterbelt and riparian	-	-	-	-	-	-	-	-
Brassica leaf miner	-	-	-	Shelterbelt	-	-	-	-	-	-	-	-

Table A2.5. Major beneficials of vegetable crops and the adjacent land types which significantly affect their population when compared with the centre of the respective field. All findings were also verified by the BN modelling.

Major beneficial	Focal crops											
	Bean		Brassica		Capsicum		Carrot		Corn		Lettuce	
	Promote	Suppress	Promote	Suppress	Promote	Suppress	Promote	Suppress	Promote	Suppress	Promote	Suppress
Ladybeetle	Pasture	-	Brassica, pasture and shelterbelt	Riparian	-	-	Shelterbelt	-	Banana, corn, shelterbelt weed	Bean and pasture	Shelterbelt riparian	Weed
Soldier beetle	-	-			-	-	-	-	Corn, shelterbelt pasture	-	-	-
Spider	Pasture	-	Riparian, corn, road, shelterbelt weed	-	Sorghum	-	-	-	Dam, pasture, shelterbelt weed	-	Shelterbelt and road	-
Red and blue beetle	-	-			-	-	-	-	Riparian, shelterbelt and weed	-	-	-
Orius species	-	-			-	-	-	-	Shelterbelt and weed	Road	-	-
Brown lacewing	-		Corn and shelterbelt	-	-	-	-	-	Riparian region	-	-	Lettuce
Green lacewing	-				Sorghum	Road	-	-	Banana plantation basil	-	-	-
Wasp	-	-	Shelterbelt and pasture		-	-	Dam, pasture, shelterbelt weed	-	-	-	Brassica riparian, road and weed.	-
Pirate bug	-	-			Weed	-	-	-	-	-	-	-
Aphid mummies	-	-	-	-	-	-	-	-	Pasture and shelterbelt	-	Brassica vegetables, weed, and road	-

Lettuce

In lettuce, whitefly (*Bemisia*) was most numerous pest, followed by Rutherglen bug (*Nysius vinitor*), thrips (*Frankliniella occidentalis*), and lettuce aphid (*Nasonovia ribisnigri*). Whitefly numbers were higher on the field edge of the lettuce fields adjacent to brassica vegetables and vineyards, and were significantly lower near roads, pasture and riparian regions when compared with the centre of the field (Fig. A2.29). Rutherglen bug numbers were higher adjacent to riparian regions and weeds (Fig. A2.30) Thrips were higher adjacent to riparian regions, brassica fields, shelterbelts, weeds and vineyards (Fig. A2.31). Lettuce aphid were significantly fewer in number adjacent to weed, riparian region and other lettuce fields (Fig. A2.32). A higher mean number of aphid mummies were recorded in the edges of the lettuce field adjacent to weed, brassica vegetables, weed and roads (Fig. A2.33).

Pooled analysis of total beneficial guild numbers at the field edge of lettuce fields showed significantly higher numbers adjacent to riparian regions and roads when compared with the centre of the lettuce fields (Fig. A2.34). Significantly higher numbers of ladybeetles found adjacent to shelterbelts, roads and weeds; wasps were significantly higher adjacent to brassica fields, riparian regions, roads and weeds (Fig. A2.35). BN models also confirm the role of, shelterbelts, roads, weeds and crops in improving the abundance of ladybeetles and reducing the number of total pests (Fig. A2.36, 37, 38, 39).

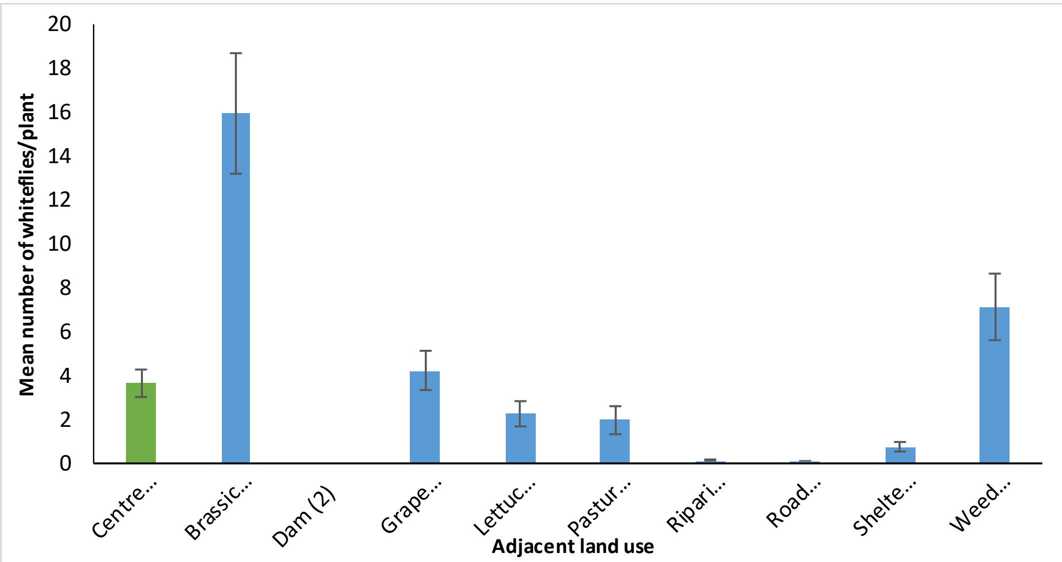


Figure A2.29. Mean numbers of whitefly in lettuce. The 'Centre' (green) column shows count at the field centre and other columns show the count at the field edge adjacent to the land use labelled. * indicates where number along the field edge is significantly different to the centre of the field at a 5% level of probability. Number in brackets show the numbers of fields with each adjacent land use.

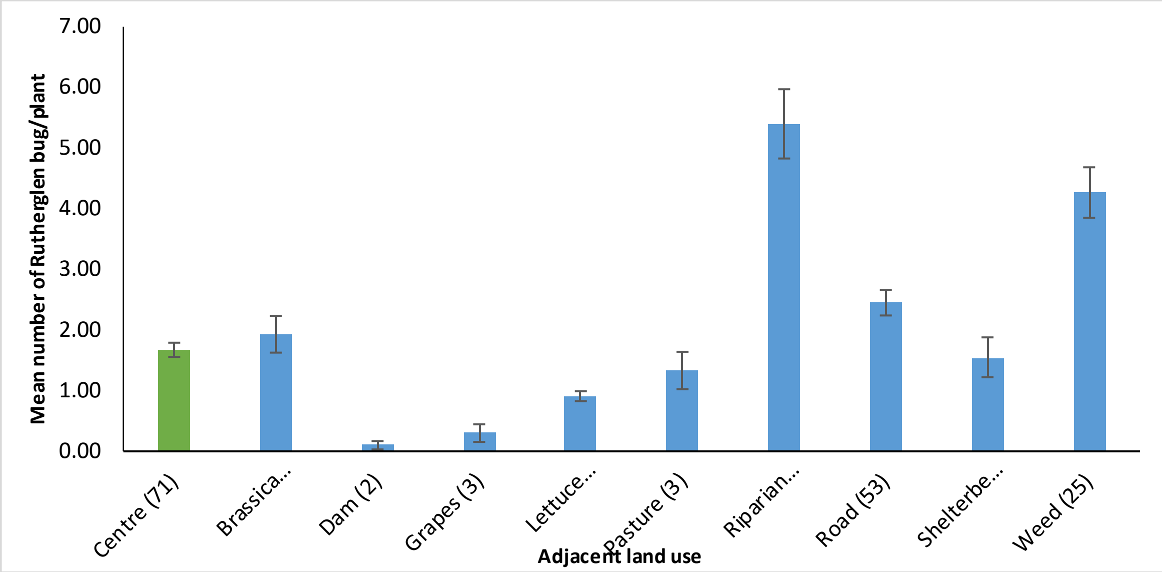


Figure A2.30. Mean number of Rutherglen bugs in lettuce. The 'Centre' (green) column shows count at the field centre and other columns show the count at the field edge adjacent to the land use labelled. * indicates where number along the field edge is significantly different to the centre of the field at a 5% level of probability. Number in brackets show the numbers of fields with each adjacent land use.

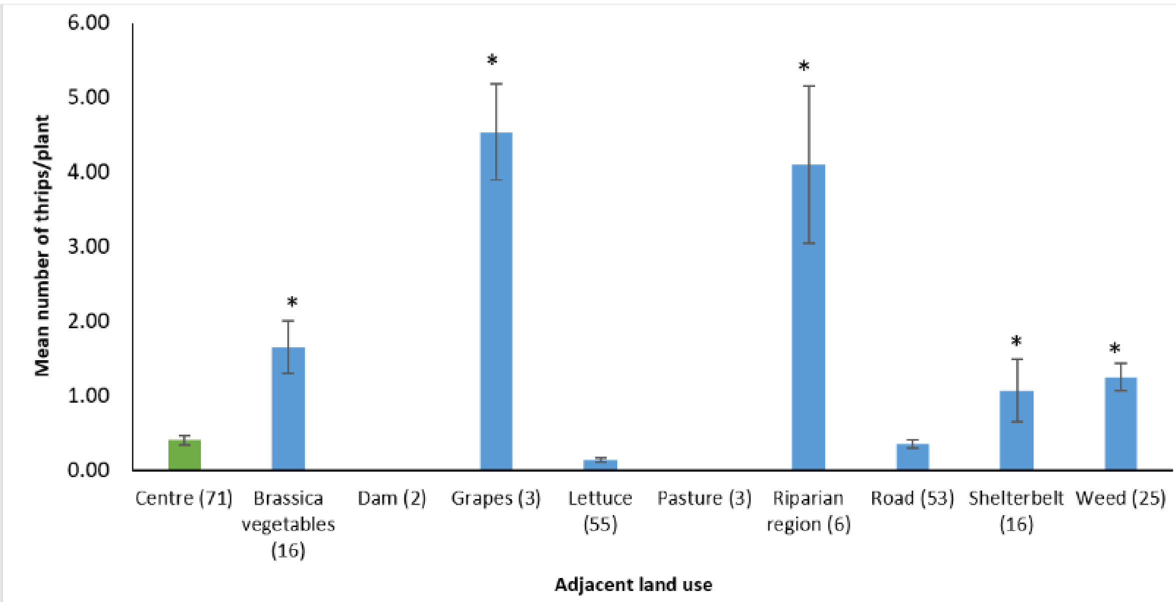


Figure A2.31. Mean number of thrips in lettuce. The 'Centre' (green) column shows count at the field centre and other columns show the count at the field edge adjacent to the land use labelled. * indicates where number along the field edge is significantly different to the centre of the field at a 5% level of probability. Number in brackets show the numbers of fields with each adjacent land use.

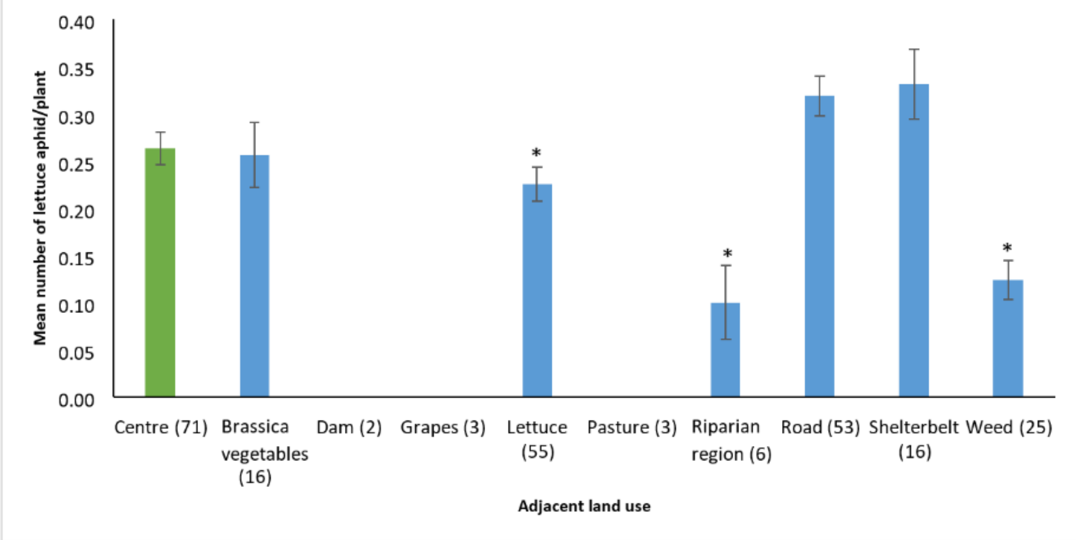


Figure A2.32. Mean number of aphid in lettuce. The 'Centre' (green) column shows count at the field centre and other columns show the count at the field edge adjacent to the land use labelled. * indicates where number along the field edge is significantly different to the centre of the field at a 5% level of probability. Number in brackets show the numbers of fields with each adjacent land use.

