BioControl (2009) 54:211–218
DOI 10.1007/s10526-008-9182-9

Effects of flowering groundcover vegetation on diversity and activity of wasps in a farm shelterbelt in temperate Australia

Sagrario Gámez-Virués · Geoff Gurr · Anantanarayanan Raman · John La Salle · Helen Nicol

Received: 25 February 2008 / Accepted: 23 June 2008 / Published online: 9 July 2008

Abstract Significant worldwide interest in conservation biological control in agricultural systems currently exists but little information is available on the usefulness of this approach in farm forestry. In a field experiment conducted in a native vegetated shelterbelt in central-west New South Wales, we measured the diversity of wasps in plots comprising *Eucalyptus blakelyi* Maiden (Myrtaceae) trees with and without a groundcover of *Lobularia maritima* (L.) Desv. (Brassicaceae). Vacuum samples revealed a greater abundance and species richness of parasitic wasps in the plots comprising trees surrounded by the *L. maritima* groundcover. *Cotesia* sp. (Hymenoptera: Braconidae), *Pteromalus* sp. (Hymenoptera: Pteromalidae), *Anagyrus* sp. (Hymenoptera: Encyrtidae), Entedoninae sp. and Eulophidae sp. 1 (Hymenoptera: Eulophidae) were the most common taxa. These were more abundant also in the trees with the *L. maritima* groundcover. *Ardozyga stratifera* (Meyrick) (Lepidoptera: Gelechiidae) larvae, that were naturally infesting the *E. blakelyi* trees, were significantly more parasitized in the trees with the *L. maritima* groundcover. Results indicate that parasitic wasps associated with a native-tree shelterbelt in Australia were amenable to manipulation via groundcover vegetation.

Keywords Conservation biological control · Habitat manipulation · Herbaceous groundcover · Hymenoptera · Native-tree shelterbelt

Introduction

Shelterbelts, hedgerows and windbreaks are landmarks of human settlements and agricultural landscapes throughout the world (Baudry et al. 2000). The widening interest in these non-crop habitats arises from their ecological, cultural and economical value in farm forestry. Non-crop habitats act as refuges for species that cannot survive elsewhere in farmlands (Stephens et al. 2006). Many arthropods, both beneficial and harmful, use these habitats (Dix and Leatherman 1988; Majer et al. 2000) for food, oviposition and shelter (Pasek 1988; Thomas et al. 1991, 1992; Pollard and Holland 2006) and as overwintering sites (Dennis et al. 1994; Thomas and Marshall 1999). Within shelterbelts, arthropods could serve as prey for birds (Gámez-Virués et al. 2007),

Handling editor: Torsten Meiners.

S. Gámez-Virués
The University of Sydney, Sydney, Australia
e-mail: sagrariogamez@hotmail.com

G. Gurr (✉) · A. Raman · H. Nicol
Charles Sturt University, Orange, NSW, Australia
e-mail: ggurr@csu.edu.au

J. La Salle
Australian National Insect Collection, CSIRO, Entomology, GPO Box 1700, Canberra, ACT 2601, Australia
e-mail: John.LaSalle@csiro.au

contribute to crop pollination (Pontin et al. 2006), and aid natural pest suppression (Tsitsilas et al. 2006). Although few studies have explored how the botanical composition of woody non-crop habitats such as shelterbelts can affect their arthropod community (e.g., Pollard and Holland 2006; Tsitsilas et al. 2006), extensive work on the effects of other non-crop habitats such as field margins (Olson and Wäckers 2007) suggest enhanced impact of natural enemies within crops (Marino and Landis 1996; Steffan-Dewenter et al. 2001; Bianchi et al. 2006, Fiedler et al. 2008). Key examples of this are the suppression of pest mites in pastures adjacent to shelterbelts by predators, which appeared to be maintained by the groundcover vegetation within shelterbelts (Tsitsilas et al. 2006); and the colonization of vineyards adjacent to a corridor of flowering plant species by generalist predators (Nicholls et al. 2001). In addition, several European landscape-scale studies highlight non-crop habitats as relevant landscape components for a better conservation of biodiversity (e.g., Kruess and Tscharntke 1994; 2000; Thies et al. 2003; Bianchi et al. 2006; Billeter et al. 2008).

