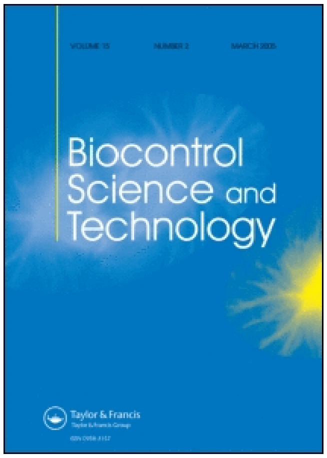

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Predation by *Halmus chalybeus* (Coleoptera: Coccinellidae) on *Ceroplastes destructor* and *C. sinensis* (Hemiptera: Coccidae: Ceroplastinae) Infesting Citrus in Northland, New Zealand

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Predation by Halmus chalybeus *(steelblue ladybird) on two species of wax scale was studied on citrus orchards in Northland, New Zealand. Field experiments using an exclusion technique of enclosing citrus branches in bags, found that larval and adult* H. chalybeus *preyed on first and second instars of both* Ceroplastes destructor *(white wax scale) and* C. sinensis *(Chinese wax scale), but not third instar* C. destructor. *Third instar* C. sinensis *and adults of both species were not tested but are rarely, if ever, attacked by* H. chalybeus. *The sampling of scale and ladybird populations and field experiments showed that few scales of either species survived past the second instar stage where* H. chalybeus *was numerous. The feeding rate of* H. chalybeus *on settled first and second instar scales was estimated inside bagged branches. Adults consumed on average 15.6* C. destructor *and 13.3* C. sinensis *per day per ladybird, while larvae ate 9.7* C. destructor *per day. These feeding rates accounted for the experimental reduction of scale populations.* H. chalybeus *is a useful natural enemy for the control of* C. destructor *and* C. sinensis *when its activity is not disrupted by pesticides.*

Keywords: Halmus chalybeus, Ceroplastes destructor, Ceroplastes sinensis, *predation*, *biological control*, *citrus*, *New Zealand*

INTRODUCTION

Ceroplastes destructor (Newstead) (white wax scale, soft wax scale in New Zealand) and *C. sinensis* Del Guercio (Chinese wax scale) (Hemiptera: Coccidae) were accidentally imported into New Zealand and Australia several decades ago. They became important pests of citrus (*Citrus* spp.) in both countries because the honeydew they excrete serves as a

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substrate for sooty mould fungi (*Capnodium* spp.). Severe infestations of fungi cover plants with a black layer that causes cosmetic injury to the fruit and reduces photosynthesis and fruit yield (Brun, 1986; Brink, 1993).

Females of both species have three instars and a sessile adult stage (Cilliers, 1967; Pollet, 1972). Adults occur on 1–2 year old stems, although about 10% of adult *C. sinensis* developed on citrus leaves in Northland (Lo *et al*., 1996). Reproduction is parthenogenetic and both species can lay over 5000 eggs (Lo, 1995; G. A. C. Beattie, pers. comm., 1999). The average fecundity is considerably fewer and depends on the average scale size which varied greatly between orchards (Lo, 1995). The eggs hatch from under the female's body into mobile crawlers that disperse on to leaves and settle. Both *C. destructor* (Snowball, 1970; Milne, 1981) and *C. sinensis* (Pollet, 1972) move from leaves to young wood as third instars before settling permanently. Neither species infests the fruit of citrus trees, unlike armoured scales.

Both *C. destructor* and *C. sinensis* are univoltine in New Zealand, but *C. destructor* eggs hatch 2–3 months before those of *C. sinensis* (Lo *et al*., 1996). In Northland, the eggs of *C. destructor* hatch mainly during December (early summer) and crawler settlement is largely completed by late January. Live second instars are found until April. Third instars and adults develop from February and March, respectively. In comparison, *C. sinensis* eggs hatch mainly in February and March, and live second instars occur through to October. Third instars and adults are found from March and June onwards, respectively.

Ladybirds (Coleoptera: Coccinellidae) have been used successfully around the world as biological control agents of scale insects for over a century. In Australia, six species of ladybird have been recorded preying on *C. destructor* (Smith, 1970; Snowball, 1972; G. A. C. Beattie, pers. comm., 1999). Five of these species were imported into New Zealand as predators for other scale insects, mealybugs and aphids (Cameron *et al*., 1987). Three of these species became established, *Halmus chalybeus* (Boisduval) (steelblue ladybird), *Rhyzobius forestieri* (Mulsant) and *Cryptolaemus montrouzieri* Mulsant. All three ladybirds occur in citrus orchards in Northland, New Zealand, but *H. chalybeus* was the dominant species (Lo, 2000). It comprised 97% of the ladybirds in visual assessments.

