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The impact of aerial baiting for control of the yellow crazy ant, *Anoplolepis gracilipes*, on canopy-dwelling arthropods and selected vertebrates on Christmas Island (Indian Ocean)

Nigel E. Stork[1*], R. L. Kitching[1], N. E. Davis[2] & K. L. Abbott[3]

Abstract. Large supercolonies of the yellow crazy ant (YCA) (*Anoplolepis gracilipes*) on Christmas Island (Indian Ocean) have had a major impact on the land crabs on the island, and an aerial baiting programme using Fipronil™ was trialed in 2002 to reduce YCA populations. To assess the potential for non-target impacts of this baiting programme, canopy-dwelling arthropods and selected vertebrates were sampled in four forest treatments: uninfested by YCA; infested but aerially baited several days earlier; infested but hand-baited 12–24 months previously; and, infested but untreated. Canopy arthropods from the lower canopy of five species of tree were sampled immediately after aerial baiting to determine the abundance and diversity of the arthropod fauna in infested and uninfested areas and the potential impact of the insecticide on the arthropod fauna. Relative abundances of terrestrial, diurnal bird species and the nocturnal Christmas Island gecko were estimated at replicate sites within the four treatments in September 2002 and April 2003 to detect the potential for immediate and medium-term effects of the baiting programme on habitat use. Non-baited infested sites and those that had recently been aerially baited showed significantly elevated levels of both YCA and scale insects in the canopy, and the relative abundances of these two taxa were highly correlated. After counts of YCA and scale insects had been removed, no significant differences in the overall abundance of arthropods or the number of orders encountered could be detected across the four treatments. Estimates of relative abundance of vertebrates immediately after baiting indicated that the only sampled species to respond to Fipronil™ was the Christmas Island white-eye, whose abundance was lower in non-baited control areas than in uninfested sites, or aerially baited sites with supercolonies of YCA. The Christmas Island imperial pigeon exhibited a response to baiting when sampled eight months after the initial baiting. The abundance of this species was significantly reduced in the aerially baited sites compared with that in uninfested sites, and overall abundance of this species declined between 2002 and 2003. Although our samples and counts were small, we conclude that, with the exception of reductions in abundance in the imperial pigeon, the immediate to medium-term impacts of the aerial baiting strategy on vertebrates and immediate impact on canopy arthropods were minimal and that, given the importance of control of YCA for the conservation of terrestrial fauna, such baiting programmes should be supported.

Key words. aerial baiting, yellow crazy ants, supercolonies, Christmas Island, Fibronil™

INTRODUCTION

The invasive yellow crazy ant (YCA) (*Anoplolepis gracilipes* Fr. Smith), was introduced to Christmas Island (Indian Ocean) between 1915 and 1934 (Donisthorpe, 1935; O'Dowd et al., 2003). Between 1934 and about 1988, the species existed in small, localised populations at a wide range of localities on the island. Polydomous, multi-queened supercolonies were discovered and became widespread after 1988, spreading to the point that they occupied as much as 27% of the undisturbed rainforest on the island in 2002 (~2700 ha; Boland et al., 2011; O'Dowd & Green, 2009; O'Dowd et al., 2003).

The ecosystem dynamics of the tropical rainforest, which still covers much of the island, are unique in as much as they depend on the detritivorous activities of the terrestrial endemic red crab (*Gecarcoidea natalis* Pocock) (Green et al., 1999). This has led to a comparatively rapid, characteristic rate of nutrient turn-over as well as a differential impact on the survival of seedlings of different tree species on the forest floor (Green, 1997; Green et al., 1999; O'Dowd & Lake, 1989, 1990). The combined effects of the associated populations of robber crabs (*Birgus latro* Linneaus) and, in wetter areas, of blue crabs (*Discoplax celeste* (Ng & Davie, 2012) produce an ecosystem unique to the island (Green, 1997).

The high levels of endemism across a range of taxa add to the unique nature of Christmas Island (Environment Australia, 2002). Accordingly, when threatening processes

[1]Environmental Futures Research Institute, Griffith School of Environment, Nathan, QLD 4111, Australia; Email: nigel.stork@griffith.edu.au (*corresponding author)

[2]Department of Zoology, The University of Melbourne, Parkville, Victoria 3010, Australia

[3]Faculty of Science, Monash University Clayton VIC 3800, Australia; Department of Zoology, University of New England Armidale NSW 2350, Australia

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such as formation of supercolonies by the YCA occur, there is considerable urgency, and international importance, in finding appropriate management solutions. The density of ants in supercolonies of YCA can reach 2254 foraging ants m^{-2} (Abbott, 2005), and in these high density areas they have devastating effects on red crab populations (Boland et al., 2011; O'Dowd et al., 2003). Not only do the YCA kill crabs, their arboreal foraging upon, and tending of, the lac scale insect (*Tachardina aurantiaca* Cockerell) have led to massive increases in scale populations (Abbott, 2004). This in turn has generated high levels of physiological stress for trees, either directly or through inhibition of photosynthetic activity as a result of sooty mould infestation consequent upon widespread honeydew 'rain' from the scale outbreaks (O'Dowd et al., 1999). Yellow crazy ants also have an impact on the abundance, behaviour, feeding and reproductive success of some of the endemic bird species (Davis et al., 2008, 2010).

Environment Australia established a plan to control YCA through the widespread application of granular bait impregnated with the broad spectrum phenyl pyrazole insecticide, Fipronil™. Following initial small scale plot trials of hand-dispensed granular bait and dosages of the insecticide in the forest in 1999–2001, a decision was made to carry out widespread, aerial deployment of the bait in areas of supercolony development in an attempt to suppress high densities of the ant pest. The delivery of the bait by helicopter in September 2002 was managed by on-site staff from Environment Australia (Boland et al., 2011).