Although provision of nectar does not always lead to enhanced parasitism of pests (Heimpel and Jervis 2005), scope to increase the value of shelterbelts for natural enemies by manipulating groundcover vegetation is possible from the success of this approach in several crop systems. For example, an increase in the abundance of the leafroller parasitoid *Dolichogenidea tasmanica* (Hymenoptera: Braconidae) occurred when groundcover plants flowered in a New Zealand apple orchard (Irvin et al. 2000) and vineyard (Berndt et al. 2002), and an elevated rate of parasitism of *Epiphyas postvittana* (Lepidoptera: Tortricidae) eggs by *Trichogramma carverae* (Hymenoptera: Trichogrammatidae) when groundcover plants flowered in an Australian vineyard (Begum et al. 2006). Laboratory experiments indicate how effects of flowering groundcovers measured under field conditions may operate (see Jervis et al. 1996). Longevity of *Diadegma insulare* (Hymenoptera: Ichneumonidae) and *Cotesia marginiventris* (Hymenoptera: Braconidae) (Johanowicz and Mitchell 2000) was greater when these parasitoids had access to *L. maritima* flowers compared with control (water only), longevity of *Microctonus hyperodae* (Hymenoptera: Braconidae) increased when flowers of *Fagopyrum esculentum* (Polygonaceae) and *Coriandrum sativum* (Apiaceae) were available (Vattala et al. 2006), and longevity and fecundity of *T. carverae* was greater in the presence of *L. maritima* than other treatments (Begum et al. 2006).

Despite the high level of interest in conservation biological control (DeBach 1964; Ehler 1998) over the last 15 years, little work has focused on habitat manipulation methods to suppress arthropods infesting linear plantations of trees in agroecosystems, 'farm shelterbelts', which provide benefits such as reduction of wind erosion and salinity risk, preservation of soil moisture, and protection for crops, pastures and livestock (Baudry et al. 2000). *Anoplognathus*, *Heteronychus arator* and *Heteronyx elongatus* (Coleoptera: Scarabaeidae), *Phylacteophaga froggatti* (Hymenoptera: Pergidae), *Mnesampela privata* (Lepidoptera: Geometridae) and *Phaulacridium vittatum* (Orthoptera: Acrididae) are few of the most common and damaging herbivores of eucalypts in farms and plantations (CSIRO 1996; Loch and Floyd 2001). Although other herbivores occur usually in low numbers their damage could affect commercial farm forestry by reducing the success of establishment of eucalypts (Loch and Floyd 2001). For example, *Ardozyga stratifera* (Meyrick) (Lepidoptera: Gelechiidae), a leaf-tier, causes malformation of leave shoots by joining them together (Common 1990; Loch and Floyd 2001).

The present study is the first empirical assessment to test amenability of Australian shelterbelt wasps to manipulation via plant community. This study aimed to measure the effects of incorporating *Lobularia maritima* (L.) Desv. (Brassicaceae) as flowering groundcover in a native-tree shelterbelt on the (i) diversity of parasitoid and phytophagous wasps and (ii) parasitism of *A. stratifera* larvae that were naturally infesting *Eucalyptus blakelyi* Maiden (Myrtaceae) trees. *L. maritima* was selected since it has been found a successful herbaceous resource in similar manipulation experiments that aimed at conservation biological control (e.g., Ambrosino et al. 2006; Begum et al. 2006; Irvin et al. 2006).

Materials and methods

A randomized block experimental design was established in a 3-year-old shelterbelt (20 × 230 m) located in the Charles Sturt University farmland in Orange city, central-west NSW (33°15′S; 149°07′E;

849 m asl). The temperature during the study was 23.9 ± 1.4°C maximum and 8.8 ± 1.5°C minimum. The shelterbelt had five rows of native trees (4 m inter-row spacing) including the following taxa: *E. blakelyi* (48 trees), *E. macrorhyncha* F. Muell. ex Benth. (48 trees), *E. melliodora* A. Cunn. ex Schauer (56 trees), *E. pauciflora* Sieber ex Spreng. (48 trees), *E. viminalis* Labill. (48 trees), *Acacia dealbata* Link (12 trees), *A. implexa* Benth. (12 trees), *A. vestita* Ker Gawl. (12 trees) and *Casuarina cunninghamiana* Miq. (36 trees). Shrubs of *Callistemon sieberi* DC. (18 trees) and *Leptospermum myrtifolium* Sieber ex DC. (18 trees) were also present.

Twenty-four *E. blakelyi* trees (mean height 157.9 ± 65.4 cm) were selected based on their uniform levels (10–20% of leaves attacked, visual estimations) of natural infestation by *A. stratifera* larvae, which was the only herbivorous arthropod established on the trees. The 24 *E. blakelyi* trees were used to investigate the diversity of wasps and parasitism of *A. stratifera* larvae in a randomized block design. Each block comprised two trees, for one of the trees, a groundcover was established by manually removing the existing sward of *Phalaris aquatica* L. (Poaceae) and planting glasshouse-grown *L. maritima* (cv. Carpet of Snow) plants to cover 1 m^2 of the area around each nominated tree (hereafter, 'treatment'). The other tree in each block retained the original groundcover of *P. aquatica* (hereafter, 'control'). *L. maritima* plants were replaced, whenever necessary, to provide consistent groundcover of flowering plants.