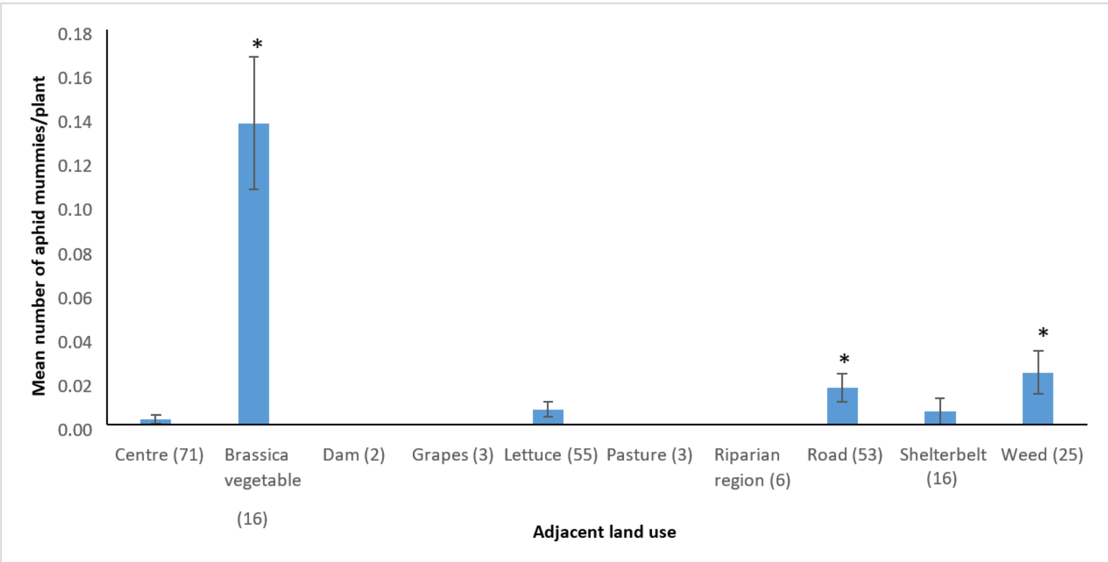


Figure A2.33. Aphid parasitoid activity in lettuce indicated by mean numbers of aphid mummies. The 'Centre' column shows count at the field centre and other columns show the count at the field edge adjacent to the land use labelled. * indicates where number along the field edge is significantly different to the centre of the field at a 5% level of probability. Number in brackets show the numbers of fields with each adjacent land use.

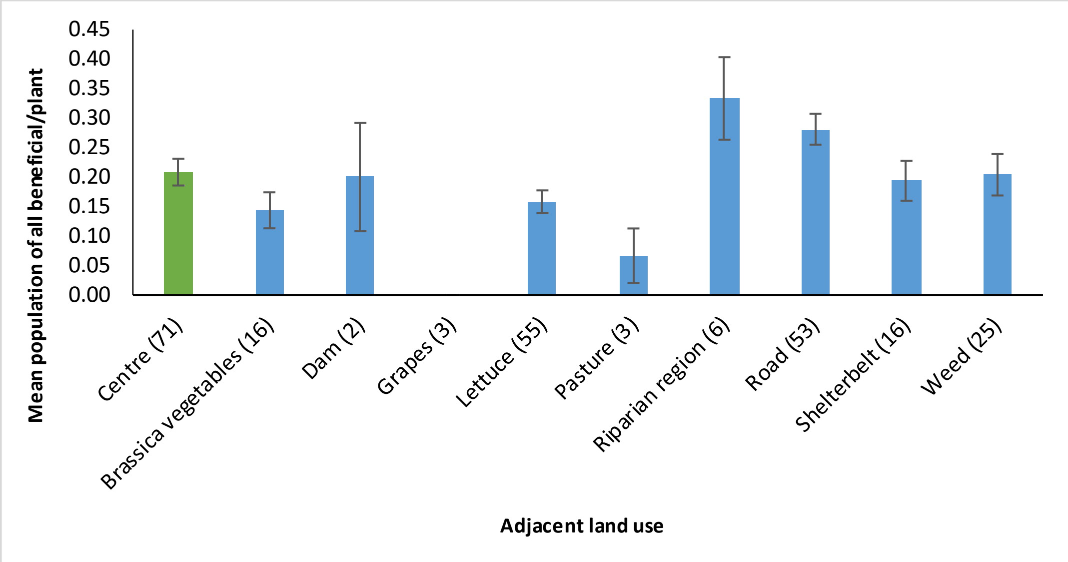


Figure A2.34. Mean number of beneficials in lettuce fields. The 'Centre' (green) column shows count at the field centre and other columns show the count at the field edge adjacent to the land use labelled. * indicates where number along the field edge is significantly different to the centre of the field at a 5% level of probability. Number in brackets show the numbers of fields with each adjacent land use.

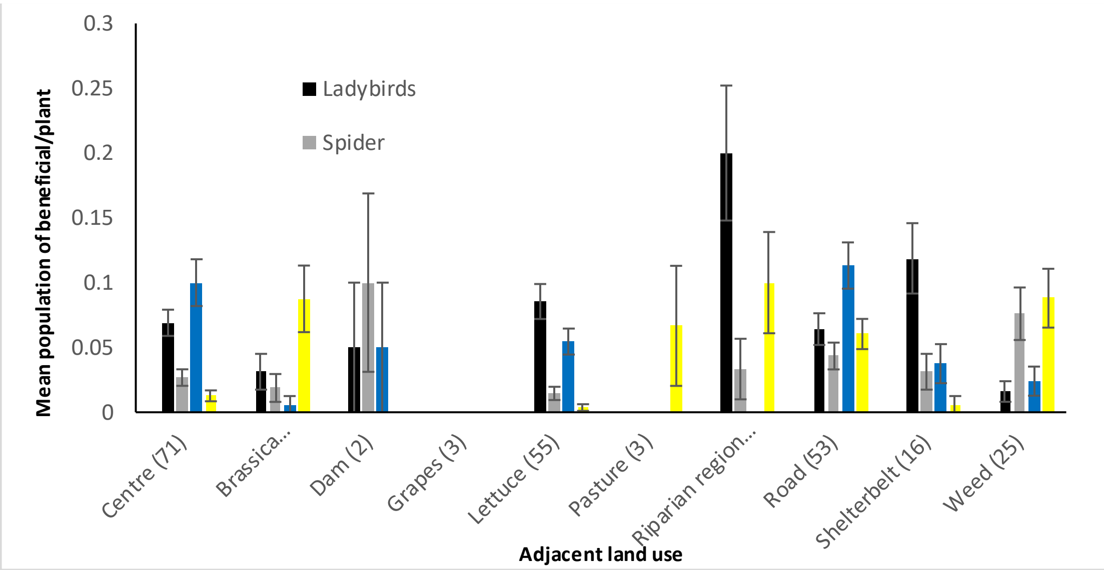


Figure A2.35. Mean number of beneficials by taxa in lettuce fields. The 'Centre' column shows count at the field centre and other columns show the count at the field edge adjacent to the land use labelled. * indicates where number along the field edge is significantly different to the centre of the field at a 5% level of probability. Number in brackets show the numbers of fields with each adjacent land use.

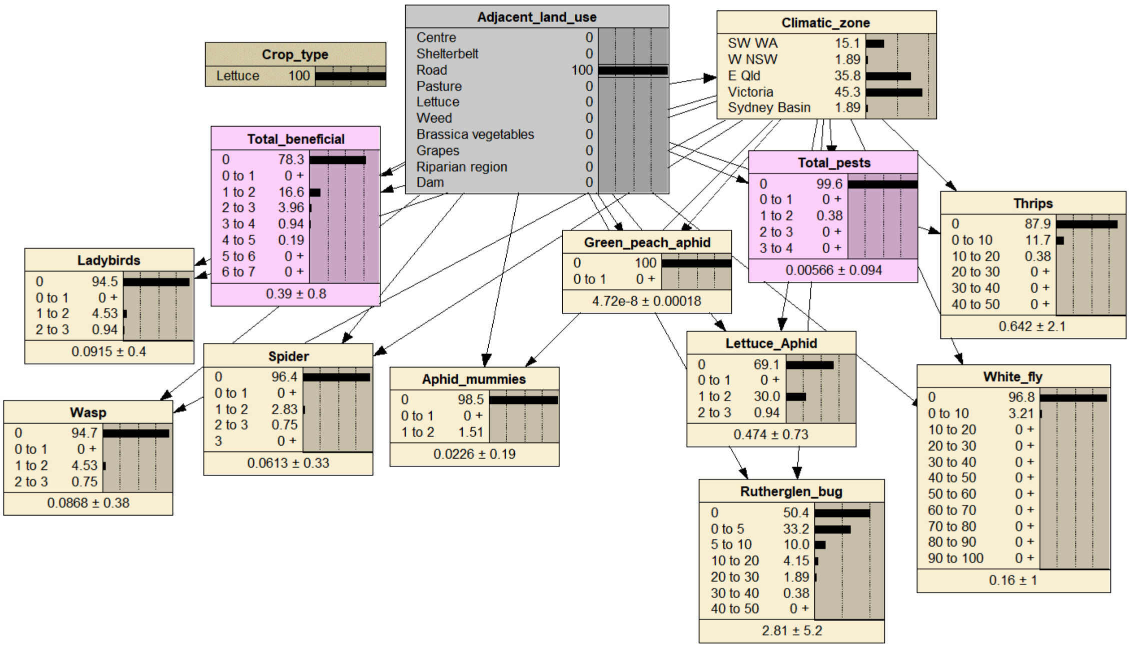


Figure A2.36. Bayesian network for the distribution of arthropods on the edge of lettuce fields adjacent to roads.

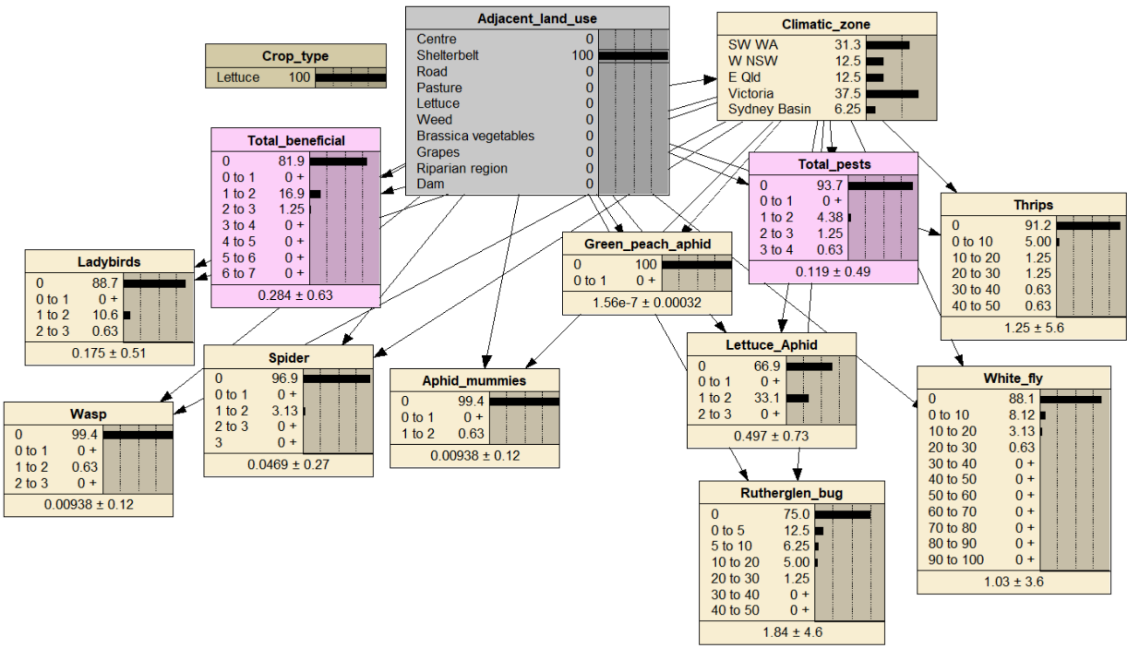


Figure A2.37. Bayesian network for the distribution of arthropods on the edge of lettuce fields adjacent to shelterbelts.