Fipronil™ is widely used to control many invertebrate pest species and is applied in a variety of ways (Tingle et al., 2003), including a spray for locust and termite control (Gautam et al., 2014) and in granular bait for the control of invasive ants, particularly YCA (Abbott & Green, 2007; O'Dowd & Green, 2009; Boland et al., 2011). Because Fipronil™ is a broad-spectrum insecticide, its use pose a potential threat to non-target invertebrates on Christmas Island. Further, even at low doses this insecticide can have an impact on vertebrates (Kitulagodage et al., 2011a). Avian exposure to Fipronil™ occurs mainly by ingesting contaminated insects or seeds and although there is little information regarding toxicological and behavioural responses of birds to Fipronil™ ingestion, studies have demonstrated that this insecticide can affect avian feeding behaviour, body condition, reproduction and development (Kitulagodage et al., 2011b). Moreover, insectivorous vertebrates may respond to the availability of moribund insects following insecticide application and redistribute themselves across the landscape accordingly (Peveling et al., 2003). The impact of an insecticide treatment either through direct mortality of invertebrates or through the response of the invertebrate fauna to the subsequent major reduction in numbers of YCA (and scale insects) could have long-term consequences for vertebrates through food-chain effects.

Our knowledge of the arthropod fauna (other than the land crabs and ants) of Christmas Island rests substantially on a few collecting trips. Much of the insect fauna, although arguably well collected, remains taxonomically poorly known. Many of the more vagile groups, such as beetles and ants, have low levels of endemism. Other insect groups, such as the Auchenorryhncha may have higher levels of endemism. The rainforest canopy has never been properly sampled and may well be as rich in endemics as the ground layers.

This paper discusses the results of the first Australian Commonwealth funded monitoring programme carried out in 2002–2003 which aimed to examine the impact of toxic baiting on the canopy arthropod fauna. Concurrent with arthropod surveys, we carried out surveys of terrestrial diurnal bird species and the nocturnal Christmas Island gecko (*Lepidodactylus listeri* Boulenger) in order to detect any immediate and medium-term changes in abundance that might be due to the control programme.

METHODS

Study sites. All sampling was carried out in September 2002 and April 2003 in the south-west quadrant of Christmas Island. All sites were located on the central plateau at an elevation of between 140 and 220 m above sea level (Gray & Clark, 1994). Sites were in closed, primary rainforest mostly on deep soil, with some areas on deep/shallow soil boundaries (see Figure 6 in Environment Australia, 2002). The vegetation has been described by DuPuy (1993). The canopy was generally 20–30 m tall and was dominated by less than 20 tree species with a well-developed woody understorey and shrub layer adding a further 35 species or so. Pandanus and Arenga palms are a highly visible component of the understorey.

Arthropod sampling. Sampling of arthropods was carried out in September 2002 using pyrethrum knock-down (canopy fogging) in four different treatments:

a) forests not infested by YCA (called *Uninfested* in the text and U in the Tables),
b) forests infested by YCA not treated with helicopter- or hand-delivered insecticide bait, Fipronil™ (*Non-baited control*, N),
c) forests previously infested by YCA but which were hand-baited in 2001 (*Old baited*, O), and
d) forests infested by YCA which had been treated with helicopter-delivered insecticide bait, Fipronil™ (*New baited*, B).

Four replicate sites of each treatment were sampled, giving a total of 16 sites (Fig. 1). The location of most of these sites was predetermined by the location of ground-baiting trials in 2000 and 2001 ('Old baited'), helicopter-baited areas ('New Baited'), and control areas where YCA were present but with no baiting undertaken ('Non-baited'). Replicate treatments were separated by a minimum of 250 m and maximum of 1 km. Through the previous hand-baiting trials, the insecticide Fipronil™, applied at concentrations of 0.1 g kg^{-1} and 4 kg ha^{-1} over areas of 25–50 hectares, had achieved greater than 99% control of YCA on the ground in supercolony areas (Green & O'Dowd, 2009; Boland et al.,