Sampling of Hymenoptera commenced in September 2005, two weeks after establishing the *L. maritima* groundcover, and was continued till March 2006 (spring–summer). Wasps were collected fortnightly using a vacuum sampler (Weed Eater®, Model GB1 30v, Poulan Co. Shreveport, Louisiana, USA) by placing the sampler tube to enclose the branches. *E. blakelyi* foliage and the groundcover within 50 cm radius of the tree trunk were sampled for 30 s per plot. Vacuum samples from each plot were stored in separate zip-lock bags at −18°C for observations later.

All wasps were identified to the family level and assigned to morphospecies. Genus and species were determined, wherever possible, using the limited databases because the Australian arthropod fauna is one of the most poorly known (Austin et al. 2004; Raven and Yeates 2007). Determinations of taxa were made using Stevens et al. (2007), Austin et al. (2005), Naumann (1991), and by consulting appropriate professionals (*vide* acknowledgement). All morphospecies were assigned to functional groups: 'parasitoids' or 'phytophagous' (including gall inducers) following Stevens et al. (2007), Austin et al. (2005), La Salle (2004), Naumann (1991) and Gauld (1984). Numbers of morphospecies and individuals of each taxon, and each functional group, were used in calculating the Shannon diversity index, H' (Magurran 1988) in each treatment, and a t-test (significance $P < 0.05$) was performed to measure statistical differences (Magurran 1988). Mean abundance of morphospecies was calculated by pooling all sampling dates together as some of the parasitoids and phytophages occurred in very low numbers. Only the mean abundance of those 'common' species of wasps (represented by more than five individuals and with an arithmetic mean greater than 1, after pooling all samples) was analysed with one-way ANOVA (GenStat® 10) after square-root transformation ($\sqrt{x} + 0.5$).

Parasitism of *Ardozyga stratifera* larvae

Ardozyga stratifera larvae form a shelter in which to live and feed by tying *Eucalyptus* leaves together. Thirty of these shelters were collected from each of the 24 trees of *E. blakelyi* in October 2005 and March 2006. *A. stratifera* larvae were removed from the shelters and individually kept in plastic containers (250 ml) with lids that allowed ventilation and under laboratory conditions (25 ± 3°C, 13 h light period). Wet cotton balls were added to retain moisture within the containers. Containers were checked twice a week to record emergence of parasitoids and fresh field-collected *E. blakelyi* leaves, without any arthropod infestation, were supplemented periodically. Parasitoids within the containers were counted and stored in 70% ethanol. Treatment effects on the abundance of parasitized and non-parasitized *A. stratifera* larvae were analysed with a χ^2 test (GenStat® 10).

Results

In total, 783 wasps, including both parasitoids and phytophages, were assigned to 50 species and 20 families. Of these wasps, 478 were parasitoids (44 species; 19 families) obtained from the treatment

($H' = 2.78$, evenness = 0.734) and 91 were parasitoids (20 species; 12 families) obtained from the control ($H' = 2.43$, evenness = 0.810) (Table 1). Shannon diversity index for parasitoids differed significantly between treatment and control ($t_{1,142} = 2.84, P < 0.01$) (Table 1). Braconidae ($F_{1,11} = 36.2$, $P < 0.001$), Diapriidae ($F_{1,11} = 7.86$, $P = 0.017$), Encyrtidae ($F_{1,11} = 42.22$, $P < 0.001$), Eulophidae ($F_{1,11} = 10.27$, $P = 0.008$), Pteromalidae ($F_{1,11} = 41.37$, $P < 0.001$) and Scelionidae ($F_{1,11} = 11.06$, $P = 0.007$) showed the greatest species richness and abundance in the treatment (Table 1). Seven parasitoid taxa (mentioned below) were adequately abundant to be considered 'common'. *Cotesia* sp. (Braconidae) ($F_{1,11} = 22.65$, $P < 0.001$), *Pteromalus* sp. (Pteromalidae) ($F_{1,11} = 42.98$, $P < 0.001$), *Anagyrus* sp. (Encyrtidae) ($F_{1,11} = 33.44$, $P < 0.001$), Entedoninae sp. ($F_{1,11} = 14.81$, $P = 0.003$) and Eulophidae sp. 1 (Eulophidae) ($F_{1,11} = 8.43$, $P = 0.014$) were significantly more abundant in the treatment than in the control; and *Cirrospilus* sp. ($F_{1,11} = 3.99, P = 0.071$) and Eulophidae sp. 2 (Eulophidae) ($F_{1,11} = 0.50$, $P = 0.495$) did not show any statistical difference (Fig. 1).