H. chalybeus belongs to the tribe Chilocorini and is native to Australia. It is relatively polyphagous among this group; its prey includes both soft (Coccidae) and armoured (Diaspididae) scales, and mites (Valentine, 1967; Beattie & Gellatley, 1983; Drea & Gordon, 1990; Flynn, 1995). Development from egg to adult took a mean of 37 days at a constant 25°C, and two females lived for 22 weeks in the laboratory (Flynn, 1995). *H. chalybeus* has at least two generations per year in northern New Zealand (Flynn, 1995). Adults are active throughout the year in Northland, while larvae are most abundant in early summer when they comprise the majority of the population (Lo, 2000). During winter small clusters of inactive adults can be found sheltering in orchards. This dormancy is not a true diapause since activity can resume immediately once temperatures rise and is described as a facultative oligopause (Flynn, 1995).

Australian studies have produced conflicting statements on the importance of ladybirds in controlling *C. destructor* and *C. sinensis*. Smith (1970) and Snowball (1972) reported that *H. chalybeus* was an important predator of *C. destructor*, without indicating the level of control achieved. Hely *et al*. (1982) stated that predators reduced, but did not control, populations of *C. destructor*. However, they also attributed a resurgence in *C. destructor* populations following insecticide applications to the elimination of ladybirds. None of these authors presented data to support their claims.

The New Zealand citrus industry is developing an integrated pest and disease management programme, preferably utilising species already present that could act as biological control agents. Lo and Chapman (1998) reported on the parasitoids and fungal pathogens that attack *C. destructor* and *C. sinensis* in Northland. This study examined the importance of *H. chalybeus* as a predator of these two pests. The objectives were to determine which scale stages were vulnerable to *H. chalybeus* and its potential value as a natural enemy.

MATERIALS AND METHODS

Scale and Ladybird Population Sampling

Populations of *C. destructor* and *H. chalybeus* were sampled at the same time and in the same citrus orchards to compare the densities of adult scales, immature scales and ladybirds. Twelve blocks up to about 1 ha in size on nine orchards within a 2 km radius near Kerikeri, Northland, were sampled for scales once or twice between 16 January and 1 February 1991. Each sample comprised 20 branches (1 per tree) for adult scales, and 50 leaves for immature scales. Branches and leaves were randomly collected from a height of 1–2 m on the outer canopy. The number of scales per branch was divided by the area of wood to calculate the density. Each twig was assumed to have the area of a cylinder with a diameter measured at its mid-point.

Populations of *H. chalybeus* were assessed by conducting 10-min searches per block, during which all larvae, pupae and adults were recorded. The foliage was not disturbed while walking slowly through the orchard. Approximately 20 trees per block were examined each time. A total of two or three counts per orchard were made on fine days between 0900–1900 h.

Ladybird Predation

Laboratory experiment. Larval and adult *H. chalybeus* were tested in the laboratory in January 1991 to confirm that both stages were predators of wax scales. Single tangelo (*Citrus reticulata* Blanco × *C. paradisi* Macf.) leaves infested with first and second instar *C. destructor* were placed in Petri dishes. The scales were counted after any obviously dead ones had been removed. The ladybirds were collected from the field and held overnight without food. One fourth instar or adult ladybird was introduced to each dish. There were seven replicates of the larval treatment, and nine of the adult treatment. The dishes with lids on were kept at 20°C under natural daylight and the scales were recounted 24 h later.

Field experiments. A series of three experiments was conducted to determine which scale instars were vulnerable to predation by *H. chalybeus*. Two further experiments measured the feeding rate of *H. chalybeus* and examined its potential for controlling scale populations. All experiments were conducted on tangelo trees. Although both scale species can occur in the same orchard, at each trial site one species dominated.

For each experiment, branches with similar densities of the desired scale stage were covered with 40 cm wide by 60 cm long terylene voile bags and ladybirds were either introduced or excluded. The replicates were located on separate trees, and treatments were randomly assigned to each branch. The number of scales was counted at the start and end of each experiment. Data were analysed by ANOVA. The homogeneity of means was tested by the variance ratio test (Zar, 1996), and where necessary the number of scales was square-root transformed. In Experiment 2, transformation of the data was unable to stabilize the variances, so rank data were analysed.