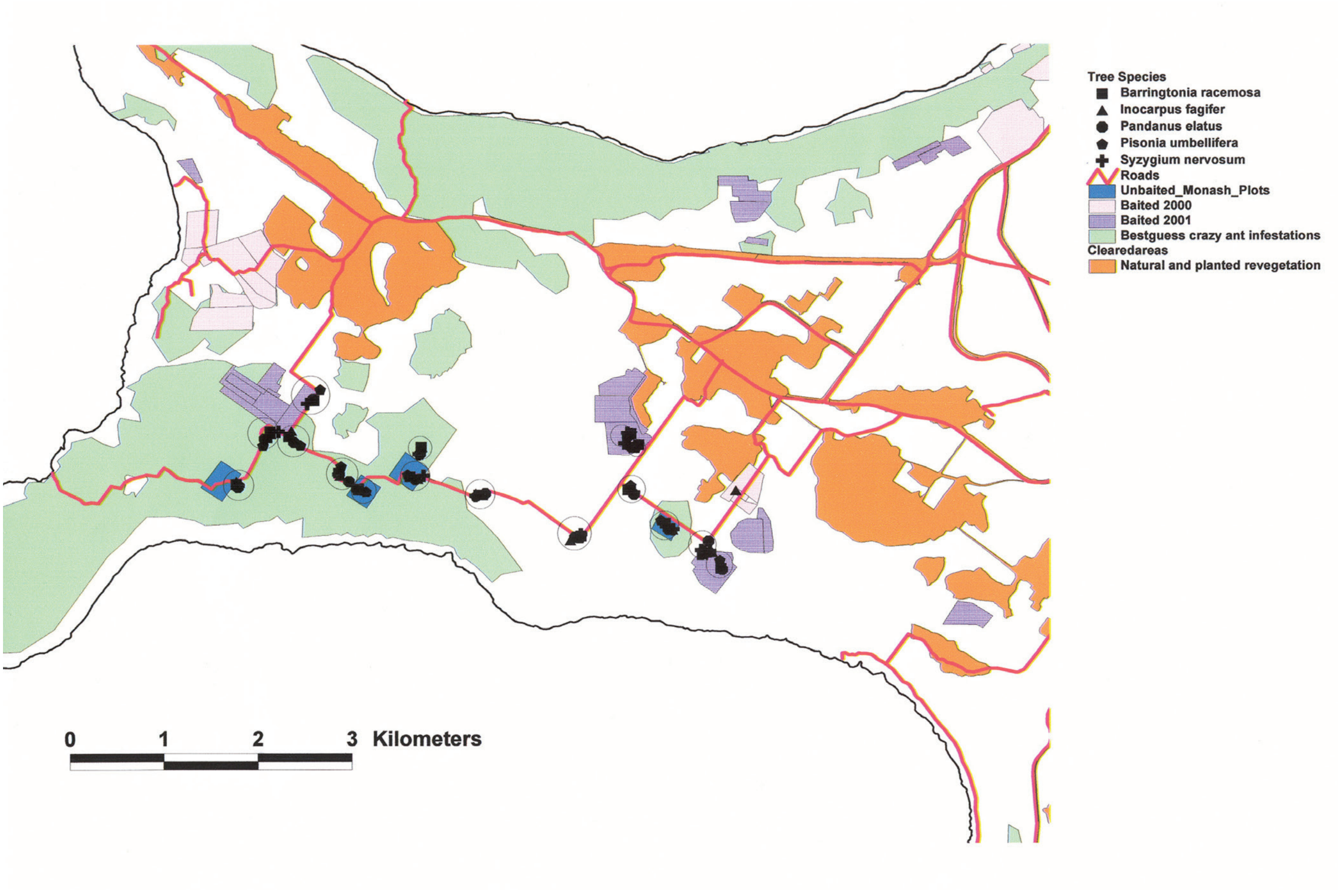

Fig. 1. Map of the central part of Christmas Island showing locations of the study sites and of individual trees of the focal species sampled. It also shows some of the locations and extent of the YCA supercolonies, and areas baited with Fipronil™ in 2000 and 2001.

2011). The new-baited sites, where delivery of Fipronil™ was by helicopter, were baited at concentrations of 4–6 kg ha^{-1} over 300 hectares in total. Our sampling of these new-baited sites was 4–8 days after the baiting occurred.

Five species of canopy tree were sampled at each site. These species were selected on the basis that they represented different families and that they were generally widespread and abundant in most forests in Christmas Island: *Syzygium nervosum* DC (Myrtaceae), *Inocarpus fagifer* (Parkinson ex Zollinger) Fosberg (Fabaceae), *Barringtonia racemosa* (L.) Spreng. (Lecythidaceae), *Pisonia umbellifera* (J. R. Forst. & G. Forst.). (Nyctaginaceae) and *Pandanus elatus* Ridl. (Pandanacae). No specimen of *Inocarpus fagifer* could be located at one of the 'old baited' sites and a substitute *I. fagifer* plant was used from an additional site of the same treatment. The YCA and various species of scale insects were known to have an association with at least two of these species, *I. fagifer* and *S. nervosum,* and, to a lesser extent, *B. racemosa* and *P. umbellifera*, hence their selection as target tree species.

At each tree, five circular collecting funnels, each 0.5 m^2 in area, were suspended under the canopy of the tree being sampled. The funnels were hung about one metre above the ground from a network of ropes tied at head height within the circumference of the tree. A Pulsfog™ fogging machine was used from the ground to release pre-mixed natural pyrethrum into the canopy of the trees to be sampled. The insecticide contained 4 g l^{-1} of pyrethrins and 12 g l^{-1} of piperonyl butoxide. Fogging was carried out between 0600 and 0700 hours when there is invariably little wind to carry the fog away. The fog rises as a warm cloud dispersing the insecticide to most parts of the canopy, usually to a maximum of 15–20 m. No trees sampled were taller than this except for the *S. nervosum* individuals which were amongst the tallest trees in the forest often exceeding 40 m. For this species, trees were selected that had low branches. No attempt was made to fog the upper canopy of the forest (above 15 m) as this would have required a much more complex sampling methodology using ropes and pulleys to hoist the fogger into the canopy and it would have been much more difficult to control the dispersion of the insecticide.

A three hour drop time was allowed before the samples were collected from the funnels. The funnels were made of a plasticised canvas and most insects slid down to the centre and into a container of 80% ethanol. Before removing the bottles, the trays were gently tapped and brushed with a large paintbrush to catch the remaining few insects. The total number of funnel samples collected was 400 (five per tree, five tree species, four treatments and four replicates per treatment). All arthropods were sorted to orders. Formicidae and Coccoidea were also separated in the counts. A separate count was made of YCA and Coccoidea in the samples. The small size of the samples made the sorting of material to finer levels of resolution inappropriate because the data matrix so generated would be sparse.

Vertebrate fauna counts. Surveys of four species of birds (the Christmas Island imperial pigeon, *Ducula whartoni* (Sharpe), emerald dove, *Chalcophaps indica* (Linneaus), the island thrush, *Turdus poliocephalus* Latham, Christmas Island white-eye, *Zosterops natalis* Lister) and one reptile (the Christmas Island gecko, *Lepidodactylus listeri* Boulenger) were made at 12 of our 16 sites (old-baited sites that had been hand-baited 12–24 months earlier were not included in the vertebrate studies since these were too small for vertebrate studies) in September 2002 and April 2003. These species of vertebrates were selected because they were associated with rainforest, common and or endemic species or subspecies to Christmas Island. During the 2002 and 2003 sampling periods, birds were surveyed at each site on six and five separate days respectively using techniques previously employed for these species on Christmas Island (Davis, 2001; Davis et al., 2008) and summarised here. All surveys were carried out in the morning and no site was sampled twice on any one day. At each study site two observation points approximately 50 m apart were established and counts of birds seen over a 20 minute period were made within a 20 m fixed-radius at each of the two observation points. For the pigeon however, the use of bird calls was necessary to estimate the relative abundance, as it is rarely seen (Reville et al., 1990) and, given unknown rates of sound attenuation with distance (Pyke & Recher, 1985), pigeon censuses required an unlimited radius. Bird counts from the two points were combined for analysis and hence the indices of interest were the number of sight or call detections (depending on species) during the count period. For reptiles, the same 12 sites were sampled during the 2002 and 2003 sampling periods on each of three and five separate nights respectively. A spotlight was used to search for geckoes systematically at each site. The number sighted was counted over a 40 minute period at each site.

