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Phenology of *Eucalyptus* weevil, *Gonipterus scutellatus* Gyllenhal (Coleoptera: Curculionidae), and chrysomelid beetles in *Eucalyptus globulus* plantations in south-western Australia

A. D. Loch

CSIRO Entomology, c/– Department of Conservation and Land Management, Brain St, Manjimup, WA 6258, Australia and National Wine and Grape Industry Centre, Locked Bag 588, Charles Sturt University, NSW 2678, Australia

Abstract

1 In south-western Australia, *Eucalyptus globulus* plantations are defoliated by a complex of beetle species, yet only scant information exists on these species under such climatic conditions. To improve management of these defoliating beetles in the region, canopy fogging and shoot clipping were conducted in plantations between 1999 and 2002 to identify and document the phenology of the beetle species present.

2 *Eucalyptus* weevil, *Gonipterus scutellatus*, was the most common and destructive defoliating beetle. *Gonipterus scutellatus* undergoes one principal generation each year with a lesser second generation or cohort in some seasons, which contrasts greatly with reports of two to four annual generations for the species in other regions. This limited reproduction by *G. scutellatus* may be due to the limited availability from summer onwards of new flushing foliage, which is essential for feeding and oviposition.

3 Several species of chrysomelid beetles were collected in plantations, but these were present in much lower numbers than *G. scutellatus* and were only a minor concern. However, some species, such as *Chrysophtharta variicollis*, appear to be capable of developing short-lived outbreaks.

4 A diverse suite of natural enemies was fogged from plantations but they were significantly less abundant than defoliating beetles and are not likely to provide significant control of beetles.

5 In terms of managing these defoliating beetles, monitoring and control should focus on *G. scutellatus*, and be conducted during spring when most damage occurs.

Keywords *Cadmus excrementarius*, *Chrysophtharta nobilitata*, *Chrysophtharta variicollis*, defoliation, eucalypt plantation, *Eucalyptus globulus Eucalyptus* weevil, *Gonipterus scutellatus*, natural enemy, phenology.

Introduction

Eucalypt plantations are a relatively recent and significant addition to the landscape of south-western Australia, yet in that short time (approximately 20 years), a significant pest complex has developed (Loch & Floyd, 2001). Of these pests, the *Eucalyptus* weevil, *Gonipterus scutellatus* Gyllenhal, and, to a lesser degree, chrysomelid beetles, *Chrysophtharta* spp. and *Cadmus excrementarius* Suffrian, and nocturnal scarab beetles, *Heteronyx* spp., are currently the most important defoliators of established plantations of *Eucalyptus globulus* Labill. These beetles feed on new shoots and leaves of eucalypts, which if of sufficient magnitude can lead to the characteristic damage of thinning of the upper crown or 'broom-topping'. Economic losses through reductions in tree height, diameter and volume, and potential growth malformation can arise from such damage, as demonstrated with *Ch. bimaculata* Olivier in Tasmania (Candy *et al.*, 1992; Elliott *et al.*, 1993; Elek, 1997).

Correspondence: A. D. Loch, National Wine and Grape Industry Centre, Locked Bag 588, Charles Sturt University, NSW 2678, Australia. Tel.: +61 26933 4082; fax: +61 26933 2107; e-mail: andrew.loch@dpi.nsw.gov.au

Defoliating beetles are also serious pests of eucalypt plantations in other parts of Australia (de Little, 1989; Bashford, 1993; Neumann, 1993; Stone, 1993; Wylie & Peters, 1993) and other countries (Cordero Rivera *et al.*, 1999; Hanks *et al.*, 2000; Lanfranco & Dungey, 2001; Withers, 2001). Management programmes against defoliating beetles have typically relied on insecticides, although some biological control successes have occurred (Tooke, 1953; Cordero Rivera *et al.*, 1999; Hanks *et al.*, 2000; Tribe & Cillie, 2000), and biocides containing *Bacillus thuringiensis* ssp. *tenebrionis* show some promise in the control of beetle larvae (Harcourt *et al.*, 1996; Elek & Beveridge, 1999; Beveridge & Elek, 2001). Integrated pest management is an industry objective, and the success of an integrated pest management programme in any crop is contingent on detailed knowledge of the ecology of the beetle complex and their natural enemies (Kogan, 1998). Although some beetle species in south-western Australia have been studied in other parts of Australia (e.g. *G. scutellatus*; Tooke, 1953), the phenology of a species may vary greatly depending on environmental conditions. To date, most Australian studies on defoliating eucalypt beetles have been concentrated in temperate climatic regions in Tasmania and mainland south-eastern Australia. Yet, for *E. globulus* plantations in south-western Australia, which has a highly pronounced Mediterranean climate, only scant information exists for the defoliating beetles and their natural enemies.

To rectify this shortcoming, regular field surveys involving canopy fogging and shoot clipping were conducted in plantations to identify the defoliating beetles were present and to document the seasonal phenology of the major damaging species. Peak periods of beetle abundance and defoliation were recorded, as were peak periods of reproductive activity, by quantifying the abundance of immature stages of beetles and by assessing adult maturity through dissection of female beetles. Because canopy fogging was employed to sample beetles during the study, other arthropods were also fogged from trees. One component of this arthropod biodiversity of particular interest comprised the natural enemies (predators and parasitoids), which were identified and counted.

Materials and methods

Plantation surveys and sampling

The seasonal phenology of defoliating beetles was studied at four *E. globulus* plantations within the plantation estate in south-western Australia. The Manjimup plantation (34°14′S, 116°11′E) comprised 2.9 ha planted in 1990, 20.5 ha planted in 1996 and 8.4 ha planted in 1997 at a stocking rate of 1250 stems per ha. At Rocky Gully (34°33′S, 117°02′E), 25 ha were planted in 1994, 429.5 ha in 1995 and 193 ha in 1996 at a stocking rate of 1000 stems per ha. The Denbarker plantation (34°44′S, 117°20′E) totalled 237.7 ha with 176.5 ha planted in 1995 and 61.2 ha planted in 1996 at a stocking rate of 1250 stems per ha. The Albany plantation (34°53′S, 118°05′E) comprised 200 ha planted in 1996 at a stocking rate of 1000 stems per ha. All four plantations had been established on ex-pasture sites and were surrounded by a mix of pasture, different aged eucalypt plantations and remnant native vegetation (mixed eucalypt forest or woodland). Mean annual rainfall for all plantations is in the range of 800–1100 mm.