Experiment 1: predation of C. destructor *crawlers.* The four treatments comprised two with closed bags, one without ladybirds and one with 1–2 adult *H. chalybeus*, open bags and no bags. The closed bag treatments had five replicates and the other two treatments had 10 replicates. The open bags were attached to branches at the proximal end with the distal end left open. The trial commenced on 11 December 1990, before the start of crawler emergence. The number of settled scales on the leaves was counted 4 weeks later. The ladybird population in the orchard was assessed five times during the experiment by 10-min visual searches.

Experiment 2: predation of settled first and second instar C. destructor *and* C. sinensis. This experiment was conducted with *C. destructor* from 1 February to 27 March 1991, at an orchard with high numbers of ladybirds. It was repeated between 5 April and 24 May 1991 at another orchard which had *C. sinensis* and few ladybirds. Branches were either bagged with ladybirds excluded or left unbagged. All adult scales and dead or damaged immature scales were removed before the initial count. All ladybird stages were counted every two weeks by 10-min visual searches.

Experiment 3: predation of third instar C. destructor. The number of scales on selected branches were counted on 11 April 1991. The branches were then bagged and zero, two or eight adult *H. chalybeus* were introduced. Four weeks later the numbers of scales were reassessed.

Experiment 4: feeding rate of H. chalybeus *on first and second instar scales.* On 7 March 1991, 12 branches with 200–500 *C. destructor* were bagged, with half receiving two ladybirds each and the rest none. Four of the bags had adult ladybirds and two had third instar larvae. The scales were recounted 7 days later. The experiment was repeated using *C. sinensis* between 28 March–3 April 1992. These branches had 1300–1800 scales and zero or eight adult ladybirds per bag. The daily consumption of scales was estimated from the difference between the loss of scales on branches with and without ladybirds.

Experiment 5: effect of adult H. chalybeus *on scale populations.* Similarly sized branches infested with adult *C. sinensis* were covered with voile bags on 3 March 1992 at the start of crawler production. Half the branches were categorized as having a 'high' density of scales (mean 35.7 breeding adults/bag) and half had a 'low' density (mean 18.0 scales/bag). Six replicates of each treatment (0, 2, 4 or 8 adult ladybirds) were randomly assigned to branches of both high and low scale densities. The numbers of breeding scales and settled first and second instar scales were counted 12 weeks later when all eggs had hatched.

RESULTS

Scale and Ladybird Population Sampling

There was no clear relationship between the density of adult scales and that of first and second instar scales (Figure 1(a)). However, the density of first and second instar scales was inversely correlated with numbers of ladybirds (Figure 1(b)). Blocks with more than about 30 ladybirds per 10-min search averaged fewer than six first and second instar scales per leaf.

Ladybird Predation

Laboratory experiment. The seven larvae ate an average of 54.0 scales (SEM 23.1), with a range of 2–138 scales, during 24 h. The respective figures for the nine adults were a mean of 27.0 scales (SEM 7.9) and a range of 2–64 scales. An average of 0.5 scales disappeared from the four control dishes without ladybirds.

Field experiment 1: predation of C. destructor *crawlers.* The enclosed branches (treatment 1) had about 1.5 times more adult scales than other treatments (Table 1). Four weeks later, however, there were approximately 12 times more scales settled on these branches than those exposed to ladybirds (treatments 2, 3, 4). There was no difference in the numbers of immature scales on exposed treatments. No scales survived to third instar on exposed branches, whereas they were subsequently observed on protected ones. There was a high number of ladybirds present in the block (mean 52.8 (SEM 2.5)/10-min count).

Field experiment 2: predation of settled first and second instar C. destructor *and* C. sinensis. This experiment was conducted twice, with distinctly different survival of scales between the two sites (Table 2). In the orchard with *C. destructor* and abundant ladybirds (mean 70.4