RESULTS

Arthropod numbers. The results of arthropod sampling are shown in Appendix 1 and summarised in Table 1. Table 1 summarises the mean number of arthropods per tree species at each site, the number of *A. gracilipes*, the numbers of Coccoidea and the numbers of orders encountered. In addition, means and error terms for the total arthropods minus YCA, and the totals minus both YCA and Coccoidea are presented. The mean numbers of individuals per tree species, other than YCA and Coccoidea (which were about 99% scale insect 'crawlers'), were very low and hence an analysis taxon by taxon is not sensible. The numbers of orders in our samples ranged from 7.3 (±0.25) to 9.5 (±1.85). As anticipated there were virtually no YCA in the uninfested sites (a total of 24 individuals in one *Inocarpus* canopy and a single YCA in a *Pandanus* crown). Counts in the old-baited sites are evidence of the efficiency of these previous control efforts (11 in a *Syzygium* canopy, 2 in *Inocarpus* canopies, 2 in a *Barringtonia* crown, and 1 in a *Pandanus* sample). In both the baited areas YCA numbers were lower than non-baited sites, ranging from 19.5 (±3.3) in *Barringtonia* in an old-baited site to 64.3 (±19.7) in *Pandanus* in a new-baited site. The YCA was the most abundant arthropod in the non-baited control areas; in *Syzygium* canopies the mean number of YCA per tree reached 1310 (±1049.9).

To examine the effects of both tree species and insecticide treatment on arthropod numbers we carried out two-way analyses of variance, the results of which are summarised in Table 2. Four such analyses were carried out using different response variables, *viz.*: totals for all arthropods, numbers of YCAs, numbers of Coccoidea and total arthropods minus YCA and Coccoidea. As indicated in Table 2, four highly significant results were obtained. The impact of tree species had a significant impact on the total arthropod abundance ($F = 4.21$, $p = 0.0045$) but not on the total number of YCA, total Coccoidea, or total arthropods (less ants and Coccoidea). Insecticide treatment showed significant effects on total arthropod abundance ($F = 30.07$, $p < 0.001$), on YCA numbers ($F = 60.741$, $p < 0.001$) and on numbers of Coccoidea ($F = 21.17$, $p < 0.001$). The very low probabilities associated with these effects obviated the need for applying Bonferroni corrections even though the four response variables used were not independent of each other. There was no significant effect of insecticide treatment on arthropod abundance once numbers of ants and Coccoidea had been removed. There were no significant interaction effects.

The significance of tree species effects on total arthropod abundance was principally due to elevated numbers on *Syzygium nervosum* particularly in the non-baited sites. This reflected principally the very large numbers of YCAs on some trees and this significance was carried through when YCA numbers alone were analysed. The highly significant effects of insecticide treatment on numbers of Coccoidea reflected higher numbers observed on all species of tree in non-baited and new-baited sites with very high numbers particularly on *Inocarpus fagifer* in non-baited sites. The numbers of ants and Coccoidea per sample were significantly positively correlated ($r^2 = 0.26$, $p < 0.001$) (Fig. 2) (see also Abbott, 2004).

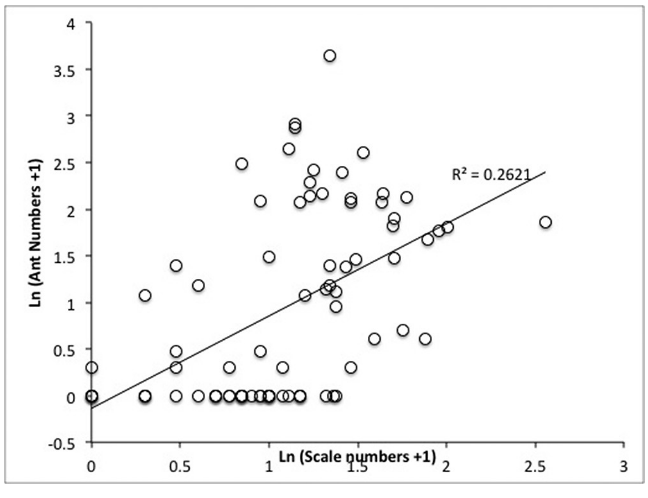

Fig. 2. Plot of logn+1 abundance of YCA against logn+1 abundance of scale insects as sampled by knockdown insecticide sampling across all plots.

Table 1. Summary of mean arthropod densities as sampled by knockdown insecticide sampling.

Treatments/ Tree Species (No. sites)	Mean Arthropods sampled (a)	Mean A. gracilipes sampled (b)	(a)-(b)	Mean Coccoidea sampled (c)	(a)-(b)-(c)	Mean number of Orders
Uninfested (U)(4)						
S. nervosum	28.3 ± 0.5	0	28.3 ± 0.5	5.5 ± 3.1	22.8 ± 3.2	6.5 ± 1.0
I. fagifer	41.8 ± 8.9	6 ± 6.0	35.8 ± 5.1	13.3 ± 3.5	22.5 ± 3.5	7.3 ± 0.3
B. racemosa	42.8 ± 6.3	0	42.8 ± 6.3	15.3 ± 3.7	27.5 ± 9.8	9.5 ± 1.9
P. umbellifera	30.5 ± 5.5	0	30.5 ± 5.5	11.3 ± 3.8	19.3 ± 5.7	8.1 ± 1.1
P. elatus	27.5 ± 2.1	0.3 ± 0.3	27.3 ± 2.2	5.3 ± 2.8	22.0 ± 2.9	8.3 ± 0.8
Non-baited with ants (N)(4)						
S. nervosum	1360 ± 1047.9	1310 ± 1049.9	50.0 ± 4.5	27.7 ± 9.5	24.3 ± 4.5	8.5 ± 0.7
I. fagifer	317 ± 53.3	180.8 ± 46.5	136.3 ± 85.8	115.5 ± 82.3	20.8 ± 4.9	8.5 ± 0.3
B. racemosa	139.5 ± 27.8	88.5 ± 29.8	51.0 ± 8.3	29.3 ± 7.3	21.8 ± 7.8	7.8 ± 1.3
P. umbellifera	285.5 ± 116.2	218.5 ± 117.7	67 ± 9.6	28.3 ± 5.7	38.8 ± 7.3	8.8 ± 0.3
P. elatus	143.5 ± 34.0	98.3 ± 28.9	45.3 ± 6.5	26.5 ± 6.2	18.8 ± 3.0	7.5 ± 0.7
Old baited 2000/2001 (O) (4)						
S. nervosum	25.3 ± 6.7	2.8 ± 2.8	22.5 ± 4.0	4 ± 2.1	18.5 ± 4.9	7.8 ± 1.1
I. fagifer	23.5 ± 4.5	0.3 ± 0.3	23.3 ± 4.4	3.8 ± 2.8	19.5 ± 3.1	8.3 ± 0.7
B. racemosa	20.0 ± 3.7	0.5 ± 0.5	19.5 ± 3.3	3.5 ± 0.7	16.0 ± 3.7	7.8 ± 0.8
P. umbellifera	21.8 ± 2.8	0	21.8 ± 2.8	3.5 ± 1.9	18.3 ± 3.7	8.5 ± 0.7
P. elatus	23.5 ± 5.0	0.3 ± 0.3	23.5 ± 5.0	6.0 ± 0.9	17.3 ± 5.0	6.8 ± 1.3
New-baited 2002 (B) (4)						
S. nervosum	188.3 ± 41.2	126.5 ± 68.0	61.8 ± 18.4	39.8 ± 16.6	22.0 ± 3.6	9 ± 0.7
I. fagifer	103.3 ± 40.5	53.3 ± 23.5	50 ± 21.6	34 ± 20.6	16.0 ± 3.5	7.5 ± 0.5
B. racemosa	118.3 ± 43.6	59 ± 45.4	50.3 ± 15.2	36.3 ± 17.1	23.0 ± 5.9	8.3 ± 0.8
P. umbellifera	290 ± 191.0	229.5 ± 195.1	60.5 ± 23.0	34.3 ± 21.95	26.3 ± 3.6	8.3 ± 0.5
P. elatus	101.3 ± 30.9	37 ± 28.0	64.3 ± 19.7	29.3 ± 15.8	35.0 ± 15.3	8.5 ± 0.9