Plantations were sampled monthly between October 1999 and February 2002, except for the Manjimup and Rocky Gully plantations, which were sampled twice monthly between November 1999 and March 2000. At all plantations, only trees established in 1996 were sampled. On each sampling occasion, two plots of 100 trees (10 × 10 trees) within the plantation were selected so that they were separated by at least 100 m. Five trees were sampled from each plot giving a total of 10 trees sampled per plantation during October 1999 and from November 2000 onwards. Between November 1999 and October 2000, ten trees were sampled from each plot giving a total of 20 trees sampled per plantation. For each sampled tree, an estimate of the percentage of total tree foliage present as adult-phase foliage was recorded. Estimates of percentage defoliation were made to juvenile-phase foliage (if present), adult-phase foliage in the upper crown (defined as the growing tip of the tree containing only new season's foliage), and in the lower crown (defined as the remaining adult foliage below the upper crown). In the present study, the terms upper and lower crown do not refer to the upper half and lower half of the tree, respectively, as is commonly reported in other studies. Percentage estimates of foliage and defoliation were made to the nearest 10% with smaller graduations near 0% (i.e. 0%, 1%, 2%, 5%, 10%) and 100% (i.e. 90%, 95%, 98%, 99%, 100%).

Two techniques commonly used to determine the abundance of invertebrates within eucalypt forests, shoot clipping and canopy fogging with insecticide (Majer & Recher, 1988), were employed to quantify numbers of different beetle species and their life stages on *E. globulus* over time. Both techniques were conducted on each sampled tree. Thus, shoot tip removal was conducted prior to canopy fogging to ensure insects remained alive on branches.

Five shoot tips, approximately 30 cm long, containing new adult-phase foliage growth were removed from various parts of each tree. Shoot tips were removed as carefully as possible to prevent dislodgement of any beetle eggs and larvae present on each tip. A percentage estimate of defoliation to each shoot tip was made to the nearest 10% with smaller graduations near 0% and 100%. All beetle eggs and larvae present on each shoot tip were counted and identified to species where possible. Egg masses and larvae of *G. scutellatus* and chrysomelid beetles are easily distinguished. Eggs of *G. scutellatus* are laid inside small brown or black cases whereas eggs of chrysomelid beetles are laid uncovered in clumps, rows or rings. Larvae of *G. scutellatus* are legless and slug-like whereas chrysomelid larvae have well-developed legs and a smooth appearance. No distinction was made between the eggs or larvae of different chrysomelid species. Egg masses of *G. scutellatus* collected by branch clipping were also returned to the laboratory to monitor for parasitism (A.D. Loch, unpublished data).

When branch-clipping was completed, a 2 × 2 m heavy cotton dropsheet was placed on one side of each tree so that the centre of one side of each sheet just touched the base of the tree. Each tree was then fogged with insecticide from a

Stihl Mistblower (Stihl, Australia) ensuring that all foliage on the tree had been treated. The contact insecticides Dominex 100 (Crop Care Australasia Pty Ltd, Brisbane, Australia), Fastac 100 (Cyanamid Agriculture Pty Ltd, Sydney, Australia) and Alphamax 100 (Artfern Pty Ltd, Melbourne, Australia) (all a.i. alpha-cypermethrin 100 g/L) were used at various times throughout the study at the rate of 1 mL per 1 L of water. During the preliminary fogging trials ($n = 10$ trees), 63% of all beetles falling within 4 h of spraying fell within the first hour and 91% of beetles had fallen after 3 h (A.D. Loch unpublished data). Therefore, all fallen insects were collected from drop-sheets 3–4 h after fogging had been completed. Insects from each drop-sheet were collected into a single vial and preserved in 70% ethanol for sorting and identification in the laboratory.

An additional plantation north of Albany (North Albany 34°57′S, 117°48′E) was sampled between October 2001 and April 2002. The North Albany plantation comprised 330 ha of trees (principally *E. globulus*) of various ages that are irrigated regularly with wastewater and treated effluent from the city of Albany. Because of the added water and nutrients, on average, trees grow at approximately twice the rate of unirrigated trees in the same area and are harvested on a shorter rotation. Coppicing *E. globulus* trees (approximately 5 m tall) were sampled to test the hypothesis that the seasonal phenology of *G. scutellatus* is limited by the availability of new flushing shoot growth. At this plantation, ten trees were selected for shoot clipping and analysis as described above. No canopy fogging was conducted at North Albany.

Voucher specimens of all beetle species are housed in the Australian National Insect Collection. Drs Tom Weir, Rolf Oberprieler, and the late Elwood Zimmerman (CSIRO Entomology) identified adult beetle species. Potential natural enemies were identified to at least Order or Family level, with specimens of Coleoptera and Hemiptera being identified to genus or species level.

Female beetle dissections

Females of the most common beetle species were collected between November 1999 and June 2001 from Manjimup and Rocky Gully and dissected to confirm whether they were sexually mature or immature. Female beetles were frozen shortly after collection to preserve reproductive systems. Females were dissected by making a longitudinal incision in the ventral abdominal wall and pulling the two sides outwards to expose the reproductive structures. Each dissected female was scored as either sexually mature or immature. Immature females had small pale coloured ovarioles, by contrast to the large, often brightly coloured ovarioles, usually containing eggs, of mature females.

Analyses

Defoliation results are presented as median values because estimates of percentage defoliation were not continuous. A sample size of 50 or 100 was used for median estimates of shoot defoliation. A sample size of 10 or 20 was used for median estimates of percentage adult foliage and defoliation to upper and lower crowns and juvenile foliage.

All plant feeding weevils other than *G. scutellatus* were grouped collectively as other weevils. All beetles except weevils, *Chrysophtharta variicollis*, *Chrysophtharta nobilitata* and *Ca. excrementarius* collected by canopy fogging were grouped collectively as other beetles. Chrysomelid egg masses and larvae refer only to species in the subfamily Chrysomelinae.

For analysis purposes, natural enemies were grouped into spiders, Neuroptera (lacewing adults and larvae), Hymenoptera (predatory and parasitic wasps and ants), Coleoptera (predatory beetles in the families Cantharidae, Carabidae and Coccinellidae), Diptera (predatory and parasitic flies in the families Asilidae, Dolichopodidae, Syrphidae and Tachinidae), Hemiptera (predatory bugs in the families Pentatomidae and Reduviidae), and others [Dermaptera (earwigs), Odonata (dragonflies and damselflies) and Mecoptera (scorpion flies)].

