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Review

Prospects for habitat management to suppress vegetable pests in Australia

Syed Z M Rizvi,[1,2]* Olivia L Reynolds,[1,3,4] Ahsanul Haque,[1] Michael J Furlong,[5] Jianhua Mo,[6] Maria C Melo,[5] Salma Akter,[7] Vivian E. Sandoval-Gomez,[8] Anne C Johnson[1] and Geoff M Gurr[1,2,4,9]

[1]*Graham Centre for Agricultural Innovation (Charles Sturt University and NSW Department of Primary Industries), Wagga Wagga, NSW 2650, Australia.*
[2]*School of Agricultural, Environmental and Veterinary Sciences, Charles Sturt University, P.O. Box 883, Orange, NSW 2800, Australia.*
[3]*Susentom, Heidelberg Heights, Melbourne, VIC 3081, Australia.*
[4]*Institute of Applied Ecology and Research Centre for Biodiversity and Eco-Safety, Fujian Agriculture and Forestry University, Fuzhou 350002, China.*
[5]*School of Biological Sciences, The University of Queensland, St Lucia, QLD 4072, Australia.*
[6]*New South Wales Department of Primary Industries, Yanco, NSW 2705, Australia.*
[7]*Department of Entomology, Sher-e-Bangla Agricultural University, Dhaka 1207, Bangladesh.*
[8]*Market Access Team, Department of Agriculture and Fisheries, GPO Box 267, Brisbane, QLD 4001, Australia.*
[9]*State Key Laboratory of Ecological Pest Control for Fujian and Taiwan Crops, Fujian Agriculture and Forestry University, Fuzhou 350002, China.*

Abstract Habitat management is an ecologically based approach to suppress pest densities, utilising properties of non-crop vegetation to improve the impact of natural enemies or to directly affect pest behaviour. Research in this approach has escalated dramatically this century, extending to uptake in some crops, but adoption in Australia has been lower than overseas. Here, we address the need of the Australian vegetable sector to reduce reliance on insecticides by assessing the scope for habitat management in brassica (Brassicaceae), lettuce (*Lactuca sativa*) (Asteraceae), capsicum (*Capsicum annuum*) (Solanaceae), carrot (*Daucus carota*) (Apiaceae), French bean (*Phaseolus vulgaris*) (Fabaceae) and sweetcorn (*Zea mays*) (Poaceae) crops. Each crop is of major economic importance, and together, they represent contrasting botanical families and production systems that are associated with different arthropod complexes. We review studies of habitat management that are based on provision of shelter, nectar, alternative prey or pollen for natural enemies (top-down effects) or changing pest behaviour (bottom-up effects) through intercropping or trap crops. The likely utility of these approaches under Australian conditions is assessed, and recommendations are made to promote adoption and for adaptive research. Nectar- and pollen-providing plants, such as alyssum (*Lobularia maritima*) (Brassicaceae), offer strong potential to promote natural enemies in multiple crops whilst trap crops, especially yellow rocket (*Barbarea vulgaris*) (Brassicaceae), have more targeted utility against diamondback moth, *Plutella xylostella* (Lepidoptera: Plutellidae), the most serious pest of brassicas. Opportunities for intercrops and banker plant species are also identified. Our recommendations serve as a platform for researchers and for farmer-led studies to help realise the full potential of habitat management approaches in Australian vegetable production systems.

Key words conservation biological control, ecological engineering, natural enemy, vegetable pest.

INTRODUCTION

Plant protection in agriculture in the 21st century is confronting immense challenges due to escalating resistance to available insecticidal compounds, restricted access to 'new' chemistries and health and environmental contamination concerns associated with older compounds (Zhang *et al*. 2011). More widely, agricultural intensification and extensive use of pesticides has led to biodiversity loss, disruption of ecosystem function, and compromised the delivery of ecosystem services including biological control of arthropod pests (Gagic *et al*. 2018; Sands 2018). Complex landscapes with natural or semi-natural habitats can promote beneficial arthropods (Landis *et al*. 2000; Gardiner *et al*. 2010), as they provide nectar resources, oviposition sites, alternative prey and hosts, physical shelter from crop disturbances and overwintering refuges (Bianchi *et al*. 2006). However, pest suppression is not an axiomatic outcome of increased landscape complexity (Karp *et al*. 2018), so local habitat management strategies are crucial.

*szmrizvi@hotmail.com

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Habitat management, a form of conservation biological control, has roots in traditional farming practices such as companion planting but, as a rigorous branch of pest management science, is a relatively new approach compared with classical or inundative biological control (Fiedler *et al.* 2008; Lu *et al.* 2015). Common habitat management tactics include provision of non-crop vegetation, such as field borders of flowering plants to provide nectar to parasitoids and intercropping with a secondary crop. Secondary crops can serve as donor habitats in which natural enemies feed, multiply and then move to parasitise or predate the target pests (Gurr *et al.* 2017). Habitat management includes the use of 'banker plants' which provide shelter and alternative prey to sustain natural enemies to provide continuity of pest suppression (Andorno & López 2014). Typically, banker plants host herbivores that are not pests of the crop but serve as an alternative food source for key natural enemies of focal pests (Huang *et al.* 2011). A less commonly used habitat management strategy is the use of trap crops to divert pests from high-value crops (Hokkanen 1991). A trap crop, which is naturally more attractive to a specific pest than the main crop as either a food source or an oviposition site, is planted next to the main crop to reduce pest pressure (Shelton & Badenes-Perez 2006). An ideal trap crop is a dead-end crop for the targeted pest; the adults are attracted to oviposit, but their offspring cannot survive (Idris & Grafius 1996). Trap crops function as a sink for pests, restricting the movement of pests to the main crop (Shelton & Badenes-Perez 2006).

There are many studies of habitat management, but most are limited to the principles, tools and tactics (Cuperus *et al.* 2000), with a minority dealing with their practical implementation (Schellhorn *et al.* 2009). Moreover, available information on habitat management for vegetable farms is further limited in its breadth and depth, especially in Australia. Most habitat management studies have been conducted in the USA and EU (Veres *et al.* 2013), but many have investigated cropping systems similar to those found in parts of Australia, so they are likely to provide valuable leads. Accordingly, this review considers opportunities for the development and use of habitat management in vegetable crops in Australia. We focus on crop species of major commercial importance: brassica vegetables (*Brassica* spp.) (Brassicaceae), lettuce (*Lactuca sativa* L.) (Asteraceae), capsicum (*Capsicum annuum* L.) (Solanaceae), carrot (*Daucus carota* L.) (Apiaceae), French beans (*Phaseolus vulgaris* L.) (Fabaceae), and sweet corn (*Zea mays* L.) (Poaceae). For each of these crops, we critically appraise overseas habitat management studies for applicability to Australian horticulture. Recommendations for use in Australia consider the strength of evidence from overseas including whether positive effects on natural enemies were observed to cascade to reduced pest numbers, lessened crop damage or economic benefit. We recognise that growers care most about the last-mentioned aspects of this series of effects, but we also consider the underlying mechanisms responsible for observed effects (such as predation rates, parasitism rates and reductions to pest immigration) for these are important in adapting and optimising interventions. From a practical perspective, we also consider whether the plant species which are used in overseas studies are available and allowable in Australia (due to their weed or exotic status).

VEGETABLE PRODUCTION IN AUSTRALIA: A BRIEF OVERVIEW

In Australia, agriculture has been expanding continuously since European settlement (Zalucki 2015). Australian horticultural production is now valued at over A$11 billion per annum, with $2.3 billion worth of export products each year (Hort Innovation 2018). Australian agricultural systems are often intensive, optimising the productivity of monocultures and rotations of specific crops with crop diversity limited to a few genetically homogeneous species (Zalucki 2015). Vegetable production systems have been criticised for heavy reliance on inputs, soil erosion, structural degradation and contamination, pesticide resistance and loss of biodiversity (Anderies *et al.* 2006; Sands 2018). Australian farmers, like others around the world, have begun to recognise the benefits of less intensive practices, partly reflecting guidance from governmental and non-governmental organisations (Edwards *et al.* 2012). Australian farming is increasingly adopting zero-till and stubble-retention tactics to protect soils and the environment, using more selective insecticides, and precision agriculture to rationalise input use (Pratley & Kirkegaard 2019).

Invertebrate pest control in Australia is heavily reliant on synthetic pesticides (Adamson *et al.* 2014). The widespread use of pesticides has led to reduced efficacy of some chemical compounds as a result of the evolution of pesticide resistance in some pest populations. For example, *Plutella xylostella* L. (Lepidoptera: Plutellidae) has become resistant to all classes of insecticides used to control this pest (Endersby *et al.* 2008; Furlong *et al.* 2013) and is ranked second in the Arthropod Pesticide Resistance Database (APRD) for the number of types of insecticide resistance (Furlong *et al.* 2013).

VEGETABLE CROPS

The vegetable crops at the focus of this review were selected to represent a range of botanical families as well as being among the most economically important species both in Australia (DAWE 2019) and globally (FAO 2018) (Table 1).

Brassica vegetables

Australian brassica vegetable production is valued at over A $300 million per annum (Horticulture Australia 2014a). Brassica vegetables are grown in a number of regions throughout Australia and, due to diverse climates, the industry supplies brassica vegetables throughout the year (Horticulture Australia 2014a). In Australia, *P. xylostella* is considered the most serious pest of brassicas and has developed resistance to a wide range of insecticides (Endersby *et al.* 2008; Rahman *et al.* 2010; Furlong *et al.* 2013). Cabbage aphid, *Brevicoryne brassicae* (L.) and green peach aphid, *Myzus persicae* (Sulzer) (Hemiptera: Aphididae) are also considered serious pests and can be found in all parts of Australia (Gu 2009). Vegetable leafminer, *Liriomyza sativae* Blanchard (Diptera: Agromyzidae) (Ridland *et al.* 2020) and a very recent incursion of serpentine

Table 1 Australian production statistics and major pests of the six vegetable crops for this review

Vegetable crop			Production area (hectare)	Production (t per annum)	Major pests			Mode of damage	References
Family	Scientific name	Common name			Order: Family	Scientific name	Common name		
Brassicaceae	1. *Brassica oleracea* L. var. *gemmifera* 2. *B. oleracea* var. *italica* 3. *B. oleracea* var. *capitata* 4. *B. oleracea* var. *botrytis* 5. *B. oleracea* var. *acephala*	1. Brussels sprouts 2. Broccoli 3. Cabbage 4. Cauliflower 5. Kale	>14 400	222 700	Lepidoptera: Noctuidae	*Helicoverpa armigera* (Hübner)	Cotton bollworm	Feeding damage to foliage (direct damage). Vectoring pathogens (indirect damage).	(Zalucki *et al.* 1986; Hort Innovation 2018)
						Helicoverpa punctigera (Wallengren)	Native budworm	Feeding damage to foliage (direct damage). Vectoring pathogens (indirect damage).	(Zalucki *et al.* 1986; DPIR & Secondary DPIR 2020; GRDC 2020)
						Chrysodeixis spp.	Loopers	Feeding damage to leaves, flower and pods.	(Horticulture Australia 2014a)
					Lepidoptera: Plutellidae	*Plutella xylostella* (L.)	Diamondback moth	Feeding damage to above ground plant parts.	
					Lepidoptera: Pieridae	*Pieris rapae* (L.)	Cabbage white butterfly	Feeding damage to foliage.	
					Hemiptera: Aphididae	*Brevicoryne brassicae* (L.) *Myzus persicae* (Sulzer)	Cabbage aphid Green peach aphid	Feeding damage to foliage (direct damage). Honey dew secretion which promotes sooty mould growth (indirect damage).	
					Hemiptera: Aleyrodidae	*Bemisia tabaci* (Gennadius)	Silverleaf whitefly	Feeding damage to foliage (direct damage). Honey dew secretion which promotes sooty mould growth (indirect damage).	(Navas-Castillo *et al.* 2011)
					Diptera: Agromyzidae	*Liriomyza huidobrensis* (Blanchard)	Polyphagous/vegetable leafminer	Feeding damage to foliage.	DPIR & Secondary DPIR 2020
						Liriomyza sativae Blanchard	Polyphagous/vegetable leafminer	Feeding damage to foliage and cobs (direct damage). Vectoring pathogens (indirect damage).	(Ridland *et al.* 2020)
Poaceae	*Zea mays* L.	Sweetcorn/ Zea maize	>49 000	450 000	Lepidoptera: Noctuidae	*Spodoptera frugiperda* (J. E. Smith)	Fall armyworm	Feeding damage to foliage.	(Zalucki *et al.* 1986; Ekman 2015; DPIR & Secondary DPIR 2020; GRDC 2020)
						Spodoptera litura (Fabricius)	Cluster caterpillar	Feeding damage to foliage.	
						H. armigera	Cotton bollworm	Feeding damage on foliage.	
						H. punctigera	Native budworm	Feeding damage to foliage, cob and stems. Honey dew secretion and transmitting pathogenic viruses.	