Table 2. Results of two-way Analysis of Variance comparing the canopy arthropod counts among treatments. U, uninfested sites; O, 2000–2001 hand-baited sites; B, 2002 aerial baited sites; and N, non-baited control sites.

Response Variable	Trees		Insecticide Treatments		Residuals	
	F value	p value	F value	p value	F value	p value
All arthropods	4.22	<0.005	30.07	<0.001	1.64	ns
A. gracilipes	1.11	ns	60.74	<0.001	0.43	ns
All Coccoidea	0.361	ns	21.17	<0.001	0.98	ns
All arthropods excluding *A. gracilipes* & Coccoidea	0.53	ns	1.44	ns	0.53	ns

Vertebrate fauna numbers. The numbers of birds and geckos encountered are presented in Table 3. The number of observation periods was possibly too few for the detection of subtle responses of vertebrates to the treatment variables. Similarly, although a repeated measure analysis of variance would normally be the method of choice for analysing data sets of this type, the numbers available are too low to make this sensible. Accordingly we have analysed each treatment on the basis of the total number of observations of the target species made within each site during the study period. Paired t-tests and one-way ANOVA have been used to compare overall relative abundance across treatments between the two census periods for each bird species (again based on the total number of observations within each site). There were no significant differences apparent across the treatments immediately after baiting for the island thrush, the imperial pigeon or the emerald dove (Table 4a). However, the Christmas Island white-eye showed significant differences

Table 3. Bird and gecko counts during the 2002 and 2003 sampling periods. Abundances were summed within sites and treatment means/standard errors (SE) were derived from these sums. Treatment symbols as in Table 2.

	2002						2003					
	Uninfested (U)		**Non-baited (N)**		**New Baited (B)**		**Uninfested (U)**		**Non-baited (N)**		**New Baited (B)**	
	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE	Mean	SE
CI Thrush	14.5	4.4	13.0	9.3	20.3	7.6	15.0	5.1	14.0	4.1	12.0	2.3
CI White-eye	63.3	13.9	16.3	5.5	113.0	35.8	35.3	8.9	49.8	16.2	70.0	16.3
CI Imperial Pigeon	65.5	5.8	61.5	3.1	65.3	4.4	48.0	2.9	39.0	3.2	23.0	6.0
Emerald Dove	2.0	1.1	0.8	0.3	3.3	0.5	4.8	1.1	1.5	1.2	3.3	0.8
CI Gecko	7.3	4.7	0.8	0.8	2.3	1.7	8.3	4.5	1.0	1.0	1.0	0.6

Table 4. Results of Analyses of Variance comparing vertebrate counts per treatment from a) 2002 and b) 2003 with results for comparisons using Tukey's post-hoc analysis included where appropriate. Treatment symbols as in Table 2.

a)

Response Variable	F value	p value	Significance	Differences
CI Thrush	0.27	0.77	ns	
CI White-eye	4.65	0.04	*	N<U,B
CI Imperial Pigeon	0.24	0.79	ns	
Emerald Dove	3.21	0.09	ns	
CI Gecko	1.41	0.29	ns	

b)

Response Variable	F value	p value	Significance	Differences
CI Thrush	0.144	0.87	ns	
CI White-eye	1.509	0.27	ns	
CI Imperial Pigeon	8.799	0.01	**	B<U
Emerald Dove	2.474	0.14	ns	

Table 5. Results of paired t-tests comparing overall relative abundance across treatments of each bird species between the 2002 and 2003 censuses.

Response Variable	p value	Significance	Differences
CI Thrush	0.58	ns	
CI White-eye	0.40	ns	
CI Imperial Pigeon	<0.00	significant	2003<2002
Emerald Dove	0.16	ns	

in abundance which indicated that fewer white-eyes were using the non-baited control areas (N) than the uninfested (U) or the aerially baited sites (B) with supercolonies of YCA. In the counts eight months after aerial baiting only the Christmas Island imperial pigeon showed a response to helicopter baiting (Table 4b). The abundance of this species was significantly reduced in the aerially baited sites compared with that in uninfested sites. Further, overall abundance of this species significantly declined between 2002 and 2003 (Table 5).

The data set for the geckoes was simply too sparse to carry out any meaningful analysis. However, more observations of Christmas Island geckoes were made at the uninfested sites than at either the non-baited or baited sites (totals of 33, 4 and 4 respectively). In both years one particular uninfested site showed an order of magnitude more geckoes (20+ compared with single figures) than any other sites. This heterogeneity suggests that factors other than ant infestation play a large role in determining gecko distributions.

