POPULATION ECOLOGY AND INTEGRATED MANAGEMENT OF SOFT WAX SCALE (*CEROPLASTES DESTRUCTOR*) AND CHINESE WAX SCALE (*C. SINENSIS*) (HEMIPTERA: COCCIDAE) ON CITRUS

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Peter L. Lo

Soft wax scale (SWS) *Ceroplastes destructor* (Newstead) and Chinese wax scale (CWS) *C. sinensis* Del Guercio (Hemiptera: Coccidae) are indirect pests of citrus (*Citrus* spp.) in New Zealand. Honeydew they produce supports sooty mould fungi that disfigure fruit and reduce photosynthesis and fruit yield. Presently, control relies on calendar applications of insecticides. The main aim of this study was to provide the ecological basis for the integrated management of SWS and CWS. Specific objectives were to compare their population ecologies, determine major mortality factors and levels of natural control, quantify the impact of ladybirds on scale populations, and evaluate pesticides for compatibility with ladybirds.

Among 57 surveyed orchards, SWS was more abundant than CWS in Kerikeri but was not found around Whangarei. Applications of organophosphates had not reduced the proportion of orchards with medium or high densities of SWS. Monthly destructive sampling of scale populations between November 1990 and February 1994 was supplemented by in situ counts of scale cohorts. Both species were univoltine, but SWS eggs hatched two months earlier than those of CWS, and development between successive instars remained two to three months ahead. The start of SWS crawler emergence varied by seven weeks between 1988-1993. A linear relationship between scale size and fecundity was found for both species. The variation in mean scale size amongst orchards corresponded to large differences in egg production.

Survivorship curves and life tables were compared between populations with high and low levels of ladybird predation. Over 90% of crawlers failed to settle. At four orchards with high numbers of ladybirds, 99% of settled first and second instar scales died. The key mortality factor occurred at this stage where ladybirds were abundant. In contrast, where ladybirds were scarce, mortality of first and second instar scales was approximately 82% and some scales survived to breed. Mortality of third instar and adult scales was approximately 80% and 50% respectively.

Parasitised scales were incubated and parasitoids identified from emerged adults. Diseased scales were cultured to identify fungal entomopathogens. One primary and one secondary parasitoid (*Euxanthellus philippiae* Silvestri and *Coccidoctonus dubius* (Girault) respectively) and two fungal pathogens (*Verticillium lecanii* (Zimmermann) Viegas and *Fusarium* spp.) attacked one or both of these stages of SWS and CWS. Parasitoids and pathogens each caused less than 30% mortality. Density-dependent mortality was not shown by any of the natural enemies.

The effect of ladybirds on scale populations was assessed by sampling and experiments where branches and trees were covered to exclude or include ladybirds. Ladybirds predated first and second instar scales and could reduce local scale populations to extinction. Both larval and adult steelblue ladybirds (SBL) *Halmus chalybeus* (Boisduval), *Rhyzobius forestieri* (Mulsant), and adult *Cryptolaemus montrouzieri* Mulsant and *Rodolia cardinalis* (Mulsant) fed on SWS in laboratory experiments. Adult SBL and *R. forestieri* consumed approximately 15 scales per day in the field. SBL comprised 98% of ladybirds in visual and manual searches.

Pesticides were screened for toxicity to SBL by a slide dip method, and for disruption to predation by the reduction in feeding on treated leaves. Fungicides and insecticides inhibited feeding by SBL and reduced their numbers. Copper-based fungicides reduced predation by about 80% compared with approximately 30% by non-copper fungicides. Buprofezin was non-toxic and non-disruptive to SBL. Mineral oils were moderately toxic but caused some disruption to predation. Organophosphates, synthetic pyrethroids and an insecticidal soap were highly toxic to SBL at recommended label rates. Three fungicides were evaluated in an orchard. Both copper and non-copper fungicides reduced numbers of ladybirds. Nine-spray programmes reduced numbers more than 5-spray programmes.

SWS were more abundant than CWS probably in part because their phenology made them less vulnerable to adverse environmental conditions and ladybirds. Currently, SBL are the key to biological control of SWS and CWS, but with present spray programmes particularly those involving organophosphates, ladybirds cannot be relied on to be sufficiently abundant at the right time of year to achieve control. Orchardists should avoid or reduce applications of copper fungicides during spring and summer to minimise disruption to predation of SWS by ladybirds. The introduction of parasitoids such as those which control SWS in South Africa and Australia would complement the existing biocontrol from ladybirds and should be investigated.

Keywords: soft wax scale, *Ceroplastes destructor*, Chinese wax scale, *Ceroplastes sinensis,* Coccidae, population ecology, biological control, integrated pest management, steelblue ladybird, *Halmus chalybeus*, parasitoids, fungal pathogens, fungicides, insecticides, citrus, New Zealand

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Chapter 1 INTRODUCTION

1.1 Citrus industry

Citrus is second only to grapes among fruit crops, in terms of world production (Jackson 1986). Citrus (*Citrus* sp.) originated in Asia, although most fruit is now produced in subtropical regions with a Mediterranean-type climate within latitudes 40^0 north and 40^0 south (Chapot 1975). The highest quality fruit are produced under conditions of warm days, cool nights and an evenly distributed annual rainfall of at least 1200 mm (Chapot 1975). Because citrus is frost tender, minimum temperatures are the main factor limiting growth. New Zealand's climate is at the lower end of the temperature range for citrus and therefore commercial production is largely restricted to warmer regions in the northern half of the North Island (Fig. 1.1).

The New Zealand citrus industry is small by world standards, with an annual production of 24,500 tonnes of fresh fruit (Anon. 1992a) from an area of 2400 ha (Anon. 1992b). The main varieties by area are oranges (35%), mandarins (21%), tangelos (20%), lemons (12%) and grapefruit (9%) (Anon. 1992b). Plantings of citrus have expanded slightly in recent years, largely through increases in mandarins which have replaced tangelos and grapefruit. Much of these new plantings are aimed at exporting to niche markets such as Japan (Laurenson 1991). Exports of fresh citrus in the year to June 1992 were mainly lemons, oranges and tangelos with a total value of $2.4M (Halsted & Carr 1992), while annual sales on the domestic market amounted to about $25M (Anon. 1993a).