Phytophagous wasps were considerably less diverse than parasitoids: 34 individuals of *Ophelimus* sp. (Eulophidae) and 21 individuals of *Megastigmus* sp. (Torymidae) were obtained from the treatment ($H' = 0.41$, evenness = 0.598), whereas 134 individuals of *Ophelimus* sp., 24 individuals of *Megastigmus* sp. and a singleton of Pergidae were obtained from the control ($H' = 0.28$, evenness = 0.258) (Table 1). Phytophagous wasps were more abundant in the control, but the numerical difference between treatment and control was not statistically significant. *Megastigmus* sp. and *Ophelimus* sp. were adequately abundant to be considered 'common', although their abundance did not differ between treatment and control (Fig. 1).

Parasitism of *Ardozyga stratifera* larvae

Fifty-five and 12 *A. stratifera* larvae were obtained from the treatment and the control, respectively, in October 2005. Of these, 11 larvae from the treatment and one from the control were parasitized by *Diaulomorpha* sp. 1 (Eulophidae). Despite the numerical difference in parasitism of *A. stratifera* larvae, treatment effect was not statistically significant ($\chi^2_1 = 0.91$, $P = 0.304$). In April 2006, 55 and 31 *A. stratifera* larvae were obtained from the treatment and the control, respectively. Of these, 17 larvae from the treatment were parasitized by *Sierola* sp. (Bethylidae), *Diaulomorpha* sp. 2 (Eulophidae) and one undetermined parasitic wasp; and three *A. stratifera* larvae from the control were parasitized by *Glyptapanteles* sp. (Braconidae) and *Neostomatoceras*

Table 1 Diversity of parasitoid and phytophagous wasps collected from the *Lobularia maritima* (*Lm*) treatment and control

Family	*Lm*		Control	
	S	N	S	N
Parasitoids				
Aphelinidae	1	1	0	0
Bethylididae	3	9	2	5
Braconidae	4	40***	2	4
Ceraphronidae	3	7	0	0
Chalcididae	1	8	1	5
Cynipidae	1	1	0	0
Diapriidae	1	5*	0	0
Encyrtidae	5	69***	1	8
Eulophidae	10	226**	4	49
Eupelmidae	0	0	1	1
Ichneumonidae	1	2	1	3
Mymaridae	2	8	1	1
Platigastridae	1	1	0	0
Pteromalidae	2	60***	1	1
Scelionidae	6	28**	2	8
Tiphiidae	1	2	0	0
Torymidae	1	9	1	5
Trichogrammatidae	1	2	1	1
Total	44	478	18	91
Shannon index, H'	2.78		2.43	
Shannon eveness, J	0.734		0.810	
t-test	$t_{1,142} = 2.84$, $P < 0.01$			
Phytophages				
Eulophidae	1	34	1	134
Pergidae	0	0	1	1
Torymidae	1	21	1	24
Total	2	55	3	159
Shannon index, H'	0.41		0.28	
Shannon eveness, J	0.598		0.258	
t-test	$t_{1,103} = 1.37$, $P > 0.05$			

S = number of species, N = number of individuals. Asterisks denote differences between treatments (one-way ANOVA * $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$)

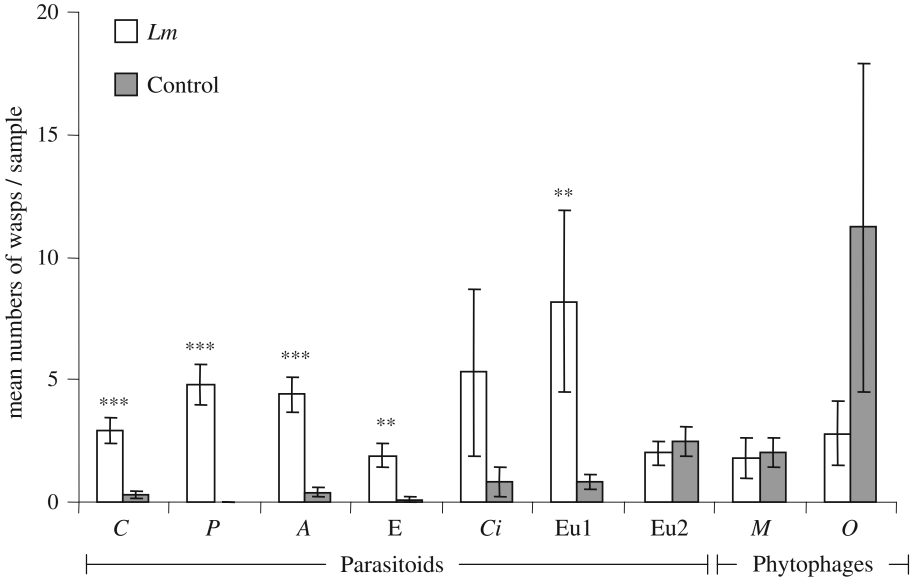

Fig. 1 Mean (±SE) abundance of the common parasitoid taxa: *C*, *Cotesia* sp.; *P*, *Pteromalus* sp.; *A*, *Anagyrus* sp.; E, Entedoninae sp., *Ci*, *Cirrospilus* sp., Eu1, Eulophidae sp. 1; and Eu2, Eulophidae sp. 2; and the common phytophagous taxa *M*, *Megastigmus* sp.; and *O*, *Ophelimus* sp.; in the *Lobularia maritima* (*Lm*) treatment and control. Asterisks denote differences between treatments (one-way ANOVA ** $P < 0.01$, *** $P < 0.001$)