DISCUSSION AND CONCLUSIONS

In this preliminary study there appears to be little detectable impact of toxic baiting with Fipronil™ on canopy arthropod communities and on vertebrate communities in the areas examined. When YCA and scale insects were removed from the dataset, there was no significant difference in the mean number of canopy-dwelling arthropods in any Order between uninfested sites and non-baited sites, suggesting that *A. gracilipes* may have less impact on the canopy fauna than the ground fauna where it is typically red crabs that reduce the abundance of litter invertebrates (Green et al., 1999) by their removal of leaf litter. Furthermore, YCA exclude generalist predatory invertebrates (e.g., spiders) from saplings in the understory of rainforest on Christmas Island (Abbott, 2004) and forests in Hawaii (Gillespie & Reimer, 1993). Hence the abundance of invertebrates might already be so reduced in the presence of YCA that toxic baiting failed to show any further reductions.

Due to the lack of previous sampling of canopy arthropods on Christmas Island we are unaware of whether the small sample sizes obtained in this study are indicative of the true abundance of canopy arthropods on the island, or whether a larger scale survey might yield numbers of insects more amenable to detecting patterns associated with *A. gracilipes* or scale insects. We cannot discount the possibility of more taxon-specific impacts, which would only become apparent via analysis of much larger samples across the year. We do not know whether there are naturally large seasonal differences in abundance and species richness of canopy insects as elsewhere (Stork & Grimbacher, 2006; Grimbacher & Stork, 2009). We know that YCA worker ants are active year round (Abbott, 2005) and so we would have expected higher numbers of organisms in our samples at this time. We note, however, that it has been hypothesized that in areas where strong biotic interactions dominate, the community level impacts should be commensurate with that strength of that interaction (Kaplan & Eubanks, 2005; Rudgers et al., 2010). The presence of ants in a facultative mutualism with wild cotton reduced arthropod richness, evenness and abundance (Rudgers et al., 2010). We confirmed in this study the concurrent increase in the numbers of scale insects in the canopy with increasing numbers of YCA workers (Fig. 2) and, in a large-scale exclusion of *A. gracilipes* from rainforest sites on Christmas Island, Abbott & Green (2007) established that scale insects are highly dependent upon YCA attendance, sanitation services and protection from natural enemies. The strength of this association was such that removal of *A. gracilipes* workers resulted in collapse of honeydew-producing scale insects in the canopy of *Inocarpus* and *Syzygium*. So we surmise that arthropods in the canopy may have been less numerous in YCA-infested or baited sites given the presence of such a strong biotic interaction. Only a spatially and temporally continuous sampling effort would reveal the extent to which this idea applies to the Christmas Island rainforest.

At the coarse, ordinal level we detected no impacts on the richness of the samples we obtained. The number of insects sampled from the canopy was extremely low and amongst the lowest we have seen in any canopy samples (Stork et al., 1997; Basset et al., 2003). This observation could also be partly reflective of seasonal variation in insect abundance (Frith & Frith, 1990).

The Fipronil™ baiting programme aimed at reducing YCA populations on Christmas Island had no immediate detectable negative impact on terrestrial diurnal bird species, nor on the nocturnal Christmas Island gecko, where an 'impact' is considered to be a reduction in relative abundance of the species. This finding is in line with work by Norelius & Lockwood (1999) which suggested that in general Fipronil™ had less impact on bird population densities compared to other insecticides, an effect they attributed to the relatively low impacts of Fipronil™ on non-target insect food resources (due to higher toxicity and therefore lower application rates) rather than to direct effects of the insecticide on birds. However, immediately after baiting, the relative abundance of the Christmas Island white-eye was greater in uninfested and aerially baited sites than in non-baited control areas with supercolonies of YCA. Further, medium-term impacts were detected for one vertebrate species, the Christmas Island imperial pigeon with the abundance of this species lower in aerially baited sites compared with uninfested sites, and an overall decline in the abundance of this species recorded eight months after baiting.

The Christmas Island white-eye is listed as 'Near Threatened' (Garnett & Crowley, 2000; Garnett et al., 2011; IUCN, 2013) and hence any effect of the baiting programme on its abundance is cause for concern. However, the relatively high white-eye abundance we observed in baited sites occurred immediately after baiting and these effects were not long-lived, having dissipated eight months after baiting. It is therefore likely that these effects reflect behavioural responses of this generalist feeder to changes in food resource availability, rather than changes in white-eye population abundance. The study sites were a maximum of 5 km apart and sometimes less than 1 km apart, and at this scale, spatial changes in white-eye distribution are likely to have occurred in response to increased availability of moribund insects following insecticide application at baited sites. The even distribution of white-eyes across treatments eight months after baiting suggests a return to pre-treatment conditions. Moribund insects would no longer be available at baited sites after the initial effects of insecticide application subsided. Similarly, Norelius & Lockwood (1999) recorded increases in the density of insectivorous birds relative to pretreatment densities in plots in Wyoming rangelands treated with insecticides, including Fipronil™, to control grasshoppers and noted that the changes in bird densities observed were almost certainly a function of alterations in the prey base.

Davis et al. (2008) demonstrated that YCA can impact on bird abundance and reproductive success. It is possible that lower white-eye abundance in non-baited sites infested by YCA relative to uninfested sites reflects long-term impacts of YCA invasion on white-eye populations, potentially associated with predation which has been documented on emerald dove chicks on Christmas Island (Garnett & Crowley, 2000). However, population-level impacts seem unlikely given the lack of variation in white-eye abundance among treatments eight months after baiting, and the lack of variation in abundance between 2002 and 2003. It is more likely that lower relative abundance in non-baited infested sites reflects indirect interactions such as interference competition (Keddy, 1989) or exploitative competition for invertebrate prey (Haemig, 1992), resulting in avoidance of infested sites by white-eyes, or greater movement from infested sites to baited sites in order to utilise novel temporary food resources immediately after baiting. These findings contrast research conducted prior to the baiting programme by Davis et al. (2008) demonstrating greater white-eye abundance and foraging success in YCA-infested forest than in uninfested forest, which was attributed to greater food resource availability in invaded forest where mutualism between the YCA and honeydew-secreting scale insects results in a super-abundance of the latter. The reversal of this trend during our study may reflect alterations in resource distribution associated with temporal shifts in YCA-scale insect dynamics since 2001/2002 when Davis et al. (2008) undertook their study.