With the New Zealand citrus industry increasingly focussed on exporting, a high degree of pest control is needed to meet the standards of fruit quality demanded by overseas markets. The main groups of citrus pests in New Zealand are scale insects, thrips, aphids, leafrollers, weevils, borers, mealybugs and mites (Anon. 1992c). This study concentrated on wax scale insects.

Figure 1.1 Locations of the major citrus-growing regions in New Zealand with their respective percentage of the total area. The location of study areas in Northland are also shown.

1.2 Scale insects

Scale insects (Hemiptera: Coccoidea) are major pests of many horticultural and ornamental crops world-wide. They are highly specialised phloem feeders, with a distinct sexual dimorphism. In females the head, thorax and abdomen are fused into a sac-like body which is wingless (Millar & Kosztarab 1979). Adult females are sessile. They become sexually mature in a nymphal form and reproduction may be sexual or parthenogenetic. Adult males are typically smaller than females and are winged but they lack functional mouthparts (Beardsley & Gonzalez 1975). Males are unknown in many species.

Most scale pests of citrus belong to two families; armoured scales (Diaspididae) and soft scales (Coccidae) (Delucchi 1975). Armoured scales infest all above ground parts of the plant including the fruit, whereas soft scales settle only on leaves and twigs and are therefore indirect pests of citrus. Soft scales excrete honeydew which serves as a substrate for sooty mould fungi (*Capnodium* spp.). The fungi can eventually cover the plants with a black layer which causes cosmetic damage to the fruit (Fig. 1.2), and reduces photosynthesis and fruit yield (Benassy 1986). Severe infestations of scale insects can result in loss of the entire crop and debilitate the trees (Podoler *et al.* 1981).

Approximately 20 species of scale insects have been recorded on citrus in New Zealand (Anon. 1992c), but the main pests are two coccids, soft wax scale (SWS) *Ceroplastes destructor* (Newstead) (Fig. 1.2) and Chinese wax scale (CWS) *C. sinensis* Del Guercio (Fig. 1.3). *Ceroplastes* is a large genus with over 130 species currently recognised, of which 11 have been listed as pests (Ben-Dov 1993). Talhouk (1975) recorded eight *Ceroplastes* species occurring on citrus, with three species in addition to SWS and CWS being of economic importance in some countries. SWS was placed in the genus *Gascardia* by DeLotto (1965), but this is now regarded as a subjective, junior synonym of *Ceroplastes* (Gimpel *et al.* 1974).

A third species of wax scale, Indian wax scale *C. ceriferus* (Fabricius) was recently discovered around Gisborne (Anon. 1992c), where it is presently restricted to four or five properties (L. Hawke pers. comm.). This species has also been recorded on citrus in India, Japan, and Australia, where it is of little economic importance (Talhouk 1975). It is a pest of ornamental plants in North America (Gimpel *et al.* 1974). The host range and pest status of Indian wax scale in New Zealand have not been determined.

1.3 Soft wax scale and Chinese wax scale

SWS is native to Africa (Williams & Watson 1990) where it is widely distributed south of the Tropic of Cancer (Ben-Dov 1993). It also occurs in India, Australia, Papua New Guinea and the Norfolk and Solomon islands (Ben-Dov 1993). SWS rarely causes problems on citrus in South Africa (Cilliers 1967, Snowball 1969). However, it is a pest in New

Figure 1.2 Soft wax scale: Preovipositional adult females (7 mm long) on 'Harward late' orange, with sooty mould covering leaves and contaminating the fruit.