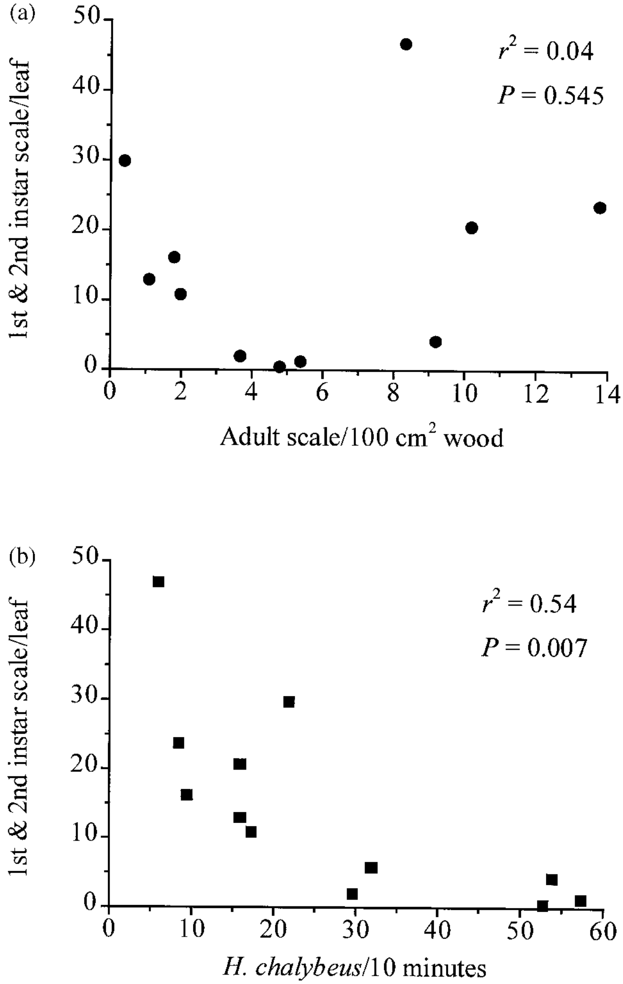

FIGURE 1. Correlations between (a) mean densities of adult, and first and second instar *C. destructor*, and (b) mean density of first and second instar *C. destructor* and mean number of all stages of *H. chalybeus* observed during 10-min searches. Adult and immature scales and ladybirds were sampled at the same time on citrus orchards in Northland between 16 January and 1 February 1991.

(SEM 11.0)/10 min), fewer than half the scales survived on exposed branches compared with 90% on those protected by bags. In contrast, where ladybirds were scarce (mean 3.7 (SEM 0.3)/10 min), a similar proportion of *C. sinensis* survived on exposed and protected branches.

Field experiment 3: predation of third instar C. destructor. There was no evidence that *H. chalybeus* preyed on third instar scales (Table 3). All three treatments had similar numbers of scales in the initial count. Four weeks later about 5% of the scales had disappeared, with and without ladybirds present. All of the ladybirds survived the trial.

Field experiment 4: feeding rate of H. chalybeus The change in the number of first and second instar *C. destructor* and *C. sinensis* on branches with and without ladybirds is shown

TABLE 1. Effect of *H. chalybeus* on settlement of *C. destructor*. Adult *C. destructor* were counted on 11 December 1990 when bags were put on, and numbers of settled first instars were assessed on 8 January 1991

		Mean no. adults /100 cm^2 wood		Mean no. first instars/leaf		
Treatment	Replicates	*n*	SEM	*n*	$\sqrt{x}$	SEM
1. Bag closed, 0 ladybirds	5	36.5	8.2	26.2	4.9	0.9
2. Bag closed, 1–2 ladybirds	5	22.3	6.4	2.2	1.0	0.4
3. Bag open	10	25.0	3.6	4.7	1.6	0.5
4. No bag	10	25.6	3.6	0.5	0.6	0.1
ANOVA		*F*	*P*		*F*	*P*
Trt. 1 vs 2, 3, 4		6.9	$<$ 0.05		61.1	$<$ 0.001
Trt. 2 vs 3, 4		0.4	ns		0.1	ns
Trt. 3 vs 4		0	ns		2.4	ns

TABLE 2. Effect of high or low numbers of *H. chalybeus* on survival of first and second instar wax scales. Trial A was conducted between 1 February and 27 March 1991, and trial B between 5 April and 24 May 1992. The two orchards had respective means of 70 and 4 ladybirds/10-min count

		Mean number of scales/branch				
Treatment	No. of bags	Initial	SEM	Final	SEM	% Decrease
A. *C. destructor*						
Bag closed, 0 ladybirds	6	505	61.1	451	51.4	10.4
No bag	6	593	41.0	285	9.0	51.3
ANOVA (rank data)		$F = 3.1$	ns	$F = 6.2$	$P < 0.05$	
B. *C. sinensis*						
Bag closed, 0 ladybirds	8	421	51.7	347	35.5	16.2
No bag	8	431	74.8	334	53.6	21.6
ANOVA		$F = 0$	ns	$F = 0.1$	ns	