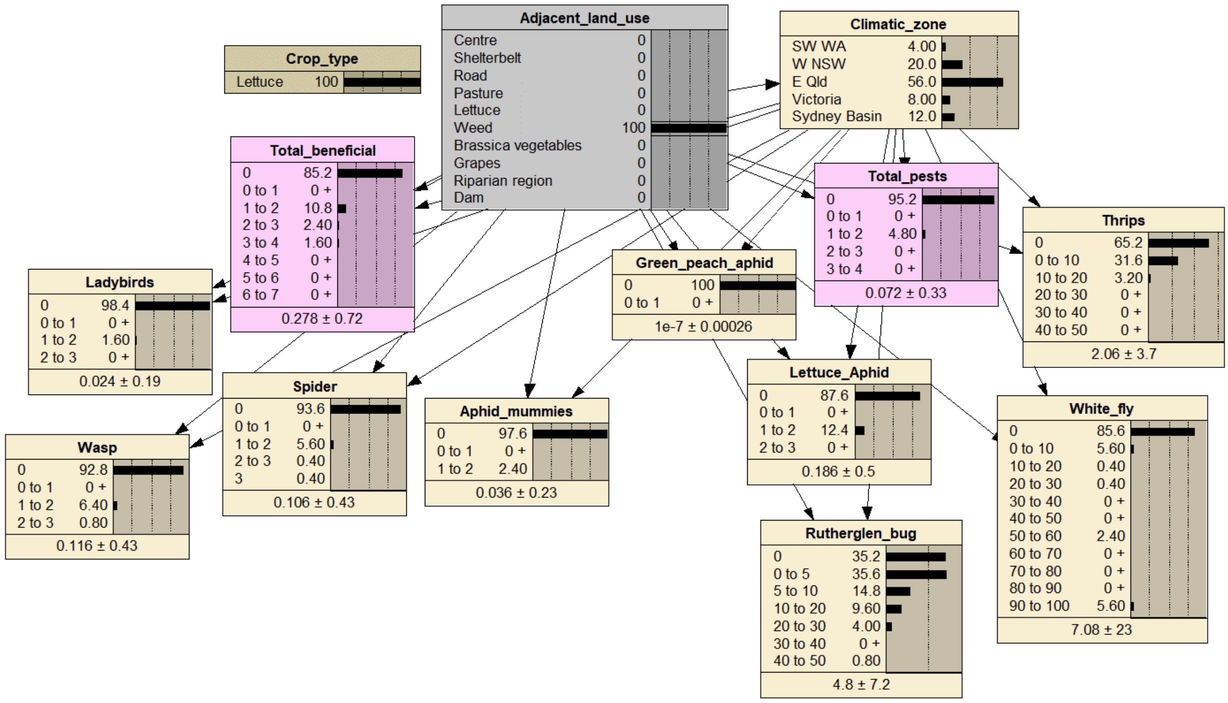


Figure A2.38. Bayesian network for the distribution of arthropods on the edge of lettuce fields adjacent to weeds.

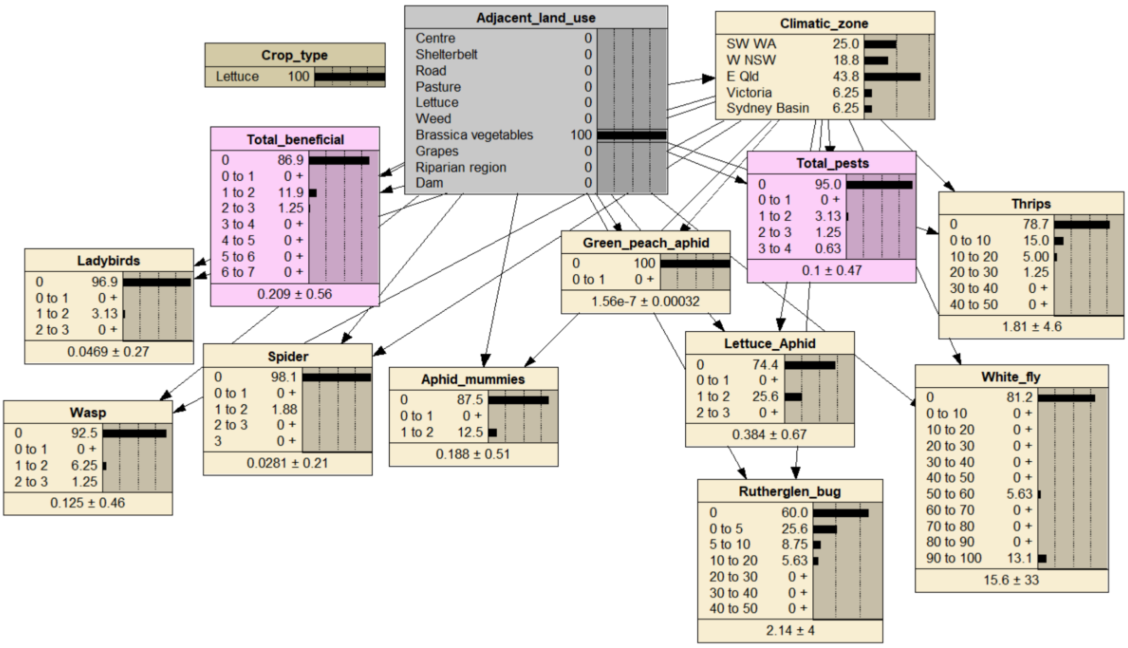


Figure A2.39. Bayesian network for the distribution of arthropods on the edge of lettuce fields adjacent to brassica vegetables.

Beans

In bean fields, tobacco cutworm, whitefly, thrips, and Rutherglen bug were the most numerous pests. Whitefly numbers were elevated on margin of the bean fields adjacent to roads but suppressed in margins adjacent to other bean fields (Fig. A2.40,41). In contrast, Rutherglen bug numbers were higher in the margins of the bean fields adjacent to other bean fields and not suppressed by any type of adjacent land use (Fig. A2.42). Thrips numbers exhibited some significant effects but sample sizes were mostly small (Fig. A2.43). Pooled analysis of beneficials were dominated by ladybirds and spiders; these showed higher numbers in crop fields adjacent to pasture when compared with the centre of the bean fields but sample size was small (Fig. A2.44, 45).

BN models of arthropod distribution on the edges of beans fields adjacent to pasture showed an abundance of beneficials, including spiders and ladybeetles (Fig. A2.46). Bean field edges adjacent to roads had an abundance of whiteflies (Fig. A2.47).

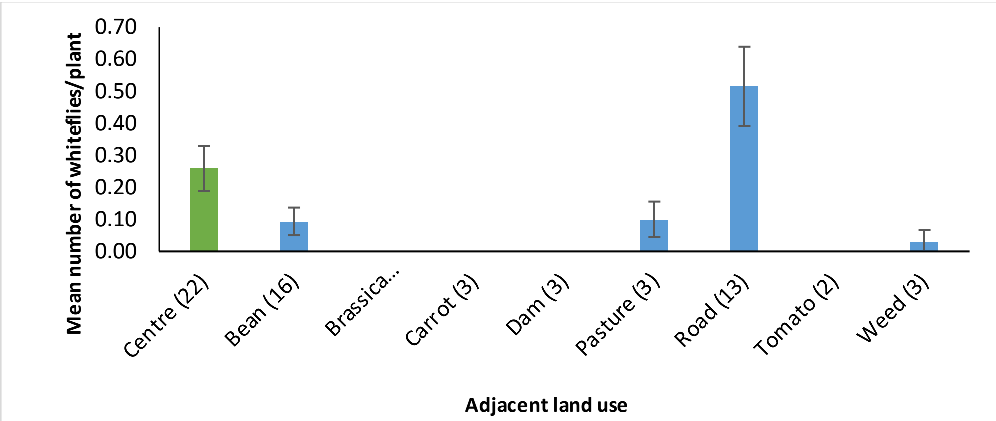


Figure A2.40. Mean number of whiteflies in bean fields. The 'Centre' (green) column shows count at the field centre and other columns show the count at the field edge adjacent to the land use labelled. * indicates where number along the field edge is significantly different to the centre of the field at a 5% level of probability. Number in brackets show the numbers of fields with each adjacent land use.

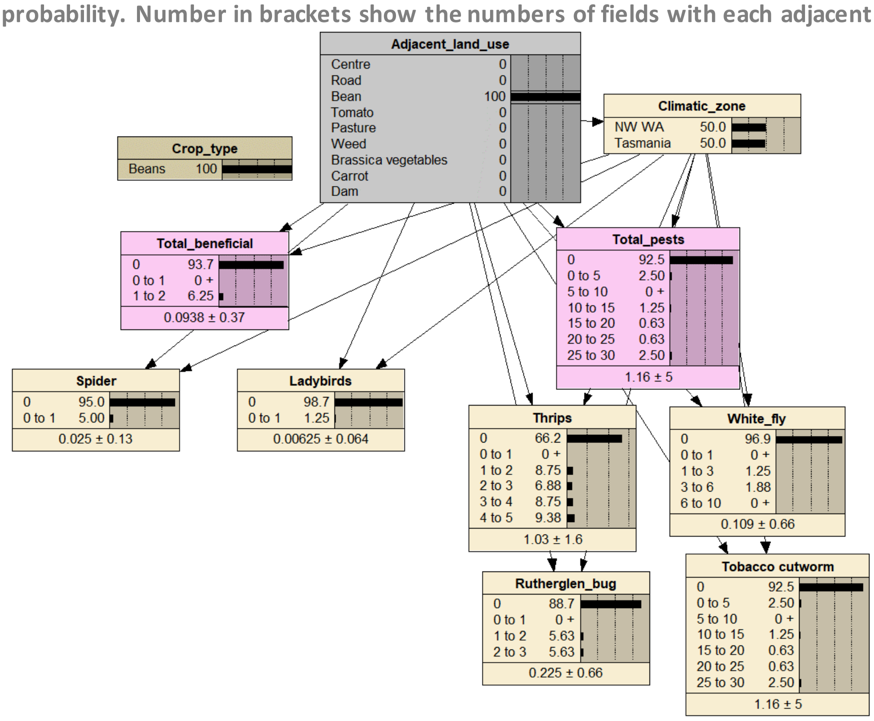


Figure A2.41. Bayesian network for the distribution of arthropods on the edge of beans fields adjacent to beans.

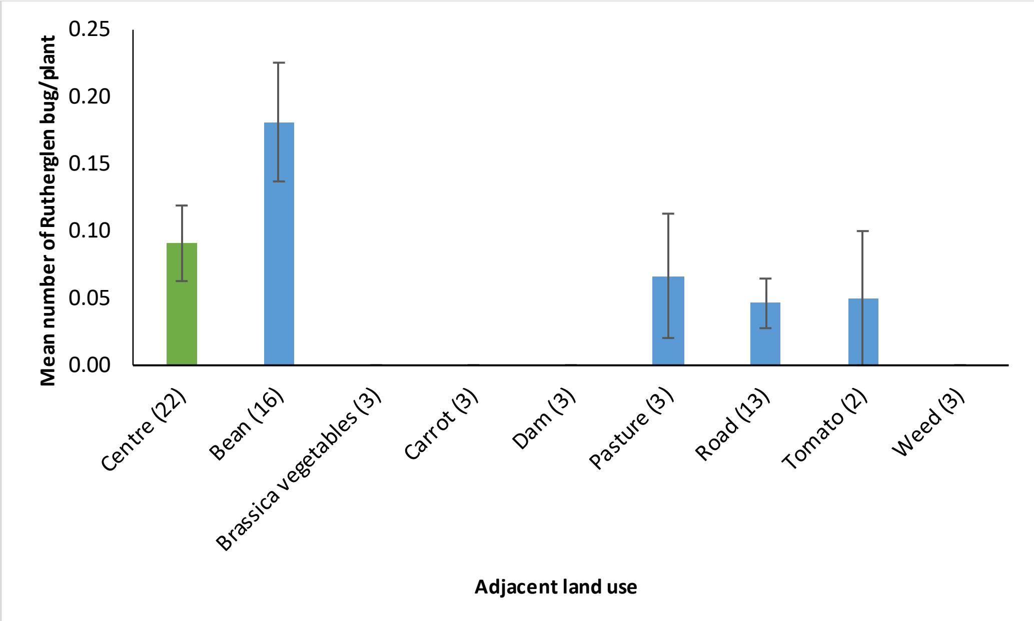


Figure A2.42. Mean number of Rutherglen bug in bean fields. The 'Centre' (green) column shows count at the field centre and other columns show the count at the field edge adjacent to the land use labelled. * indicates where number along the field edge is significantly different to the centre of the field at a 5% level of probability. Number in brackets show the numbers of fields with each adjacent land use.

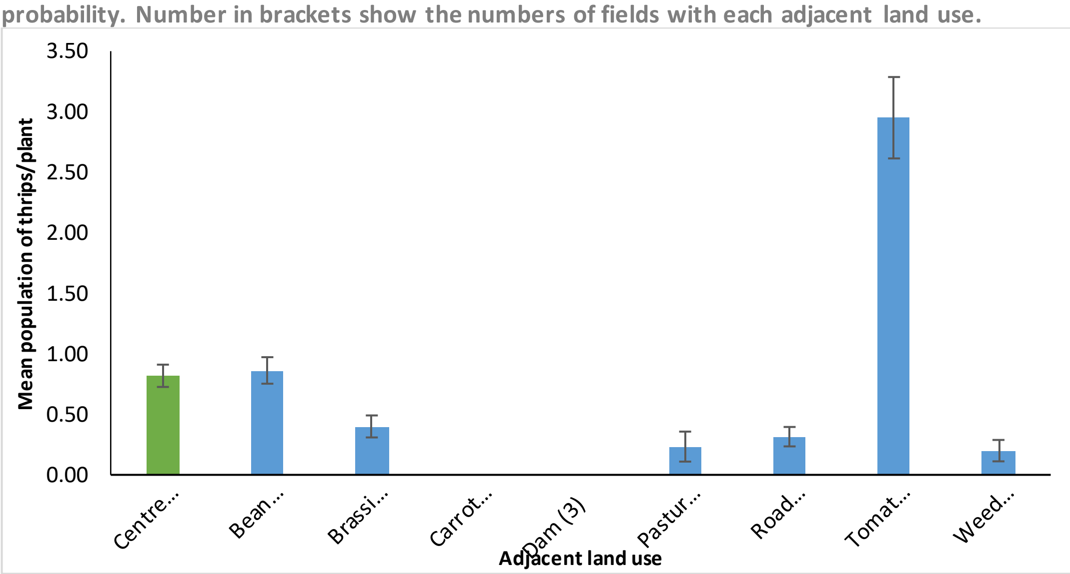


Figure A2.43. Mean number of thrips in bean fields. The 'Centre' (green) column shows count at the field centre and other columns show the count at the field edge adjacent to the land use labelled. * indicates where number along the field edge is significantly different to the centre of the field at a 5% level of probability. Number in brackets show the numbers of fields with each adjacent land use.