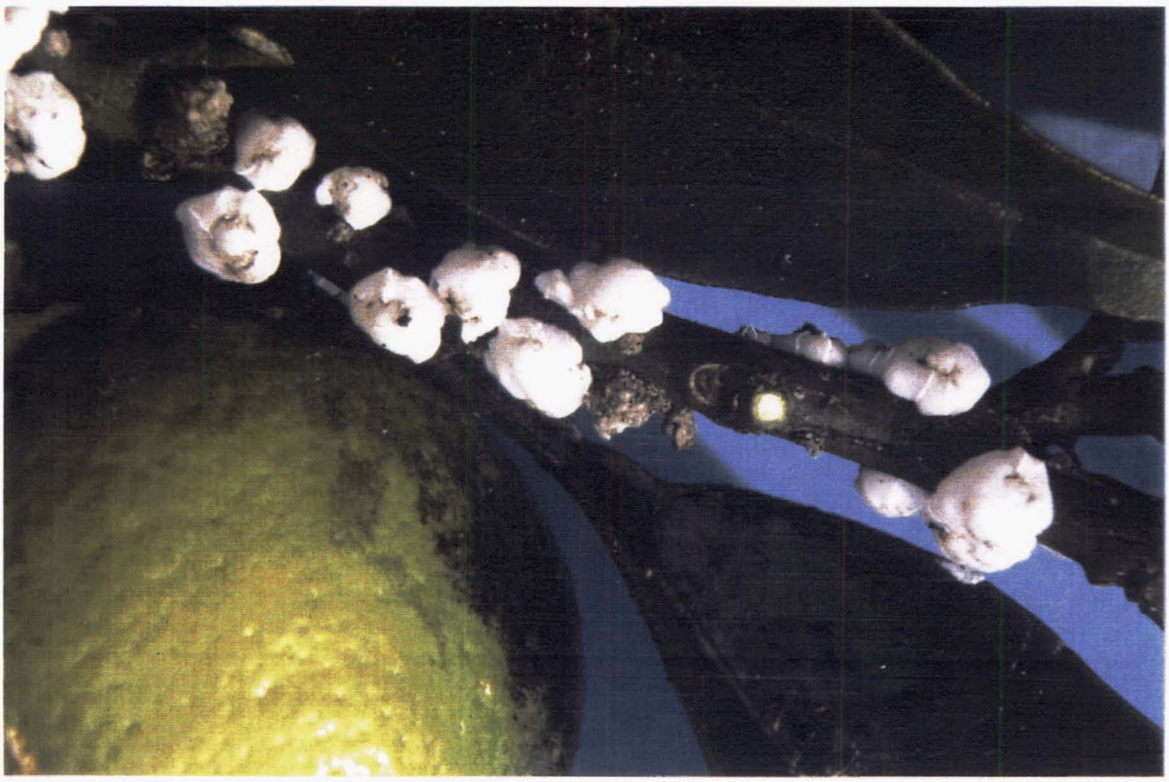
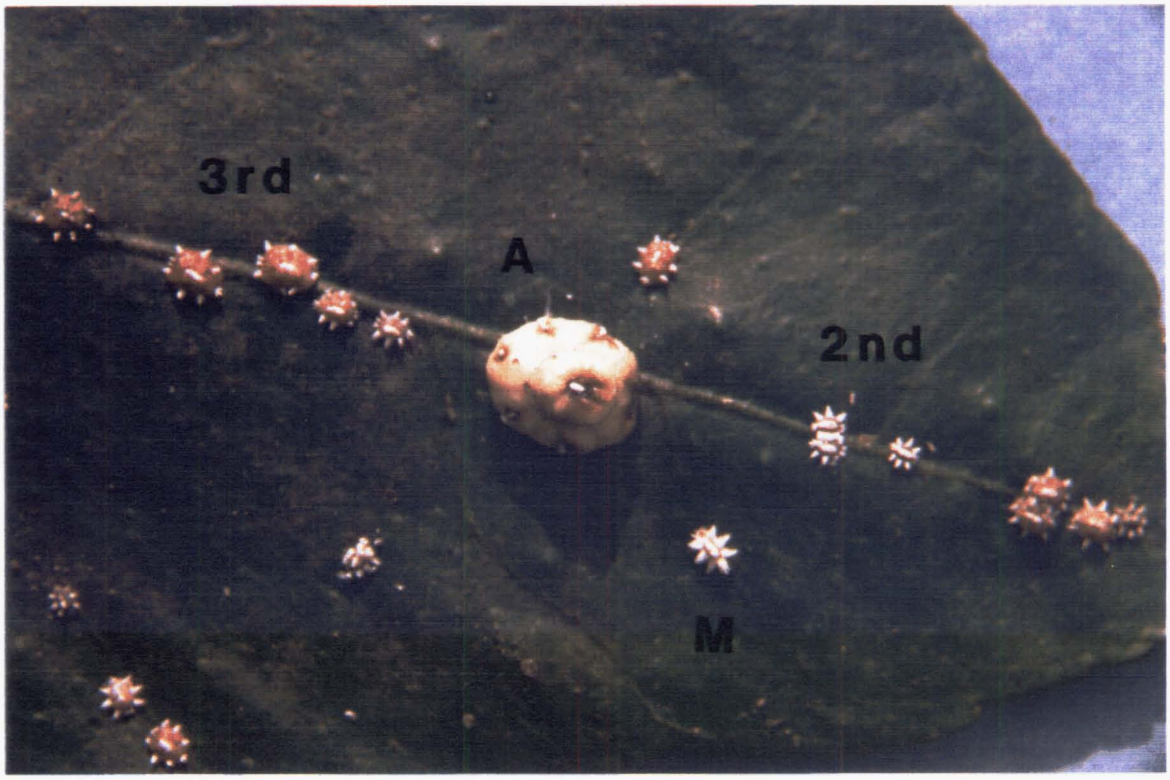


Figure 1.3 Chinese wax scale: Adult female (6 mm long) (A), pink coloured third instars (3rd), smaller "rosette" stage second instars (2nd) and a male (M).



Zealand (Olson *et al.* 1993, Blank *et al.* in press) and was formerly a pest in Australia (Snowball 1969, Hely *et al.* 1982) and Papua New Guinea (Williams 1986).

CWS originated in Central and/or northern South America (Qin 1993) and has spread to southern Europe, northern Africa, North America, Australia and New Zealand (Snowball 1970, Ben-Dov 1993). CWS does not occur in China despite its common name and scientific name "*sinensis*" (Qin 1993). It is of little economic importance in most of its range, but has been recorded as a pest in Italy (Viggiani 1989), Brazil (Talhouk 1975), Australia (Beattie 1988) and New Zealand (Sale 1977).

SWS and CWS have been present in New Zealand for over 50 years and infest the five main varieties of citrus grown here. CWS were first noticed in 1932 by Muggeridge (1933), whose misidentification was corrected by Cottier (1939). The earliest record of SWS was by Greig (1940), but it is not known when it arrived. CWS occurs on citrus throughout the northern North Island as far south as Hawke's Bay, and in Nelson in the South Island (Anon. 1992c). SWS is less widespread than CWS, having been recorded in Northland, Auckland, Waikato, Bay of Plenty and Gisborne (Anon. 1992c, Olson *et al.* 1993). This study was located in the Kerikeri and Whangarei districts of Northland (Fig. 1.1).

Both SWS and CWS have three nymphal instars which are distinguishable by the number of setae on the anal plates or stigmal grooves (Cilliers 1967, Pollet 1972). Adult females (Figs. 1.2, 1.3) are covered by a thick layer of wax and lay eggs under the body before dying. The eggs hatch into crawlers which move onto leaves and settle mainly on the adaxial surface and begin feeding. Crawlers may also be dispersed by wind, birds, insects and people (Hely *et al.* 1982). The majority of surviving scale on leaves eventually migrate to young twigs where they mature into adults.

First instar SWS nymphs secrete a white wax with a central dorsal pad within 2-4 days of settling (Cilliers 1967). This is surrounded by marginal wax rays producing a "star-like" or "rosette" appearance. Second instars are larger than first instars but otherwise appear similar. The migration from leaves to wood occurs as second instars according to Cilliers (1967), whereas Snowball (1970) and Milne (1981) contend that it is as third instars. SWS settle permanently after this move. Third instars produce a wetter type of wax with the consistency of soft butter that forms a white dome covering the body. The body enlarges considerably in the adult stage and the wax continues to expand, forming a thick layer which remains soft and moist. SWS moults at approximately monthly intervals (Cilliers 1967). Male SWS are unknown (Hely *et al.* 1982).