Results

Percentage defoliation

Trees sampled at all four plantations had most of their total foliage present as adult foliage on all sampling occasions. When sampling began in October 1999, median estimates of percentage adult foliage were 70–80% at all plantations. These estimates increased gradually at subsequent censuses, and were usually 100% for all sampling dates after October 2000. Throughout the study period, the percentage defoliation of juvenile foliage was in the range 0–5% on all sampling occasions at both plantations.

Estimates of defoliation of the lower crown were least variable at all four plantations, and in the range 10–20% at all sampling dates. Trends in defoliation estimates to the upper crown and shoot tips closely tracked each other at each plantation. Defoliation levels generally peaked twice each growing season during November to December and February to April (Fig. 1). This defoliation pattern was most pronounced at Manjimup and Rocky Gully whereas, at Denbarker and Albany, the two distinct defoliation peaks did not occur every growing season. Defoliation levels were very low (usually $<$ 5%) between July and September.

Canopy fogging

Gonipterus scutellatus was the dominant beetle species recorded by canopy fogging at most times of the year at all plantations (Fig. 2). Across the four plantations, *G. scutellatus* comprised on average 93–99% of all weevils (Curculionidae, Attelabidae and Belidae) and 64–83% of total beetles collected by canopy fogging. The pattern of abundance of *G. scutellatus* was similar at all four plantations, although adult numbers were generally much lower at Manjimup (Fig. 2). Adult *G. scutellatus* were present throughout the year at the four plantations, but numbers were lower

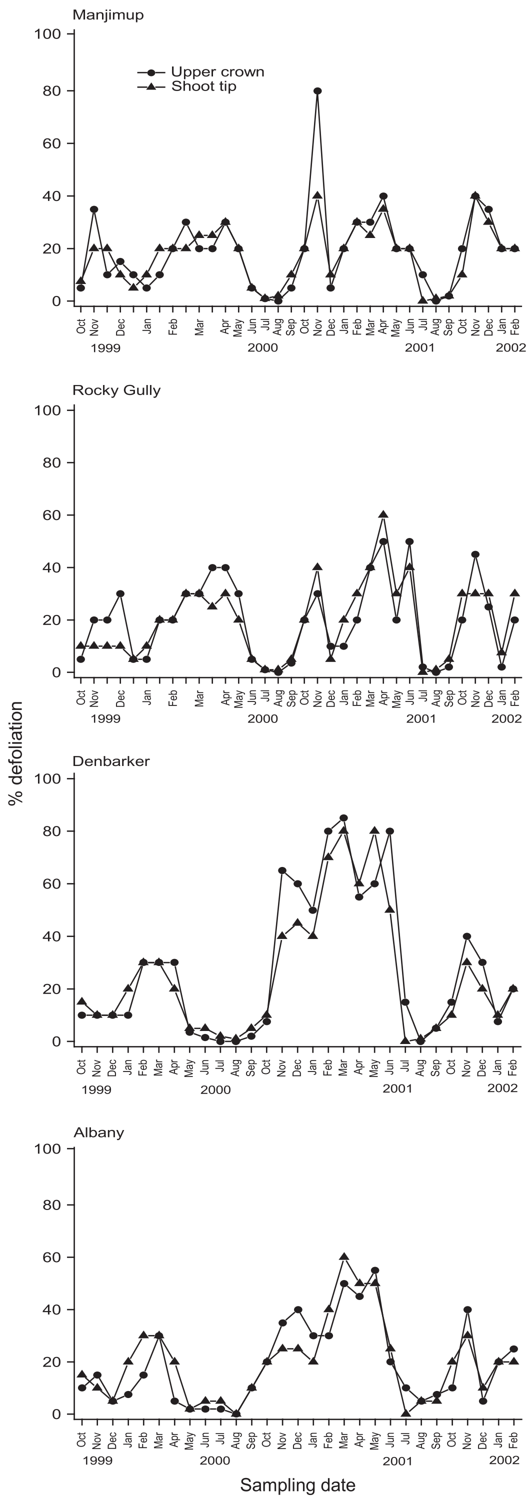

Figure 1 Median percentage defoliation estimates for the upper crown and shoot tip foliage at Manjimup, Rocky Gully, Denbarker and Albany plantations between October 1999 and February 2002. Sample size was 10 for estimates of defoliation to the upper crown and 50 for shoot tip estimates for October 1999 and from November 2000 onwards. Between November 1999 and October 2000, the sample size was 20 for estimates of defoliation to the upper crown and 100 for shoot tip estimates.

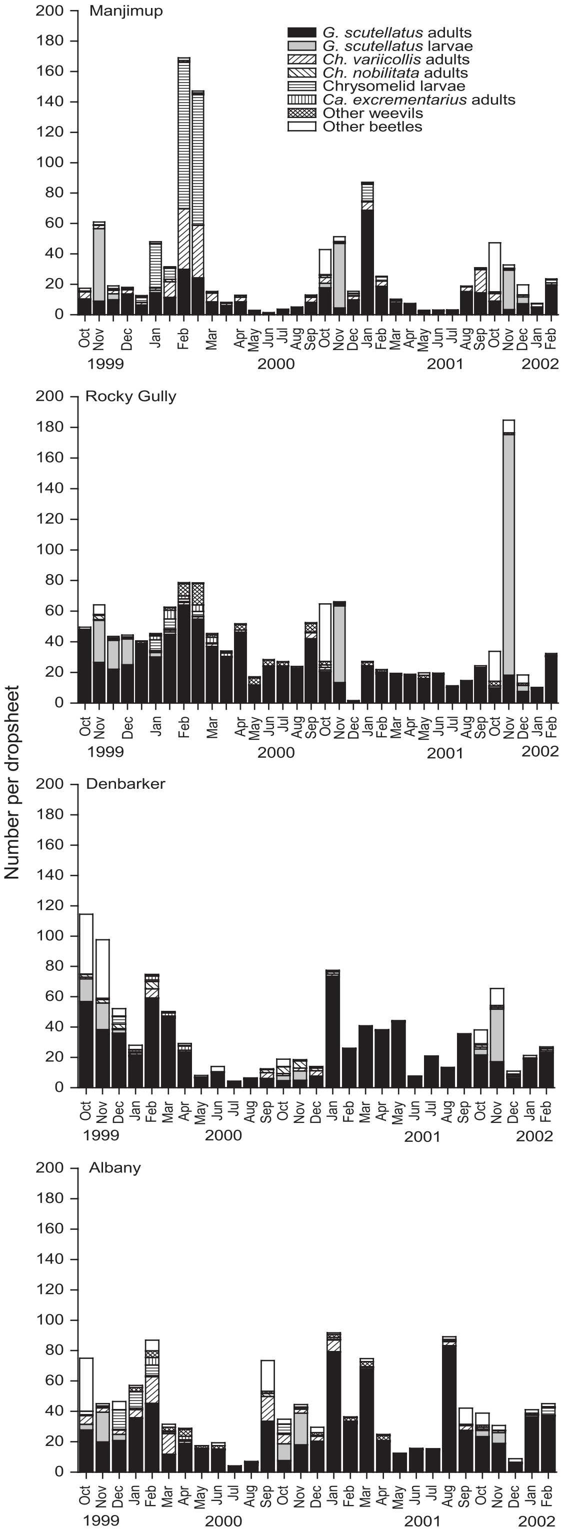

Figure 2 Mean number of beetles recorded per 2 × 2m dropsheet after canopy fogging at Manjimup, Rocky Gully, Denbarker and Albany plantations between October 1999 and February 2002. Sample size was 10 for October 1999 and from November 2000, and 20 between November 1999 and October 2000.