TABLE 3. Effect of adult *H. chalybeus* on survival of third instar *C. destructor* inside closed bags. Scales were counted on 11 April 1991, when *H. chalybeus* were introduced to the bags, and 4 weeks later on 8 May

		Mean number of scales/branch				
Treatment	No. of bags	Initial	SEM	Final	SEM	% Decrease
0 Ladybirds	6	120.5	6.5	114.0	8.2	5.4
2 Ladybirds	6	104.2	6.0	100.5	5.8	4.5
8 Ladybirds	6	112.3	6.3	106.0	6.2	5.6
ANOVA		$F = 1.7$	ns	$F = 1.0$	ns	

in Table 4. The feeding rate of adult *H. chalybeus* on *C. destructor* was calculated as follows: the change in number of first and second instar scale on control branches (1.0) was subtracted from the number that disappeared with ladybirds (32.2). This figure of 31.2 was then divided by the number of ladybirds to give a rate of 15.6 scales/day/ladybird (Table 4). Similar feeding rates were estimated for adult ladybirds on *C. sinensis* scales. There was no mortality of ladybirds.

Field experiment 5: effect of H. chalybeus *on scale populations*. All three densities of ladybird significantly reduced numbers of settled scales at both densities of adult scales

TABLE 4. Feeding rates (number of scales/day/ladybird) of *H. chalybeus* on first and second instar wax scales. Trial A on *C. destructor* was conducted between 7–14 March 1991. Trial B on *C. sinensis* was conducted between 28 March and 3 April 1992

Trial and scale species Treatment	No. of bags	Mean number of scales/branch Initial	SEM	Final	SEM	Change in no./day	Feeding rate
A. *C. destructor*							
0 Ladybirds	6	243.5	39.0	236.2	36.5	− 1.0	—
2 Adult ladybirds	4	410.5	48.5	185.0	77.2	− 32.2	15.6
2 Larval ladybirds	2	404.0	98.0	261.0	48.0	− 20.4	9.7
B. *C. sinensis*							
0 Ladybirds	2	1164.0	121.0	1178.0	103.0	+ 2.3	—
8 Adult ladybirds	8	1505.0	53.2	881.9	129.7	− 103.9	13.3

TABLE 5. Effect of adult *H. chalybeus* on settlement of *C. sinensis*. Number of breeding scales per bagged branch on 3 March 1992, when *H. chalybeus* were introduced, for branches with low and high densities of adult scales. The number of immature scales was assessed 12 weeks later on 29 May

Scale density	Treatment	No. of bags	Mean no. breeding scales/branch		Mean no. live immature scales/branch		
			Initial	SEM	Final	$\sqrt{x}$	SEM
Low	1. 0 Ladybirds	6	18.6	1.9	821	28.4	0.6
	2. 2 Ladybirds	6	18.0	2.3	30	3.9	0.4
	3. 4 Ladybirds	6	16.0	0.7	27	2.9	0.5
	4. 8 Ladybirds	6	19.3	1.4	3	0.9	0.1
High	1. 0 Ladybirds	6	40.0	2.7	743	27.2	0.2
	2. 2 Ladybirds	6	37.5	2.5	202	10.7	0.6
	3. 4 Ladybirds	6	34.5	4.1	192	9.8	0.8
	4. 8 Ladybirds	6	30.7	3.6	23	3.5	0.2
ANOVA			*F*	*P*		*F*	*P*
Among treatments			1.3	ns		42.3	< 0.001
Trt 1 vs 2, 3, 4			2.4	ns		122.3	< 0.001
Between scale densities			92.2	< 0.001		4.6	ns
Interaction Trt vs Density			1.4	ns		1.2	ns

(Table 5). The eight ladybird treatment had a greater effect than two or four ladybirds, which reduced scales to similar levels. All ladybirds were alive at the end of the trial. There was a difference of up to about 800 scales settled on branches with 0 or 2–8 ladybirds. This difference could be accounted for by the estimated feeding rate. Assuming a constant rate of 13 scales per day throughout the experiment, two ladybirds would consume approximately 2300 scales (26 scales × 87 days).