First and second instar CWS appear similar to the same stages of SWS with a central wax pad surrounded by rays (Fig. 1.3), except that the rays are pointed in CWS and rounded in SWS. Female third instar CWS secrete a firm pink wax with the marginal rays remaining visible around the edge of the wax coat (Fig. 1.3). In the fourth and final instar, the wax thickens, hardens and fades to off-white. As with SWS it is unclear which instar migrates from leaves to wood. According to Pollet (1972) and Gimpel *et al.* (1974), CWS move as third instars whereas Snowball (1970) states that the adults migrate. Males comprise a small proportion (2.5%) of the population (Snowball (1970).

1.4 Methods of control

In New Zealand, present methods of controlling wax scales rely on the calendar application of insecticides. Orchardists have traditionally been advised to control these pests by spraying with mineral oils and organophosphate insecticides (Cottier 1956, Helson 1973, Sale 1977, 1988; Smith & Ironside 1977). Consumer pressure for reduced pesticide residues on crops has increased the need to emphasise less environmentally-harmful methods of pest control.

The New Zealand citrus industry is currently in the early stages of developing an integrated management programme for pests and diseases. However, it lacks the information needed to adopt alternative strategies to pesticides for pest control. Little research has been conducted on SWS in New Zealand, except for some information on its phenology (Cottier 1956, Olson *et al.* 1993). Overseas, the biology of SWS was studied in South Africa by Cilliers (1967). Virtually all other information about the ecology, and biological and chemical control of SWS is from Australia (e.g., Snowball 1969; Smith 1970; Smith & Ironside 1974, 1977; Milne 1981, Beattie 1988, Beattie *et al.* 1990). The only previous research on CWS in New Zealand was by Spiller (1943) and Cumber (1972), who studied its phenology and parasitism respectively. The ecology of CWS has been studied in Australia (Snowball 1970, Beattie 1988) and Virginia (Pollet 1972). Its control by pesticides was discussed by Nucifora *et al.* (1986) and Beattie *et al.* (1991).

Scale insects are more amenable to biological control than other groups of organisms because of their sessile habit and colonial distribution (DeBach *et al.* 1971). Several important scale pests of citrus have been brought under biological control by introduced predators and parasites around the world (DeBach & Rosen 1991). For example, soft and pink wax scale (*C. rubens* Maskell) were formerly major pests of citrus in Australia (Snowball 1969, Smith 1974, 1976), but since the establishment of parasitoids, insecticide applications against both scale species have been unnecessary (Smith & Papacek 1985, Sands *et al.* 1986). This success in controlling these species suggests that there are good prospects for biological control of wax scales in New Zealand and considerable potential for reducing pesticide applications by adopting an integrated approach to pest management.

1.5 Integrated Pest Management

The shortcomings of a solely chemically-based means of controlling pests have led to the development of Integrated Pest Management (IPM). IPM seeks to combine biological and chemical methods of pest control with cultural techniques, to alter the ecological balance away from pests and towards their natural enemies and the crop, in a way that minimises damage to the environment. The first priority of an IPM programme should be to utilise the indigenous biological control operating within an agroecosystem (Rosen 1986, Luck *et al.* 1988). Alternative strategies such as establishing additional or pesticide-resistant natural enemies, the use of resistant cultivars and habitat manipulation are also incorporated where possible.

Biological control is selective, can permanently lower pest densities and is relatively inexpensive. It seeks to reduce but not eliminate pests, and therefore does not always reduce pest populations below damaging levels. With indirect pests such as wax scales, a higher level of infestation can be tolerated than for direct pests because the crop is not usually affected until yields are reduced and sooty mould does not contaminate the fruit at low densities of scale. In addition, if orchardists fail to prevent the development of sooty mould, it can be removed by washing fruit in a bleach solution (Sale 1991) or by rinsing with high pressure water jets (Bedford 1990). This gives the opportunity to raise damage thresholds, increasing the viability of biological control while reducing the need for pesticides (Rosen 1986, Bedford 1990).

Ideally, biological and cultural methods of control are supplemented by selective pesticides only where absolutely necessary. The main advantage of pesticides is their ability to reduce pest populations rapidly, albeit only temporarily. Their disadvantages include being generally non-selective and therefore often highly toxic to non-target organisms, resulting in the resurgence of pests or an increase of secondary pests due to the destruction of their natural enemies (DeBach & Rosen 1991) Another disadvantage is the development of resistance to pesticides by pests (DeBach & Rosen 1991). Despite the problems caused by pesticides, when alternative methods of pest control become inadequate or fail, pesticides may be the only means of control available. The success of an IPM programme may depend on the correct choice and timing of pesticides.

The major components of an IPM programme are the identification of pests, field monitoring of pests and their natural enemies, control action thresholds and appropriate methods for controlling pests (Anon. 1991). Monitoring of pests and their natural enemies provides information on population changes that can be used to predict potential problems. Action thresholds provide guidelines to indicate when management action is needed. They require information on pest densities at which a loss in quality or yield of the crop occurs (economic injury level), and the pest density at which control measures need to be implemented to avoid crop losses (economic or action threshold) (Stern 1973).

Comprehensive IPM programmes are already in place for the citrus industries of California (Anon. 1991), Florida (Knapp 1983), Queensland (Smith & Papacek 1985) Israel and South Africa (DeBach & Rosen 1991). Similar programmes are being developed in several

Mediterranean countries. The New Zealand citrus industry can draw on information from these programmes, but each country has unique conditions and different combinations of pests. Hence IPM programmes need to be developed for each country.

1.6 Aim and objectives

The main aim of this study was to provide the ecological basis for the integrated management of SWS and CWS on citrus in New Zealand. Specific objectives were to:

1) Compare aspects of the population ecologies of these two species including their relative abundance, phenology and fecundity.
2) Determine the main mortality factors and the levels of natural control.

The population dynamics of SWS and CWS are discussed in Chapter 2. Parasitism and diseases of SWS and CWS are covered in Chapter 3.

3) Quantify the impact of ladybirds on scale populations.

Ladybirds were identified in this study as being the most important natural enemies of SWS and CWS. Therefore it was important to determine what level of control they exert. The results of population sampling and field experiments are reported in Chapter 4.

4) Determine which pesticides would be least disruptive to predation of scale by ladybirds.

Pesticides are likely to remain an important means of controlling pests and diseases on New Zealand citrus orchards for the foreseeable future. To develop an IPM programme it is necessary to know which chemicals are most compatible with beneficial insects. Laboratory and field experiments on the effect of insecticides and fungicides on the activity of ladybirds are discussed in Chapter 5.