from late autumn to winter (May to August). Two seasonal peaks in *G. scutellatus* adult numbers were usually observed at plantations, one between September and November and the second in January and February (Fig. 2). Larvae of *G. scutellatus* were fogged from trees between August and January, with peak numbers recorded during November (Fig. 2).

Chrysomelid beetles were the second most abundant beetle group collected by fogging on most sampling occasions, accounting for 6–25% of total beetles on average across the four plantations. Several species of chrysomelid beetles were sampled during the study (Table 1), but most species were present in very low numbers. Species in the subfamily Chrysomelinae were usually the most abundant with *Ch. variicollis* and *Ch. nobilitata* the major species present at all four plantations. *Chrysophtharta variicollis* accounted for 93%, 53%, 40% and 82% of total adult chrysomelines fogged from Manjimup, Rocky Gully, Denbarker and Albany plantations, respectively. Adult *Ch. nobilitata* comprised 5%, 34%, 57% and 11% of total adult chrysomelines fogged from Manjimup, Rocky Gully, Denbarker and Albany plantations, respectively. The remainder of fogged chrysomelines from the four plantations included *Chrysophtharta amoena* (1–8%), *Paropsis* spp. (0.5–6%), and *Chrysophtharta mentatrix*, *Paropsisterna* spp., *Trachymela* spp. and *Faex transversomaculata* (collectively $< 1\%$). Chrysomelid larvae were collected between September and April with numbers peaking at most plantations between December and February (Fig. 2). Chrysomelid larvae were usually not common, although large numbers were fogged at Manjimup during February 2000. Different species of chrysomelid larvae could not be distinguished but most would have been *Ch. variicollis* or *Ch. nobilitata*.

Cadmus excrementarius accounted for less than 2% of total beetles fogged at all plantations but was the most common chrysomelid in the subfamily Cryptocephalinae at Rocky Gully, Denbarker and Albany, and comprised 94%, 85% and 85% of fogged cryptocephalines, respectively. At Manjimup, only 36% of fogged cryptocephalines were *Ca. excrementarius*. Adults of *Ca. excrementarius* were only collected between December and June, with peak numbers occurring between January and April (Fig. 2). Other cryptocephalines recorded were several species from the genera *Cadmus*, *Aporocera* and *Brachycaulus* (Table 1), but these occurred in only low numbers. Two species of *Edusella* and *Terrillus suturalis* (Chrysomelidae: Eumolpinae) were only rarely fogged from plantations. Several other species of weevils in the families Attelabidae, Belidae and Curculionidae (Table 1) were fogged from plantations and usually in low numbers. However, higher numbers of other weevil species were recorded at Rocky Gully and Albany (Fig. 2). Adults of *Oxyops* spp. were collected in low numbers throughout the year at all plantations with larvae present between March and October *Oxyops* larvae closely resemble *G. scutellatus* larvae but could be distinguished by their complete covering of faecal material. Six species of Scarabaeidae and three species of Cerambycidae (Table 1) were collected by fogging with all species present in low numbers.

Table 1 Plant feeding adult Coleoptera (beetles) sampled from *Eucalyptus globulus* plantations by canopy fogging between October 1999 and February 2002

Family	Species
Attelabidae	*Auletobius* sp.
Belidae	*Araiobelus acicularis* (Pascoe)
	Rhinotia sp.
Cerambycidae	*Bethelium* spp. (2 spp.)
	Obrida sp.
	Phoracantha semipunctata (Fabricius)
Chrysomelidae	*Aporocera bynoei* (Saunders)
	Aporocera spp. (3 spp.)
	Brachycaulus sp.
	Cadmus breweri Baly
	Cadmus crucicollis Boisduval
	Cadmus excrementarius Suffrian
	Cadmus nothus Lea
	Chrysophtharta amoena (Clark)
	Chrysophtharta mentatrix (Blackburn)
	Chrysophtharta nobilitata (Erichson)
	Chrysophtharta variicollis (Chapuis)
	Edusella spp. (2 spp.)
	Faex transversomaculata Clark
	Geloptera tuberculata Baly
	Paropsis geographica Baly
	Paropsis yilgarnensis Blackburn
	Paropsis spp. (3 spp.)
	Paropsisterna picta Chapuis
	Paropsisterna sp.
	Terrillus suturalis Blackburn
	Trachymela spp. (3 spp.)
Curculionidae	*Aromagis* sp.
	Atelicus sp.
	Atrichonotus taeniatulus (Berg)
	Catasarcus impressipennis (Boisduval)
	Cryptoplus sp.
	Cryptorhynchini indet.
	Emplesis spp. (2 spp.)
	Erytenna dispersa Blackburn
	Essolithna sp.
	Gerynassa sp.
	Gonipterus scutellatus Gyllenhal
	Haplonyx sp.
	Hypsomus sp.
	Meriphus sp.
	Myllorhinus dentiferus (Boheman)
	Naupactus leucoloma Boheman
	Notomagdalis sp.
	Orthorhinus sp.
	Otiorhynchus cribricollis Gyllenhal
	Oxyops farinosus Pascoe
	Oxyops cf. *pictipennis* Blackburn
	Pantomorus cervinus (Boheman)
	Pantoreites sp.
	cf. *Pelororhinus angustatus* Fahraeus
	Phlyctinus callosus Schoenherr
	Polyphrades oesalon Pascoe
	Psapharus aureolus (Pascoe)
	Rhadinosomus lacordairei Pascoe
	Rhinaria aberrans Lea
Scarabaeidae	*Aplopsis* sp. nov. nr *punctulata* (Blackburn)
	Automolius immitis Blackburn
	Colymbomorpha lineata Blanchard
	Heteronyx elongatus Blanchard
	Liparetrus jenkinsi Britton
	Liparetrus luridipennis Macleay

Shoot clipping

Gonipterus scutellatus was the most common defoliating beetle recorded on shoot tips on most sampling dates (Fig. 3). Egg masses of *G. scutellatus* were first detected on shoot tips in July and could be found through until February Numbers of *G. scutellatus* egg masses generally peaked between September and October but, during the 1999/2000 and 2001/2002 growing seasons, further peaks were recorded during December and January at some plantations (Fig. 3). *Gonipterus scutellatus* larvae were recorded between September and February, with peak abundance during October and November.