(*Continues*)

Table 1 (Continued)

Vegetable crop			Production area (hectare)	Production (t per annum)	Major pests			Mode of damage	References
Family	Scientific name	Common name			Order: Family	Scientific name	Common name		
					Hemiptera: Aphididae	*Rhopalosiphum maidis* (Fitch)	Corn aphid	Feeding damage to foliage.	
Asteraceae	*Lactuca sativa* L.	Lettuce	>8500	138 000	Lepidoptera: Noctuidae	*H. armigera*	Cotton bollworm	Feeding damage and transmitting pathogenic viruses.	(Barrière *et al*. 2014; Horticulture Australia 2014d)
					Hemiptera: Aphididae	*Nasonovia ribisnigri* (Mosley)	Currant lettuce aphid	Feeding damage and transmitting viruses (e.g. lettuce mosaic virus).	
						M. persicae	Green peach aphid	Feeding damage to foliage.	
					Hemiptera: Aleyrodidae	*B. tabaci*	Silverleaf whitefly	Feeding damage to foliage.	
					Hemiptera: Lygaeidae	*Nysius vinitor* Bergroth	Rutherglen bug	Feeding damage and transmitting pathogenic viruses.	
					Thysanoptera: Thripidae	*Frankliniella occidentalis* (Pergande)	Western flower thrips	Feeding damage and transmitting pathogenic viruses.	
						Frankliniella schultzei (Trybom)	Tomato thrips	Feeding damage and transmitting pathogenic viruses.	
					Thysanoptera: Thripidae	*Thrips tabaci* Lindeman	Onion thrips	Feeding damage to foliage.	
					Hemiptera: Aleyrodidae	*Trialeurodes vaporariorum* (Westwood)	Glasshouse whitefly	Feeding damage to foliage.	
Apiaceae	*Daucus carota* L.	Carrot	>5700	330 000	Lepidoptera: Noctuidae	*Agrotis* spp.	Cutworm	Feeding damage to leaves.	(Horticulture Australia 2014c)
					Hemiptera: Lygaeidae	*N. vinitor*	Rutherglen bug	Feeding damage and transmitting pathogenic viruses.	
					Hemiptera: Aphididae	*Cavariella aegopodii* (Scopoli)	Willow-carrot aphid/carrot aphid	Feeding damage and transmitting pathogenic viruses.	
					Thysanoptera: Thripidae	*F. occidentalis*	Western flower thrips	Feeding damage to leaves.	
						Thrips imaginis Bagnall	Plague thrips	Feeding damage (leaves by damaging surface tissues).	
						Heliothrips haemorrhoidalis (Bouché)	Greenhouse thrips		
					Coleoptera: Tenbrionidae	*Gonocephalum* spp.	False wireworms	Feeding damage to foliage, seedlings and fruits.	
Fabaceae	*Phaseolus vulgaris* L.	French bean	>8000	33 000	Lepidoptera: Noctuidae	*H. armigera*	Cotton bollworm	Feeding damage (seedling and fruits near the ground and leaves).	(Zalucki *et al*. 1986; Hort Innovation 2018)
						H. punctigera	Native budworm	Feeding damage to all developmental stages.	
					Lepidoptera: Crambidae	*Maruca vitrata* (Fabricius)	Bean pod borer	Feeding damage and transmitting pathogenic viruses.	
						F. schultzei	Tomato thrips		

(*Continues*)

Table 1 (Continued)

Vegetable crop			Production area (hectare)	Production (t per annum)	Major pests			Mode of damage	References
Family	Scientific name	Common name			Order: Family	Scientific name	Common name		
					Thysanoptera: Thripidae			Feeding damage to foliage-causing stunted pods, whitish and shrivelled.	
					Acari: Tetranychidae	*Tetranychus urticae* Koch	Two-spotted mite/red spider mite	Feeding damage to foliage.	
					Hemiptera: Lygaeidae	*N. vinitor*	Rutherglen bug	Feeding damage to stem of seedling near ground, occasionally foliage.	
Solanaceae	*Capsicum annuum* L.	Capsicum	>2000	76 000	Lepidoptera: Noctuidae	*Agrotis* spp.	Cutworm	Feeding damage to fruits.	(Hort Innovation 2018; Horticulture Australia 2014b)
					Lepidoptera: Crambidae	*Sceliodes cordalis* (Doubleday)	Eggfruit caterpillar	Feeding damage and transmitting pathogenic viruses.	
					Hemiptera: Aphididae	*M. persicae*	Green peach aphid	Feeding damage to fruits.	
					Diptera: Tephritidae	*Bactrocera tryoni* (Froggatt)	Queensland fruit fly	Feeding damage (fruits).	
						Ceratitis capitata (Wiedemann)	Mediterranean fruit fly		
					Thysanoptera: Thripidae	*F. occidentalis*	Western flower thrips	Feeding damage to foliage (direct damage). Vectoring pathogens (indirect damage).	

leafminer, *Liriomyza huidobrensis* (Blanchard) (Diptera: Agromyzidae) (DPIR & Secondary DPIR 2020) pose a serious threat to brassicas, and other horticultural crops including lettuce, beans and capsicum (Table 1).

Sweetcorn

Sweetcorn is valued at more than $60 M per annum (Hort Innovation 2018) and its production has been expanding due to increasing domestic consumption, export demand and reduced import replacement (Hort Innovation 2018). Cotton bollworm, *Helicoverpa armigera* (Hübner) and native budworm, *Helicoverpa punctigera* (Wallengren) (Lepidoptera: Noctuidae) are considered the most damaging pests of sweetcorn (Table 1), reducing yield and market value by attacking the cobs. Feeding damage reduces the market value and renders the damaged crop vulnerable to secondary pest infestation and pathogen infection (Zalucki *et al*. 1986). Insecticide dependence for *Helicoverpa* spp. management has already led to the development of insecticide resistance to many insecticide groups (Murray *et al*. 2005). Fall armyworm, *Spodoptera frugiperda* (J. E. Smith) (Lepidoptera: Noctuidae), which is known to cause significant economic loss in sweetcorn in other parts of its now global range, has recently been identified in sweetcorn fields in Queensland, Northern Territory and Western Australia (DPIR & Secondary DPIR 2020; GRDC 2020) (Table 1).

Lettuce

Lettuce is grown in all states of Australia and valued at over $147 M per annum (Hort Innovation 2018). The currant lettuce aphid, *Nasonovia ribisnigri* (Mosley) (Hemiptera, Aphididae), and *M. persicae* are the major pests and can significantly damage the crop by feeding and vectoring viruses, such as the lettuce mosaic virus (Barrière *et al*. 2014; Horticulture Australia 2014d). *Nasonovia ribisnigri* tends to be found under the wrapper leaves that protect them from insecticides (Kift *et al*. 2004), which can lead to crop rejection at market due to the contamination (Table 1).

Carrot

Carrots are mostly produced in Queensland in winter and in Tasmania in summer months and have a value of over $215 M per annum (Hort Innovation 2018). In Australia, willow-carrot aphid, *Cavariella aegopodii* (Scopoli) (Hemiptera: Aphididae) and western flower thrips, *Frankliniella occidentalis* (Pergande) (Thysanoptera: Thripidae) are considered the major pests of carrot (Horticulture Australia 2014c) and they inflict yield loss by feeding and by transmitting several plant pathogenic viruses (Table 1).

French bean

In Australia, French bean is produced in all states, with a value of more than $77 M per annum (Hort Innovation 2018). Bean pod borer, *Maruca vitrata* (Fabricius) (Lepidoptera: Crambidae) is the major pest (Turner 1978) which feeds on all developmental stages of the crop (Sharma 1998). *Helicoverpa* spp. can also cause significant damage in beans by feeding on leaves, flowers and developing pods (Zalucki *et al*. 1986) (Table 1).

Capsicum

Several Australian states produce capsicum; Queensland accounts for two-thirds of the A$155 M of national production (Hort Innovation 2018). Queensland fruit fly, *Bactrocera tryoni* (Froggatt) (Diptera: Tephritidae) is the main pest in the east whilst Mediterranean fruit fly, *Ceratitis capitata* (Wiedemann) (Diptera: Tephritidae) is the principal pest in Western Australia. Larvae of *B. tryoni* and *C. capitata* feed on the fruits, causing premature ripening and rotting (Wilson *et al*. 2012) (Table 1).

INSECTICIDE RESISTANCE: A MAJOR CHALLENGE FOR INSECT PEST MANAGEMENT IN AUSTRALIA

Intensive use of synthetic pesticides often leads to changes in pest complexes, including development of pesticide resistance in pests, secondary pest outbreaks (Gurr *et al*. 2005) and the disruption of organisms in higher trophic levels, resulting in reduced pest suppression (Stark *et al*. 2007). For example, *M. persicae* has become resistant to a wide range of insecticides (Bass *et al*. 2014), making it one of the most widely and strongly resistant species worldwide (www.pesticideresistance.org). In Australia, as in other parts of the world, broad-spectrum pesticides are part of standard agricultural pest management and are often used prophylactically as 'insurance', rather than as means to control pest and pathogen outbreaks (Lamine *et al*. 2010). Pesticide use in Australia has risen dramatically in recent decades, increasing from less than 0.4 kg/ha on average to over 1.0 kg/ha across all croplands between 1990 and 2016 (FAO 2019). Reliance on frequent and indiscriminate use of broad-spectrum pesticides has led to a sometimes ineffective and unsustainable situation resulting from the disruption of natural pest regulation that can be afforded by the functional diversity within arthropod assemblages in crop fields (Furlong *et al*. 2004; Moonen & Bàrberi 2008). More sustainable pest control strategies are needed to overcome the negative impacts of pesticides on the environment and human health, effects on natural habitat and emerging pesticide resistant pests. Beneficial insects can play an important role in pesticide resistance management as they target prey/hosts irrespective of the pests' degree of resistance or resistance mechanism and thus can help to slow down the resistance selection process (Gurr *et al*. 2017).

ECOLOGICAL BASIS FOR NATURAL PEST SUPPRESSION

There is strong evidence that the population density of insect herbivores tends to reach higher levels in simple agroecosystems compared with more diverse systems (Root 1973; Horne *et al*. 2008). In early work, Root (1973) proposed two possible mechanisms for this: (1) 'the resource concentration hypothesis', which considers that herbivorous pests more easily locate and then stay in and reproduce in large patches (monocultures) of their host plants, and (2) 'the enemy's hypothesis', which proposes that the predators and parasitoids of herbivorous pests are more effective at controlling pest populations in more diverse systems. These mechanisms of pest suppression are not mutually exclusive; they can operate simultaneously.

HABITAT MANAGEMENT

Landscape complexity, as conferred by the preservation or reintroduction of non-crop habitat, can have a positive impact on the abundance and diversity of natural enemies in a system (Fiedler *et al*. 2008; Macfadyen *et al*. 2015; Parry *et al*. 2015). However, the effects are inconsistent (Karp *et al*. 2018) and we remain with a far from complete understanding of how landscape characteristics might be exploited to achieve long-term pest suppression (Tscharntke *et al*. 2012). This challenge is compounded by the practical considerations that landscape effects can operate at scales of several kilometres and are often promoted by slow-growing woody vegetation (Perović *et al*. 2010). These spatial and temporal factors make it challenging for the manager of an extensive property and still more difficult if management requires active cooperation by multiple neighbours. Accordingly, there is a great interest in habitat management strategies that farmers can employ at a smaller scale (e.g. farm or field) and use annual plants (Landis *et al*. 2000; Gurr *et al*. 2005) to maintain the population of relevant natural enemies. Especially valuable is the identification of plant species which can provide benefits to the beneficial insects in a selective manner, denying benefit to key pest species (Baggen & Gurr 1998; Gurr *et al*. 1998). Whilst the present review draws from successful overseas studies, a limitation of the available literature is that studies of improved efficacy of natural enemies and reduced pest numbers often do not measure effects on plant yield or, especially, the economics of production (Gurr *et al*. 2016; Johnson *et al*. 2020). This deficiency weakens the value proposition to growers (who care most about yield and profit and less about natural enemy densities) and has likely been a factor in the limited levels of uptake despite large numbers of research studies. To date, the most widely adopted forms of habitat management are nectar plant borders to rice fields in Asia (Lu *et al*. 2015; Gurr *et al*. 2016) and the 'push–pull' system in East African maize (Khan *et al*. 2010).

Against this background, we examined the global literature, focusing primarily on field studies of habitat management that were conducted in our selected crops, to identify the strategies that offer the best scope for adoption in Australian horticultural vegetable crops.

LOCATION AND FILTERING OF LITERATURE

Web of Science (Institute of Scientific Information) was searched using the following search terms: *habitat management*, *habitat manipulation*, *pest management*, *natural enemies*, *conservation biological control*, *conservation biocontrol* and *beneficial insect*, with each of these terms linked to the common or scientific name of each of our focal crop species. Results were filtered to retain field studies in which plants were purposefully established to (1) improve availability of shelter, nectar, alternative prey or pollen for natural enemies (top-down effect) or (2) change arthropod pest behaviour (bottom-up effect) including intercropping or trap crops. Laboratory studies and reviews were excluded, unless important in revealing a mechanism for observed field effects.

GLOBAL HABITAT MANAGEMENT WORK

Brassica vegetables

Growing flowering plants in or around brassica fields has led to pest reductions (Lee & Heimpel 2005; Liu *et al*. 2005). This includes selective conservation of pre-existing non-crop flowering vegetation as well as by establishing strips of insectary plants (Gontijo 2011). Australian and overseas field studies showed that flowering plants such as alyssum, buckwheat (*Fagopyrum esculentum* Moench) (Polygonaceae), cornflower (*Centaurea cyanus* L.) (Asteraceae) and dill (*Anethum graveolens* L.) (Apiaceae) increased the densities of generalist predators such as spiders (Araneae), ladybeetles (Coccinellidae), hoverflies (Syrphidae) and *Orius* spp. (Anthocoridae), which, in turn, reduced the numbers of aphids and increased the parasitism rate of *P. xylostella* (Keller & Baker 2003; Balmer *et al*. 2013; Ribeiro & Gontijo 2017) (Table 2). Parasitoids too were shown to benefit from buckwheat strips. Parasitism rates have been enhanced for *P. xylostella* by *Diadegma semiclausum* (Helen) (Hymenoptera: Ichneumonidae), cabbage looper, *Trichoplusia ni* (Hübner) (Lepidoptera: Noctuidae) by *Voria ruralis* (Fallén) (Diptera: Tachinidae) and cabbage white butterfly, *Pieris rapae* (L.) (Lepidoptera: Pieridae) by *Cotesia rubecula* (Marshall) (Hymenoptera: Braconidae) (Lavandero *et al*. 2005; Lee & Heimpel 2005; Balmer *et al*. 2013) (Table 2).

Intercropping in brassica fields has improved natural enemy impact and reduced pest pressure (e.g. Simpson *et al*. 2011b; Nilsson *et al*. 2012; Gordon *et al*. 2013; Hatt *et al*. 2018). Aside from natural enemy-mediated effects, intercropping can directly affect pests when plants act as physical barriers to the movement of the insect pest, and/or when chemical or visual communication between the pest and the host is disrupted (Sheehan 1986). For instance, compounds such as rutin from tomato (*Solanum lycopersicum* L.) (Solanaceae) and coumarin from yellow clover (*Melilotus officinalis* (L.) Pall.) (Fabaceae) have been reported to deter *P. xylostella* and *P. rapae* oviposition (Renwick & Radke 1985; Tabashnik 1985) when these plants are intercropped with brassicas (Bach & Tabashnik 1990; Hooks & Johnson 2002). Onion (*Allium cepa* L.) (Amaryllidaceae), tomato, black pepper (*Piper nigrum* L.) (Piperaceae) and barley (*Hordeum vulgare* L.) (Poaceae) intercrops have shown promising results in supressing major brassica pests (Bukovinszky *et al*. 2004; Asare-Bediako *et al*. 2010) (Table 2).