Of more concern than the likely short-term behavioural responses of white-eyes to the baiting programme are the negative trends observed for the Christmas Island imperial pigeon. Eight months after baiting, pigeon abundance was lower in aerially baited sites than in uninfested sites and the overall abundance of this species had significantly declined across all treatments. Sampling in 2002 was conducted in spring, while sampling in 2003 was conducted in autumn and it is possible that lower counts of pigeons in 2003 reflect seasonal variation in call frequency. If long term effects on the bird community were to occur following baiting, one would expect the mechanism to be indirect (e.g., through the food chain, following alteration of invertebrate food resource availability). As such, the pigeon (which is largely a frugivore) seems the land-bird species least likely to experience non-target impacts of baiting. It is conceivable that more complicated processes (e.g., pollination frequency) have been influenced by YCA supercolony formation on Christmas Island with flow-on effects for the pigeon. Considering the time-scale of this investigation, however, it is unlikely that cascade effects of baiting would have altered such processes to the point where they would impact upon birds at the population level. Since others have found elsewhere that oral doses of Fipronil™ impact on the feeding behaviour of birds and also impact egg hatchability and reproduction in birds (Kitulagodage et al., 2011a, 2011b), we are concerned that the long-term use of this bait to control YCA may have similar impacts on the important bird fauna of Christmas Island.

Although no impacts of the baiting programme were detected on the nocturnal Christmas Island gecko, the data provide a solid indication of a negative impact of *A. gracilipes* on this species. Loss of insect food for the gecko is the most likely driver, as found in Madagascar for herpetofauna when Fipronil™ was applied to control locusts (Peveling et al., 2003). The greater number of gecko observations at the uninfested sites than at either the non-baited or baited sites almost certainly indicates a negative impact of ants (present and past) on the gecko at the population level, but many more observations would be needed to make this statement statistically valid. There is considerable concern about the fate of the six native species of terrestrial reptiles on Christmas Island, including *Lepidodactylus listeri*, the subject of our study, with reports that five of these species are near extinction (Smith et al., 2012).

Despite the sparse data, it appears that the baiting treatments had no gross effect on the vertebrate fauna surveyed. However, it will be important to repeat the survey in the near future in order to detect any longer term toxicological impacts or effects operating through the food chain. In particular, further monitoring is essential to provide the baseline data we lacked for our study and to determine whether the medium-term decline demonstrated for the imperial pigeon was an artefact of the survey design, or whether real declines are occurring in this species, either related to YCA invasion (directly due to predation or indirectly due to changes in resource availability), the baiting programme, or to other threats. This is important given the 'Near Threatened' status of this species (IUCN, 2013) and because changes in the abundance of this frugivore may impact upon key ecosystem processes such as seed dispersal.

Our study indicates that non-target impacts of Fipronil™ on the arthropod and vertebrate fauna of Christmas Island are negligible and that the use of this insecticide is appropriate to control YCA. However, our study was focused on the immediate and medium-term effects of baiting with Fipronil™ on both the target (YCA) and non-target insects in the canopy and selected vertebrates. Sampling in later years is required to determine if low abundances of *A. gracilipes* post-baiting are sustained and if there are indirect, food-chain based impacts of the baiting programme on arthropod and vertebrate abundance and diversity, or population-level responses of these groups to the strong biotic interaction between *A. gracilipes* and scale insects.

Had the successful deployment of Fipronil™ in 2002 (O'Dowd & Green, 2009; Boland et al., 2011) and ongoing management of YCA on Christmas Island not been undertaken or as successful, invasional meltdown ascribable to the outbreak of populations of *A. gracilipes* would be in a more advanced stage than it is on the island (O'Dowd & Peter, 2010; Green et al., 2011). Accordingly, even had some canopy level, non-target impact been detected, the authorities concerned really had no choice but to proceed with management of YCA supercolonies. The fact that we detected limited effects of the baiting programme (at this stage and based on the limited data we have been able to collect) is a welcome bonus.

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Appendix. Mean (M) and Standard Error (SE) of arthropod abundance for four samples from each tree species per treatment.