sp. (Chalcididae). Of these parasitoids from *A. stratifera* larvae, only *Sierola* sp. ($n = 5$ individuals) were represented in the vacuum sample catches. Parasitism of *A. stratifera* larvae was significantly greater in the treatment than in the control ($\chi^2_1 = 5.01, P = 0.025$) in April 2006.

Discussion

This study shows that incorporation of *L. maritima* groundcover around individual *E. blakelyi* trees had positive effects on the diversity of parasitic wasps, indicating their amenability to manipulation via the plant community.

The positive effect of floral resources on the activity and density of several parasitoids has been demonstrated extensively in laboratory (e.g., Baggen and Gurr 1998; Jacob and Evans 2004; Short and Steinbauer 2004) and field conditions (e.g., Siemann et al. 1998; Bostanian et al. 2004; Lavandero et al. 2005). Most of these investigations have established that the nectar of herbaceous plants (e.g., *L. maritima*) added value to the agro-ecosystems (e.g., orchards, Bugg and Waddington 1994) through enhanced longevity of parasitoids (Johanowicz and Mitchell 2000; Begum et al. 2006), although greater longevity was not always achieved when tested under laboratory conditions (Sivinski et al. 2006). The positive effects of the floral resources on diversity of parasitoids are consistent with, but not necessarily indicative of, nectar feeding behaviour of the wasps (Heimpel and Jervis 2005). Although floral resources are critical for some parasitoids, other factors, such as moderated microclimate, shelter and supporting alternative host or prey organisms, will need to be factored here as having key effects on the efficacy of parasitoid performance.

Parasitism of *A. stratifera* larvae was numerically higher in those collected from the treatment than from the control, but was statistically significant only in April 2006. Three of the five parasitoid taxa reared from *A. stratifera* larvae belonged to Eulophidae (two) and Braconidae (one), which were the families, among six, that showed greater abundance and species richness in the treatment. These results indicate that flowering-plant groundcover plays a role in either attracting or retaining parasitoids (also see Stephens et al. 1998), and possibly affecting longevity and fecundity by making available nectar. *A. stratifera* larvae were numerically more in the treatment on both sampling occasions (October 2005; April 2006), thus an aggregative response by the parasitoids to *A. stratifera* density is also possible and could account for differences in parasitism.

The present work establishes a positive relationship between wasps and flowering groundcover at small scale (1 m^2), by adding value to the performance of shelterbelts. Effects of floral resources on parasitoids and predators have been investigated at the farm (Fitzgerald and Solomon 2004; Woodcock et al. 2005) and landscape scales (Thies et al. 2003; Bianchi et al. 2005). Presence of *L. maritima* influenced the abundance and the activity of parasitoids at a small spatial scale trialled in this field-based experiment. Parasitoids such as *Hyposter* sp. (Ichneumonidae), *Macrocentrus* sp., *Trichogramma* sp. (Trichogrammatidae) (Freeman-Long et al. 1998) and *Lysiphebus testaceipes* (Braconidae) (Fernandes et al. 1997) have shown movements up to 76, 30, 6, and 60 m distances, respectively, into the crop areas after visiting a floral source. *Diadegma semiclausum* (Hymenoptera: Ichneumonidae) reached distances of over 80 m in four days after feeding on a plot with flowers, but parasitism rates on *Plutella xylostella* (Lepidoptera: Plutellidae) were lower in a plot without flowers separated by a distance of 60 m (Lavandero et al. 2005). These findings establish that the distances, which the wasps travel and the scale at which they parasitize hosts are not always related (Lavandero et al. 2005). Moreover, effects of groundcover vegetation on parasitoids at small and large spatial scales are not always consistent. For example, the addition of *L. maritima* to apple orchards infested with the leafroller *E. postvittana* did not influence parasitism by *Dolichogenidea* spp. (Hymenoptera: Braconidae) but the characteristics of the surrounding landscape affected the rates of parasitism (Bell et al. 2006). Therefore, evaluation of potential food plants for parasitoids and their amenability to manipulation in shelterbelts and similar non-crop habitats will need to consider the scale effects and also use larger and more widely spaced plots than the present study.