Chrysomelid egg masses were collected from shoot tips between September and February, and chrysomelid larvae were collected between October and February. Chrysomelid larvae were relatively abundant at Manjimup and Albany compared with Rocky Gully and Denbarker (Fig. 3). Larval chrysomelid abundance across all plantations generally peaked between October and November, and December and February.

At the effluent-irrigated North Albany site, *G. scutellatus* egg masses were present between October 2001 and February 2002 (Fig. 4). Numbers of *G. scutellatus* egg masses were highest during December 2001 at approximately 2.5 egg masses per shoot (Fig. 4), which is comparable with results from some unirrigated plantations during December 1999 and 2001, but higher than December 2000 (Fig. 3). *Gonipterus scutellatus* larvae were most abundant at North Albany during October 2001 and decreased at later sampling dates with no larvae present between January and April 2002 (Fig. 4). Chrysomelid larvae were recorded between November 2001 and February 2002 at North Albany.

Beetle dissections

Sexually mature female *G. scutellatus* were present only between August and December (Table 2). In the related weevil genus *Oxyops*, females were mature over a longer period, with immature females mainly collected during winter months (June to August). The three chrysomelines, *Ch. variicollis*, *Ch. nobilitata* and *Ch. amoena*, that were dissected showed similar seasonal patterns of sexual maturity. Females of these three species were principally mature between September and January (Table 2). Dissection results from the two plantations broadly agreed on most dates but 100% of female *Ch. variicollis* from Rocky Gully ($n = 8$) were mature on February 2000, by contrast to 0% maturity at Manjimup ($n = 15$) at the same time. Females of the cryptocephaline, *Ca. excrementarius*, were sexually mature between January and May.

Natural enemies

Total numbers of natural enemies were generally greatest at all four plantations during the warmer months between October and April (Fig. 5). Spiders were the most abundant natural enemy collected by canopy fogging on most sampling dates at all four plantations (Fig. 5). Spider numbers were greatest during warmer months and particularly between September and December. Spider numbers were also greatest during 1999 at the beginning of sampling at all four plantations.

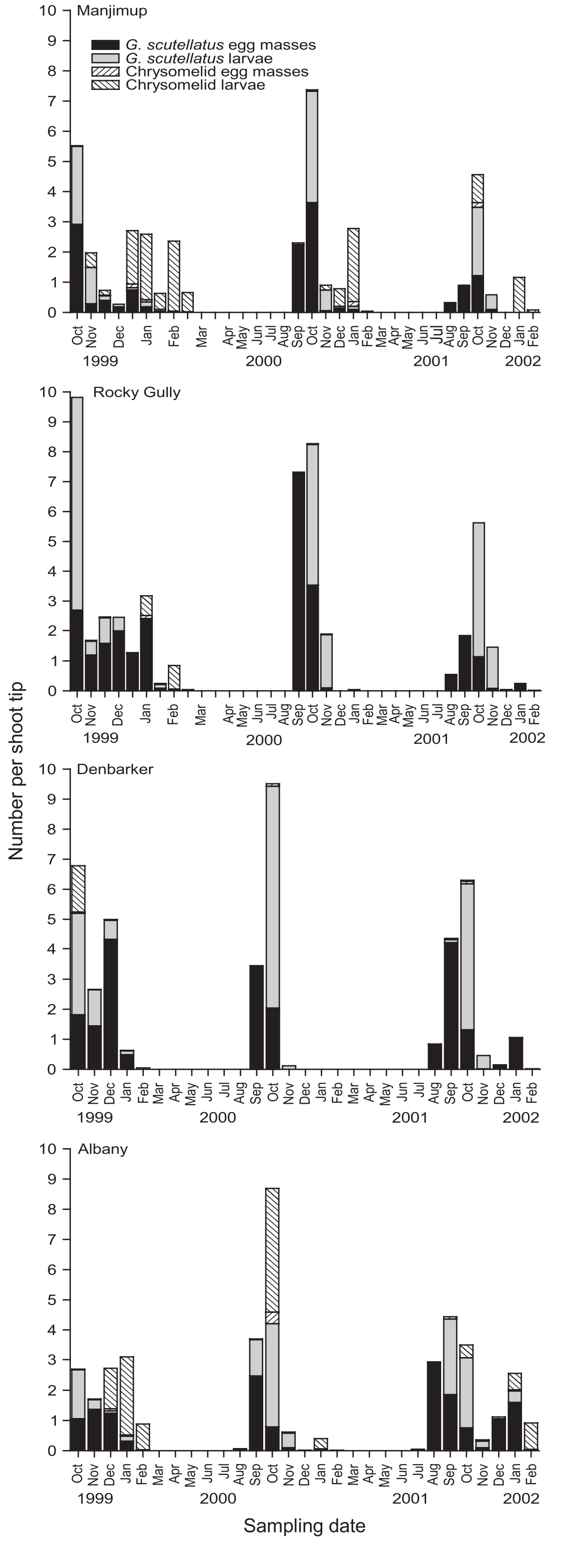

Figure 3 Mean number of *Gonipterus scutellatus* and chrysomelid egg masses and larvae recorded per shoot tip ($n = 100$) at Manjimup, Rocky Gully, Denbarker and Albany plantations between October 1999 and February 2002. Sample size was 50 for October 1999 and from November 2000, and 100 between November 1999 and October 2000.