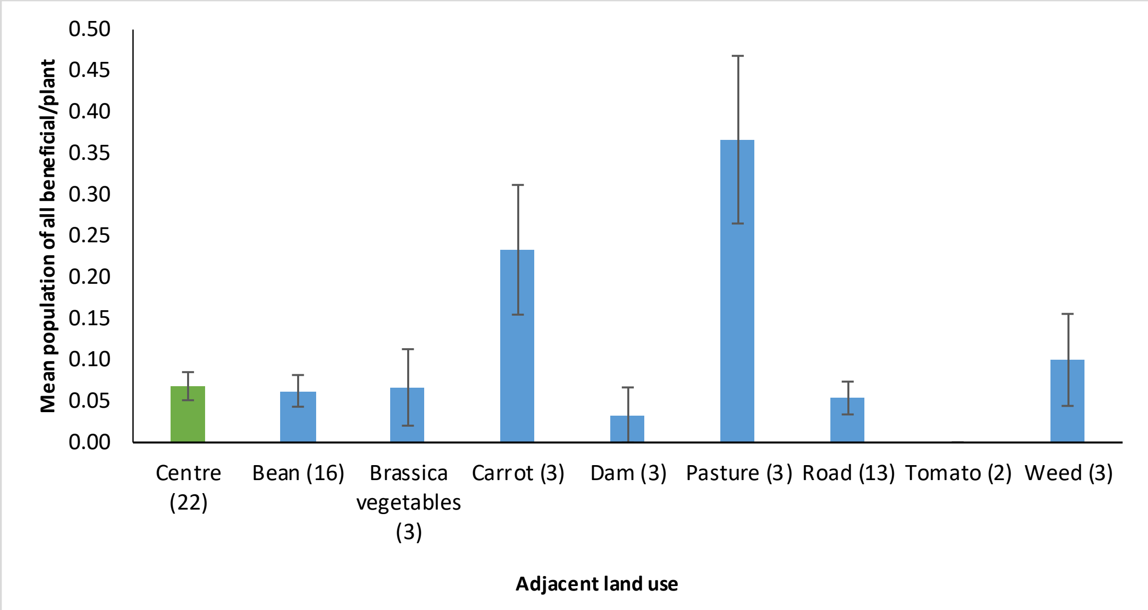


Figure A2.44. Mean number of beneficials in bean fields. The 'Centre' (green) column shows count at the field centre and other columns show the count at the field edge adjacent to the land use labelled. * indicates where number along the field edge is significantly different to the centre of the field at a 5% level of probability. Number in brackets show the numbers of fields with each adjacent land use.

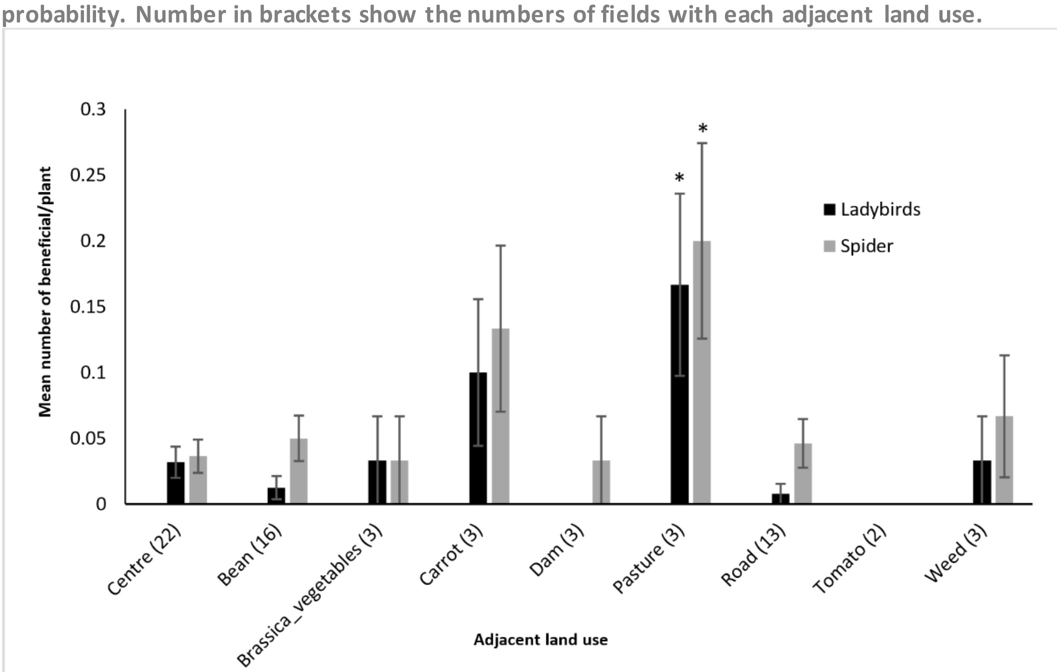


Figure A2.45. Mean number of ladybeetles and spiders in bean fields. The 'Centre' column shows count at the field centre and other columns show the count at the field edge adjacent to the land use labelled. * indicates where number along the field edge is significantly different to the centre of the field at a 5% level of probability. Number in brackets show the numbers of fields with each adjacent land use.

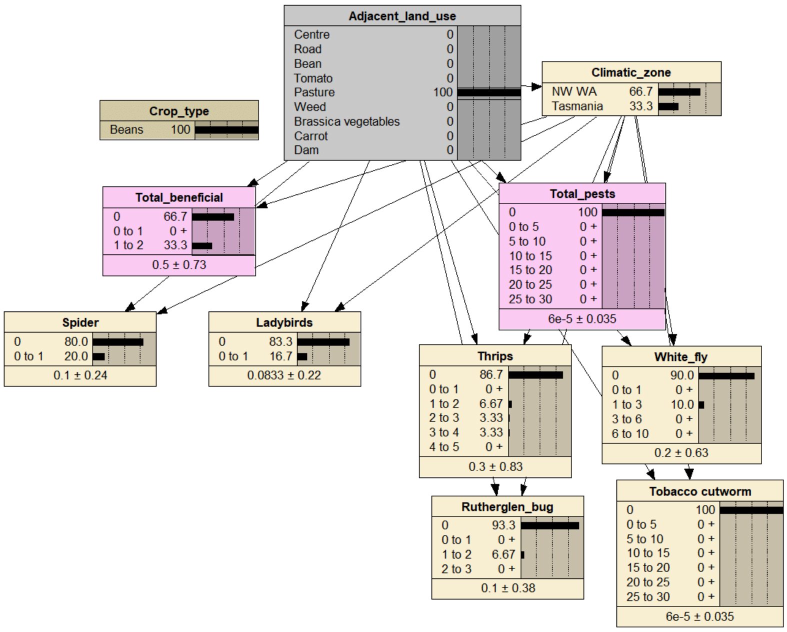


Figure A2.46. Bayesian network for the distribution of arthropods on the edge of beans fields adjacent to pasture.

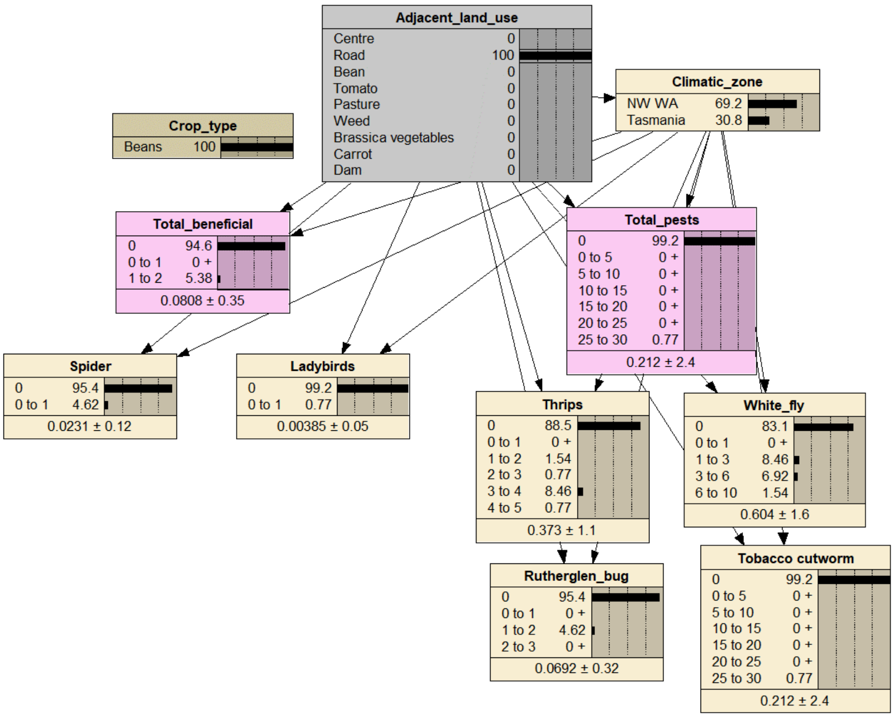


Figure A2.47. Bayesian network for the distribution of arthropods on the edge of beans fields adjacent to road.

Capsicum

Rutherglen bugs, whiteflies, thrips and fruit flies ('medfly', *Ceratitis capitata* (WA only)) were the most numerous pests in capsicum fields. Rutherglen bugs were higher in the field edges of the capsicum fields adjacent to roads and other capsicum fields (Fig. A2.48). The abundance of all other pests was not affected by adjacent land use types when compared with the centre. Fruit fly numbers were high in the centre of capsicum fields but completely absent at the field edge adjacent to sorghum and roads with large sample sizes. Significantly higher numbers of beneficials were present in the edges of capsicum fields adjacent to sorghum fields when compared to the centre of the capsicum fields (Fig. A2.49). Analysis of individual beneficial taxa shows the numbers of green lacewing was significantly higher in margins of capsicum fields near sorghum but significantly fewer in number near roads (Fig. A2.50).

The abundance of beneficials and pests were also verified by BN modelling. Pirate bugs were predominant on the edge of capsicum fields adjacent to weed (Fig. A2.51). Capsicum crop adjacent to sorghum had higher numbers of lacewings and lower numbers of thrips, whiteflies, and fruit flies (Fig A2.52). Rutherglen bug was numerous near the margin of the capsicum fields adjacent to road and capsicum (Fig. A2.53-54).

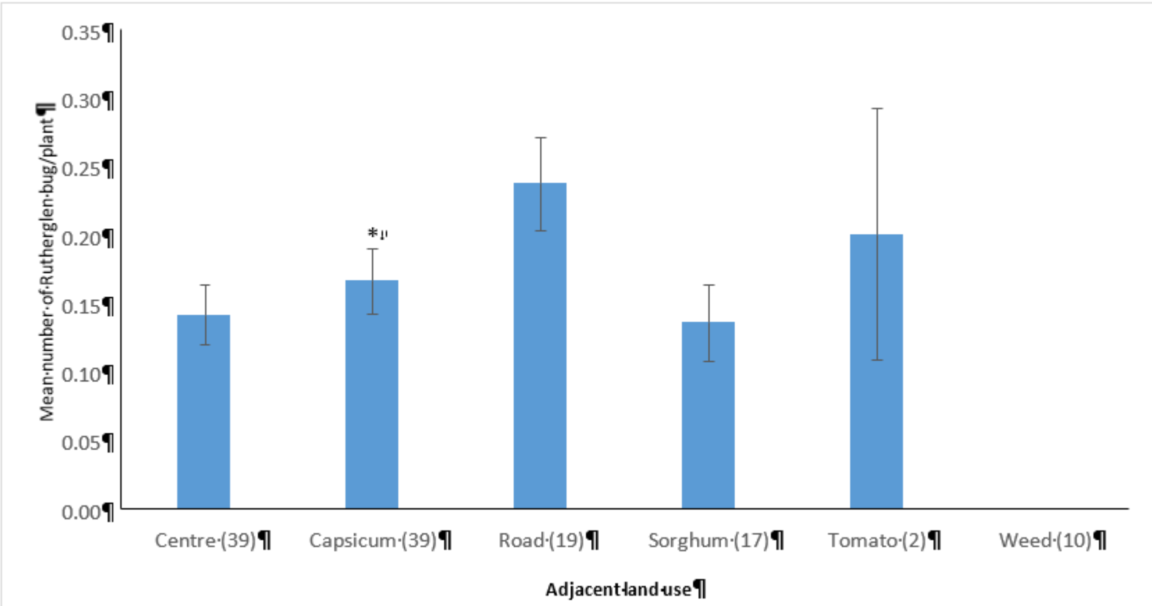


Figure A2.48. Mean number of Rutherglen bug in capsicum fields. The 'Centre' column shows count at the field centre and other columns show the count at the field edge adjacent to the land use labelled. * indicates where number along the field edge is significantly different to the centre of the field at a 5% level of probability. Number in brackets show the numbers of fields with each adjacent land use.