These findings are in broad agreement with those reported by Tsitsilas et al. (2006) who have investigated the impact of arthropod predators in shelterbelts and adjacent cropland on the pest arthropods of pastures in Victoria Australia. The present study provides evidence that the enhanced abundance of parasitoids impacts on the pest arthropods of shelterbelts, which are attracting greater attention as farm forestry. However, the effects of shelterbelt botanical composition, including not only groundcover vegetation, on diversity and activity of wasps and other arthropods needs to be investigated further, particularly in relation to identifying plant species that provide benefit to natural enemies more selectively and to ‘scaling-up’. The present work using the food plant *L. maritima* as a flowering groundcover for the conservation of the existing biological control in a native vegetated shelterbelt indicates that parasitoids are amenable to manipulation via addition of flowering groundcover.

Acknowledgements We thank Andrew Mitchell (Orange Agriculture Institute, NSW) and Ted Edwards (Australian National Insect Collection, CSIRO, Canberra) for confirming *Ardozyga stratifera* (Lepidoptera); Matthew Buffington (USDA/SEL, Washington) for determining Figitidae and Cynipidae (Hymenoptera); Andrew Austin (The University of Adelaide, SA) for determining *Glyptapanteles* sp. (Hymenoptera: Braconidae); and Marja Simpson for help in field work. This study was supported by the Joint Venture Agroforestry Program [Project # US-117A] and Australian National Field Days, NSW, Australia.

References

Ambrosino MD, Luna JM, Jepson PC, Wratten SD (2006) Relative frequencies of visits to selected insectary plants by predatory hoverflies (Diptera: Syrphidae), other beneficial insects, and herbivores. Environ Entomol 35:394–400

Austin AD, Yeates DK, Cassis G, Fletcher MJ, La Salle J, Lawrence JF, McQuillan PB, Mound LA, Bickel DJ, Gullan PJ, Hales DF, Taylor GS (2004) Insects ‘Down Under’—diversity, endemism and evolution of the Australian insect fauna: examples from select orders. Aust J Entomol 43:216–234

Austin AD, Johnson NF, Dowton M (2005) Systematics, evolution and biology of scelionid and platygastrid wasps. Annu Rev Entomol 50:553–582

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). Biol Control 11:9–17

Baudry J, Bunce RGH, Burel F (2000) Hedgerows: an international perspective on their origin, function and management. J Environ Manage 60:7–22

Begum M, Gurr GM, Wratten SD, Hedberg P, Nicol HI (2006) Using selective food plants to maximize biological control of vineyard pests. J Appl Ecol 43:547–554

Bell VA, Brightwell RJ, Lester PJ (2006) Increasing vineyard floral resources may not enhance localized biological control of the leafroller *Epiphyas postvittana* (Lepidoptera: Tortricidae) by *Dolichogenidea* spp. (Hymenoptera: Braconidae) parasitoids. Biocontrol Sci Technol 16:1031–1042

Berndt LA, Wratten SD, Hassan P (2002) Effects of buckwheat flowers on leafroller (Lepidoptera: Tortricidae) parasitoids in a New Zealand vineyard. Agric For Entomol 4:39–45

Bianchi FJJA, van Wingerden WKRE, Griffioen AJ, van der Veen M, van der Straten MJJ, Wegman RMA, Meeuwsen HAM (2005) Landscape factors affecting the control of *Mamestra brassicae* by natural enemies in Brussels sprout. Agric Ecosyst Environ 107:145–150

Bianchi FJJA, Booij CJH, Tscharntke T (2006) Sustainable pest regulation in agricultural landscapes: a review on landscape composition, biodiversity and natural pest control. Proc R Soc Lond B Biol Sci 273:1715–1727

Billeter R, Liira J, Bailey D, Bugter R, Arens P, Augenstein I, Aviron S, Baudry J, Bukacek R, Burel F, Cerny M, De Blust G, De Cock R, Diekötter T, Dietz H, Dirksen J, Dormann C, Durka W, Frenzel M, Hamersky R, Hendrickx F, Herzog F, Klotz S, Koolstra B, Lausch A, Le Coeur E, Maelfait JP, Opdam P, Roubalova M, Schermann A, Schermann N, Schmidt T, Schweiger O, Smulders MJM, Speelmans M, Simova P, Verboom J, van Windergen WKRE, Zobel M, Edwards PJ (2008) Indicators for biodiversity in agricultural landscapes: a pan-European study. J Appl Ecol 45:141–150

Bostanian NJ, Goulet H, O'Hara J, Masner L, Racette G (2004) Towards insecticide free apple orchards: flowering plants to attract beneficial arthropods. Biocontrol Sci Technol 14:25–37

Bugg RL, Waddington D (1994) Using cover crops to manage arthropod pests of orchards: a review. Agric Ecosyst Environ 50:11–28

Common IFB (1990) Moths of Australia. Melbourne University Press, Australia

CSIRO (1996) Insect pests of eucalypts of farmland and in plantations in southeastern Australia. Australia Identification Leaflet Series, Leaflets 1-15, CSIRO Publishing, Collingwood, Victoria, Australia