Table 2 Summary of habitat management strategies of relevance to major Australian vegetable crops

Primary crop: Family	Primary crop: Species	Habitat management approach	Intervention plant species	Status of intervention plant species in Australia	Country where study conducted
Brassicaceae	*Brassica oleracea* L. var. '*Manteiga*'	Flowering plant	*Lobularia maritima* (L.) Desv. (Brassicaceae)	Ornamental/flowering	Brazil
	B. oleracea var. *italica*		*L. maritima*	Ornamental/flowering	Australia
			Brassica rapa var. *chinensis* (Brassicaceae)	Vegetable	
			Anethum graveolens L. (Apiaceae)	Vegetable/flowering	
			Fagopyrum esculentum L. (Polygonaceae)	Ornamental/flowering	New Zealand
	B. oleracea var. *capitata*		*F. esculentum*	Ornamental/flowering	USA
			F. esculentum	Ornamental/flowering	Switzerland
			Centaurea cyanus L. (Asteraceae)	Ornamental/flowering	
		Intercropping	*Allium cepa* L. (Amaryllidaceae)	Vegetable	Ghana
			Solanum lycopersicum L. (Solanaceae)	Vegetable	
			Piper nigrum L. (Piperaceae)	Vegetable	
	B. oleracea var. *Maximus*		*Hordeum vulgare* L. (Poaceae)	Cereal	The Netherlands
	B. oleracea var. *botrytis*	Banker plant	*B. oleracea* var. *Sabauda* (Brassicaceae)	Vegetable	Switzerland
			B. rapa L. var. *Majalis* (Brassicaceae)		
		Trap plant	*Barbarea vulgaris* W. T. Aiton (Brassicaceae)	Biennial herbs	Spain
	B. oleracea var. *alba*		*Brassica juncea* L. (Brassicaceae)	Weed	Sweden
	B. oleracea var. *capitata*		*B. oleracea* var. *acephala*	Vegetable	USA
Poaceae	*Zea mays* L.	Flowering plant	*Helianthus annuus* L. (Asteraceae)	Seed oil/flowering/ornamental	USA
			F. esculentum	Ornamental/flowering	USA
			Vigna unguiculata L. (Fabaceae) (used as alternative oviposition site for *Trichogramma* spp.)	Vegetable	
			Crotalaria juncea L. (Fabaceae) (used as alternative oviposition site for *Trichogramma* spp.)	Cover crop	
		Attract and reward HIPVs	*F. esculentum* aided with herbivore-induced plant volatiles	Synthetic ornamental/flowering	Australia
		Intercropping	*Phaseolus vulgaris*	Vegetable	Kenya
			Vigna radiata L. (Fabaceae)	Vegetable	China
			Ipomoea batatas L. (Convolvulaceae)	Vegetable	
			Melinis minutiflora P. Beauv. (Poaceae)	Weed	Kenya
		Trap plant	*Brassica nigra* L. (Brassicaceae)	Black mustard	New Zealand
			Panicum maximum Jacq. (Poaceae)	Weed	Kenya
		Push–pull		Weed	East Africa

(*Continues*)

Table 2 (Continued)

Primary crop		Habitat management approach	Intervention plant species	Status of intervention plant species in Australia		Country where study conducted
Family	Species					
			Brachiaria var. *mulato* II (Poaceae) (acted as attractant or 'pull') *Desmodium intortum* (Mill.) Urb. (Fabaceae) (acted as repellent or 'push')			
			Brachiaria var. *mulato* II (acted as attractant or 'pull')	Weed		East Africa
			D. intortum (acted as repellent or 'push')			
			Pennisetum purpureum Schumach (Poaceae) (acted as attractant or 'pull')	Weed		Kenya
			M. minutiflora (acted as repellent or 'push')			
			P. purpureum (acted as attractant or 'pull')	Weed		
			Desmodium uncinatum Jacq. and *D. intortum* (acted as repellent or 'push')			
Asteraceae	*Lactuca sativa* L.	Flowering plant	*L. maritima*	Ornamental/flowering	Mixed flowering	Spain
			C. cyanus	Ornamental/flowering		
			Vicia sativa L. (Fabaceae)	Weed		
			Lupinus hispanicus Boiss. & Reut (Fabaceae)	Weed		
			Coriandrum sativum L. (Apiaceae)	Vegetable/flowering		Spain
			Chrysanthemum segetum L. (Asteraceae)	Ornamental/flowering		
			L. maritima	Ornamental/flowering		USA
			C. sativum	Vegetable/flowering	Mixed flowering	UK
			A. graveolens	Vegetable/flowering		
			Anthemis arvensis L. (Asteraceae)	Weed		
			Centaurea cynanus L. (Asteraceae)	Ornamental/flowering		
			C. segetum	Dryland pasture/sometime weed		
			Trifolium incarnatum L. (Fabaceae)	Weed		
			Melilotus officinalis (L.) Pall. (Fabaceae)	Weed in some states		
			Trifolium repens L. (Fabaceae)	Weed		
			Trifolium pratense L. (Fabaceae)	Weed		
			L. maritima	Ornamental/flowering		
			Amaranthus caudatus L. (Amaranthaceae)	Weed		
Apiaceae	*Daucus carota* L.	Flowering plant	*Tagetes patula* L. (Asteraceae)	Weed		Poland
			C. sativum	Vegetable/flowering		Poland
			Satureja hortensis L. (Lamiaceae)	Flowering/annual herb		
			Medicago sativa L. (Fabaceae)	Annual herb		Sweden
		Intercropping	*A. cepa*	Vegetable		Nigeria
			Trifolium subterraneum L. (Fabaceae)	Weed		The Netherlands
		Trap plant	*D. carota* var. *calibra* and *bolero*	Vegetable		Sweden

Table 2 (Continued)

Primary crop		Habitat management approach	Intervention plant species	Status of intervention plant species in Australia	Country where study conducted
Family	Species				
Fabaceae	*P. vulgaris* L.	Flowering plant	*C. sativum*	Vegetable/flowering	India
			C. sativum	Vegetable/flowering	Egypt
			Trigonella foenum-graecum L. (Fabaceae)	Vegetable	
		Intercropping	*Z. mays*	Cereal crop	Venezuela
			H. annuus	Seed oil/flowering/ornamental	Kenya
			Z. mays	Cereal crop	
			Solanum tuberosum L. (Solanaceae)	Vegetable	
			Z. mays and *H. annuus*	Vegetable and seed oil/flowering/ornamental	
			S. tuberosum and *H. annuus*	Vegetable and seed oil/flowering/ornamental	
			Tagetes erecta L. (Asteraceae)	Ornamental/flowering	Kenya
			D. carota	Vegetable	
			C. sativum	Vegetable/flowering	
			B. oleraceae var. *Acephala*	Vegetable	
			Capsicum annuum	Vegetable	
			Z. mays	Cereal crop	
Solanaceae	*C. annuum* L.	Flowering plant	*A. graveolens*	Vegetable/flowering	USA
			C. sativum	Vegetable/flowering	
			F. esculentum	Flowering	
			F. esculentum	Flowering	USA
		Intercropping	*Z. mays*	Cereal crop	Malaysia
			A. cepa	Vegetable	India
			Allium sativum	Vegetable	
		Trap plant	*C. annuum* var. *cherry bomb*	Vegetable	UK
			H. annuus	Seed oil/flowering/ornamental	USA
			Sorghum bicolor (L.) Moench (Poaceae)	Cereal crop	
		Banker plant	*S. bicolor*	Cereal	Brazil

Primary crop		Influence of intervention on beneficials	Influence of intervention on pests	Other benefits	Mechanism studied	References
Family	Species					
Brassicaceae	*Brassica oleracea* L. var. '*Manteiga*'	Densities of Araneae, Coccinellidae, Syrphidae and *Orius* spp. (Hemiptera: Anthocoridae) increased.	Densities of *Myzus persicae* and *Plutella xylostella* decreased up to 83% and 75%, respectively.		Numbers of pest and beneficial arthropods were counted (1) directly on *B. oleracea*, (2) by beating *B. oleracea* and *L. maritima* flowers and (3) by using pitfall traps.	(Ribeiro & Gontijo 2017)
	B. oleracea var. *italica*		Parasitism of *P. xylostella* by *Diadegma semiclausum* (Helen)		Larvae and pupae of *P. xylostella* were collected from	(Keller & Baker 2003)

(*Continues*)

Table 2 (Continued)

Primary crop: Family	Primary crop: Species	Influence of intervention on beneficials	Influence of intervention on pests	Other benefits	Mechanism studied	References
		New Zealand	(Hymenoptera: Ichneumonidae) increased up to 72% and 28% by *Apanteles ippeus* Nixon (Hymenoptera: Braconidae).	Parasitism of *P. xylostella* by *D. semiclausum* increased 2 times.	experimental site and inspected for parasitism.	Sentinel *B. oleracea* carrying 3rd instar larvae of *P. xylostella* were used to assess the levels of parasitism.
	(Lavandero *et al*. 2005)					
	B. oleracea var. *capitata*		Parasitism rates by *Voria ruralis* (Fallén) (Diptera: Tachinidae) on *Trichoplusia ni* (Hübner) (Lepidoptera: Noctuidae) larvae and *Cotesia rubecula* (Marshall) (Hymenoptera: Braconidae) on *Pieris rapae* larvae increased up to 7% and 6%, respectively.		Eggs of *T. ni* and *P. rapae* were collected from the field and reared in the laboratory to assess levels of parasitism.	(Lee & Heimpel 2005)
		Abundance of Carabids increased by 37%, Syrphidae by 4% and Araneae by 6%.	Parasitism of *P. xylostella* increased up to 80%.		Pitfall traps were used to measure predators' abundance whilst predation was verified by molecular analysis of gut contents of captured predators. Sentinel egg clutches were used to assess the levels of parasitism.	(Balmer *et al*. 2013)
			Abundance of *P. xylostella* decreased to 36–38%.		Numbers of *P. xylostella* were visually counted.	(Asare-Bediako *et al*. 2010)
	B. oleracea var. *Maximus*		Abundance of *P. xylostella* decreased up to 10%.		Clear sticky traps were used to assess the population of *P. xylostella*.	(Bukovinszky *et al*. 2004)
	B. oleracea var. *botrytis*	Abundance of *Diaeretiella rapae* (McIntosh) (Hymenoptera: Braconidae) increased.			Aphid mummies were collected from the field and checked for parasitoids' emergence.	(Freuler *et al*. 2003)
		Abundance of Coccinellidae, Chrysomelidae, and *Diadegma insulare* (Cresson) (Hymenoptera: Ichneumonidae) and *Diadromus collaris* (Gravenhorst) (Hymenoptera: Ichneumonidae) increased.	Parasitism of *P. xylostella* increased up to 1.7 and 4.0 times by *D. insulare* and *D. collaris*, respectively. Abundance of *Eurydema ornata* (L.) (Hemiptera: Pentatomidae) significantly reduced.		Arthropods were sampled from the fields. Larvae and pupae of *P. xylostella* were reared to verify and measure the parasitism rate.	(Badenes-Perez *et al*. 2017)
	B. oleracea var. *alba*		*P. xylostella* laid 3.4 times fewer eggs on *B. oleracea* planted with trap crop than monocultured *B. oleracea*.		Eggs of *P. xylostella* were visually counted.	(Åsman 2002)

Table 2 (Continued)

Primary crop		Influence of intervention on beneficials	Influence of intervention on pests	Other benefits	Mechanism studied	References
Family	Species					
B. oleracea var. *capitata*	*B. oleracea* var. *acephala*	*P. xylostella* laid 60% fewer eggs on primary crop with trap crop than control.	Pesticide input was reduced by 62%.	Larvae of *P. xylostella* were visually counted.	(Mitchell *et al*. 2000)	
Poaceae	*Zea mays* L.	Abundance of natural enemies such as *Peucetia viridans* (Hentz) (Araneae: Oxyopidae), Coccinellidae, *Geocoris* spp. predatory Pentatomidae, Reduviidae, Sphecidae, Tiphiidae, Trichogrammatidae increased nearly doubled within 1 m of sunflower strips.	Pest abundance was the greatest on sunflower strips and significantly reduced in the crop with distance away from the sunflower strips.	Natural enemies abundance was the greatest on sunflower strips; such effect reduced with increasing distance from the strips, such that there was little effect at a distance of 10 m.	Arthropods densities were assessed through field surveys.	(Jones and Gillett 2005)
		Increased the abundance of *Orius* spp.	Parasitism of *Helicoverpa zea* eggs significantly increased.		Corn ears were beaten to collect *Orius* spp. and *H. zea* eggs. Eggs were then reared to check the emergence of *Trichogramma* spp.	(Manandhar & Wright 2015)
		Increased the abundance of *Trichogramma* spp.	Parasitism of *Lampides boeticus* (L.) (Lepidoptera: Lycaenidae) eggs significantly increased.		*L. boeticus* eggs were reared in the laboratory to check the emergence of *Trichogramma* spp.	
		Increased the abundance of *Orius* spp. and *Trichogramma* spp.	Parasitism of *L. boeticus* eggs significantly increased.			
		The abundance of natural enemies such as Braconidae, Trichogrammatidae, Scelionidae, Eulophidae, Mymaridae Ceraphronidae, Coccinellidae, Neuroptera, Syrphidae and Araneae increased.	Abundance of *Helicoverpa* larvae reduced by 74%.	Damage by *Helicoverpa* spp. was significantly reduced.	Clear sticky traps were used to observe the arthropods abundance. In the end of the study, corn cobs were harvested and *Helicoverpa* spp. were counted and damages to the cobs were assessed.	(Simpson *et al*. 2011a)
		The densities of *Orius* spp. and *Ceranisus* spp significantly increased.	Population of *Megalurothrips sjostedti* Trybom, *Frankliniella schultzei*, *Frankliniella occidentalis* and *Hydatothrips*	Yield loss/rejection due to thrips damage was reduced up to 30%.	Arthropods were visually counted.	(Nyasani *et al*. 2012)

(*Continues*)

Table 2 (Continued)

Primary crop		Influence of intervention on beneficials	Influence of intervention on pests	Other benefits	Mechanism studied	References
Family	Species					
			aldolfifriderici (Karny) (Thysanoptera: Thripidae) significantly reduced.			
		Densities of Araneae and Coccinellidae increased more than 21%. Densities of Araneae and Coccinellidae increased more than 83%.	The number of *Ostrinia furnacalis* (Guenée) (Lepidoptera: Crambidae) larvae decreased by 77% which reduced the damage up to 56%.		Arthropods densities were assessed through field surveys.	(Tian *et al*. 2012)
		Population density of *Cotesia sesamiae* (Cameron) (Hymenoptera: Braconidae) significantly increased.	Parasitism of *Chilo partellus* (Swinhoe) (Lepidoptera: Pyralidae) by *C. sesamiae* increased by 74%.	*C. polychrysus* infestation of the *Z. mays* by 88%.	*Z. mays* were inspected and the larvae of *C. partellus* captured from the field and reared in the laboratory to verify the parasitism.	(Khan *et al*. 1997)
			Population of *Nezara viridula* (L.) (Hemiptera: Pentatomidae) significantly decreased.	Up to 95% less crop damage was measured.	Numbers of *N. viridula* were visually counted.	(Rea *et al*. 2002)
		Densities of major predators from Forficulidae, Araneidae, Lycosidae and Formicidae were significantly increased.	Density of *C. partellus* significantly reduced.		*Z. mays* were inspected and arthropods were visually counted.	(Koji *et al*. 2007)
			Population of *Spodoptera frugiperda* reduced up to 82.7%.	Plant damage reduced up to 86.7% which increased the yield up to 2.7 times.	*Z. mays* were visually inspected and pest's damage was assessed. Larvae of *S. frugiperda* were visually counted.	(Midega *et al*. 2018)
			Population of *C. partellus* was reduced by 6 times. *Striga hermonthica* (Del.) Benth. (Orobanchaceae), a parasitic weed, was suppressed by 18 times.	Mean yields were 2.5 times higher. Farmers rated push–pull significantly superior in reducing *S. hermonthica* infestation and *C. partellus* damage rates and in improving soil fertility and maize grain yields.	*Z. mays* were inspected and damage was assessed. Numbers of *C. partellus* were visually counted.	(Midega *et al*. 2015)
		Parasitism of *C. partellus* by *Cotesia* spp. increased by 139%.	Population density of *C. partellus* decreased by 75%.	Damage to maize was reduced by 65%, which increased the yield by 27%.	*Z. mays* were inspected and the larvae of *C. partellus* were counted. The larvae were reared to determine parasitism.	(Khan *et al*. 2001)
		Parasitism of *C. partellus* by *Cotesia* spp. increased by 68.6%.	Population density of *C. partellus* decreased by 83%; *Desmodium* spp. significantly reduced damage to maize.	Damage to maize was reduced by 76%, which increased the yield by 25%.		