Chapter 2 POPULATION DYNAMICS OF SOFT AND CHINESE WAX SCALE

2.1 Introduction

Populations of organisms usually fluctuate between certain limits in a dynamic equilibrium resulting from the interaction of the biotic potential of the species to increase and the environmental factors that limit population growth (DeBach & Rosen 1991). Unlimited growth does not occur for long, before some negative feedback process comes into operation whose effect is greater or smaller according to whether the population is increasing or decreasing (Varley *et al.* 1973). Pest species become pests only when their population exceeds some level of abundance that reduces the quantity or quality of a crop or commodity which is of value to humans. Understanding what causes population densities to change over time is fundamental to the sound management of pests.

Scale insects have several attributes that make them particularly suitable subjects for population studies. Their largely sessile habit simplifies the collection of census data and fecundity can be readily estimated because the eggs are laid under the body. Scales remain attached to the substrate after they die which enables mortality data on parasites and disease to be collected.

The aim of the research presented in this chapter is to study six aspects of the population dynamics of SWS and CWS, to provide the ecological basis for the development of an IPM programme. The population densities of SWS and CWS were compared to see whether one species was relatively more abundant than the other (Section 2.2). Determining the phenology of both species (Section 2.3) is important for understanding their ecology and establishing the most effective timing of control measures. The first step in examining population changes is to quantify recruitment and losses. Measurements of the fecundity of SWS and CWS are given in Section 2.4. The decline of scale populations with time is graphically represented as survivorship curves (Section 2.5). A more detailed examination of mortality factors is given in age-specific life tables (Section 2.6). Life tables summarise a large body of detailed information in a form where the main mortality factors affecting a population can be readily identified. Once major mortality factors were identified, the next stage was to determine which factors were the main causes of fluctuations in numbers and which, if any, had the potential to regulate populations (Section 2.7). Life tables were analysed by the key-factor approach of Varley & Gradwell (1960).

2.2 Relative abundance

Objective

To determine the relative abundance of SWS and CWS.

Methods

A total of 57 commercial orchards and a few home gardens around Kerikeri and Whangarei were visited in October and November 1990 to determine the relative abundance of SWS and CWS. Some of the orchards were known to have problems with scale, but the majority were chosen without knowing their level of scale infestation. Growers were asked whether insecticides had been applied during the previous year.

Approximately 5-10 min was spent walking around orchard blocks visually searching the leaves and young wood for scales. The intensity of scale infestations was classified using a method similar to that of Kosztarab (1990): low - either no scale seen or scattered individuals with occasional groups of less than five scales; medium - infestation more numerous and widespread, with small clusters (less than about 20 scale per branch), but little or no development of sooty mould; high - scale populations dense enough to smother some branches accompanied by thick deposits of sooty mould. The number of orchards in the low, and medium and high categories were compared by chi-square tests.

Results

SWS was observed on all except six of the Kerikeri orchards and its abundance was classified as medium or high at half of them (Table 2.1). Of these medium or high density infestations, 76% of the orchards had received organophosphate insecticides in the past year. When SWS infestations were compared between Kerikeri orchards with and without organophosphate programmes, there was no significant ($\chi^2 = 3.1$, df=1, $P > 0.05$) difference in the proportion of low compared to medium and high densities. SWS was not found on any Whangarei orchards and it had not been seen by growers. CWS was observed on two thirds of all the orchards, usually at low densities. In Kerikeri, SWS was at medium or high densities on a significantly ($\chi^2 = 19.3$, df=1, $P < 0.001$) greater proportion of orchards than CWS.

Table 2.1 Number of citrus orchards with various levels of abundance of soft and Chinese wax scale in October/November 1990, categorised according to whether organophosphate insecticides had been applied in the previous 12 months.

District	Organo-phosphates	Soft wax scale Low	Medium	High	Chinese wax scale Low	Medium	High
Kerikeri	Used	8	8	5	20	1	0
(34 sites)	Not used	9	2	2	13	0	0
Whangarei	Used	13	0	0	12	1	0
(23 sites)	Not used	10	0	0	9	1	0

Discussion

SWS arrived in the Kerikeri district over 50 years ago (Greig 1940) and was widespread on the orchards surveyed. Its absence around Whangarei was surprising since Kerikeri is only 60 km north. SWS has been recorded on a smaller range of host plants than has CWS (Spiller & Wise 1982, Ben-Dov 1993). This may have limited its spread compared with CWS, which was widely distributed around both Kerikeri and Whangarei. Climatic differences do not account for the absence of SWS from Whangarei because it is established further south. The distance between Kerikeri and Whangarei may have prevented spread by birds and the prevailing winds are in the wrong direction. SWS may be absent from Whangarei simply because there have not been any transfers of infected nursery trees. This was how SWS apparently spread to the Gisborne region (E. Hampton pers. comm.).

There was a clear difference in pest status between the two scale species. CWS was not observed at high densities in this survey in contrast to SWS. Although not all insecticides were applied principally to control wax scales, the use of organophosphates had not reduced the proportion of orchards where SWS populations were either at, or potentially nearing densities where sooty mould could cause problems. The possibility that this was due to the disruption of biological control is investigated further in Chapter 5.

The survey did not attempt to quantify scale densities but aimed to compare the relative abundance of the two scale species at one particular time. Most orchards were not resurveyed in subsequent years, but a change in abundance of scale was noticed on some orchards during the following three seasons. Several formerly high density infestations had virtually disappeared while other populations had greatly increased during this time. An outbreak of CWS occurred at one orchard in the season following the application of an organophosphate to control SWS. However, SWS remained the more abundant of the two species.

2.3 Phenology

Objectives

To compare the life cycles of SWS and CWS and the time of development of different instars.

Methods

Scale populations were monitored on commercial orchards over three seasons from November 1990 to December 1993 (SWS), and from March 1991 to February 1994 (CWS). Blocks or parts of blocks that received no insecticides were chosen to avoid artificial disturbances to the populations. SWS were sampled initially from one orchard, then SWS and CWS were sampled from six and four orchards respectively during 1991 and 1992, and from two orchards each in 1993. Not all properties were monitored for a whole season because some populations died out. These were replaced by sampling from other sites.