DeBach P (1964) The scope of biological control. In: DeBach P (ed) Biological control of insect pests and weeds. Chapman and Hall, London, UK, pp 3–20

Dennis P, Thomas MB, Sotherton NW (1994) Structural features of field boundaries which influence the overwintering densities of beneficial arthropod predators. J Appl Ecol 31:361–370

Dix ME, Leatherman D (1988) Insect management in windbreaks. Agric Ecosyst Environ 22(23):513–537

Ehler LE (1998) Conservation biological control: past, present, and future. In: Barbosa P (ed) Conservation biological control. Academic Press, USA, pp 1–8

Fernandes OA, Wright RJ, Baumgarten KH, Mayo ZB (1997) Use of rubidium to label *Lysiphlebus testaceipes* (Hymenoptera: Braconidae), a parasitoid of green bugs (Homoptera: Aphididae), for dispersal studies. Environ Entomol 26:1167–1172

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

Fitzgerald JD, Solomon MG (2004) Can flowering plants enhance numbers of beneficial arthropods in UK apple and pear orchards? Biocontrol Sci Technol 14:291–300

Freeman-Long R, Corbett A, Lamb C, Reberg-Horton C, Chandler J, Stimmann M (1998) Beneficial insects move from flowering plants to nearby crops. Calif Agric September–October:23–26

Gámez-Virués S, Bonifacio RS, Gurr GM, Kinross C, Raman A, Nicol HI (2007) Arthropod prey of shelterbelt-associated birds: linking faecal samples with biological control of agricultural pests. Aust J Entomol 46:335–341

Gauld ID (1984) An introduction to the Ichneumonidae of Australia. British Museum (Natural History), London, UK

Heimpel GE, Jervis MA (2005) Does floral nectar improve parasitoid efficacy? In: Wäckers FL, van Rijn PCJ, Bruin J (eds) Plant-provided food for carnivorous insects: a protective mutualism and its applications. Cambridge University Press, Cambridge, UK, pp 267–304

Irvin NA, Wratten SD, Frampton CM, Chapman RB, Tylianakis JM (2000) Understory management for the enhancement of the leafroller parasitoid *Dolichogenidea tasmanica* (Cameron) in orchards at Canterbury, New Zealand. In: Austin AD, Dowton M (eds) Hymenoptera: evolution biodiversity and biological control. CSIRO Publishing, Collingwood, VIC, Australia, pp 396–403

Irvin NA, Scarratt SL, Wratten SD, Frampton CM, Chapman RB, Tylianakis JM (2006) The effects of floral understoreys on parasitism of leafrollers (Lepidoptera: Tortricidae) on apples in New Zealand. Agric For Entomol 8:25–34

Jacob HS, Evans EW (2004) Influence of different sugars on the longevity of *Bathyplectes curculionis* (Hym., Ichneumonidae). J Appl Entomol 128:316–320

Jervis MA, Kidd NAC, Heimpel GE (1996) Parasitoid adult feeding and biological control: a review. Biocontrol News Inf 17:1N–22N

Johanowicz DL, Mitchell ER (2000) Effects of sweet alyssum flowers on the longevity of the parasitoid wasps *Cotesia marginiventris* (Hymenoptera: Braconidae) and *Diadegma insulare* (Hymenoptera: Ichneumonidae). Fla Entomol 83:41–47

Kruess A, Tscharntke T (1994) Habitat fragmentation, species loss, and biological control. Science 264:1581–1584

Kruess A, Tscharntke T (2000) Species richness and parasitism in a fragmented landscape: experiments and field studies with insects on *Vicia sepium*. Oecologia 122:129–137

La Salle J (2004) Biology of gall inducers and evolution of gall induction in Chalcidoidea (Hymenoptera: Eulophidae, Eurytomidae, Pteromalidae, Tanaostigmatidae, Torymidae). In: Raman A, Schaeffer CW, Withers TM (eds) Biology, ecology and evolution of gall-inducing arthropods. Science Publishers, Enfield, USA, pp 507–537

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. Biol Control 34:152–158

Loch AD, Floyd RB (2001) Insect pests of Tasmanian blue gum, *Eucalyptus globulus globulus,* in southwestern Australia: history, current perspectives and future prospects. Austral Ecol 26:458–466

Magurran AE (1988) Ecological diversity and its measurement. Croom Helm, London

Majer JD, Recher H, Keals N (2000) Canopy arthropod faunas in fragmented agricultural landscapes. In: Hobbs RJ, Yates CJ (eds) Temperate eucalypt woodlands in Australia. Surrey Beatty & Sons Pty Limited and The Royal Australasian Ornithologists Union, Chipping Norton, NSW, Australia, pp 235–247