Table 2 (Continued)

Primary crop		Influence of intervention on beneficials	Influence of intervention on pests	Other benefits	Mechanism studied	References
Family	Species					
Asteraceae	*Lactuca sativa* L.	The abundance of Syrphidae and *Orius* spp. increased.	Population of *Nasonovia ribisnigri* reduced by 95%.		Pitfall traps and entomological nets were used to assess arthropods' densities.	(Alomar *et al*. 2008)
		The abundance of predatory Syrphidae increased by 43%.	Population of *N. ribisnigri* reduced by 50%.		*L. sativa* were visually inspected to assess the abundance of *N. ribisnigri* and Syrphidae.	(Pascual-Villalobos *et al*. 2006)
		The abundance of predatory Syrphidae increased by 41%.	Population of *N. ribisnigri* reduced by 37%.			
			Significantly decreased in the abundance of *M. persicae*.		The population of *M. persicae* was visually assessed on *L. sativa* and *L. maritima*.	(Chaney 1998)
		Natural enemies (Chrysopidae, Syrphidae, Coccinellidae, Anthocoridae, Carabidae, Staphylinidae and Araneae) increased up to 3 times.	Aphids' population decreased up to 63%.		Pest and beneficial arthropods were visually counted.	(Skirvin *et al*. 2011)
Apiaceae	*Daucus carota* L.		Population of *Psila rosae* (Fabricius) (Diptera: Psilidae) and *Trioza viridula* (Zett.) (Hemiptera: Triozidae) reduced up to 60% and 70%.	Marketable yield of carrot increased up to 164% in the first year, though no difference was noted at the end of the study.	*D. carota* were visually inspected for *P. rosae* damage. Pest arthropods were visually counted.	(Jankowska *et al*. 2012)
		Coccinellidae and Syrphidae abundance increased by 245% and 197%, respectively.	Population of *P. rosae* and *Cavariella aegopodii* reduced up to 66% and 57%, respectively.		*D. carota* were inspected and pest and beneficial arthropods were visually counted.	(Jankowska & Wojciechowicz-Żytko 2016)
		Coccinellidae and Syrphidae abundance increased by 109% and 140%, respectively.	Population of *P. rosae* and *C. aegopodii* reduced up to 80% and 50%, respectively.			
		The abundance of Araneae, Carabidae and Staphylinidae increased.	Infestation of *P. rosae* decreased by up to 75% which reduced the damage up to 20%.		Pitfall traps were used to assess the abundance of beneficial arthropods. *P. rosae* were sampled using vacuum suction.	(Rämert & Ekbom 1996)
		Increased the abundance of Carabidae by 14%. Staphylinidae by 24%.	Reduced the abundance of *C. aegopodii* and *P. rosae* by 40% and 11%, respectively.		*C. aegopodii* were sampled from carrot crown and surrounding soil.	(Uvah & Coaker 1984)
					Pitfall traps were used to assess the abundance of beneficial arthropods. Predation of *P. rosae*	

(*Continues*)

Table 2 (Continued)

Primary crop		Influence of intervention on beneficials	Influence of intervention on pests	Other benefits	Mechanism studied	References
Family	Species					
					was assessed by exposing marked *P. rosae* eggs. Pupae of *P. rosae* were sampled to assess the parasitism.	
			The damage from *P. rosae* and *Pythium* spp. reduced up to 83.5% and 48%, respectively.	Marketable yield of carrot increased 22–120% during the 4 years.	*D. carota* were inspected to count *P. rosae* larvae and to assess the damage.	(Theunissen & Schelling 2000
			The number of eggs laid by *T. viridula* on high-value carrot crop reduced up to 90%.		Eggs were visually counted on each trap crop.	(Cotes *et al*. 2018)
Fabaceae	*P. vulgaris* L.	The abundance of Coccinellidae significantly increased.	Population of *Aphis craccivora* Koch (Hemiptera: Aphididae), *M. sjostedti* and *Maruca vitrata* significantly reduced.		*P. vulgaris* were sampled to check for the abundance of pest and beneficial arthropods.	(Sharmah & Rahman 2017)
			Population of *A. craccivora* decreased by 24%. Population of *A. craccivora* significantly decreased by 39%.	Seed yield increased up to 4%. Seed yield significantly increased up to 17%.	*P. vulgaris* were sampled and numbers of *A. craccivora* were visually counted.	(Abdullah & Fouad 2016)
			Population of *Empoasca kraemeri* Ross & Moore (Hemiptera: Cicadellidae), *Diabrotica balteata* LeConte (Coleoptera: Chrysomelidae) and *S. frugiperda* reduced by 26%, 46% and 14%, respectively. Parasitism of *E. kraemeri* by *Anagrus* sp. (Hymenoptera: Mymaridae) increased by 20%.		*P. vulgaris* were sampled and arthropods were counted. Larvae of *E. kraemeri* were reared in the laboratory to verify the parasitism.	(Francis *et al*. 1976)
		The abundance of *Orius* spp. increased up to two-fold.	*M. sjostedti* decreased.	Yield loss due to thrips damage was reduced up to 60%.	*P. vulgaris* was visually assessed for damage. Arthropods were visually counted.	(Nyasani *et al*. 2012)

(*Continues*)

Table 2 (Continued)

Primary crop		Influence of intervention on beneficials	Influence of intervention on pests	Other benefits	Mechanism studied	References
Family	Species					
		The abundance of *Orius* spp. increased up to two-fold.	Population of *M. sjostedti*, *F. schultzei*, *F. occidentalis* and *H. aldolfifriderici* significantly decreased.	Yield loss due to thrips damage was reduced up to 62%.		
		The abundance of *Orius* spp. increased up to three-fold.	Population of *M. sjostedti* significantly decreased.	Yield loss due to thrips damage was reduced up to 47%.		
		The abundance of *Orius* spp. increased up to four-fold.	Population of *M. sjostedti* significantly decreased.	Yield loss due to thrips damage was reduced up to 57%.		
		No significant difference in abundance of *Orius* spp. was noted.	Population of *M. sjostedti* significantly decreased.	Yield loss due to thrips damage was reduced up to 37%.		
			The density of *F. occidentalis* significantly reduced. The density of *F. occidentalis* significantly reduced. The density of *F. occidentalis* significantly reduced. No significant difference in abundance of *F. occidentalis* was noted. No significant difference in abundance of *F. occidentalis* was noted. The density of *F. occidentalis* significantly reduced.		Flowers of *P. vulgaris* were sampled and numbers of *F. occidentalis* were visually counted.	(Kasina *et al*. 2006)
Solanaceae	*C. annuum* L.		Predation of *Ostrinia nubilalis* (Hübner) (Lepidoptera: Crambidae) eggs by *Orius insidiosus* (Say) (Hemiptera: Anthocoridae) and *Coleomegilla maculata* (DeGeer) (Coleoptera: Coccinellidae) increased up to 80% and 50%, respectively.		Sticky traps were used to determine population density of *O. nubilalis* and *O. insidiosus*. Sentinel *C. annuum* carrying eggs of *O. nubilalis* were exposed to assess the levels of predation.	(Bickerton & Hamilton 2012)
		Density of *M. persicae* decreased by 48%.			The number of *M. persicae* was visually counted.	(Russell & Bessin 2009)

(*Continues*)

Table 2 (Continued)

Primary crop		Influence of intervention on beneficials	Influence of intervention on pests	Other benefits	Mechanism studied	References
Family	Species					
		Coccinellidae, Nabidae, Reduviidae and Syrphidae increased by 44%, 50%, 16% and 36%, respectively.	Parasitism of *O. nubilalis* egg by *Trichogramma ostriniae* (Peng & Chen) (Hymenoptera: Trichogrammatidae) increased up to 53% which reduced the *O. nubilalis* infestation by 16%.		Sentinel eggs masses of *O. nubilalis* were used to assess the parasitism rate. Yellow sticky traps were used to determine the abundance of beneficial arthropods.	
		The abundance of Coccinellidae and Araneae significantly increased.	*Aphis gossypii* population reduced to 50%.		*C. annuum* were inspected and arthropods were visually counted.	(Idris & Roff 1999)
			Pests' infestation reduced by 85%.	Yield increased by 51%.	Sticky traps and polythene sleeve traps baited with pheromone lures were used to determine the population densities of pest and beneficial arthropods.	(Aswathanarayanareddy *et al*. 2006)
			Pests' infestation reduced by 81%.	Yield increased by 44%.		
			Trap crop was sprayed with insecticide which reduced the infestation of *Zonosemata electa* (Say) (Diptera: Tephritidae) up to 98%.		*Z. electa* were captured using ammonia-baited traps. *C. annuum* fruits were collected and inspected for feeding damage by *Z. electa*	(Boucher *et al*. 2003)
			Halyomorpha halys (Stål) (Hemiptera: Pentatomidae) population reduced by 49%.		*C. annuum* were inspected and the numbers of *H. halys* were visually counted.	(Mathews *et al*. 2017)
		Harboured *Lysiphlebus testaceipes* (Cresson) (Hymenoptera: Braconidae) against *A. gossypii*.			Sentinel *C. annuum* were used to assess the parasitism of *A. gossypii* by *L. testaceipes*.	(Rodrigues *et al*. 2001)

Banker plants can effectively sustain populations of natural enemies during overwintering and/or after harvesting of the main crop and can provide greater continuity of pest suppression (Huang *et al.* 2011). For example, Savoy cabbage (*Brassica oleracea* var. *sabauda* L.) (Brassicaceae) can serve as a banker plant when sown 1 month before the principal crop, cauliflower (*B. oleracea* var. *botrytis* L.) (Brassicaceae); the parasitoids, *Diaeretiella rapae* (McIntosh) (Hymenoptera, Aphidiinae) were promoted by early arriving *Brevicoryne brassicae* and *Myzus persicae* (Freuler *et al.* 2003) (Table 2). Banker plant systems have, however, received relatively little attention compared to other habitat management strategies, despite their potential to improve biological control efficacy (Frank 2010).

Trap crops such as Indian mustard (*Brassica juncea* (L.) Czern.) have been shown to attract gravid *P. xylostella*, which resulted in higher oviposition on trap crops than on the focal crop (*B. oleracea* var. *alba* L.) (Åsman 2002). Trap crops functioned as a sink for *P. xylostella* larvae, as larval survival was reduced significantly on trap crops. In a laboratory study, *P. xylostella* laid significantly more eggs on yellow rocket and *Barbarea verna* (Mill.) Asch. (Brassicaceae) than on cabbage (*B. oleracea* var. *capitata* L.) (Badenes-Perez *et al.* 2014). Kale (*B. oleracea* var. *acephala* L.) borders around cabbage fields resulted in significantly less *P. xylostella* eggs on cabbage which reduced pesticide input by 62% (Mitchell *et al.* 2000) (Table 2).

If a flowering trap crop shows the same effectiveness as it does when it is not flowering, this would open the possibility to use it to then attract and nourish parasitoids. For instance, a laboratory study showed that flowering and nonflowering yellow rocket were equally attractive to ovipositing *P. xylostella* (Lu *et al.* 2004), while, in another study, flowering yellow rocket attracted significantly greater number of *Diadegma insulare* (Cresson) (Hymenoptera: Ichneumonidae), a parasitoid of *P. xylostella* (Idris & Grafius 1997). Integrating flowering yellow rocket in cauliflower has resulted in greater numbers of generalist predators and higher rates of *P. xylostella* parasitism (Badenes-Perez *et al.* 2017) (Table 2).

Sweetcorn

Habitat management research in sweetcorn is largely dominated by interventions using flowering strips and trap crops with large potential benefits. Plants such as buckwheat, cowpea (*Vigna unguiculata* (L.) Walp.) (Fabaceae) and sunn hemp (*Crotalaria juncea* L.) (Fabaceae) have been extensively used to enhance the efficacy of a wide range of natural enemies (Manandhar & Wright 2015) (Table 2). Flowering strips have been reported to lower pest pressure by providing nectar and pollen to natural enemies but also to enhance pest 'fitness' (Duffield & Steer 2006). Sunflower (*Helianthus annuus* L.) (Asteraceae) strips around a sweetcorn field have been reported to significantly increased the abundance of natural enemies (Jones & Gillett 2005) but seem ultimately to be unsuitable because they are a preferred oviposition and feeding site for *Helicoverpa* spp. (Zalucki *et al.* 1986; Duffield & Steer 2006).