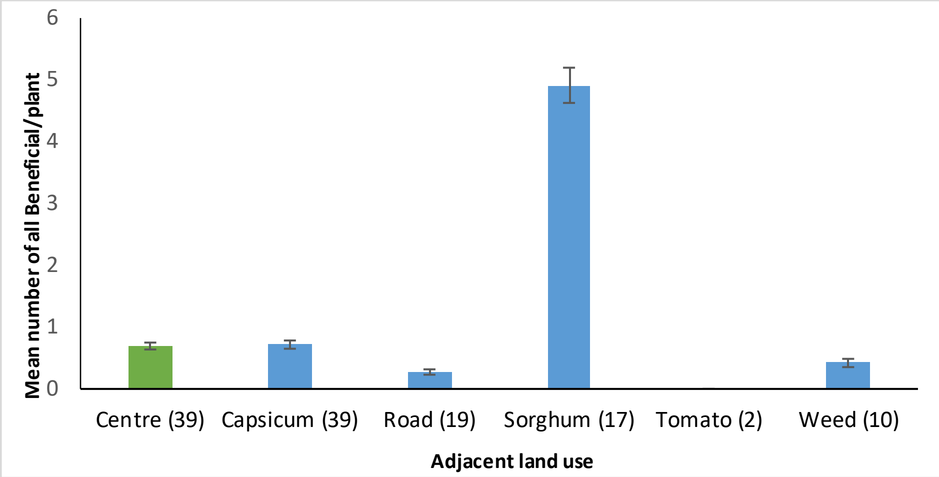


Figure A2.49. Mean number of beneficial in capsicum fields. The 'Centre' (green) column shows count at the field centre and other columns show the count at the field edge adjacent to the land use labelled. * indicates where number along the field edge is significantly different to the centre of the field at a 5% level of probability. Number in brackets show the numbers of fields with each adjacent land use.

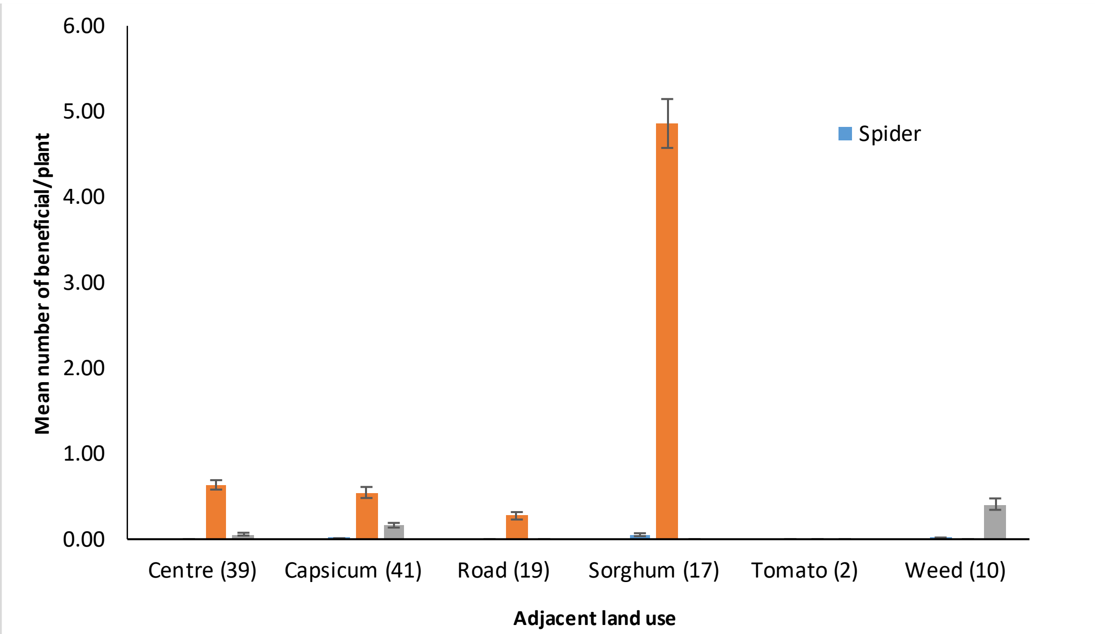


Figure A2.50. Mean number of beneficials by taxa in capsicum fields. The 'Centre' (green) column shows count at the field centre and other columns show the count at the field edge adjacent to the land use labelled. * indicates where number along the field edge is significantly different to the centre of the field at a 5% level of probability. Number in brackets show the numbers of fields with each adjacent land use.

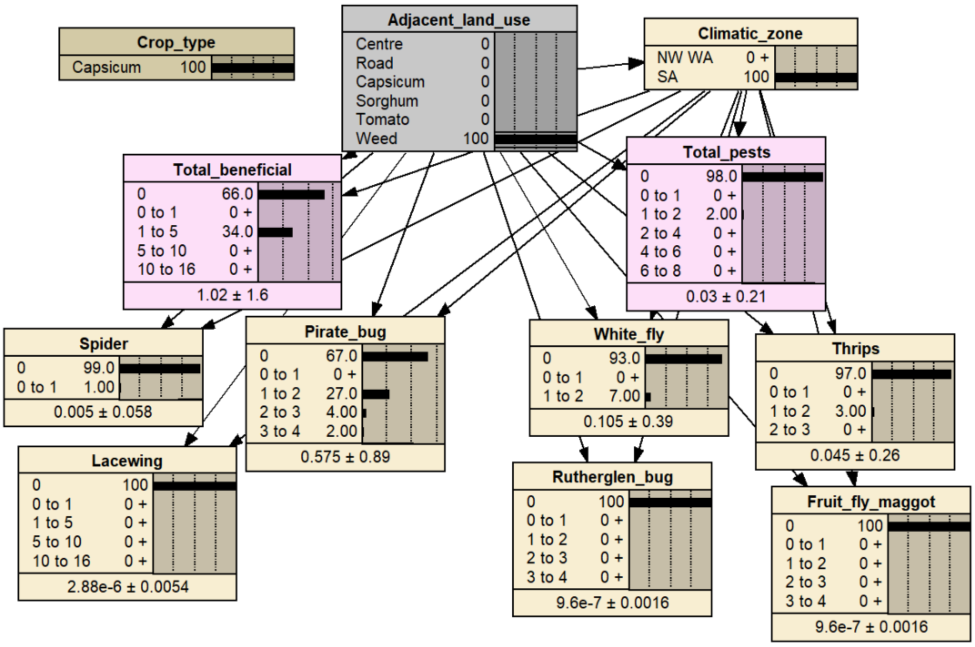


Figure A2.51. Bayesian network for the distribution of arthropods on the edge of capsicum fields adjacent to weed.

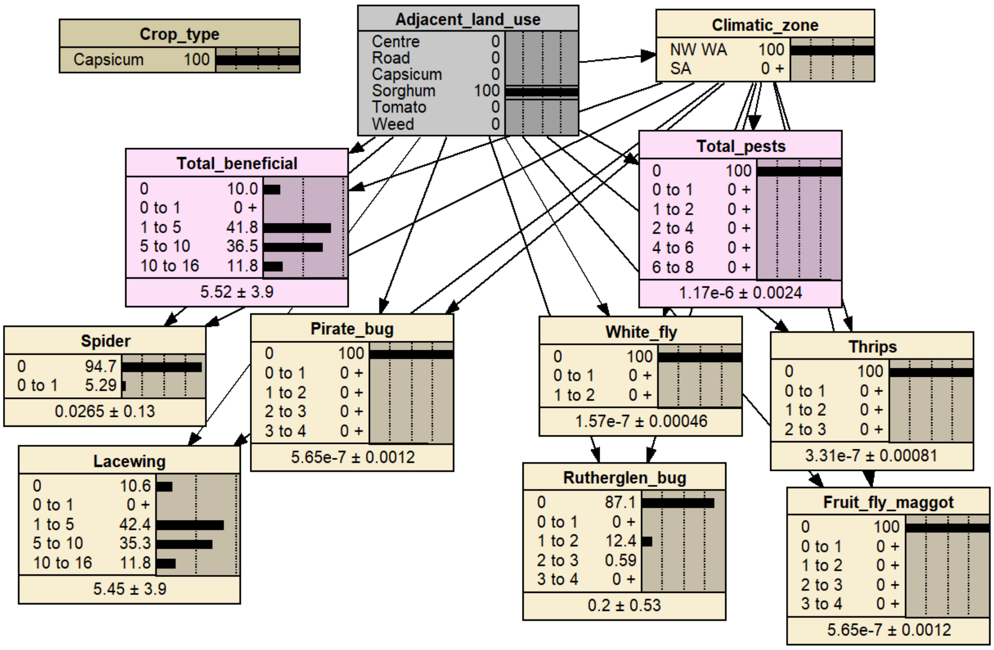


Figure A2.52. Bayesian network for the distribution of arthropods on the edge of capsicum fields adjacent to sorghum.

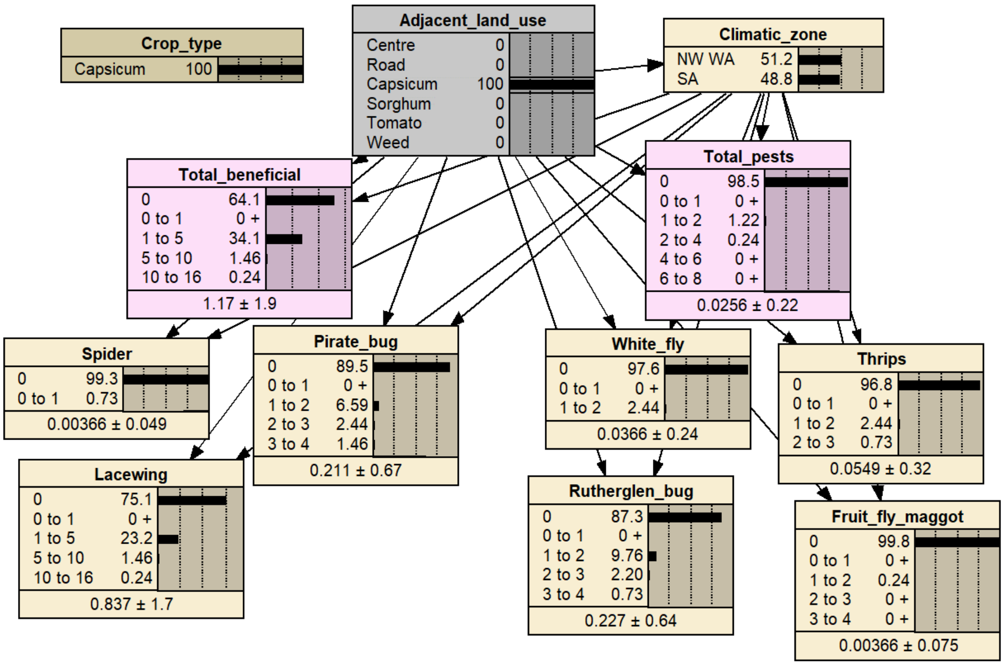


Figure A2.53. Bayesian network for the distribution of arthropods on the edge of capsicum fields adjacent to capsicum.

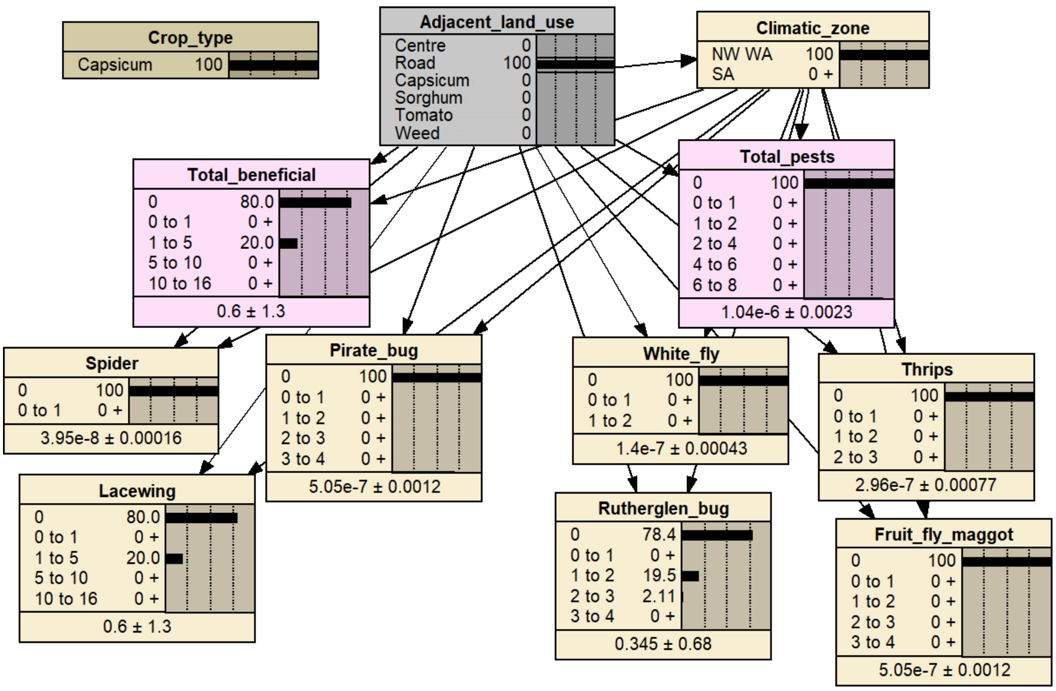


Figure A2.54. Bayesian network for the distribution of arthropods on the edge of capsicum fields adjacent to road.