Numbers of scale on both leaves and wood were assessed. Leaf samples were collected while walking through a block, by picking 1-2 leaves per tree from the outer canopy at a height of 1-2 m without looking at the tree. SWS were sampled in different months in each season depending on the timing of breeding. In 1991, 50 leaves were collected twice per orchard in January or February. In later seasons, 3-6 samples of 10 leaves per orchard were collected approximately fortnightly sometime between December and April, for the duration of leaf settlement. Monthly leaf samples of CWS were collected throughout the year. Samples comprised 30 leaves per orchard collected as for SWS or from the branches used in wood samples. When scale densities exceeded approximately 20 per leaf, samples were reduced to 10 leaves with a minimum total of 400 scales.

Wood samples were collected monthly throughout the year. They comprised branches with up to two-year-old wood as determined from growth flushes. Initially, 20 branches per block were randomly sampled (for SWS only). However, this included many branches with few or no scale, since their distribution within trees was highly clumped. Subsequently 10 branches were selected. In the second and third seasons, 4-10 branches per block with approximately 400 scale (fewer when only adults were present) were sampled. Branches were assessed immediately whenever possible, or stored at 5^{0}C for up to three weeks.

Scales were observed with a stereomicroscope to determine their instar and condition. The keys of Cilliers (1967) and Pollet (1972) for SWS and CWS respectively, were used initially to determine scale instars based on the number of spiracular setae. This was compared with their external appearance (Section 1.3), which was subsequently used to determine the instar. First and second instars were not distinguished owing to their similar appearance. All scale stages were turned over to determine their condition. Live scales were a yellow to red colour and turgid. If the body was brown and/or drying up, or there was evidence of parasitism, disease or predation (Chapter 3), they were recorded as dead.

The proportions of CWS instars were different on leaves and wood. To determine the monthly percentage of each instar present for the whole population, the percentages from leaf and wood samples were weighted according to the proportion of the population on each substrate (Appendix 1). This proportion was calculated from counts of scales on the leaves and wood of labelled branches (Section 2.5) or from the branches used in wood samples. The overall monthly percentages of each instar were the mean of three seasons' data. For each season, the monthly percentages from different orchards were averaged.

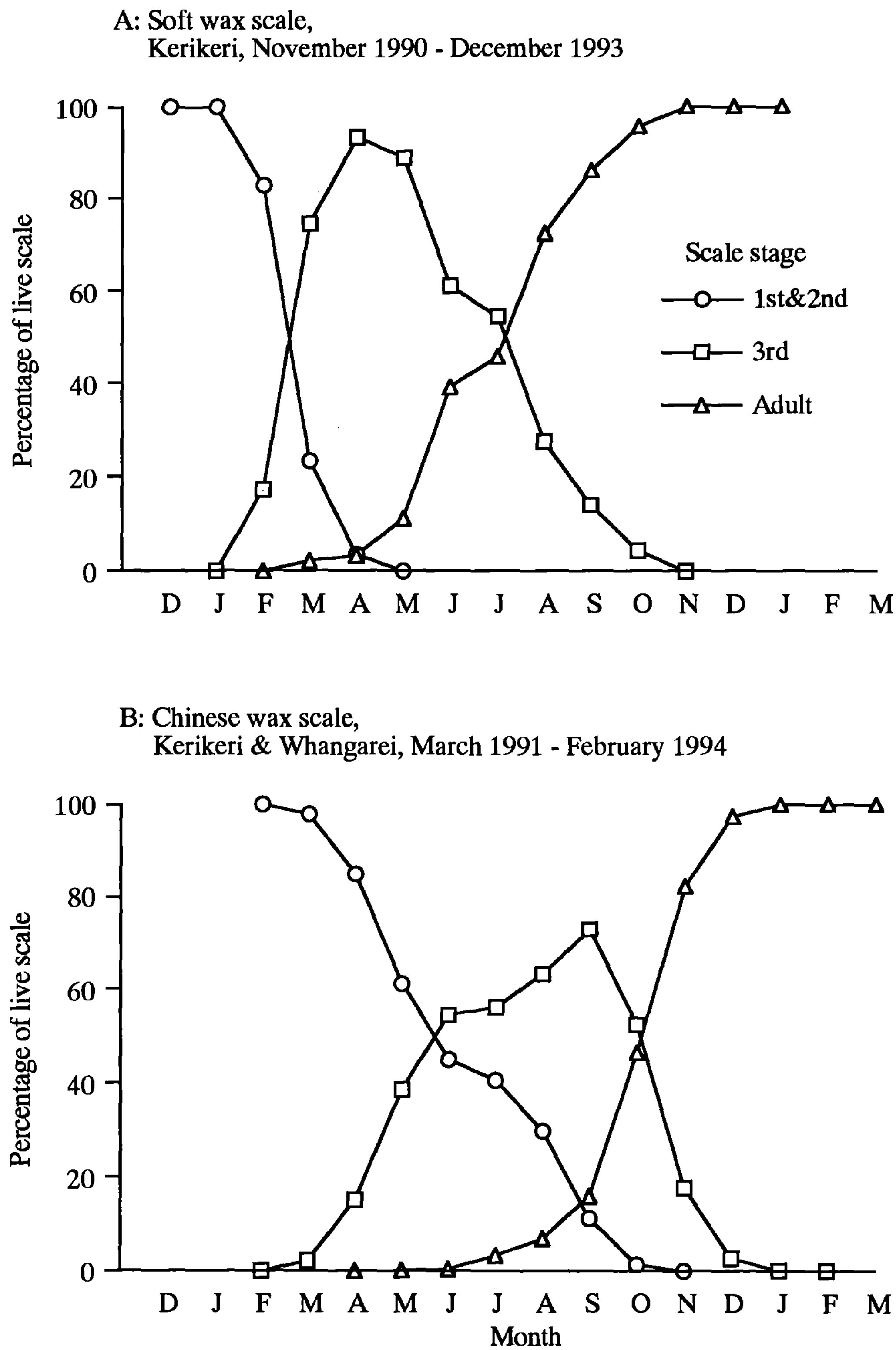
Differences in the earliest appearance of first instar SWS between years were compared with the annual number of degree-days (^{0}D). The number of degree-days was calculated by the formula: (maximum - minimum temperature) ÷ 2 - lower developmental threshold (Zalom *et al.* 1983). Daily maximum and minimum temperatures were obtained from the HortResearch station at Kerikeri from December 1987 to November 1993. These temperatures were converted to monthly averages to calculate the monthly number of degree-days. The lower developmental threshold temperature used was 12^{0}C (Beattie 1988). The dates of scale settlement at one orchard in Kerikeri for the two years preceding this study (Olson *et al.* 1993) are included to give data from six years.