A related approach, 'attract and reward', combines the use of flowering plants with applications of herbivore-induced plant volatiles (HIPVs) to attract natural enemies to the area (Gurr *et al.* 2017; Furlong *et al.* 2018), and this is one case where small-scale evaluations have shown promise in sweetcorn in Australia (Simpson *et al.* 2011a). The combination of habitat manipulation with plant volatiles can be an effective approach because of benign nature of both strategies to beneficial arthropods and the principle that strategies that support ecological functions in multiple – rather than single – ways are preferable (Gentz *et al.* 2010). For example, sweetcorn sprayed with synthetic HIPVs and at the same time surrounded by buckwheat strips significantly elevated the abundance of natural enemies which, in turn, reduced the larval population of *Helicoverpa* spp. up to 74% (Simpson *et al.* 2011a) (Table 2). Despite this promise, however, the commercial partner involved in that research launched an HIPV-based product (Eco Oil) which has been commercially successful as a stand-alone technology rather than being combined with habitat management. This is likely to reflect the familiarity of growers with spray-on products and the ease of use compared with the inherent complexities of habitat management.

Intercropping other crops with sweetcorn has shown effective results on pest suppression. French bean, mung bean (*Vigna radiata* (L.) Wilczek) (Fabaceae) and sweet potato (*Ipomoea batatas* L.) (Convolvulaceae) intercrops have significantly increased the natural enemy abundance and decreased pest pressure (Nyasani *et al.* 2012; Tian *et al.* 2012) (Table 2).

A particular form of trap cropping, the 'push–pull' system deployed in East Africa (Khan *et al.* 2006), provides control of Lepidoptera pests such as spotted stem borer, *Chilo partellus* (Swinhoe) (Lepidoptera: Crambidae). The approach makes use of preferred oviposition hosts such as Napier grass (*Pennisetum purpureum* Schumach) and (*Brachiaria* cv. *Mulato* II) (Poaceae) to 'pull' gravid moths from the maize crop. Larvae hatching from eggs laid on these grassy borders do not survive, making the trap crop a dead-end host. This effect is complemented by a 'push' from growing pest-repellent molasses grass (*Melinis minutiflora* Beauv.) (Poaceae) within the maize field which also attract parasitoids (Khan *et al.* 2001; Khan *et al.* 2006; Khan *et al.* 2010). Other candidate plants including black mustard (*Brassica nigra* L.) (Brassicaceae) (Rea *et al.* 2002), guinea grass (*Panicum maximum* Jacq.) (Poaceae) (Koji *et al.* 2007) and *Desmodium* spp. (Fabaceae) (Midega *et al.* 2018) have been extensively used as trap crop in maize fields against a wide range of pests (Table 2). Whilst the push–pull system has proven successful in East African maize, it has not been adapted for or trialled in sweetcorn (Khan *et al.* 2010) (Table 2).

Lettuce

The use of flowering strips with lettuce has been explored in several studies. Nectar-rich, non-crop flowering plants in the field margins such as alyssum, cornflower, common vetch (*Vicia sativa* L.) and lupins (*Lupinus hispanicus* Boiss. & Reut.) (Fabaceae), and corn daisy (*Chrysanthemum segetum* (L.) Fourr.) (Asteraceae), increased the abundance of generalist predators (mostly hoverflies, ladybeetles and *Orius* spp.), promoting the biological control of *Nasonovia ribisnigri* and *Frankliniella* *occidentalis* (Pascual-Villalobos *et al*. 2006; Alomar *et al*. 2008), and *M. persicae* (Chaney 1998). Flower strips maintained the population of *Orius* spp. during the crop-free period (Alomar *et al*. 2008) (Table 2). The use of multiple plant species, such as alyssum, cornflower, common vetch, lupins, Indian chrysanthemum (*Chrysanthemum indicum* L.) (Asteraceae), chamomile (*Anthemis arvensis* L.) (Asteraceae) and clover species in lettuce, increased abundance of natural enemies three-fold, which, in turn, significantly decreased the abundance of *N. ribisnigri* (Skirvin *et al*. 2011). The decrease in the aphid population was greatest close to the flowering strips with the effect rapidly decaying with distance from the strips, such that there was little effect at a distance of 10 m from the flowers (Alomar *et al*. 2008; Skirvin *et al*. 2011). Other candidate plants such as coriander (*Coriandrum sativum* L.) (Apiaceae) and dill have also been used successfully in lettuce to support a wide range of natural enemies (Pascual-Villalobos *et al*. 2006; Alomar *et al*. 2008) (Table 2).

Carrot

The establishment of flowering strip margins is one of the most common habitat management techniques to promote conservation biological control in carrot (Rämert & Ekbom 1996; Jankowska *et al*. 2012). Coriander, summer savoury (*Satureja hortensis* L.) (Lamiaceae), French marigold (*Tagetes patula* L.) (Asteraceae), subterranean clover (*Trifolium subterraneum* L.) (Fabaceae) and water medic (*Medicago littoralis* Lois) (Fabaceae) all significantly increased the abundance of predatory arthropods, reducing carrot fly, *Psila rosae* (Fabricius) (Diptera: Psilidae) and carrot psyllid, *Trioza viridula* (Zett.) (Hemiptera: Triozidae). Importantly, this led to an increase of up to 164% in the marketable yield (Rämert & Ekbom 1996; Jankowska *et al*. 2012; Jankowska & Wojciechowicz-Żytko 2016), an indicator of success that is not frequently available for studies of habitat management (Table 2).

Intercropping carrot with onion significantly reduced the abundance of *Cavariella aegopodii* and *P. rosae* by promoting carabids (Carabidae) and rove beetles (Staphylinidae) (Uvah & Coaker 1984). In another study, intercropping carrot with subterranean clover significantly reduced root damage to carrots from *P. rosae* and *Pythium* spp. which increased the marketable yield of carrot up to 120% (Theunissen & Schelling 2000).

Trap cropping is also practised in carrot; Cotes et al. (2018) identified two fast-growing carrot cultivars ('Calibra' and 'Bolero'), as trap crops to manage carrot psyllid. Ovipositing females preferred to lay eggs on these more phenologically advanced carrot cultivars (Rygg 1977) and the numbers of eggs laid on the main carrot crop was significantly reduced compared with carrot without a trap crop (Cotes *et al*. 2018) (Table 2).

French bean

French beans are one of the least tested vegetable crops for habitat management strategies, despite being an important economic crop worldwide (FAO 2018). Field margin plants such as coriander and fenugreek (*Trigonella foenum-graecum* L.) (Fabaceae) significantly reduced densities of aphids, thrips and bean pod borer and increased the abundance of predatory arthropods (Abdullah & Fouad 2016; Sharmah & Rahman 2017). Recent work in Tanzania showed perennial vegetation in field margins harboured natural enemies that were tracked moving into the main crop (Mkenda *et al*. 2019) (Table 2). Intercropping French bean with sunflower, sweetcorn, fenugreek, potato (*Solanum tuberosum* L.) (Solanaceae), Mexican marigold (*Tagetes erecta* L.) (Asteraceae) and carrot significantly reduced the abundance of aphids, thrips, whitefly, pod borer, bean leaf hopper, *Empoasca kraemeri* (Ross & Moore) (Hemiptera: Cicadellidae), banded cucumber beetle, *Diabrotica balteata* (LeConte) (Coleoptera: Chrysomelidae) and *Spodoptera frugiperda* and increased the number of parasitoids, ladybeetles, spiders and *Orius* spp. (Francis *et al*. 1976; Kasina *et al*. 2006; Nyasani *et al*. 2012) (Table 2).

Capsicum

Flowering plants such as dill, coriander and buckwheat increased predation and parasitism of European corn borer, *Ostrinia nubilalis* (Hübner) (Lepidoptera: Crambidae) and aphids, with a significant increase in the populations of *Orius* spp., ladybeetle, damsel bugs (Nabidae), assassin bugs (Reduviidae) and hoverflies (Russell & Bessin 2009; Bickerton & Hamilton 2012). Intercropping with sweetcorn resulted in fewer cotton aphid, *Aphis gossypii* (Glover) (Hemiptera: Aphididae) with a significant increase in the abundance of ladybeetles and spiders (Idris & Roff 1999), whilst use of onion and garlic (*Allium sativum* L.) (Amaryllidaceae) with capsicum significantly reduced the overall pest infestation and increased the yield by 51% and 44%, respectively (Aswathanarayanareddy *et al*. 2006) (Table 2).

Trap cropping was investigated by Boucher et al. (2003), using capsicum cultivar 'Cherry Bomb' to protect the focal capsicum crop from oviposition and infestation of pepper fly, *Zonosemata electa* (Say) (Diptera: Tephritidae). Similarly, sunflower and sorghum (*Sorghum bicolor* (L.) Moench) (Poaceae) were also effective as border trap crops in capsicum fields, reducing brown marmorated stink bug, *Halyomorpha halys* (Stål) (Hemiptera: Pentatomidae) (Mathews *et al*. 2017) (Table 2).

Banker plant systems have shown promising results in terms of controlling capsicum pests and promoting natural enemies (Ramakers & Voet 1995). Sorghum, as border crop around capsicum field, not only harbours generalist predators (Chrysopidae, Coccinellidae) but also impedes the movement of pests (e.g. aphids) into the primary crop (Hewlett *et al*. 2019). For instance, sorghum, faba bean (*Vicia faba* L.) (Fabaceae) and castor bean (*Ricinus communis* L.) (Euphorbiaceae) were found effective as a banker plant in harbouring natural enemies such as *Lysiphlebus testaceipes* Cresson (Hymenoptera: Braconidae), *Amblyseius degenerans* (Berlese) (Acari: Phytoseiidae) and *Aphidoletes aphidimyza* (Rond.) (Diptera: Cecidomyiidae), against aphids and thrips (Hansen 1983; Ramakers & Voet 1995; Rodrigues *et al*. 2001) (Table 2).

ECOSYSTEM DISSERVICES IN HABITAT MANAGEMENT

Habitat management can have unwanted negative impacts on ecosystem functions, which generate 'ecosystem disservices' as a result of detrimental direct effects on the focal crop through increased competition for water, light and nutrients or by allelopathic effects. For example, when alfalfa (*Medicago sativa* L.) (Fabaceae) was grown as living mulch in a soybean field, the natural enemy abundance increased by 45% when compared to monocultured soybean, resulting in delayed establishment of *Aphis glycine*s (Matsumura) (Hemiptera: Aphididae), but the alfalfa consumed nutrients, resulting a soybean yield reduction of 26% (Schmidt *et al*. 2007). An additional risk is the potential for introduced vegetation to become weedy (Gurr *et al*. 2016). For example, if not managed, common vetch may pose a weed threat (Jursík & Holec 2009; Lockowandt *et al*. 2019).

Habitat management can also lead to indirect effects on the focal crop by enhancement of species other than the targeted natural enemies, which, in turn, may increase pest pressure (Zhang *et al*. 2007; Gurr *et al*. 2017). For instance, an Australian laboratory study found larval development and adult longevity of *Epiphyas postvittana* (Walker) (Lepidoptera: Tortricidae), a major polyphagous pest, were significantly improved in the presence of flowering starflower (*Borago officinalis* L.) (Boraginaceae) and buckwheat, which demonstrates the importance of identifying selective flowering plants that can only be exploited by the natural enemies (Begum *et al*. 2006). Though laboratory studies do not necessarily mean that pests will derive benefit from such plants under field conditions, they can lead to the identification of 'safer bet' plant species that cannot be utilised by pests even under non-choice conditions. This concept is evident in another Australian study, in which coriander, buckwheat and *B. officinalis* significantly increased the parasitism of potato moth, *Phthorimaea operculella* (Zeller) (Lepidoptera: Gelechiidae) by *Copidosoma koehleri* Blanchard (Hymenoptera: Encyrtidae), but coriander and buckwheat were also fed upon by *P. operculella*. Accordingly, only *B. officinalis* was identified as a 'selective food plant' (Baggen & Gurr 1998) and favoured for later field testing. In a contrasting system, buckwheat cover crops in vineyards attracted 27 times more beneficial arthropods compared with the vineyard without irrigated buckwheat field, but the density of pests, *Erythroneura elegantula* Osborn and *Erythroneura variabilis* Beamer (Hemiptera: Cicadellidae) was elevated up to 240% (Irvin *et al*. 2016).

RECOMMENDATIONS FOR HABITAT MANAGEMENT IN AUSTRALIAN AGROECOSYSTEMS

Distilling the global literature, our recommendations for habitat management in Australian vegetable crop systems are based on selecting plant species that (1) are present and readily available in Australia, (2) are well adapted to the climate in the relevant Australian vegetable production districts, (3) flower quickly and for long enough to cover the focal crop's vulnerable period to pest attack (Fig. 1) and (4) do not lead to ecosystem disservices. As is clear from the foregoing account of predominately international studies, habitat manipulation normally involves the use of a single tactic (e.g. trap cropping or banker plants) and using a single, intervention species, e.g. alyssum alone rather than seed mixes of multiple flowering plants (though this is not always the case). The plants used in overseas studies represent a tiny fraction of the plant kingdom, and a wider range of species needs to be investigated and guiding principles for their use developed. A recent attempt at resolving this issue has been to assess candidate flowering plants from the perspective of their ecological traits (rather than their taxonomy) (Zhu *et al*. 2020). Whilst that work generated some generalisable findings, e.g. plants with compound umbel or raceme inflorescences and shallow corollas showed positive influence on parasitoid longevity (Zhu *et al*. 2020), it was hampered by the lack of available data for many ecological traits that are likely to be important.

Secondary to the foregoing selection criteria, we recommend plant species that have shown effective in overseas work against pest species that are present and of importance in Australia. For example, Napier grass, guinea grass and molasses grass used as trap crops in African maize (Khan *et al*. 2010) (Table 2) were not considered for use in Australian sweetcorn because they are active against corn stem borer, which is not present in Australia. Finally, we highlighted the strategies that did not employ plant species with weedy potential. For example, Indian mustard used for controlling *P. xylostella*, or *Desmodium intortum* for *Spodoptera frugiperda* have weed status in Australia (Oram *et al*. 2005).