Brassicas

A total of 246 fields of different brassica vegetables were surveyed. Diamondback moth (*Plutella xylostella*), green peach aphids, cabbage aphid (*Brevicoryne brassicae*) and whitefly (*Bemisia tabaci*) were the major pests species encountered. Geographical location and adjacent land use significantly influenced the total pest population (Fig. A2.55, 56). Significantly fewer pests were recorded near shelterbelts and other brassica crops whereas, significantly higher numbers of pests were found near corn and pasture when compared to the centre of the brassica fields (Fig. A2.55). Among individual pests, diamondback moth (DBM) was the most prevalent pest of brassica vegetables, found in all regions (Fig. A2.56). Shelterbelts adjacent to brassica fields significantly reduced the number of DBM on the edge of the field compared to the number in the centre of the fields (Fig. A2.57). Cabbage white butterfly was reduced in edges close to riparian vegetation, other brassica fields and shelterbelts (Fig A2.57). Thrips were significantly higher adjacent to corn and dams (Fig. A2.58). Green peach aphids were significantly fewer adjacent to lettuce, corn and beans (Fig. A2.59) whereas, cabbage aphids were significantly fewer in number adjacent to weedy areas and more abundant close to shelterbelts (Fig. A2.60). There was no significant effect of adjacent land use type on the activity of parasitoids as indicated by of aphid mummies. Pooled analysis of total beneficials showed significantly higher numbers in the margins adjacent to shelterbelts, roads and corn fields when compared with the centre of the brassica fields (Fig. A2.61). Analysis of individual beneficial taxa showed the numbers of brown lacewing, ladybeetle, and parasitoids were significantly higher at margin of brassica fields near shelterbelts when compared with the centre of field (Fig. A2.62). There were other minor pests and beneficials found in brassica fields and significantly different when compared with the centre of field (Table 2 & 3).

BN models of arthropods distribution on the edges of brassica field adjacent to shelterbelt, roads and corn fields showed the higher number of beneficials including, ladybeetles, wasps, spiders and lacewings (Fig. A2.63, 64, 61). Pasture fields next to the brassica fields attracted DBM and green peach aphids (Fig. A2.65).

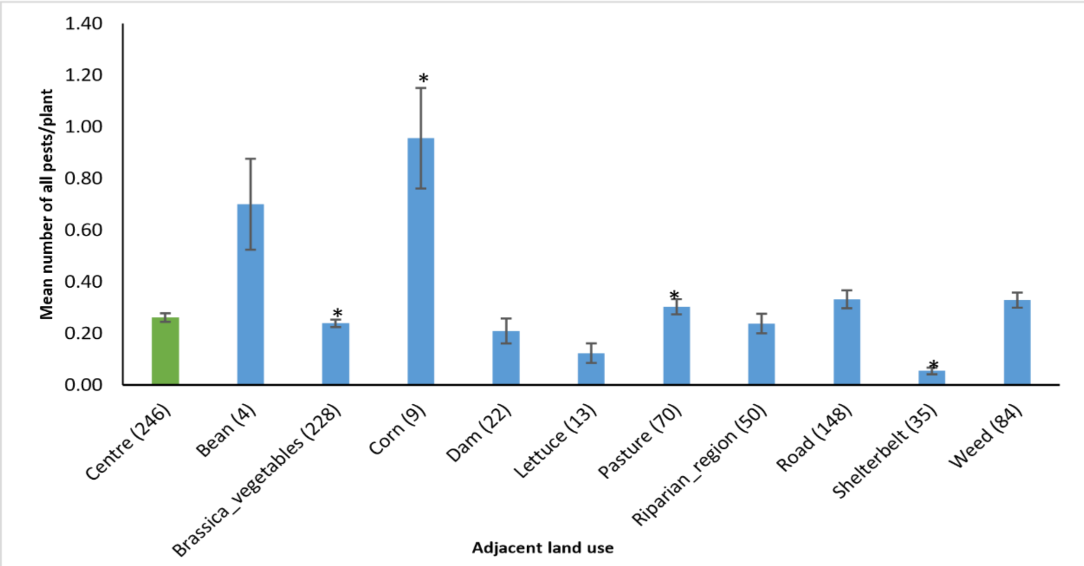


Figure A2.55. Mean number of pests in brassica fields. The 'Centre' (green) column shows count at the field centre and other columns show the count at the field edge adjacent to the land use labelled. * indicates where number along the field edge is significantly different to the centre of the field at a 5% level of probability. Number in brackets show the numbers of fields with each adjacent land use.

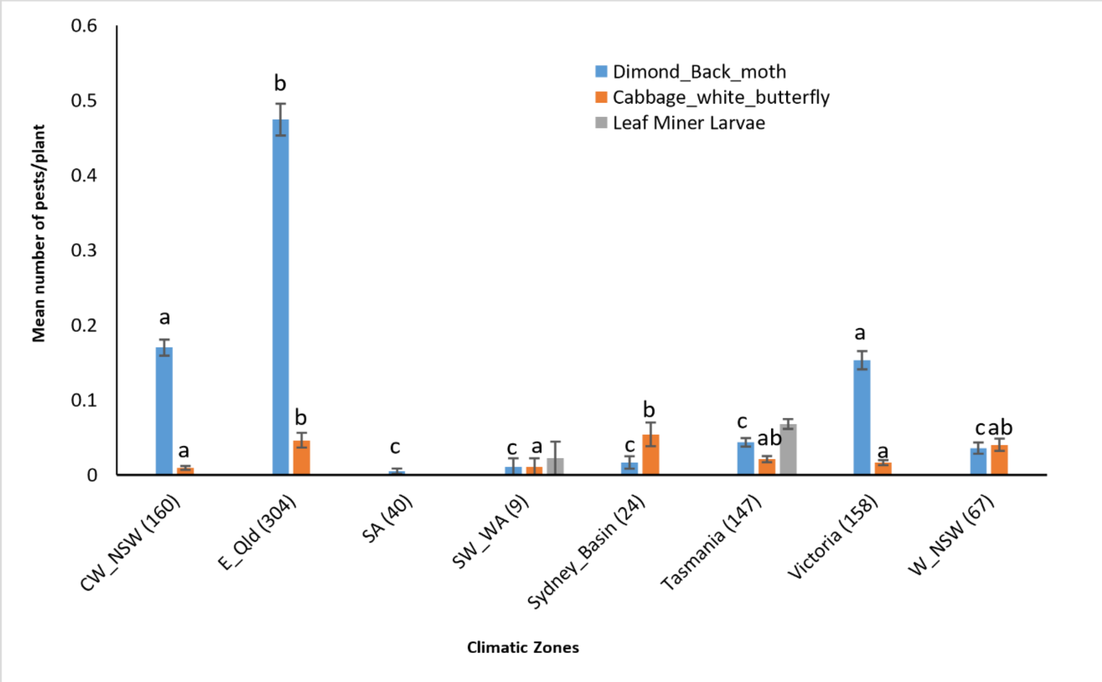


Figure A2.56. Mean number of pests by taxa in brassica fields in different geographical zones of Australia. Letters indicate significant difference between geographical zone at 5% level of probability. Number in brackets shows the number of fields.

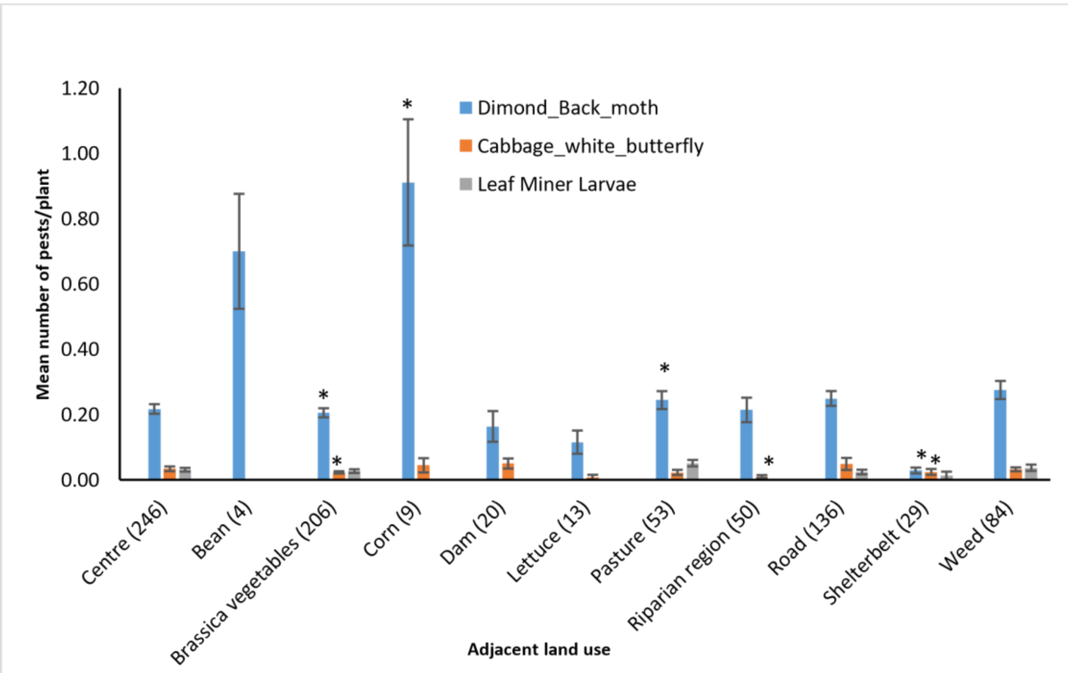


Figure A2.57. Mean number of pest by taxa in brassica fields. The 'Centre' column shows count at the field centre and other columns show the count at the field edge adjacent to the land use labelled. * indicates where number along the field edge is significantly different to the centre of the field at a 5% level of probability. Number in brackets show the numbers of fields with each adjacent land use.

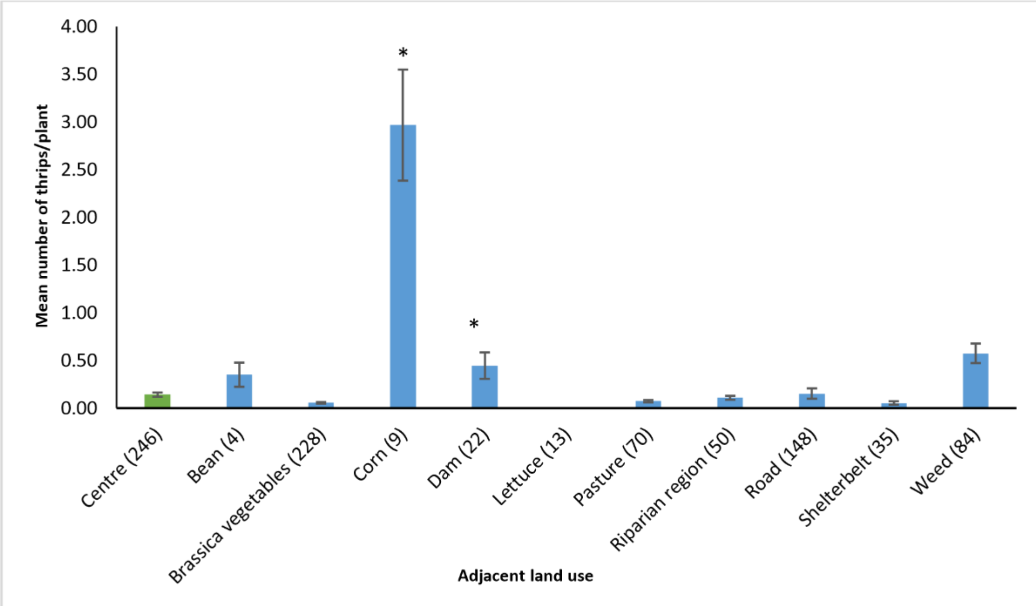


Figure A2.58. Mean number of thrips in brassica fields. The 'Centre' (green) column shows count at the field centre and other columns show the count at the field edge adjacent to the land use labelled. * indicates where number along the field edge is significantly different to the centre of the field at a 5% level of probability. Number in brackets show the numbers of fields with each adjacent land use.