Results

Both scale species had one generation per year, but SWS eggs started hatching about two months earlier than those of CWS and development from one instar to the next remained two to three months ahead (Fig. 2.1). SWS crawlers (first instar) emerged over about six weeks, mainly during December and January (Fig. 2.1a, Appendix 2). An occasional SWS with eggs was seen as late as early March, so hatching overlapped slightly between the two scale species. Settled first and second instar SWS were present on leaves from December to April. Third instars first appeared in February, and comprised the majority of the population in autumn with a few persisting through to spring. The earliest occurrence of adults was in March, and the majority of the population had reached this stage by about late July. The first gravid adults appeared in October, and by November and December most scales were laying eggs. In 1991, the phenology of SWS was about a month ahead of the two following years.

CWS populations hatched over approximately 10 weeks and most crawlers settled between February and April (Fig. 2.1b, Appendix 3). In contrast to SWS, the proportion of first and second instars decreased gradually over the next six months with a few present as late as October. Third instar CWS first appeared in March, and during winter and early spring they comprised the majority of the population. Adults first appeared in May but comprised only a small proportion of the population until spring. The remaining third instars had developed into adults by December. Gravid scales were present from December, with eggs laid mainly from December to March. Some CWS (6-13% of adult scale) remained on leaves throughout their life, in contrast to SWS which all migrated from leaves to wood to complete their development. As with SWS, the life cycle of CWS was slightly earlier in 1991 than the later two seasons.

Figure 2.1 Phenology of wax scales on citrus, expressed as mean percentage of live scale.



During the six years between 1988 and 1993, the start of SWS crawler emergence varied by about seven weeks from mid-November to early January (Table 2.2). The start of crawler emergence was earlier in years with a higher number of degree-days.

Table 2.2 Annual degree-days above 12^{0}C for the year to November, and starting date of soft wax scale crawler emergence at Kerikeri.

Year	Degree-days	Start of crawler emergence
1988	1360	mid-late November [1]
1989	1400	late November - early December [1]
1990	1280	mid-late December
1991	1080	late December
1992	950	late December - early January
1993	1000	early January

[1] From Olson *et al.* 1993

Discussion

The finding that both scales were univoltine in Northland confirms previous data in New Zealand from SWS (Cottier 1956, Olson *et al.* 1993), and CWS (Cottier 1939, Spiller 1943). SWS is also univoltine in South Africa (Cilliers 1967) and most of New South Wales (Gellatley 1968, Milne 1981, Beattie 1988). It produces two generations a year in northern New South Wales (Gellatley 1968) and Queensland (Smith 1970, Smith & Ironside 1974). One generation a year has been recorded for CWS in New South Wales (Snowball 1970, Beattie 1988), Virginia (Pollet 1972), and Sicily (Nucifora *et al.* 1986).

Temperature is a major factor controlling the rate of development and voltinism in armoured scales (Beardsley & Gonzalez 1975). This also applies to coccids. The annual number of degree-days above 12^{0}C at Kerikeri (1200^{0}D), Gosford, New South Wales (1200^{0}D, Beattie 1988), and Nambour, Queensland (2900^{0}D, Maroochy Horticultural Research Station) explains the different number of generations produced by SWS at these locations. The lower developmental threshold for SWS is unknown, but is likely to be similar to the 12.5^{0}C threshold for pink wax scale (Beattie pers. comm.). Beattie *et al.* (1990) used 12^{0}C as the lower developmental threshold for SWS. The number of generations produced by pink wax scale similarly depends on its location. It is univoltine in Japan (Itioka & Inoue 1991) and bivoltine in Queensland (Smith 1976).

The life cycles of SWS and CWS were similar, but differed in the timing of development of successive instars. In New South Wales, crawlers emerged at about the same time of year as in Northland, with a similar two month lag between the two species (Beattie 1988). SWS had a rapid transition from second to third instars, and a gradual change between third instars and adults, whereas the opposite occurred in CWS. This may have been due to the effect of temperature on development at different times of the year. The longer period of hatching in CWS than SWS (Spiller 1943, Beattie 1988, this study) and the likelihood of slower development of first and second instars, meant that these stages were present for much longer in CWS than in SWS.

The large variation from year to year in the appearance of scale crawlers is important for the timing of insecticide applications. Insecticides are most effective against first and second instar SWS (Smith 1970). The critical period extends from the emergence of crawlers until the scale migrate to the wood and secrete a full wax cover. This lasts for about six to eight weeks in individual scale and over approximately three months in any one year for SWS populations, due to the variation in time of egg hatch amongst females.

In the same season, scale could vary in their phenology by a month or more on different orchards. This may be due to differences in aspect and degree of shelter, which affects each orchard's microclimate and the accumulation of degree-days. In addition, the host plant itself may have a profound effect on scale phenology (Flanders 1970). SWS and CWS on citrus trees with high levels of nitrogen matured earlier than those on trees with low levels of nitrogen (Beattie *et al.* 1990). The elongate hemlock scale *Fiorinia externa* Ferris, also developed faster on trees with high nitrogen levels compared with unfertilised trees (McClure 1980). There were insufficient data from different citrus varieties to determine whether host phenology affected either species of scale insect in this study.

2.4 Scale size and fecundity

Objectives

To compare the size of scales amongst orchards and determine the relationship between scale size and fecundity, and to estimate the proportion of eggs that hatch.

Methods

SWS and CWS with eggs were randomly sampled from nine and four orchards respectively. Body length was measured with callipers. The soft wax of *C. destructor* was removed before measuring. Measurements of CWS included wax and were compared with two samples which were also measured without wax. Scale length was measured over two successive years at three properties.