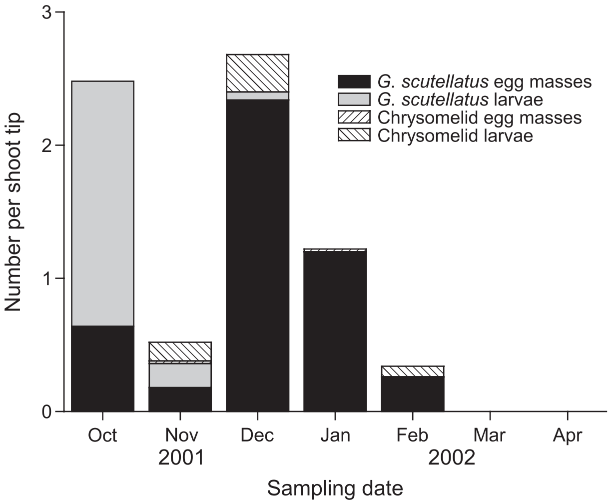

Figure 4 Mean number of *Gonipterus scutellatus* and chrysomelid egg masses and larvae recorded per shoot tip (n = 50) at the North Albany plantation between October 2001 and April 2002.

Diptera were collected mainly between October and April, with greatest numbers found during March. The composition of Diptera differed between plantations. The fly families Tachinidae and Dolichopodidae comprised 44% and 40% of Diptera, respectively, at Manjimup with Syrphidae and Asilidae contributing only 8% each. At Rocky Gully, 46% of Diptera were Dolichopodidae, with lesser contributions by Tachinidae (20%), Syrphidae (21%) and Asilidae (13%). Syrphidae and Dolichopodidae were the dominant Diptera families at Denbarker with 47% and 30%, respectively; a further 16% comprised Asilidae and 7% were Tachinidae. Syrphidae predominated at Albany with 69% of total flies, with Tachinidae (7%), Dolichopodidae (22%) and Asilidae (2%) comprising the remainder.

Species from five families of Neuroptera were fogged from plantations: Chrysopidae, Hemerobiidae, Mantispidae, Myrmeleontidae and Nymphidae (Table 3), with most collected between October and December (Fig. 5). The predatory shield bugs, *Cermatulus nasalis* and *Oechalia schellenbergii* (Pentatomidae), and *Gminatus australis* (Reduviidae) were the only species of predatory Hemiptera fogged from trees during the study (Table 3). Predatory bugs were mainly collected between December and March (Fig. 5).

Low numbers of predatory Coleoptera were collected throughout the year. Coccinellidae were the most common predatory beetles and were collected at all times but mainly during warmer months. Ladybirds comprised 87%, 57% and 86% of all predatory beetles from Manjimup, Rocky Gully and Denbarker, respectively. By contrast, Cantharidae were the most common predatory beetle at Albany with 54% compared with ladybirds, which accounted for 18% of predatory beetles. Soldier beetles comprised 9%, 39% and 14% of predatory beetles fogged at Manjimup, Rocky Gully and Denbarker, respectively. Two species of soldier beetles, *Chauliognathus*

Table 2 Percentage of females of some defoliating beetle species, which had a mature reproductive system. Numbers in parentheses indicate the total number of female beetles of that species that were dissected

		Gonipterus scutellatus		*Oxyops* spp.		*Chrysophtharta variicollis*		*Chrysophtharta nobilitata*		*Chrysophtharta amoena*		*Cadmus excrementarius*	
Year	Date	Manjimup	Rocky Gully	Manjimup	Rocky Gully	Manjimup	Rocky Gully	Manjimup	Rocky Gully	Manjimup	Rocky Gully	Manjimup	Rocky Gully
1999	Nov	41 (17)	22 (9)	100 (2)		83 (24)	67 (3)	100 (5)	50 (2)	100 (1)	100 (1)		
	Dec	0 (12)	44 (16)		50 (2)	60 (20)	0 (2)	33 (3)	17 (6)	100 (4)	100 (6)		
	Dec	42 (12)	29 (17)			78 (18)	100 (1)	50 (2)	100 (1)				
2000	Jan	0 (14)	0 (7)	50 (2)	100 (1)	58 (12)		0 (3)	0 (3)	100 (11)		100 (1)	63 (16)
	Jan	0 (8)	0 (10)			13 (16)	0 (4)						
	Feb	0 (10)	0 (9)		100 (2)	0 (15)	100 (8)		0 (1)	0 (1)			82 (11)
	Feb	0 (7)	0 (6)			0 (20)	0 (4)						75 (12)
	Mar	0 (9)	0 (15)	100 (2)	100 (1)	0 (17)	0 (1)		0 (1)				100 (7)
	Mar	0 (12)	0 (12)			0 (11)	0 (7)		0 (2)			100 (2)	100 (10)
	Apr	0 (6)	0 (12)			0 (14)	0 (3)						100 (15)
	May	0 (8)	0 (10)	0 (1)		0 (4)							100 (1)
	Jun	0 (6)	0 (8)	100 (2)	0 (1)								
	Jul		0 (11)										
	Aug	0 (10)	18 (11)	0 (1)	0 (1)	100 (3)							
	Sep	100 (9)	100 (11)	0 (3)		100 (5)	86 (7)	100 (2)	0 (2)				
	Oct	100 (10)	100 (10)	67 (3)	0 (2)	82 (11)	83 (12)	89 (9)	85 (13)	100 (1)	100 (4)		
	Nov	100 (9)	75 (8)			33 (3)	100 (1)	100 (2)	100 (2)				
	Dec	67 (15)	100 (1)		0 (5)	100 (10)		100 (2)		100 (1)			
2001	Jan	0 (10)	0 (10)	100 (4)	50 (2)	91 (11)	50 (2)					100 (1)	100 (1)
	Feb	0 (10)	0 (10)	100 (1)	100 (8)	0 (10)	0 (4)						100 (1)
	Mar	0 (12)	0 (10)	100 (2)	100 (4)	0 (4)	0 (1)						100 (5)
	Apr	0 (10)	0 (10)	100 (3)		0 (1)							100 (10)
	May	0 (10)	0 (10)	100 (1)	100 (3)								100 (1)
	Jun	0 (10)	0 (10)	100 (1)									