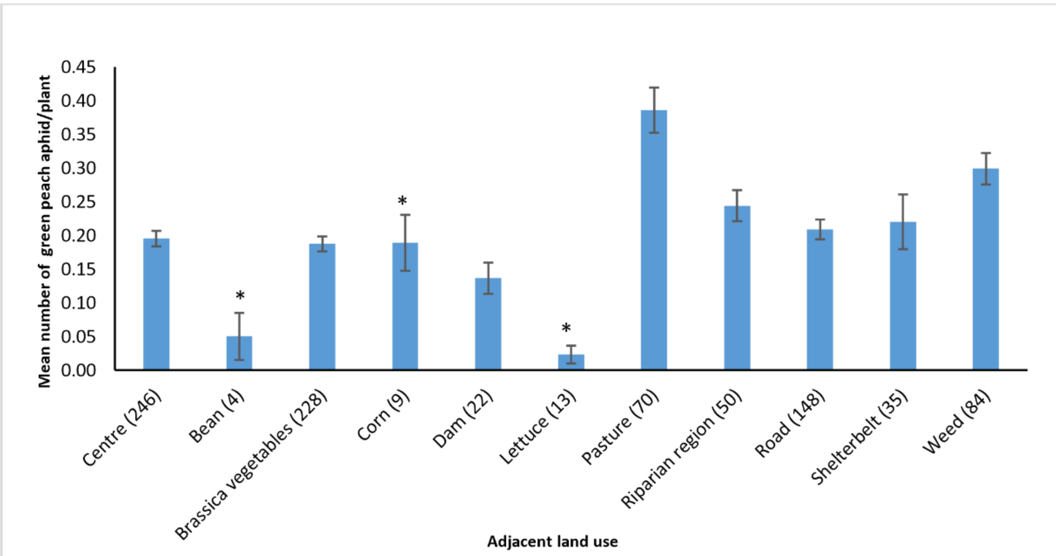


Figure A2.59. Mean number of green peach aphid in brassica fields. The 'Centre' column shows count at the field centre and other columns show the count at the field edge adjacent to the land use labelled. * indicates where number along the field edge is significantly different to the centre of the field at a 5% level of probability. Number in brackets show the numbers of fields with each adjacent land use.

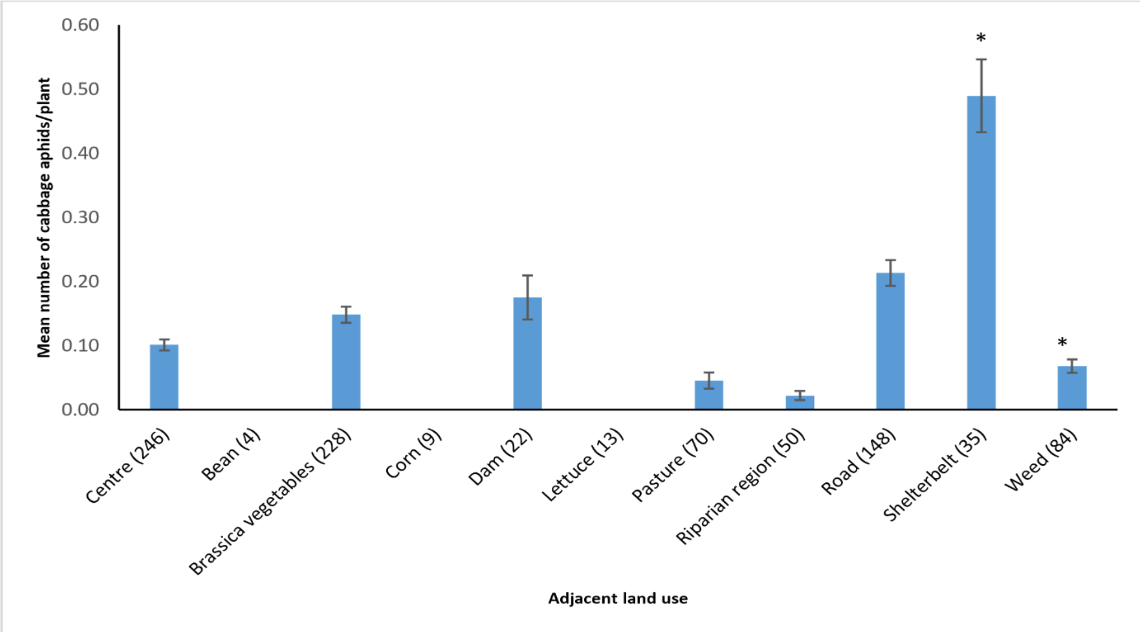


Figure A2.60. Mean number of cabbage aphid in brassica fields. The 'Centre' column shows count at the field centre and other columns show the count at the field edge adjacent to the land use labelled. * indicates where number along the field edge is significantly different to the centre of the field at a 5% level of probability. Number in brackets show the numbers of fields with each adjacent land use.

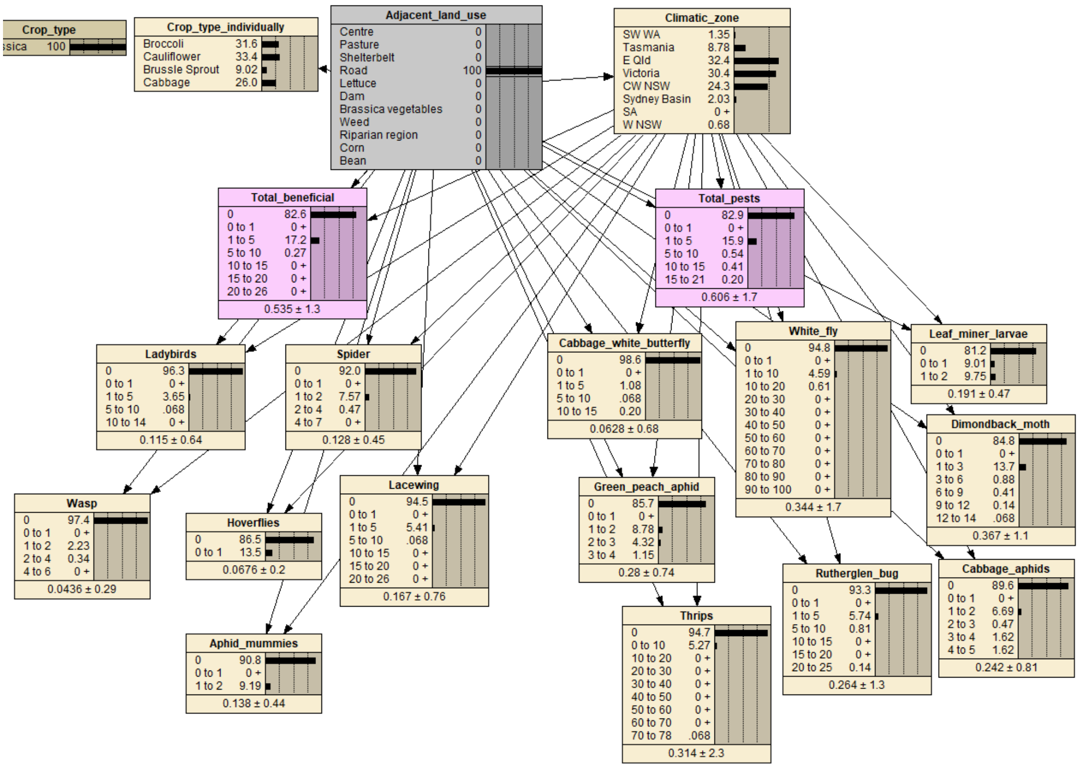


Figure A2.61. Bayesian network for the distribution of arthropods on the edge of brassica fields adjacent to road.

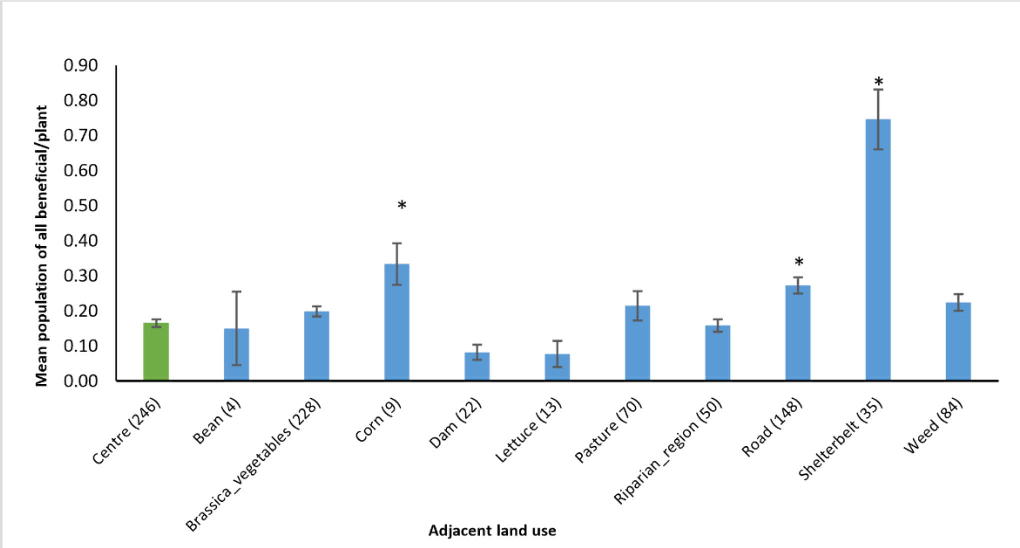


Figure A2.62. Mean number of beneficials in brassica fields. The 'Centre' (green) column shows count at the field centre and other columns show the count at the field edge adjacent to the land use labelled. * indicates where number along the field edge is significantly different to the centre of the field at a 5% level of probability. Number in brackets show the numbers of fields with each adjacent land use.

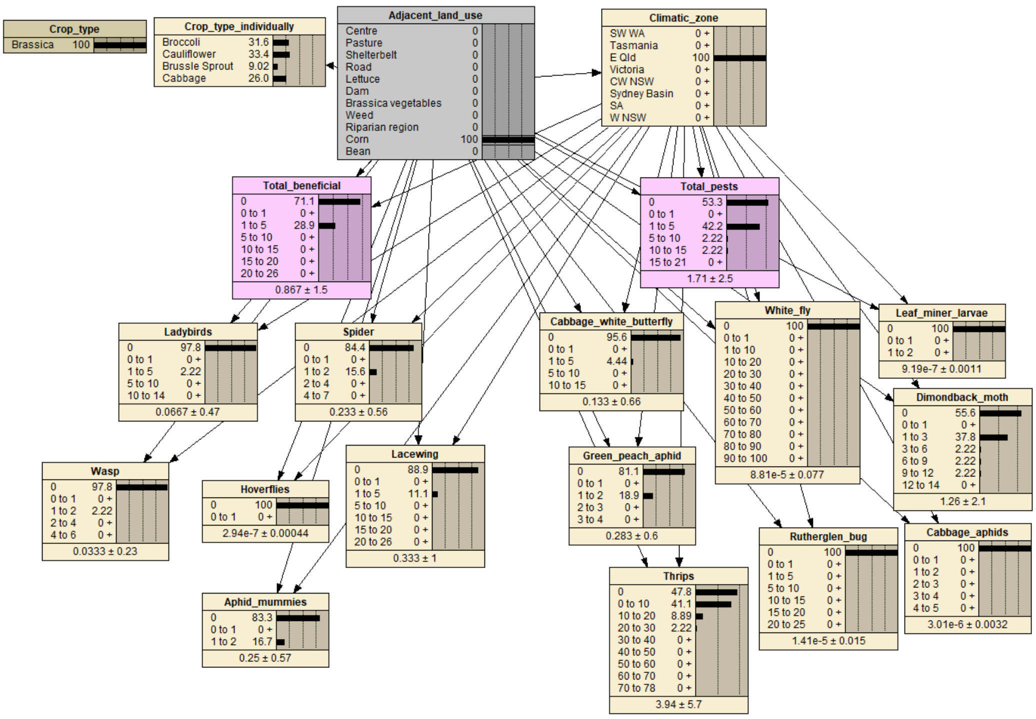


Figure A2.63. Bayesian network for the distribution of arthropods on the edge of brassica fields adjacent to corn.