Taxon	***S. nervosum***		***I. fagifer***		***B. racemosa***		***P. umbellifera***		***P. elatus***	
	M	SE	M	SE	M	SE	M	SE	M	SE
Uninfested (U)										
Collembola	0.3	0.3	0.0	0.0	1.0	0.4	0.0	0.0	0.0	0.0
Blattodea	0.3	0.3	0.0	0.0	0.3	0.3	0.3	0.3	0.3	0.3
Orthoptera	0.0	0.0	0.0	0.0	1.3	1.3	0.3	0.3	0.0	0.0
Phasmatodea	0.0	0.0	0.0	0.0	0.3	0.3	0.0	0.0	0.0	0.0
Psocoptera	1.8	1.4	1.3	0.6	2.5	1.3	2.3	1.0	2.3	1.1
Auchenorrhyncha and Sternorrhyncha	5.5	3.1	13.3	3.5	15.3	3.7	11.3	3.8	5.3	2.8
Heteroptera	0.0	0.0	0.0	0.0	1.5	1.2	0.8	0.5	0.8	0.5
Thysanoptera	0.0	0.0	1.0	0.7	0.8	0.5	1.3	0.3	0.5	0.3
Neuroptera	0.0	0.0	0.3	0.3	0.5	0.3	0.0	0.0	0.0	0.0
Coleoptera	4.0	3.3	3.5	1.3	3.0	1.8	3.0	0.8	5.3	2.9
Diptera	2.8	0.8	4.0	1.4	3.0	1.4	4.0	2.8	1.8	1.1
Lepidoptera	4.3	1.8	4.3	2.4	4.3	2.9	1.3	0.3	1.3	0.8
A. gracilipes	0.0	0.0	6.0	6.0	0.0	0.0	0.0	0.0	0.3	0.3
Other ants	6.8	3.5	5.0	0.8	3.8	2.2	2.3	0.3	4.3	1.2
Other Hymenoptera	1.3	0.3	1.8	0.9	2.0	1.2	1.0	0.4	2.0	1.1
Isopoda	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Araneida	0.5	0.3	1.0	0.4	0.0	0.0	0.8	0.5	1.5	0.5
Acari	1.0	0.4	0.5	0.3	3.3	0.5	2.0	1.4	1.8	0.8
Pseudoscorpiones	0.0	0.0	0.0	0.0	0.3	0.3	0.0	0.0	0.5	0.3
Diplopoda	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.3	0.0	0.0
Aerially Baited (B)										
Collembola	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.5	0.3
Blattodea	0.0	0.0	0.3	0.3	0.3	0.3	0.0	0.0	0.5	0.5
Orthoptera	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Phasmatodea	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Psocoptera	6.8	2.1	2.5	0.3	6.5	1.3	5.5	2.1	11.8	7.8
Auchenorrhyncha and Sternorrhyncha	39.8	16.6	34.0	20.6	36.3	17.1	34.3	22.0	29.3	15.8
Heteroptera	0.5	0.3	0.0	0.0	0.5	0.3	0.0	0.0	0.0	0.0
Thysanoptera	1.0	0.6	1.3	0.5	1.5	0.6	2.8	0.5	1.0	0.4
Neuroptera	1.0	0.4	0.0	0.0	0.0	0.0	0.3	0.3	0.3	0.3
Coleoptera	0.5	0.3	0.3	0.3	1.8	1.4	2.3	1.6	1.5	0.5
Diptera	3.3	1.7	2.5	0.9	1.5	0.6	4.3	1.3	3.0	2.0
Lepidoptera	0.8	0.3	2.3	1.6	2.5	1.3	2.3	1.1	2.8	1.3
A. gracilipes	126.5	68.0	53.3	23.5	59.0	45.4	229.5	195.1	37.0	28.1
Other ants	1.3	0.3	2.0	0.9	3.8	2.2	3.5	1.3	1.5	1.0
Other Hymenoptera	1.8	0.8	1.5	0.9	1.5	1.2	1.8	0.5	0.8	0.5
Isopoda	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Araneida	1.8	0.6	0.0	0.0	1.0	1.0	0.8	0.3	2.3	0.6
Acari	1.5	1.0	1.5	0.9	1.3	0.5	2.8	0.9	9.3	6.3
Pseudoscorpiones	2.0	0.7	2.0	1.4	1.0	0.4	0.3	0.3	0.0	0.0
Diplopoda	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Taxon	*S. nervosum*		*I. fagifer*		*B. racemosa*		*P. umbellifera*		*P. elatus*	
	M	SE	M	SE	M	SE	M	SE	M	SE
Non-baited control (N)										
Collembola	0.3	0.3	0.3	0.3	0.5	0.5	0.0	0.0	0.0	0.0
Blattodea	0.0	0.0	0.0	0.0	0.3	0.3	0.0	0.0	0.3	0.3
Orthoptera	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Phasmatodea	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Psocoptera	5.0	1.5	3.0	0.4	1.5	0.9	10.3	2.7	2.8	1.4
Auchenorrhyncha and Sternorrhyncha	25.8	8.0	115.5	82.3	29.3	7.3	28.3	5.7	26.5	6.2
Heteroptera	0.5	0.3	0.3	0.3	0.0	0.0	0.0	0.0	0.3	0.3
Thysanoptera	0.3	0.3	0.0	0.0	0.3	0.3	1.0	0.4	1.0	0.4
Neuroptera	0.0	0.0	0.5	0.3	0.5	0.5	0.0	0.0	0.0	0.0
Coleoptera	1.3	0.3	1.3	0.3	1.0	0.4	2.8	1.2	1.3	0.6
Diptera	2.8	1.1	3.8	1.5	3.8	2.5	4.3	1.8	2.5	1.0
Lepidoptera	6.5	3.1	7.3	2.5	6.8	4.0	5.3	2.2	3.3	2.9
A. gracilipes	1310.0	1049.9	180.8	46.5	88.5	29.8	218.5	117.7	98.3	28.9
Other ants	4.0	2.4	2.0	0.9	3.0	2.4	6.8	3.2	2.5	1.2
Other Hymenoptera	0.8	0.5	0.5	0.5	0.8	0.3	2.0	0.7	1.3	0.9
Isopoda	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Araneida	1.5	0.5	0.0	0.0	0.8	0.5	3.0	0.9	0.3	0.3
Acari	1.0	0.6	1.3	0.3	2.5	0.9	3.5	1.0	2.3	0.9
Pseudoscorpiones	0.5	0.5	0.8	0.5	0.3	0.3	0.0	0.0	1.3	0.6
Diplopoda	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Old Baited (O)										
Collembola	0.3	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.3
Blattodea	0.3	0.3	0.8	0.5	0.0	0.0	0.0	0.0	0.0	0.0
Orthoptera	0.0	0.0	0.8	0.8	0.5	0.5	0.5	0.3	0.0	0.0
Phasmatodea	0.0	0.0	0.0	0.0	0.3	0.3	0.0	0.0	0.0	0.0
Psocoptera	1.0	0.6	2.0	0.4	2.0	1.7	2.0	0.4	0.8	0.5
Auchenorrhyncha and Sternorrhyncha	4.0	2.1	3.8	2.8	3.5	0.6	3.5	1.8	6.0	0.9
Heteroptera	0.3	0.3	0.0	0.0	0.0	0.0	0.3	0.3	0.0	0.0
Thysanoptera	0.3	0.3	1.5	0.9	0.5	0.3	1.0	0.4	0.8	0.5
Neuroptera	0.3	0.3	0.3	0.3	0.0	0.0	0.0	0.0	0.3	0.3
Coleoptera	1.0	0.4	0.5	0.5	1.3	0.5	0.5	0.3	1.3	0.8
Diptera	1.8	1.1	5.5	1.5	3.3	1.6	5.3	2.7	3.0	0.8
Lepidoptera	2.3	1.1	1.8	0.9	2.8	0.8	2.8	1.2	3.0	1.1
A. gracilipes	2.8	2.8	0.5	0.3	0.5	0.5	0.0	0.0	0.3	0.3
Other ants	7.8	3.3	3.3	1.9	2.3	0.9	2.8	1.0	5.5	1.9
Other Hymenoptera	1.3	0.5	0.8	0.3	0.8	0.3	1.0	0.6	1.3	0.5
Isopoda	0.0	0.0	0.0	0.0	0.3	0.3	0.0	0.0	0.0	0.0
Araneida	1.3	0.6	0.8	0.5	1.3	0.5	1.3	0.3	0.8	0.5
Acari	0.8	0.5	1.5	0.6	1.0	0.7	1.0	0.4	0.3	0.3
Pseudoscorpiones	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Diplopoda	0.3	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.3