Alyssum, buckwheat, cornflower and dill significantly reduced densities of insect pests by enhancing the impact of natural enemy communities in brassica and lettuce overseas (Lavandero *et al*. 2005; Ribeiro & Gontijo 2017). In a laboratory assay, alyssum has been shown to be a potential habitat management candidate as it enhances the performance of *Cotesia vestalis* (Haliday) (Hymenoptera: Braconidae), but *P. xylostella* derives no benefit from its flowers (Chen *et al*. 2020). Similarly, buckwheat, cowpea and sunn hemp have potential to manage *Helicoverpa* spp. (Lepidoptera: Noctuidae) and thrips (*Frankliniella occidentalis* and *Frankliniella williamsi* Hood) (Thysanoptera: Thripidae) in sweetcorn (Jones & Gillett 2005; Manandhar & Wright 2015), whilst buckwheat and basil can be recommended to control lepidopteran pests, and sunflower to control *Halyomorpha halys* in capsicum fields (Skirvin *et al*. 2007; Bickerton & Hamilton 2012). Though *H. halys* is not established in Australia, its detection in imported goods is quite common (Horwood *et al*. 2019), indicating a need to minimise opportunities for it to become established and to have strategies for mitigation should it establish. These flowering plants are inexpensive, well adapted to a wide range of Australian climate, and some make effective cover crops or are economically important as secondary crops (Ngouajio *et al*. 2003; Björkman & Shail 2013). These plants also flower quickly and for long enough to cover the focal crop's vulnerable period to pest attack (Fig. 1). More generally, the blooming period of habitat management plants can be manipulated for optimal effects by the timing of planting. No ecosystem

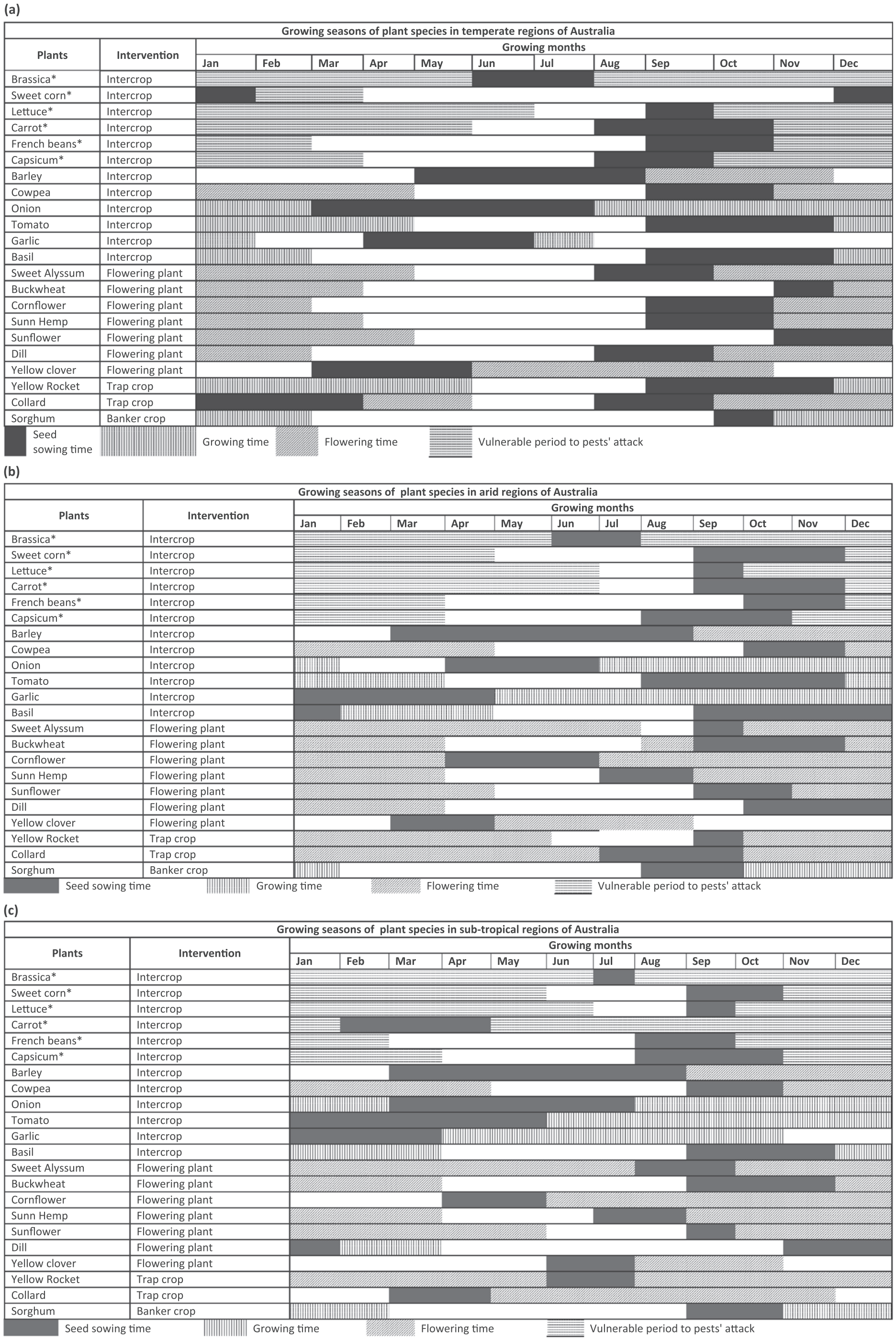

Fig. 1. Crop calendar for vegetable crops and plants that have potential in habitat management to suppress pests in (a) temperate, (b) arid and (c) sub-tropical zones of Australia. *Vegetable crops in current review. Vegetable crops are annotated as 'intercrop' because they can be used in this manner in a second, focal vegetable crop. Habitat management strategies are usually based on the use of one additional plant species. Seasons' information was adapted from Department of Primary Industries, Australia.

disservices were reported among studies on our targeted vegetables, but this could reflect the lack of comprehensive evaluation (Schellhorn *et al*. 2009; Gagic *et al*. 2018). Therefore, we recommend that additional pilot studies should be conducted by researchers and farmers before these plant species are widely promoted. An additional caveat is that economic factors have been little investigated in habitat management research (Shields *et al*. 2019; Johnson *et al*. 2020) so the benefit : cost ratios of each technique need evaluation. Practical considerations, such as capacity to accommodate flower strips in irrigation rows rather than occupying productive, crop growing space, will influence the ratio of benefit to cost as well as general ease with which habitat management plants can be established and maintained.

Intercropping is attractive as a habitat management option because it involves the production of a secondary crop that can be harvested for profit. It has been well explored in brassica with a diverse range of other crops such as onion, black pepper, tomato, barley and yellow clover and can be effective in management of *P. xylostella* (Bach & Tabashnik 1990; Hooks & Johnson 2002; Bukovinszky *et al*. 2004). Similarly, intercropping in sweetcorn can employ mung beans and French beans (Nyasani *et al*. 2012; Tian *et al*. 2012) and carrot intercropped with onion reduced the abundance of *Cavariella aegopodii* whilst increasing the population of beneficial carabids and rove beetles (Uvah & Coaker 1984). When capsicum was intercropped with onion or garlic (Aswathanarayanareddy *et al*. 2006), the pests' population was significantly reduced. These intercrop species are well established in many Australian vegetable production districts (Fig. 1) and can be adopted more readily than in broadacre crops because vegetable production often involves relatively small areas, often as sequentially planted strips with high edge to area ratios. Most intensive producers, however, focus on optimising the productivity of monocultures and intercropping involves a level of additional labour requirement and complexity of management and marketing. Further, some intercropping systems such as onion-brassica, garlic-brassica or garlic-sweetcorn may require capital investment for new farm machinery for bulb-type crops (Heisswolf 2004).

Trap cropping avoids the aforementioned agronomic complexities because the trap crop is usually closely related to the focal crop and is usually not harvested. Among trap crops used successfully overseas and meriting experimentation in Australia are yellow rocket, Chinese cabbage and collards to manage *P. xylostella* infestation in brassica vegetables (Badenes-Perez *et al*. 2017). Yellow rocket is a dead-end host for *P. xylostella* larvae (Idris & Grafius 1996) and, whilst it has weedy potential (Tahvanainen & Root 1970; MacDonald & Cavers 1991), we recommend evaluation in Australia because it is biennial, offering scope for use as an annual (Fig. 1) to serve as a trap crop in the year of sowing followed by destruction before any risk of setting seed (Badenes-Perez *et al*. 2004).

Banker plants have received relatively little attention compared to other habitat management strategies. We consider the major opportunity to be the use of sorghum for supressing pests and harbouring natural enemies of capsicum pests, an approach now being trialled by growers in Western Australia (Rizvi's personal observation).

CONCLUSION

There is increasing interest in habitat management among growers, researchers and governmental organisations around the world (Landis 2017). A number of studies illustrating the advantages of increased agricultural complexity and its relationship to ecosystem functions and ecosystem services have chiefly come from Europe, North America, with a few from Asia (Gurr *et al*. 2016; Gagic *et al*. 2018). For each of our targeted vegetable crops, we identified successful examples of habitat management techniques such as flowering nectar plant strips and groundcovers, intercropping, trap plants and banker plants. Most commonly reported were positive effects on the diversity and abundance of beneficial insects, but many studies also had cascading benefits on pest densities and crop damage. Whilst ecosystem disservices that lead to negative outcomes for growers are possible outcomes of habitat management studies, such risks can be managed by using the recommendations made in this review as a starting point for pilot studies. Accordingly, the habitat management strategies that appear most promising for use in the targeted vegetable crop systems identified in this review will serve as a platform for future, farmer participatory research and development.

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REFERENCES

Abdullah SS & Fouad HA. 2016. Effect of intercropping agroecosystem on the population of black legume aphid, *Aphis craccivora* Koch and yield of faba bean crop. *Journal of Entomology and Zoology Studies* **4**, 1367–1371.

Adamson D, Zalucki MP & Furlong MJ. 2014. Pesticides and integrated pest management practice, practicality and policy in Australia. In: *Integrated Pest Management* (eds R Peshin & D Pimentel), pp. 387–411. Springer, Netherlands, Dordrecht.

Alomar O, Arnó J & Gabarra R. 2008. Insectary plants to enhance the biological control of *Nasonovia ribisnigri* and *Frankliniella occidentalis* in lettuce. In: *Landscape Mangement for Function Biodiversity*, Vol. 34 (eds WAH Rossing, H-M Poehling & M van Helden), pp. 9–12. International Organization for Biological and Integrated Control, Bordeaux, France.

Anderies JM, Ryan P & Walker BH. 2006. Loss of resilience, crisis, and institutional change: lessons from an intensive agricultural system in Southeastern Australia. *Ecosystems* **9**, 865–878.

Andorno AV & López SN. 2014. Biological control of *Myzus persicae* (Hemiptera: Aphididae) through banker plant system in protected crops. *Biological Control* **78**, 9–14.

Asare-Bediako E, Addo-Quaye AA & Mohammed A. 2010. Control of Diamond back Moth (*Plutella xylostella*) on Cabbage (*Brassica oleracea* var capitata) using Intercropping with non-host crops. *American Journal of Food Technology* **5**, 269–274.

Åsman K. 2002. Trap cropping effect on oviposition behaviour of the leek moth *Acrolepiopsis assectella* and the diamondback moth *Plutella xylostella*. *Entomologia Experimentalis et Applicata* **105**, 153–164.

Aswathanarayanareddy N, Kumar C & Gowdar S. 2006. Effect of inter cropping on population dynamics of major pests of chilli (*Capsicum annuum* L.) under irrigated conditions. *Indian Journal of Agricultural Research* **40**, 294–297.

Bach CE & Tabashnik BE. 1990. Effects of nonhost plant neighbors on population-densities and parasitism rates of the diamondback moth (Lepidoptera, Plutellidae). *Environmental Entomology* **19**, 987–994.

Badenes-Perez FR, Shelton AM & Nault BA. 2004. Evaluating trap crops for diamondback moth, *Plutella xylostella* (Lepidoptera: Plutellidae). *Journal of Economic Entomology* **97**, 1365–1372.

Badenes-Perez FR, Reichelt M, Gershenzon J & Heckel DG. 2014. Using plant chemistry and insect preference to study the potential of Barbarea

(Brassicaceae) as a dead-end trap crop for diamondback moth (Lepidoptera: Plutellidae). *Phytochemistry* **98**, 137–144.

Badenes-Perez FR, Marquez BP & Petitpierre E. 2017. Can flowering *Barbarea* spp. (Brassicaceae) be used simultaneously as a trap crop and in conservation biological control? *Journal of Pest Science* **90**, 623–633.

Baggen LR & Gurr GM. 1998. The influence of food on *Copidosoma koehleri* (Hymenoptera: Encyrtidae), and the use of flowering plants as a habitat management tool to enhance biological control of potato moth, *Phthorimaea operculella* (Lepidoptera: Gelechiidae). *Biological Control* **11**, 9–17.

Balmer O, Pfiffner L, Schied J *et al*. 2013. Noncrop flowering plants restore top-down herbivore control in agricultural fields. *Ecology and Evolution* **3**, 2634–2646.

Barrière V, Lecompte F, Nicot PC, Maisonneuve B, Tchamitchian M & Lescourret F. 2014. Lettuce cropping with less pesticides. A review. *Agronomy for Sustainable Development* **34**, 175–198.

Bass C, Puinean AM, Zimmer CT *et al*. 2014. The evolution of insecticide resistance in the peach potato aphid, *Myzus persicae*. *Insect Biochemistry and Molecular Biology* **51**, 41–51.

Begum M, Gurr GM, Wratten SD, Hedberg PR & Nicol HI. 2006. Using selective food plants to maximize biological control of vineyard pests. *Journal of Applied Ecology* **43**, 547–554.

Bianchi FJJA, Booij CJH & Tscharntke T. 2006. Sustainable pest regulation in agricultural landscapes: a review on landscape composition, biodiversity and natural pest control. *Proceedings of the Royal Society of London, Series B: Biological Sciences* **273**, 1715–1727.

Bickerton MW & Hamilton GC. 2012. Effects of intercropping with flowering plants on predation of *Ostrinia nubilalis* (Lepidoptera: Crambidae) eggs by generalist predators in bell peppers. *Environmental Entomology* **41**, 612–620.

Björkman T & Shail JW. 2013. Using a buckwheat cover crop for maximum weed suppression after early vegetables. *HortTechnology* **23**, 575–580.

Boucher TJ, Ashley R, Durgy R, Sciabarrasi M & Calderwood W. 2003. Managing the pepper maggot (Diptera: Tephritidae) using perimeter trap cropping. *Journal of Economic Entomology* **96**, 420–432.

Bukovinszky T, Trefas H, van Lenteren JC, Vet LEM & Fremont J. 2004. Plant competition in pest-suppressive intercropping systems complicates evaluation of herbivore responses. *Agriculture Ecosystems & Environment* **102**, 185–196.