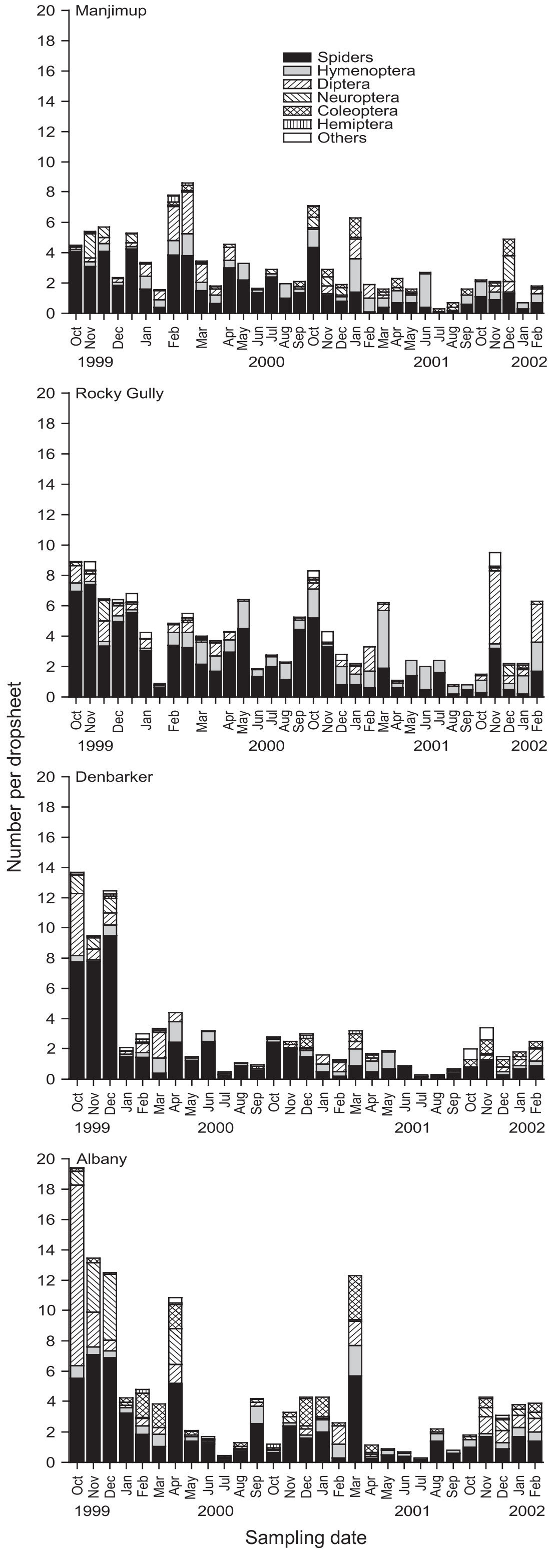

Figure 5 Mean number of potential natural enemies recorded per 2 × 2m dropsheet after canopy fogging at Manjimup, Rocky Gully, Denbarker and Albany plantations between October 1999 and February 2002. Sample size was 10 for October 1999 and from November 2000, and 20 between November 1999 and October 2000.

Table 3 Potential natural enemies sampled from *Eucalyptus globulus* plantations by canopy fogging between October 1999 and February 2002

Class	Order	Family	Species
Arachnida	Aranea		Several
Insecta	Coleoptera	Cantharidae	*Chauliognathus* sp.
			Heteromastix sp.
		Carabidae	*Amblytelus leai* Sloane
			Amblytelus sp.
			Demetrida infuscata (Chaudoir)
			Demetrida vittata (Dejean)
			Sarothrocrepis sp.
			Trigonothops longiplaga Chaudoir
		Coccinellidae	*Cleobora mellyi* (Mulsant)
			Coccinella transversalis Linnaeus
			Coccinella umdecimpunctata Linnaeus
			Exochomus quadripustulatus (Linnaeus)
			Rhyzobius sp.
			Scymnus sp.
	Dermaptera		
	Diptera	Asilidae	
		Dolichopodidae	
		Syrphidae	
		Tachinidae	
	Hemiptera	Pentatomidae	*Cermatulus nasalis* (Westwood)
			Oechalia schellenbergii (Guérin-Méneville)
		Reduviidae	*Gminatus australis* (Erichson)
	Hymenoptera		Several
	Mecoptera	Bittacidae	
	Neuroptera	Chrysopidae	
		Hemerobiidae	
		Mantispidae	
		Myrmeleontidae	
		Nymphidae	
	Odonata		

sp. and *Heteromastix* sp., which are also flower-feeders, were collected by fogging at the four sites and mainly between October and April. Several species of Carabidae were also collected (Table 3) and accounted for only 1–3% of total predatory beetles at each of the plantations.

Low numbers of Hymenoptera were fogged from trees throughout the year (Fig. 5). Of the other predatory groups, Dermaptera were most abundant between October and April, Mecoptera were collected only during October and November from Manjimup and Rocky Gully, and a single Odonata was fogged at Denbarker in October 1999.

Discussion

Gonipterus scutellatus was the most common and destructive defoliating beetle of established *E. globulus* plantations in south-western Australia. Adults were present all year but were most abundant between spring and autumn when defoliation levels to shoot tips and the upper crown could reach 40–80%. Larvae were present between late winter and summer with numbers peaking during October and November when high levels of defoliation were recorded. Although chrysomelid beetles, which were present in much lower numbers, would have caused some of this defoliation, *G. scutellatus* is probably the principal defoliator of *E. globulus* ≥ 2 years old (i.e. with adult foliage) in south-western Australia.

Only two other studies have investigated the arthropod fauna of *E. globulus* in south-western Australia. Cunningham *et al.* (2005) fogged *E. globulus* plantations between 1999 and 2001 within 50–100 km of the Denbarker, Albany and North Albany plantations surveyed in the present study and found *G. scutellatus* to be the dominant species present. By contrast, Abbott *et al.* (1999) fogged no *G. scutellatus* between 1993 and 1994 from *E. globulus* plantations at Darkan and West Dale, which are approximately 150–350 km north of the plantations in the present study. *Gonipterus* sp. was reported causing damage in other *E. globulus* plantations in south-western Australia (Abbott *et al.*, 1999), yet the only defoliating beetles recorded were *Oxyops* sp. and chrysomelid beetles, which accounted for 1% and 8%, respectively, of the total arthropod biomass from trees approximately 3 years old.

Currently, in northern parts of the *E. globulus* plantation estate, including West Dale and Darkan, *G. scutellatus* is either absent or has recently been reported for the first time (M. Matsuki, pers. comm.). The Insect Collection Database at the Western Australian Department of Agriculture reports several species of *Gonipterus* but no specimens are identified as *G. scutellatus*. These findings strongly support the hypothesis that *G. scutellatus* is a recently introduced species to south-western Australia (Loch & Floyd, 2001; Cunningham *et al.*, 2005) and that its distribution is still expanding. It is also possible that *G. scutellatus* has existed in low numbers in south-western Australia for some time, either naturally or through introduction, and has rapidly expanded through the recent introduction and expansion of plantations of *E. globulus*.