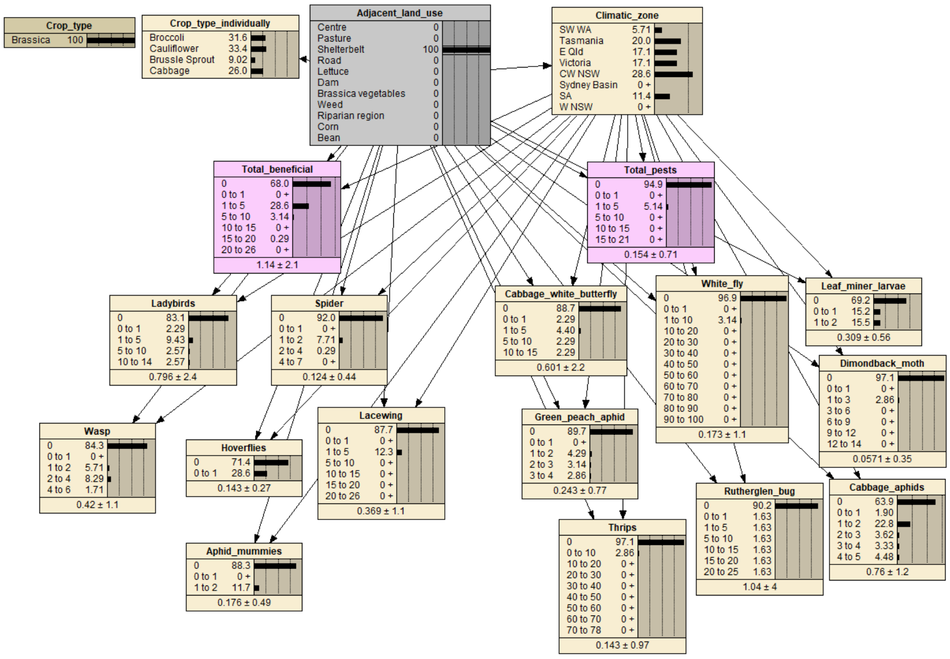


Figure A2.64. Bayesian network for the distribution of arthropods on the edge of brassica fields adjacent to shelterbelt.

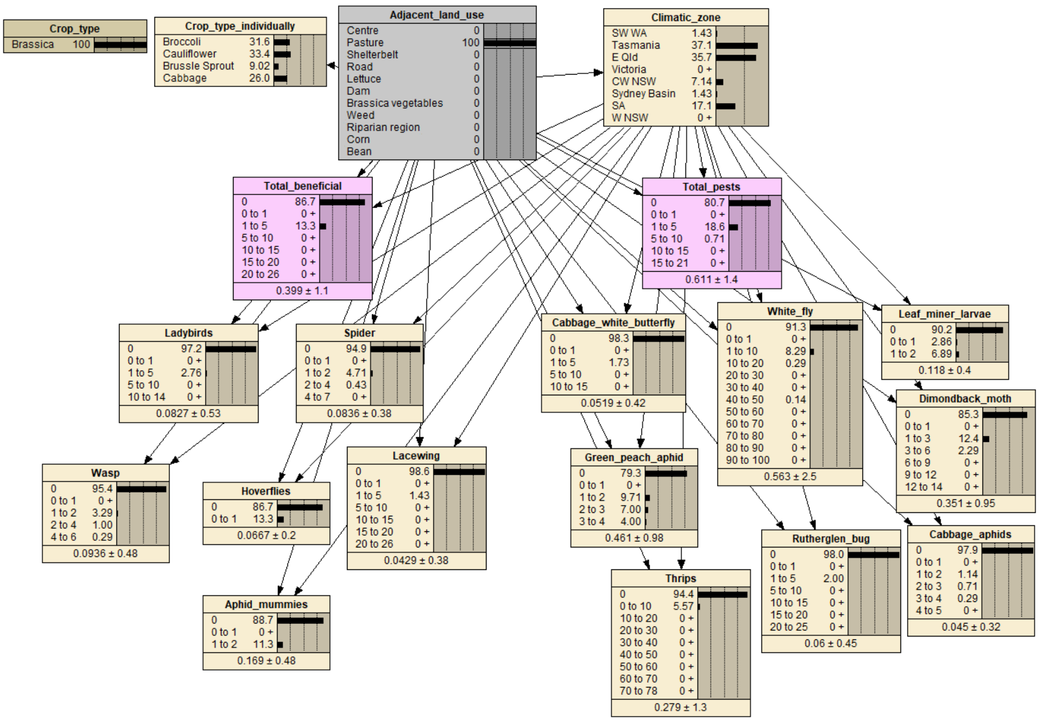


Figure A2.65. Bayesian network for the distribution of arthropods on the edge of brassica fields adjacent to pasture.

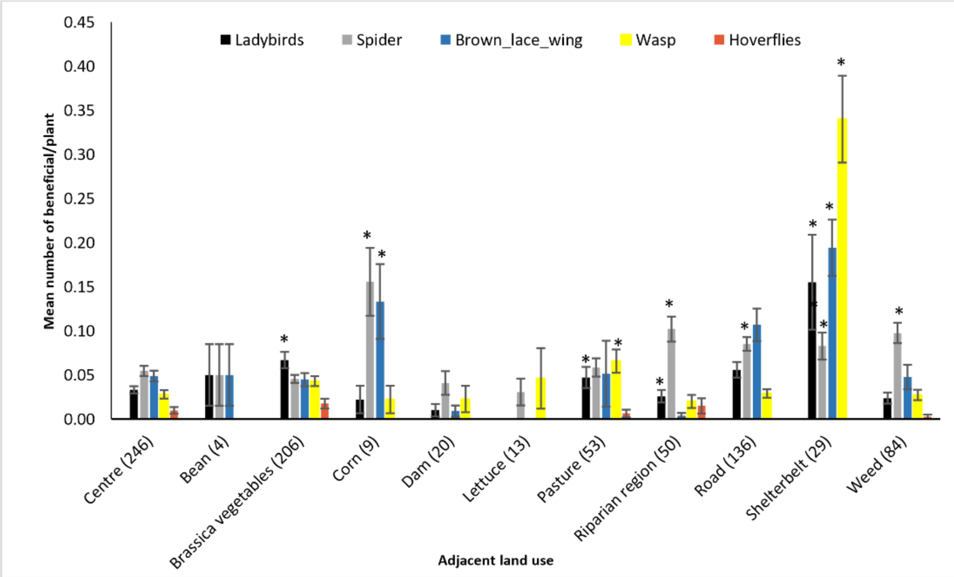


Figure A2.66. Mean number of beneficials by taxa in brassica fields. The 'Centre' column shows count at the field centre and other columns show the count at the field edge adjacent to the land use labelled. * indicates where number along the field edge is significantly different to the centre of the field at a 5% level of probability. Number in brackets show the numbers of fields with each adjacent land use.

Insecticide types

The number of beneficial insects was significantly higher in the fields sprayed only with biological insecticides compared to those where a mixture of insecticides were used. The number of pests was similar regardless of insecticide use type (Fig. A2.67, 68).

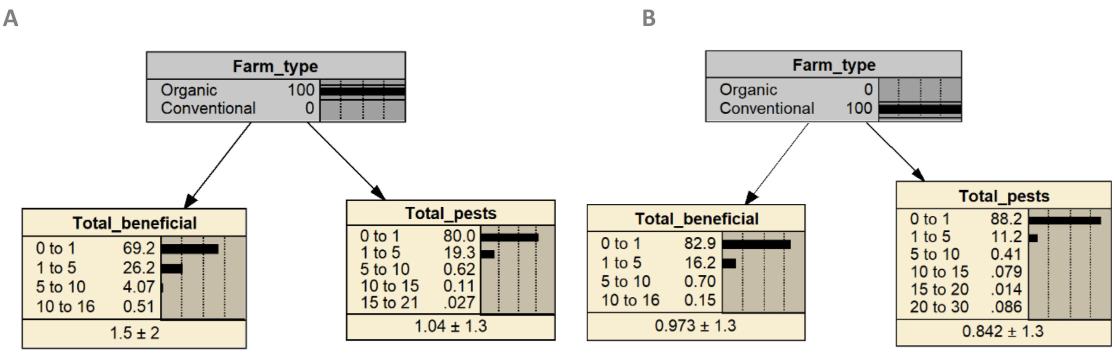


Figure A2.68. Bayesian network for the overall distribution of arthropods. Fields sprayed only with biological insecticides (A) are label 'organic' (even though farm was not totally organic), fields where synthetic insecticides were used (B) are labelled 'conventional'.

Pests and beneficial population among focal crops

Pooled analysis of total pest and beneficial populations among six focal crops (sweet corn, beans, capsicum, carrot, lettuce, and brassica vegetables) showed a significant effect of focal crops on pest and beneficial numbers (Fig. 69). The densities of pests in bean crops were significantly higher than in other crops and densities of beneficials significantly lower. In capsicum by contrast, beneficials were significantly more common and pests more scarce. Corn crops also had relatively high densities of beneficials and moderately high pest densities, comparable with those observed in brassicas and carrot. Lettuce had low pest densities and moderate densities of beneficials, comparable with levels observed in brassicas and carrot. BN models for populations of total pest and beneficial are verify the above findings (Fig. A2.70).

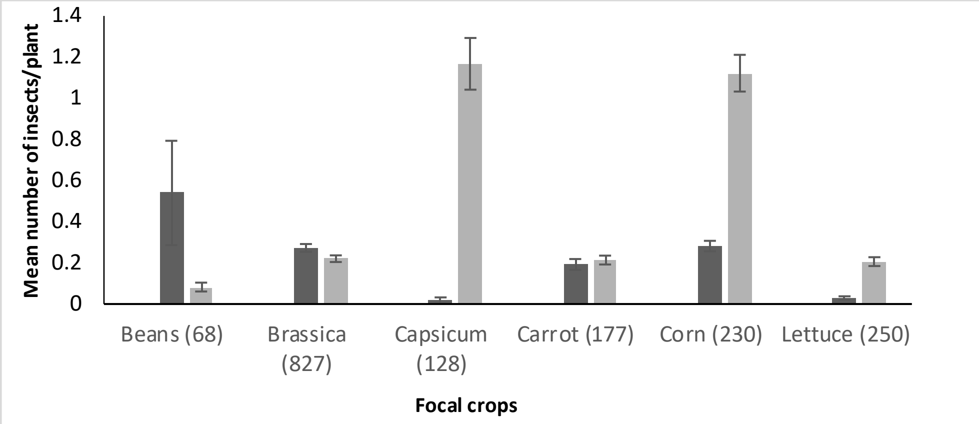


Figure A2.69. Number of pests and beneficial among focal crops. Letters indicate significant difference among the guilds at 5% level of probability. Number in brackets show the numbers of fields.

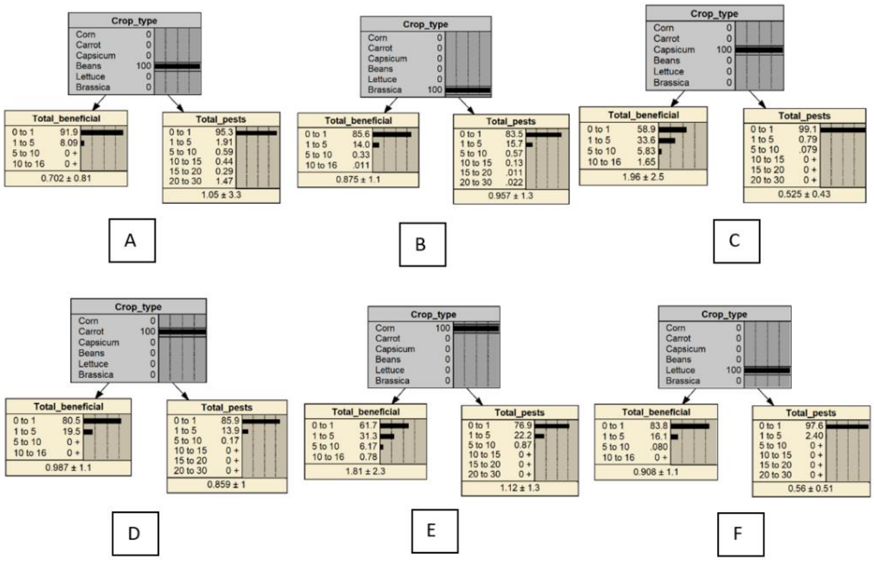


Figure A2.70. Bayesian network for the overall distribution of arthropods in the (A) beans (B) brassica (C) capsicum (D) carrot (E) corn (F) lettuce.

References

Düspohl, M., Frank, S., and Döll, P. (2012). A review of Bayesian networks as a participatory modeling approach in support of sustainable environmental management. Journal of Sustainable Development 5, 1.

Gu, Y., Peiris, D. R., Crawford, J. W., NcNicol, J., Marshall, B., and Jefferies, R. (1994). An application of belief networks to future crop production. In "Proceedings of the Tenth Conference on Artificial Intelligence for Applications", pp. 305-309. IEEE.

Korb, K. B., and Nicholson, A. E. (2010). "Bayesian artificial intelligence," CRC press.

Kristensen, K., and Rasmussen, I. A. (2002). The use of a Bayesian network in the design of a decision support system for growing malting barley without use of pesticides. Computers and Electronics in Agriculture 33, 197-217.

Marcot, B. G., Steventon, J. D., Sutherland, G. D., and McCann, R. K. (2006). Guidelines for developing and updating Bayesian belief networks applied to ecological modeling and conservation. Canadian Journal of Forest Research 36, 3063-3074.

Tari, F. (1996). A Bayesian network for predicting yield response of winter wheat to fungicide programmes. Computers and electronics in agriculture 15, 111-121.

Appendix 3: Factsheets