Chaney W. 1998. Biological control of aphids in lettuce using in-field insectaries. In: *Enhancing Biological Control* (eds CH Pickett & RL Bugg), pp. 73–83. University of California Press, Berkeley, CA.

Chen Y, Mao J, Reynolds OL *et al*. 2020. Alyssum (*Lobularia maritima*) selectively attracts and enhances the performance of *Cotesia vestalis*, a parasitoid of *Plutella xylostella*. *Scientific Reports* **10**, 6447.

Cotes B, Rämert B & Nilsson U. 2018. A first approach to pest management strategies using trap crops in organic carrot fields. *Crop Protection* **112**, 141–148.

Cuperus G, Mulder P & Royer T. 2000. Implementation of ecologically-based IPM. In: *Insect Pest Management: Techniques for Environmental Protection* (eds JE Rechcigl & NA Rechcigl), pp. 171–204. Lewis Publishers, Boca Raton, Florida. https://doi.org/10.1201/9781439822685.ch6 [Accessed 11th August 2021]

DAWE. 2019. Department of Agriculture Water and the Environment: vegetable industry. Available from: https://www.agriculture.gov.au/abares/research-topics/surveys/vegetables [Accessed 16th October 2021]

DPIR & Secondary DPIR. 2020. Department of Primary Industry and Resources: Fall armyworm detected in the Northern Territory. Available from: https://industry.nt.gov.au/news/2020/march/fall-armyworm-detected-in-the-nt [Accessed 16th October 2021]

Duffield S & Steer A. 2006. The ecology of *Helicoverpa* spp. (Lepidoptera: Noctuidae) in the Riverina region of south-eastern Australia and the implications for tactical and strategic management. *Bulletin of Entomological Research* **96**, 583–596.

Edwards J, Umbers A & Wentworth S. 2012. GRDC Farm Practices Survey Report 2012. In: *Secondary GRDC Farm Practices Survey Report 2012* (eds J Edwards, A Umbers & Wentworth). Grains Research and Development Corporation, Canberra, ACT. Available from: https://grdc.com.au/__data/assets/pdf_file/0021/82830/grdc-farm-practices-survey-2012.pdf.pdf [Accessed 10th October 2018]

Ekman J. 2015. Pests, diseases and disorders of sweet corn: a field identification guide. In: *Secondary Pests, Diseases and Disorders of Sweet Corn: A Field Identification Guide* (ed J Ekman). Horticulture Innovation Australia Limited, Australia. Available from: http://ahr.com.au/wp-content/uploads/2015/08/Sweet-Corn-Pest-and-Disease-Guide.pdf [Accessed 10th October 2018]

Endersby N, Ridland P & Hoffmann A. 2008. The effects of local selection versus dispersal on insecticide resistance patterns: longitudinal evidence from diamondback moth (*Plutella xylostella* (Lepidoptera: Plutellidae)) in Australia evolving resistance to pyrethroids. *Bulletin of Entomological Research* **98**, 145–157.

FAO. 2018. Global production of vegetables in 2017. In Secondary Global Production of Vegetables in 2017, vol. Volume (ed. Secondary FAO). Available from: http://www.fao.org/faostat/en/#home [Accessed 10th January 2019]

FAO. 2019. Food Agriculture Organization of the United Nations. Available from: http://www.fao.org/faostat [Accessed 05-05-2021].

Fiedler AK, Landis DA & Wratten SD. 2008. Maximizing ecosystem services from conservation biological control: the role of habitat management. *Biological Control* **45**, 254–271.

Francis CA, Flor Montoya CA & Prager Mosquera M. 1976. *Potentials of the Bean-Corn Association in the Tropics*. International Center for Tropical Agriculture, Colombia.

Frank SD. 2010. Biological control of arthropod pests using banker plant systems: past progress and future directions. *Biological Control* **52**, 8–16.

Freuler J, Fischer S, Mittaz C & Terrettaz C. 2003. The role of banker plants in the enhancement of the action of *Diaeretiella rapae* (M'Intosh) (Hymenoptera, Aphidiinae) the primary parasitoid of the cabbage aphid *Brevicoryne brassicae* (L.). *IOBC wprs Bulletin* **26**, 277–300.

Furlong MJ, Zu-Hua S, Yin-Quan L *et al*. 2004. Experimental analysis of the influence of pest management practice on the efficacy of an endemic arthropod natural enemy complex of the diamondback moth. *Journal of Economic Entomology* **97**, 1814–1827.

Furlong MJ, Wright DJ & Dosdall LM. 2013. Diamondback moth ecology and management: problems, progress, and prospects. *Annual Review of Entomology* **58**, 517–541.

Furlong MJ, Ang GC, Silva R & Zalucki MP. 2018. Bringing ecology back: how can the chemistry of indirect plant defenses against herbivory be manipulated to improve pest management? *Frontiers in Plant Science* **9**, 1436.

Gagic V, Paull C & Schellhorn NA. 2018. Ecosystem service of biological pest control in Australia: the role of non-crop habitats within landscapes. *Austral Entomology* **57**, 194–206.

Gardiner MM, Landis DA, Gratton C *et al*. 2010. Landscape composition influences the activity density of Carabidae and Arachnida in soybean fields. *Biological Control* **55**, 11–19.

Gentz MC, Murdoch G & King GF. 2010. Tandem use of selective insecticides and natural enemies for effective, reduced-risk pest management. *Biological Control* **52**, 208–215.

Gontijo LM. 2011. Integrated biological control of woolly apple aphid in Washington State. In: *Department of Entomology*, vol. Doctor of Philosophy (ed LM Gontijo), p. 163. Washington State University, Pullman, Washington. http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.953.5833&rep=rep1&type=pdf

Gordon G, Wratten SD, Jonsson M, Simpson M & Hale R. 2013. 'Attract and reward': combining a herbivore-induced plant volatile with floral resource supplementation – multi-trophic level effects. *Biological Control* **64**, 106–115.

GRDC. 2020. Grain Research & Development Corporation: Fall armyworm: a crop invader on the march. Australia. Available from: https://grdc.com.au/resources-and-publications/resources/fall-armyworm [Accessed 10th May 2020]

Gu H. 2009. Cold tolerance and overwintering of the diamondback moth (Lepidoptera: Plutellidae) in Southeastern Australia. *Environmental Entomology* **38**, 524–529.

Gurr G, Van Emden H & Wratten S. 1998. Habitat manipulation and natural enemy efficiency: implications for the control of pests. In: *Conservation Biological Control* (ed P Barbosa), pp. 155–183. Academic Press, San Diego CA, USA. https://doi.org/10.1016/B978-012078147-8/50055-4 [Accessed 10th January 2019]

Gurr GM, Wratten SD, Kehrli P & Scarratt S. 2005. Cultural manipulations to enhance biological control in Australia and New Zealand: progress and prospects. In: *Second International Symposium on Biological Control of Arthropods* (ed MS Hoddle), pp. 154–166. U.S. Dept. of Agriculture, Forest Service, Switzerland.

Gurr GM, Lu Z, Zheng X *et al*. 2016. Multi-country evidence that crop diversification promotes ecological intensification of agriculture. *Nature Plants* **2**, 1–4.

Gurr GM, Wratten SD, Landis DA & You M. 2017. Habitat management to suppress pest populations: progress and prospects. *Annual Review of Entomology* **62**, 91–109.

Hansen L. 1983. Introduction of *Aphidoletes aphidimyza* (Rond.) (Diptera: Cecidomyiidae) from an open rearing unit for the control of aphids in glasshouses. *Bulletin SROP* **6**, 146–150.

Hatt S, Uyttenbroeck R, Lopes T *et al*. 2018. Effect of flower traits and hosts on the abundance of parasitoids in perennial multiple species wildflower strips sown within oilseed rape (*Brassica napus*) crops. *Arthropod-Plant Interactions* **12** (6), 787–797.

Heisswolf S. 2004. Queensland Department of Agriculture and Fisheries: Brassica information kit. Reprint – information current in 2004. Queensland, Australia. Available from: http://era.daf.qld.gov.au/id/eprint/1965/5/brassica-grower5.pdf [Accessed 10th June 2019]

Hewlett JA, Szczepaniec A & Eubanks MD. 2019. The effects of sugarcane aphid density in sorghum on predation by lady beetles and lacewings. *Biological Control* **129**, 171–177.

Hokkanen HMT. 1991. Trap cropping in pest management. *Annual Review of Entomology* **36**, 119–138.

Hooks CRR & Johnson MW. 2002. Lepidopteran pest populations and crop yields in row intercropped broccoli. *Agricultural and Forest Entomology* **4**, 117–125.

Horne PA, Page J & Nicholson C. 2008. When will integrated pest management strategies be adopted? Example of the development and implementation of integrated pest management strategies in cropping systems in Victoria. *Australian Journal of Experimental Agriculture* **48**, 1601–1607.

Hort Innovation. 2018. *Australian Horticulture Statistics Handbook: Vegetables 2017/2018*, p. 119. Horticulture Innovation Australia, Sydney, Australia.

Horticulture Australia. 2014a. Brassica: Strategic Agrichemical Review Process. In: *Secondary Brassica: Strategic Agrichemical Review Process* (ed Secondary Horticulture Australia). Horticulture Innovation, Sydney, Australia. https://ausveg.com.au/biosecurity-agrichemical/crop-protection/brassicas/

Horticulture Australia. 2014b. Capscum: strategic agrichemical review process. In: *Secondary Capscum: Strategic Agrichemical Review Process* (ed Secondary Horticulture Australia). Horticulture Innovation Australia, Sydney, Australia. https://ausveg.com.au/app/uploads/2017/05/Peppers_SARP_report_10_March_2014.pdf

Horticulture Australia. 2014c. Carrots: strategic agrichemical review process. In: *Secondary Carrots: Strategic Agrichemical Review Process* (ed Secondary Horticulture Australia). Horticulture Innovation Australia, Sydney, Australia. https://ausveg.com.au/app/uploads/2017/05/Carrot_SARP_Report_5_Feb_2014.pdf

Horticulture Australia. 2014d. Lettuce: strategic agrichemical review process. In: *Secondary Lettuce: Strategic Agrichemical Review Process* (ed Secondary Horticulture Australia). Horticulture Innovation Australia, Sydney, Australia. https://ausveg.com.au/app/uploads/2017/05/Lettuce_SARP_report_15_Feb_2014.pdf

Horwood M, Milnes JM & Cooper WR. 2019. Brown marmorated stink bug, *Halyomorpha halys* (Hemiptera: Pentatomidae), detections in Western Sydney, New South Wales, Australia. *Austral Entomology* **58** (4), 857–865.

Huang NX, Enkegaard A, Osborne LS *et al*. 2011. The banker plant method in biological control. *Critical Reviews in Plant Sciences* **30**, 259–278.

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.

Idris A & Grafius E. 1997. Nectar-collecting behavior of *Diadegma insulare* (Hymenoptera: Ichneumonidae), a parasitoid of diamondback moth (Lepidoptera: Plutellidae). *Environmental Entomology* **26**, 114–120.

Idris A & Roff MM. 1999. The population abundance of *Aphis gossypii* Glover and its predators on chilli (*Capsicum annuum*) plants intercropped with other crops. *Journal of Plant Protection in the Tropics* **12**, 45–54.

Irvin NA, Bistline-East A & Hoddle MS. 2016. The effect of an irrigated buckwheat cover crop on grape vine productivity, and beneficial insect and grape pest abundance in southern California. *Biological Control* **93**, 72–83.

Jankowska B & Wojciechowicz-Żytko E. 2016. Effect of intercropping carrot (*Daucus carota* L.) with two aromatic plants, coriander (*Coriandrum sativum* L.) and summer savory (*Satureja hortensis* L.), on the population density of select carrot pests. *Folia Horticulturae* **28**, 13–18.

Jankowska B, Jedrszczyk E & Poniedzialek M. 2012. Effect of intercropping carrot (*Daucus carota* L.) with french marigold (*Tagetes patula nana* L.) and pot marigold (*Calendula officinalis* L.) on the occurrence of some petsts and quality of carrot yield. *Acta Agrobotanica* **65** (4), 133–138.

Johnson AC, Liu J, Reynolds O *et al*. 2020. Conservation biological control research is strongly uneven across trophic levels and economic measures. *Pest Management Science* **77** (5), 2165–2169.

Jones GA & Gillett JL. 2005. Intercropping with sunflowers to attract beneficial insects in organic agriculture. *Florida Entomologist* **88**, 91–96.

Jursík M & Holec J. 2009. Biology and control of another important weeds of the Czech Republic: cornflower (*Centaurea cyanus* L.). *Listy Cukrovarnické a Reparské* **125**, 90.

Karp DS, Chaplin-Kramer R, Meehan TD *et al*. 2018. Crop pests and predators exhibit inconsistent responses to surrounding landscape composition. *Proceedings of the National Academy of Sciences* **115**, 7863–7870.

Kasina J, Nderitu J, Nyamasyo G *et al*. 2006. Evaluation of companion crops for thrips (Thysanoptera: Thripidae) management on French bean *Phaseolus vulgaris* (Fabaceae). *International Journal of Tropical Insect Science* **26**, 121–125.

Keller M & Baker G. 2003. Impact of conservation biological control practices on natural enemies: a case study of diamondback moth and its parasitoids. In: *1st International Symposium on the Biological Control of Arthropods*, pp. 215–219. USDA Forest Service, Honolulu, Hawaii.

Khan Z, Ampong-Nyarko K, Chiliswa P *et al*. 1997. Intercropping increases parasitism of pests. *Nature* **388**, 631–632.

Khan Z, Pickett J, Wadhams L & Muyekho F. 2001. Habitat management strategies for the control of cereal stemborers and striga in maize in Kenya. *International Journal of Tropical Insect Science* **21**, 375–380.

Khan ZR, Midega CA, Hutter NJ, Wilkins RM & Wadhams LJ. 2006. Assessment of the potential of Napier grass (*Pennisetum purpureum*) varieties as trap plants for management of *Chilo partellus*. *Entomologia Experimentalis et Applicata* **119**, 15–22.

Khan ZR, Midega CA, Bruce TJ, Hooper AM & Pickett JA. 2010. Exploiting phytochemicals for developing a 'push–pull' crop protection strategy for cereal farmers in Africa. *Journal of Experimental Botany* **61**, 4185–4196.

Kift N, Mead A, Reynolds K *et al*. 2004. The impact of insecticide resistance in the currant-lettuce aphid, *Nasonovia ribisnigri*, on pest management in lettuce. *Agricultural and Forest Entomology* **6**, 295–309.