Marino PC, Landis DL (1996) Effect of landscape structure on parasitoid diversity and parasitism in agroecosystems. Ecol Appl 6:276–284

Naumann ID (1991) Hymenoptera. The insects of Australia, vol 2, 2nd edn. Merlbourne University Press, Carlton, Australia, pp 916–1000

Nicholls CI, Parrella M, Altieri MA (2001) The effects of a vegetational corridor on the abundance and dispersal of insect biodiversity within a northern California organic vineyard. Landscape Ecol 16:133–146

Olson DM, Wäckers FL (2007) Managements of field margins to maximize multiple ecological services. J Appl Ecol 44:13–21

Pasek JE (1988) Influence of wind and windbreaks on local dispersal of insects. Agric Ecosyst Environ 22(23): 539–554

Pollard KA, Holland JM (2006) Arthropods within the woody element of hedgerows and their distribution pattern. Agric For Entomol 8:203–211

Pontin DR, Wade MR, Kehrli P, Wratten SD (2006) Attractiveness of single and multiple species flower patches to beneficial insects in agroecosystems. Ann Appl Biol 148:39–47

Raven PH, Yeates DK (2007) Australian biodiversity: threats for the present, opportunities for the future. Aust J Entomol 46:177–187

Short MW, Steinbauer MJ (2004) Floral nectar versus honeydew as food for wasp parasitoids: implications for pest management in eucalypt plantations. Aust For 67: 199–203

Siemann E, Tilman D, Haarstad J, Ritchie M (1998) Experimental tests of the dependence of arthropod diversity on plant diversity. Am Nat 152:738–750

Sivinski J, Aluja M, Holler T (2006) Food sources for adult *Diachasmimorpha longicaudata*, a parasitoid of tephritid fruit flies: effects on longevity and fecundity. Entomol Exp Appl 118:193–202

Steffan-Dewenter I, Müzenberg U, Tscharntke T (2001) Pollination, seed set, and seed predation on a landscape scale. Proc R Soc Lond B Biol Sci 268:1685–1690

Stephens MJ, France CM, Wratten SD, Frampton C (1998) Enhancing biological control of leafrollers (Lepidoptera: Tortricidae) by sowing buckwheat (*Fagopyrum esculentum*) in an orchard. Biocontrol Sci Technol 8:547–558

Stephens C, Schellhorn NA, Wood GM, Austin AD (2006) Parasitic wasp assemblages associated with native and weedy plant species in an agricultural landscape. Aust J Entomol 45:176–184

Stevens NB, Stephens CJ, Iqbal M, Jennings JT, La Salle J, Austin AD (2007) What wasp is that? [cd-rom]: an interactive identification guide to the Australian families of Hymenoptera. Australian Biological Resources Study and Centre for Biological Information Technology (ABRS identification series), Canberra, ACT, Dewey Number: 595.79099

Thies C, Steffan-Dewenter I, Tscharntke T (2003) Effects of landscape context on herbivory and parasitism at different spatial scales. Oikos 101:18–25

Thomas CFG, Marshall EJP (1999) Arthropod abundance and diversity in differently vegetated margins of arable fields. Agric Ecosyst Environ 72:131–144

Thomas MB, Wratten SD, Sotherton NW (1991) Creation of 'island' habitats in farmland to manipulate populations of beneficial arthropods: predator densities and emigration. J Appl Ecol 28:906–917

Thomas MB, Wratten SD, Sotherton NW (1992) Creation of 'island' habitats in farmland to manipulate populations of beneficial arthropods: predator densities and species composition. J Appl Ecol 29:524–531

Tsitsilas A, Stuckey S, Hoffmann AA, Weeks AR, Thomson LJ (2006) Shelterbelts in agricultural landscapes suppress invertebrate pests. Aust J Exp Agr 46:1379–1388

Vattala HD, Wratten SD, Phillips CB, Wäckers FL (2006) The influence of flower morphology and nectar quality on the longevity of a parasitoid biological control agent. Biol Control 39:179–185

Woodcock BA, Westbury DB, Potts SG, Harris SJ, Brown VK (2005) Establishing field margins to promote beetle conservation in arable farms. Agric Ecosyst Environ 107:255–266

Author Biographies

Sagrario Gámez-Virués is devoted to analyse the correlations between shelterbelts and conservation biological control in Australian farmlands.

Geoff Gurr leads an active research group working in a range of pest management disciplines. A current priority is developing approaches that farmers can implement to maximise biological control whilst simultaneously delivering other ecosystem services.

Anantanarayanan Raman studies the ecology of insect–plant interactions, with particular reference to the nutritional physiology and population dynamics of gall-inducing arthropods.

John La Salle is interested in the systematics and biology of parasitic wasps, and their impact in natural and agricultural ecosystems.

Helen Nicol is a Biometrician with extensive experience with biological and agricultural experimental design and data analysis.