DISCUSSION

This study demonstrated that *H. chalybeus* is an important natural enemy of *C. destructor* and *C. sinensis* in New Zealand. Both adult and larval ladybirds preyed on crawlers and settled first and second instars of the two scale species. Although predation of third instar *C. sinensis* and adult scales of either species was not experimentally tested, these stages are rarely, if ever, prey for *H. chalybeus*. During many hours of study (Lo, 1994), adult and immature *H. chalybeus* were observed feeding on third instar *C. sinensis* only once and were never seen feeding on adults of either species. First and second instar *C. destructor* and *C. sinensis* secrete a dryish wax that only partially covers the body, whereas third instars produce a different type of wax that obscures the whole dorsal surface and expands greatly in adults. *H. chalybeus* was presumably deterred from attacking these later stages by their thicker and complete layer of wax. Nevertheless, the later stages of wax scales are not necessarily invulnerable to predation by ladybirds. The larvae of *R. forestieri* prey on the later instars of *Ceroplastes rubens* Maskell (Richards, 1981).

Population sampling provided indirect evidence that ladybirds were an important mortality factor for wax scales. Logically, there should be a positive correlation between the number of adult *C. destructor* and the number of crawlers produced, as Yardeni and Ravid (1984) found for *Ceroplastes floridensis* Comstock in Israel. Instead, the lack of a relationship between the densities of adult *C. destructor* and their settled progeny amongst orchards suggested that a mortality factor acted unequally on each population. The inverse correlation between settlement of the next generation of scales and the abundance of ladybirds suggested that this factor was predation. Although scale crawlers are highly vulnerable to environmental conditions (Hill, 1980; Milne, 1981; Mendel *et al.*, 1984), these factors act in a largely density-independent manner and were therefore unlikely to cause the observed pattern.

The field experiments showed that *H. chalybeus* could reduce populations of first and second instar scales of both species to levels at which Lo (1994) found few scales were likely to survive to maturity. In the two orchards where predation on first and second instar scales was investigated, few scales survived on exposed branches where ladybirds were abundant. Further evidence of the importance of predation was the numerous remains of wax fragments consistent with feeding by ladybirds that were left on the leaves. Also, more scales disappeared from some exposed branches than other exposed branches (P. L. Lo, unpublished data), showing that mortality acted unevenly on the population. If environmental factors were the main mortality factor, then losses would have been more evenly distributed in time and space. Furthermore, scales killed by environmental factors remain on the leaves for some time and this did not occur.

The estimated feeding rate of adult *H. chalybeus* on *C. sinensis* in Experiment 4, was more than sufficient to account for the disappearance of scales in Experiment 5. However, the rate may have been artificially high because the ladybirds were confined to branches with a high density of prey. Consequently they were likely to spend less time searching than normal. In Experiment 5, the fecundity of an average sized adult *C. sinensis* was estimated to be 1268 eggs (Lo, 1995). The 'low' and 'high' densities of adults in this experiment would therefore produce an estimated 23 000 and 45 000 eggs per branch. In the absence of predation, an estimated 98.3% of the eggs produced by *C. sinensis* failed to reach the third instar (Lo, 1994). At this level of mortality 400–800 scales per branch would survive to third instar, which was similar to the numbers in the control treatment. Predation by *H. chalybeus* would need to add a further 1.3–1.6% mortality to reduce the numbers of scales on branches with ladybirds to those observed in Experiment 5.

Life table studies of *C. destructor* and *C. sinensis* showed that *H. chalybeus* was crucial to the successful biological control of these pests (Lo, 1994). Few scales of either species survived past the second-instar stage where this ladybird was numerous. *H. chalybeus* breeds at a similar time of year as *C. destructor*, so its larvae are most abundant when the vulnerable scale stages are present. Predation by *H. chalybeus* complements the activity of *Euxanthellus philippiae* Silvestri (Hymenoptera: Aphelinidae), which is the only parasitoid of *C. destructor* and *C. sinensis* in New Zealand (Lo & Chapman, 1998). *E. philippiae* attacks the later stages of these two species. A different situation exists in Australia, where a suite of parasitoids was introduced against *C. destructor*. The decline of the pest there was attributed largely to two of the introduced species of encyrtid wasps (Milne, 1981; Sands *et al.*, 1986).

Since this study was conducted, the abundance of wax scales in Northland has declined greatly to the extent that they are now scarce (A. Harty, J. Willetts, pers. comm., 1999). There is circumstantial evidence that this change in pest status may have been brought about by changes in spray programmes. Organophosphate insecticides and copper fungicides are highly disruptive to predation of wax scales by *H. chalybeus* (Lo & Blank, 1992; Lo, 1994), but the use of these products has declined in recent years. A compatible pesticide spray programme is needed to maximize the effectiveness of *H. chalybeus* as a predator of scale insects.

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