Koji S, Khan ZR & Midega CAO. 2007. Field boundaries of *Panicum maximum* as a reservoir for predators and a sink for *Chilo partellus*. *Journal of Applied Entomology* **131**, 186–196.

Lamine C, Barbier M, Blanc J *et al*. 2010. Reducing the dependence on pesticides: a matter of transitions within the whole agri-food system. In: *Transitions Towards Sustainable Agriculture: From Farmers to Agro-Food Systems, 9th European IFSA Symposium* (eds I Darnhofer & M Grötzer), pp. 4–7. International Farming Systems Association, Vienna (Austria).

Landis DA. 2017. Designing agricultural landscapes for biodiversity-based ecosystem services. *Basic and Applied Ecology* **18**, 1–12.

Landis DA, Wratten SD & Gurr GM. 2000. Habitat management to conserve natural enemies of arthropod pests in agriculture. *Annual Review of Entomology* **45**, 175–201.

Lavandero B, Wratten S, Shishehbor P & Worner S. 2005. Enhancing the effectiveness of the parasitoid *Diadegma semiclausum* (Helen): movement after use of nectar in the field. *Biological Control* **34**, 152–158.

Lee JC & Heimpel GE. 2005. Impact of flowering buckwheat on Lepidopteran cabbage pests and their parasitoids at two spatial scales. *Biological Control* **34**, 290–301.

Liu S, Shi Z, Furlong MJ & Zalucki M. 2005. Conservation and enhancement of biological control helps to improve sustainable production of Brassica vegetables in China and Australia. In: *Second International Symposium on Biological Control of Arthropods* (ed MS Hoddle), Vol. 1, pp. 254–266. USDA Forest Service Riverside, Davos, Switzerland.

Lockowandt L, Pinela J, Roriz CL *et al*. 2019. Chemical features and bioactivities of cornflower (*Centaurea cyanus* L.) capitula: the blue flowers and the unexplored non-edible part. *Industrial Crops and Products* **128**, 496–503.

Lu J-H, Liu S-S & Shelton A. 2004. Laboratory evaluations of a wild crucifer *Barbarea vulgaris* as a management tool for the diamondback moth *Plutella xylostella* (Lepidoptera: Plutellidae). *Bulletin of Entomological Research* **94**, 509–516.

Lu Z, Zhu P, Gurr GM, Zheng X, Chen G & Heong KL. 2015. Rice pest management by ecological engineering: a pioneering attempt in China. In: *Rice Planthoppers: Ecology, Management, Socio Economics and Policy* (eds KL Heong, J Cheng & MM Escalada), pp. 161–178. Springer Netherlands, Dordrecht. https://doi.org/10.1007/978-94-017-9535-7_8 [Accessed 10th May 2019]

MacDonald MA & Cavers PB. 1991. The biology of Canadian weeds.: 97. *Barbarea vulgaris* R. Br. *Canadian Journal of Plant Science* **71**, 149–166.

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.

Manandhar R & Wright MG. 2015. Effects of interplanting flowering plants on the biological control of corn earworm (Lepidoptera: Noctuidae) and thrips (Thysanoptera: Thripidae) in sweet corn. *Journal of Economic Entomology* **109**, 113–119.

Mathews CR, Blaauw B, Dively G *et al*. 2017. Evaluating a polyculture trap crop for organic management of *Halyomorpha halys* and native stink bugs in peppers. *Journal of Pest Science* **90**, 1245–1255.

Midega CA, Bruce TJ, Pickett JA, Pittchar JO, Murage A & Khan ZR. 2015. Climate-adapted companion cropping increases agricultural productivity in East Africa. *Field Crops Research* **180**, 118–125.

Midega CA, Pittchar JO, Pickett JA, Hailu GW & Khan ZR. 2018. A climate-adapted push-pull system effectively controls fall armyworm, *Spodoptera frugiperda* (JE Smith), in maize in East Africa. *Crop Protection* **105**, 10–15.

Mitchell E, Hu G & Johanowicz D. 2000. Management of diamondback moth (Lepidoptera: Plutellidae) in cabbage using collard as a trap crop. *HortScience* **35**, 875–879.

Mkenda PA, Ndakidemi PA, Stevenson PC *et al*. 2019. Field margin vegetation in tropical African bean systems harbours diverse natural enemies for biological pest control in adjacent crops. *Sustainability* **11**, 6399.

Moonen A-C & Bàrberi P. 2008. Functional biodiversity: an agroecosystem approach. *Agriculture, Ecosystems & Environment* **127**, 7–21.

Murray DA, Lloyd RJ & Hopkinson JE. 2005. Efficacy of new insecticides for management of *Helicoverpa* spp.(Lepidoptera: Noctuidae) in Australian grain crops. *Australian Journal of Entomology* **44**, 62–67.

Navas-Castillo J, Fiallo-Olive E & Sanchez-Campos S. 2011. Emerging virus diseases transmitted by whiteflies. *Annual Review of Phytopathology* **49**, 219–248.

Ngouajio M, McGiffen M Jr & Hutchinson C. 2003. Effect of cover crop and management system on weed populations in lettuce. *Crop Protection* **22**, 57–64.

Nilsson U, Rannback LM, Anderson P & Ramert B. 2012. Herbivore response to habitat manipulation with floral resources: a study of the cabbage root fly. *Journal of Applied Entomology* **136**, 481–489.

Nyasani J, Meyhöfer R, Subramanian S & Poehling HM. 2012. Effect of intercrops on thrips species composition and population abundance on French beans in Kenya. *Entomologia Experimentalis et Applicata* **142**, 236–246.

Oram R, Kirk J, Veness P, Hurlstone C, Edlington J & Halsall D. 2005. Breeding Indian mustard [*Brassica juncea* (L.) Czern.] for cold-pressed, edible oil production – a review. *Australian Journal of Agricultural Research* **56**, 581–596.

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.

Pascual-Villalobos M, Lacasa A, Gonzalez A, Varo P & Garcia M. 2006. Effect of flowering plant strips on aphid and syrphid populations in lettuce. *European Journal of Agronomy* **24**, 182–185.

Perović DJ, Gurr GM, Raman A & Nicol HI. 2010. Effect of landscape composition and arrangement on biological control agents in a simplified agricultural system: a cost–distance approach. *Biological Control* **52**, 263–270.

Pratley J & Kirkegaard J. 2019. *Australian Agriculture in 2020: From Conservation to Automation*. Agronomy Australia and Charles Sturt University, Wagga Wagga.

Rahman T, Roff MNM & Bin Abd Ghani I. 2010. Within-field distribution of *Aphis gossypii* and aphidophagous lady beetles in chili, *Capsicum annuum*. *Entomologia Experimentalis Et Applicata* **137**, 211–219.

Ramakers P & Voet S. 1995. Use of castor bean, *Ricinus communis*, for the introduction of the thrips predator *Amblyseius degenerans* on glasshouse-grown sweet peppers. *Mededelingen-Faculteit Landbouwkundige En Toegepaste Biologische Wetenschappen* **60**, 885–892.

Rämert B & Ekbom B. 1996. Intercropping as a management strategy against carrot rust fly (Diptera: Psilidae): a test of enemies and resource concentration hypotheses. *Environmental Entomology* **25**, 1092–1100.

Rea JH, Wratten SD, Sedcole R, Cameron PJ, Davis SI & Chapman RB. 2002. Trap cropping to manage green vegetable bug *Nezara viridula* (L.) (Heteroptera: Pentatomidae) in sweet corn in New Zealand. *Agricultural and Forest Entomology* **4**, 101–107.

Renwick JAA & Radke CD. 1985. Constituents of host plants and non-host plants deterring oviposition by the cabbage butterfly, *Pieris rapae*. *Entomologia Experimentalis et Applicata* **39**, 21–26.

Ribeiro AL & Gontijo LM. 2017. Alyssum flowers promote biological control of collard pests. *BioControl* **62**, 185–196.

Ridland PM, Umina PA, Pirtle EI & Hoffmann AA. 2020. Potential for biological control of the vegetable leafminer, *Liriomyza sativae* (Diptera: Agromyzidae), in Australia with parasitoid wasps. *Austral Entomology* **59**, 16–36.

Rodrigues SM, Bueno VH & Bueno F. 2001. Development and evaluation of an open rearing system for the control of *Aphis gossypii* glover (Hymenoptera: Aphidiinae) by *Lysiphlebus testaceipes* (cresson) (Hymenoptera: Aphidiinae) in greenhouses. *Neotropical Entomology* **30**, 433–436.

Root RB. 1973. Organization of a plant-arthropod association in simple and diverse habitats: the fauna of collards (*Brassica oleracea*). *Ecological Monographs* **43**, 95–124.

Russell K & Bessin R. 2009. Integration of *Trichogramma ostriniae* releases and habitat modification for suppression of European corn borer (*Ostrinia nubilalis* Hübner) in bell peppers. *Renewable Agriculture and Food Systems* **24**, 19–24.

Rygg T. 1977. Biological investigations on the carrot psyllid *Trioza apicalis* foerster (Homoptera: Triozidae). *Norges Landbruksh Nonoysk* **56**, 1–20.

Sands DP. 2018. Important issues facing insect conservation in Australia: now and into the future. *Austral Entomology* **57**, 150–172.

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* (eds R Peshin & A Dhawan), pp. 575–597. Springer Press, Dordrecht, The Netherlands. https://doi.org/10.1007/978-1-4020-8992-3_19 [Accessed 10th October 2020]

Schmidt NP, O'Neal ME & Singer JW. 2007. Alfalfa living mulch advances biological control of soybean aphid. *Environmental Entomology* **36**, 416–424.

Sharma HC. 1998. Bionomics, host plant resistance, and management of the legume pod borer, *Maruca vitrata* – a review. *Crop Protection* **17**, 373–386.

Sharmah D & Rahman S. 2017. Management of the major pests of French bean through development and validation of certain IPM modules, Assam, India. *Journal of Applied and Natural Science* **9**, 674–679.

Sheehan W. 1986. Response by specialist and generalist natural enemies to agroecosystem diversification: a selective review. *Environmental Entomology* **15**, 456–461.

Shelton A & Badenes-Perez F. 2006. Concepts and applications of trap cropping in pest management. *Annual Review of Entomology* **51**, 285–308.

Shields MW, Johnson AC, Pandey S *et al*. 2019. History, current situation and challenges for conservation biological control. *Biological Control* **131**, 25–35.

Simpson M, Gurr GM, Simmons AT *et al*. 2011a. Attract and reward: combining chemical ecology and habitat manipulation to enhance biological control in field crops. *Journal of Applied Ecology* **48**, 580–590.

Simpson M, Gurr GM, Simmons AT *et al*. 2011b. Field evaluation of the 'attract and reward' biological control approach in vineyards. *Annals of Applied Biology* **159**, 69–78.

Skirvin DJ, Kravar-Garde L, Reynolds K, Jones J, Mead A & Fenlon J. 2007. Supplemental food affects thrips predation and movement of *Orius laevigatus* (Hemiptera: Anthocoridae) and *Neoseiulus cucumeris* (Acari: Phytoseiidae). *Bulletin of Entomological Research* **97**, 309–315.

Skirvin D, Kravar-Garde L, Reynolds K, Wright C & Mead A. 2011. The effect of within-crop habitat manipulations on the conservation biological control of aphids in field-grown lettuce. *Bulletin of Entomological Research* **101**, 623–631.

Stark JD, Vargas R & Banks JE. 2007. Incorporating ecologically relevant measures of pesticide effect for estimating the compatibility of pesticides and biocontrol agents. *Journal of Economic Entomology* **100**, 1027–1032.

Tabashnik BE. 1985. Deterrence of diamondback moth (Lepidoptera: Plutellidae) oviposition by plant compounds. *Environmental Entomology* **14**, 575–578.

Tahvanainen JO & Root RB. 1970. The invasion and population outbreak of *Psylloides napi* (Coleoptera: Chrysomelidae) on Yellow Rocket (*Barbarea vulgaris*) in New York. *Annals of the Entomological Society of America* **63**, 1479–1480.

Theunissen J & Schelling G. 2000. Undersowing carrots with clover: suppression of carrot rust fly (*Psila rosae*) and cavity spot (*Pythium* spp.) infestation. *Biological Agriculture and Horticulture* **18**, 67–76.

Tian Y, Liang G, Zeng L & Lu Y. 2012. Influence of intercropping on dynamics of insect pests, natural enemies and the damage of *Ostrinia furnacalis* in sweet corn field. *Acta Phytophylacica Sinica* **39**, 1–6.

Tscharntke T, Tylianakis JM, Rand TA *et al*. 2012. Landscape moderation of biodiversity patterns and processes-eight hypotheses. *Biological Reviews* **87**, 661–685.

Turner JW. 1978. Pests of grain legumes and their control in Australia. In: *Pests of Grain Legumes: Ecology and Control* (eds SR Singh, HF van Emden & JA Taylor), pp. 73–81. Academic Press, London, UK.

Uvah I & Coaker T. 1984. Effect of mixed cropping on some insect pests of carrots and onions. *Entomologia Experimentalis et Applicata* **36**, 159–167.

Veres A, Petit S, Conord C & Lavigne C. 2013. Does landscape composition affect pest abundance and their control by natural enemies? A review. *Agriculture, Ecosystems & Environment* **166**, 110–117.

Wilson AJ, Schutze M, Elmouttie D & Clarke AR. 2012. Are insect frugivores always plant pests? The impact of fruit fly (Diptera: Tephritidae) larvae on host plant fitness. *Arthropod-Plant Interactions* **6**, 635–647.

Zalucki MP. 2015. From natural history to continental scale perspectives: an overview of contributions by Australian entomologists to applied ecology – a play in three acts. *Austral Entomology* **54**, 231–245.

Zalucki M, Daglish G, Firempong S & Twine P. 1986. The biology and ecology of *Heliothis armigera* (Hubner) and *Heliothis punctigera* Wallengren (Lepidoptera, Noctuidae) in Australia – what do we know? *Australian Journal of Zoology* **34**, 779–814.

Zhang W, Ricketts TH, Kremen C, Carney K & Swinton SM. 2007. Ecosystem services and dis-services to agriculture. *Ecological Economics* **64**, 253–260.

Zhang W, Jiang F & Ou J. 2011. Global pesticide consumption and pollution: with China as a focus. *Proceedings of the International Academy of Ecology and Environmental Sciences* **1**, 125.

Zhu P, Zheng X, Xie G, Chen G, Lu Z & Gurr G. 2020. Relevance of the ecological traits of parasitoid wasps and nectariferous plants for conservation biological control: a hybrid meta-analysis. *Pest Management Science* **76**, 1881–1892.

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