In south-western Australia *G. scutellatus* appear to undergo one annual generation, although there was a second egg-laying peak in some seasons, suggesting it may have a second lesser generation in some seasons. This contrasts with reports of two to four annual generations for the species elsewhere in Australia (Tooke, 1953) and in other countries (Cordero Rivera *et al.*, 1999; Hanks *et al.*, 2000; Lanfranco & Dungey, 2001). The second lesser oviposition period that occured in some seasons between late spring and summer in south-western Australia could also be a second cohort of the spring generation because there was no corresponding second peak in adult female sexual maturity. This second cohort or generation is made even more insignificant because of high rates of parasitism by *A. nitens* and on any surviving larvae by tachinid flies (A. Loch, unpublished data).

The most likely explanation for limited oviposition by *G. scutellatus* during summer is the scarcity of suitable new flushing foliage, which is required by *G. scutellatus* for feeding and reproduction (Tooke, 1953). Summer and autumn temperatures in south-western Australia should be ideal for *G. scutellatus* reproduction and development, but most foliage growth and development in *E. globulus* was confined to winter and early summer after winter rainfall, which is typical of this Mediterranean environment. *Eucalyptus globulus* continues to produce new foliage during summer and autumn, albeit at slower rates than in spring, but this new foliage tends to be removed quickly by adult beetles (M. Matsuki, unpublished data). Therefore, suitable foliage is available but either is of insufficient quantity for *G. scutellatus* reproduction, or the rapid removal of new foliage inhibits oviposition. Two peaks in oviposition were recorded at the effluent-irrigated North Albany plantation where new foliage growth should be available for longer periods and/or in greater quantities (Fig. 4). However, two peaks were also recorded at Denbarker and Albany but not at Manjimup and Rocky Gully during the same growing season (Fig. 3). Results from North Albany neither support, nor refute the claim that *G. scutellatus* reproduction is limited by *E. globulus* growth phenology, but must be treated tentatively because sampling was conducted for only 6 months. Other factors may affect *G. scutellatus* reproduction, which needs to be addressed by further research.

A diverse number of species of chrysomelid beetles were collected during the study (Table 1), although much less abundant than *G. scutellatus* at most times at all plantations. Phenology of chrysomelid beetles in the subfamily Chrysomelinae was not clear because egg masses and larvae could not be accurately identified to species, although most would be *Ch. variicollis* or *Ch. nobilitata*. However, based on peak times of oviposition, larval abundance and female sexual maturity, one to two annual generations was likely for most species, which is agreement with data on other Australian *Chrysophtharta* spp. (de Little, 1983; Nahrung & Allen, 2004a, b).

Although chrysomelid beetles are only a minor concern relative to *G. scutellatus*, some chrysomelid species such as *Ch. variicollis* appear capable of developing short-lived (1–2 months) outbreak populations. During February 2000 at the Manjimup plantation, adult and larval chrysomelid numbers increased to 120–140 individuals per dropsheet (Fig. 2) and approximately one to two larvae were recorded per shoot tip (Fig. 3). However, there was no corresponding sharp increase in defoliation suggesting that beetle populations were not sufficient to cause high levels of defoliation or that beetle populations were controlled by natural enemies. The latter is possible because tachinid flies sometimes parasitize chrysomelid larvae at high rates (A.D. Loch, unpublished data).

Successful integrated pest management of the defoliating beetle complex in south-western Australian *E. globulus* plantations requires careful timing of monitoring and, if required, control. The key beetle pest, *G. scutellatus*, must be monitored between September and November If insecticidal control is warranted, insecticides must be sprayed when adult beetles and young larvae are present and particularly before larvae inflict high levels ($\geq$ 50%) of defoliation to the upper crown. Sprays must also be scheduled to occur after most or all weevil egg masses have hatched between October and early November because weevil egg masses provide effective protection to developing eggs from insecticides (Loch, 2005).

Adults of *Ca. excrementarius* emerge from late December and thus cannot be controlled by insecticide sprays during October and November (Loch, 2005). Only the adult of this species is damaging as larvae live in faecal-constructed cases on the ground and feed on vegetative matter (Loch & Floyd, 2001; dos Anjos *et al.*, 2002a,b). The species has a patchy distribution in south-western Australia and does not affect all *E. globulus* plantations (dos Anjos *et al.*, 2002b). In the present study, *Ca. excrementarius* was present at Rocky Gully, Denbarker and Albany plantations but was virtually absent at Manjimup. Monitoring for *Ca. excrementarius* will be necessary in January and particularly for younger plantations with juvenile foliage.

Subsequent to the completion of the present study, a species complex of nocturnal feeding *Heteronyx* has been increasingly causing more defoliation to *E. globulus* plantations (M. Matsuki, pers. comm.). These species present a challenge because their nocturnal habits render them difficult to detect, monitor and control. Predicting when and where outbreaks of *Heteronyx* will arise is also problematic. In addition, the different species may have a vastly different ecology and behaviour that could require different management methods. Although low numbers of *H. elongatus* were fogged during the study, fogging would need to be conducted at night to sample these beetles accurately.

Of the weevils collected in this study (Table 1), only *G. scutellatus*, *Oxyops* spp. and *Catasarcus impressipennis* can be confirmed as defoliators of eucalypts. *Myllorhinus dentiferus* is a shoot borer of eucalypts (Jones & Potts, 2000). Several introduced weevil pests of Australian crops including the small lucerne weevil *Atrichonotus taeniatulus*, whitefringed weevil *Naupactus leucoloma*, apple weevil *Otiorhynchus cribricollis*, garden weevil *Phlyctinus callosus*, and Fuller's rose weevil *Pantomorus cervinus*, were collected in low numbers. These species may feed on eucalypts but they are not known pests of established eucalypt plantations, although they may cause problems for eucalypts at establishment. Species of *Orthorhinus* are borers of a number of plant species, including eucalypts (Elliott & de Little, 1984). The other weevil species collected may feed on eucalypts but are likely to have another plant species as their usual host. *Phoracantha semipunctata* is the only recognized cerambycid pest of eucalypts in Australia that was collected in the present study and, of the Scarabaeidae collected, *Heteronyx elongatus* and *Liparetrus jenkinsi* are serious pests of trees at establishment (Loch & Floyd, 2001).

The present study also revealed a diverse array of generalist natural enemies. Although their contribution to control was not quantified, they were significantly less abundant than defoliating beetles and would not be likely to provide significant control of beetles. *Eucalyptus globulus* plantations tend to have lower numbers of some types of natural enemies than remnant native forests in south-western Australia (Cunningham *et al.*, 2005), and this is likely to be a common theme in *Eucalyptus* plantations elsewhere. Rectifying such imbalances between pests and natural enemies in plantations might lead to improved control but the underlying processes that affect natural enemy numbers must first be understood.

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