The fecundity of SWS was measured from six orchards with tangelos, oranges and mandarins, and from four blocks of tangelos for CWS. Counts were made by transferring eggs from adult females onto moist filter paper in a Petri dish and counting under a stereomicroscope. Healthy eggs were dark pink; those which were brown or desiccated were recorded as infertile.

Fecundity was also estimated by measuring the volume of unhatched eggs. The bottom of a 200 μl pipette was taped and eggs tipped in using a funnel. After tapping the pipette to settle the eggs, the length of pipette occupied by eggs was measured with callipers. The number of eggs was estimated by multiplying this value by the number of eggs per mm of pipette, which was previously determined for a few scales at each orchard. The number of eggs per mm also provided a measure of egg size.

Scales used to measure fecundity were selected to include the whole range of sizes of scales with eggs. Only scale that had completed oviposition and whose eggs had not started hatching were used. The end of oviposition was indicated by the complete retraction of the ventral body surface upwards against the dorsal surface, as eggs were transferred from within the body to the cavity formed under the scale. The scales were kept for several days after counting to check whether any further eggs were laid. Hatching was indicated by the presence of crawlers or white eggshells.

Scale length was regressed against fecundity. The smallest females (SWS < 2.1 mm and CWS < 2.5 mm) were outliers from the majority of the population and contribute few eggs, so they were excluded from the regression. For each orchard, the mean number of eggs per adult was calculated from the equations in Fig. 2.1 using the average scale size. One-way ANOVA was used to compare mean scale length amongst orchards, between successive years on the same orchard, fecundity between SWS and CWS, and egg size amongst orchards and between the two species.

The proportion of eggs hatching and emerging as crawlers was also estimated. Samples of scales from the same orchards used to gather fecundity data were assessed once all live crawlers had emerged. At the completion of oviposition, the cavity under the body is filled with eggs. The percentage of crawlers emerged was estimated as < 10, 10-50, 50-90 or >90 by comparing the size of the cavity with the volume of unhatched eggs or dead crawlers. The presence of mites and disease in the egg cavity was recorded. The mites were identified by G. Ramsey (Landcare Research, Auckland, N.Z.). In some adults, the body had been opened and the egg cavity was empty. This was attributed to predators, and crawler emergence was classified as <10%, due to the absence of eggshells.

<u>Results</u>

The mean scale size, fecundity and egg size of SWS and CWS and the range from different orchards are summarised in Table 2.3. Data from individual orchards are given in Appendix 4. The mean length of both SWS and CWS differed amongst orchards. There was no change in mean size of SWS in successive years at the orchards of Strang and Fiske, but the mean size of CWS decreased significantly between successive years at Willetts's orchard. There was a high correlation ($r = 0.98$, $P < 0.001$, n = 85) between the lengths of CWS measured with and without wax.

Table 2.3 Adult size, fecundity and egg size of soft and Chinese wax scale on citrus orchards, and ANOVA between orchards and years.

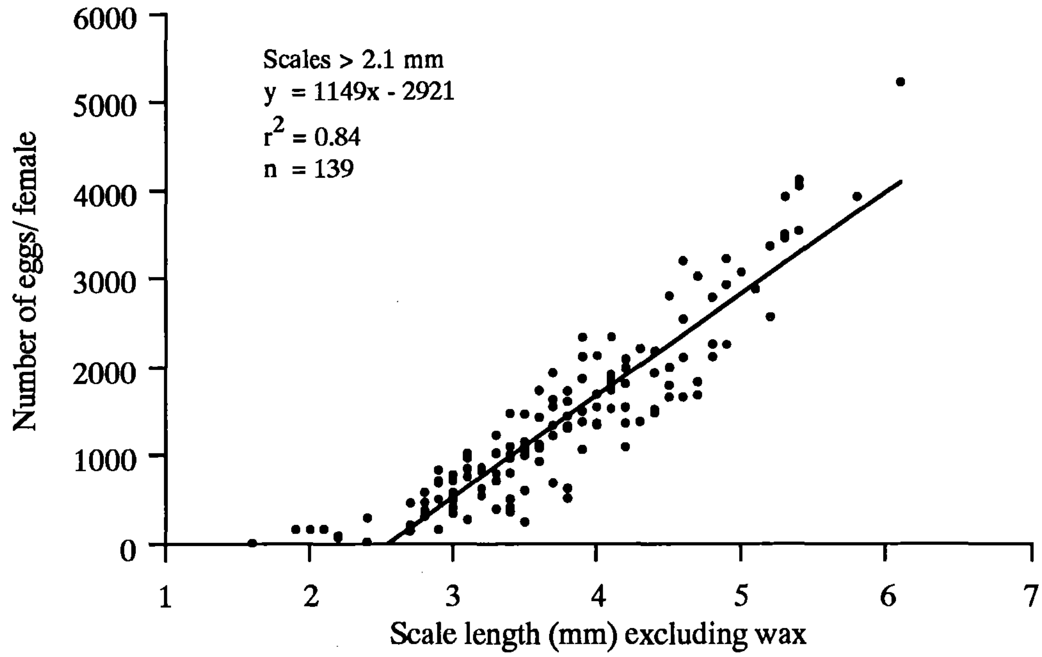
	No. samples (No. scale)	Mean	SEM	Orchard range	F ratio	Significance
Scale size (mm)						
Soft wax scale	11 (575)	3.8	0.1	3.2-4.6	23.5	$P < 0.001$
Strang 1992vs1993		3.9 vs 3.9	0.5 & 0.6	-	0.2	ns
Fiske 1993vs1994		3.2 vs 3.2	0.5 & 0.4	-	0.3	ns
Chinese wax scale	5 (289)	4.1	0.2	3.5-4.6	23.1	$P < 0.001$
Willetts 1992vs1993		4.4 vs 3.5	0.8 & 0.5	-	51.0	$P < 0.001$
Fecundity (eggs/adult female)						
Soft wax scale	11 (139)	1410	148.1	754-2402		
Chinese wax scale	5 (104)	1207	222.5	430-1750		
SWS vs CWS					0.58	ns
Egg size (eggs/mm of pipette)						
Soft wax scale	5 (27)	347	9.1	328-371	7.26	$P < 0.01$
Chinese wax scale	4 (33)	301	4.1	292-311	1.62	ns
SWS vs CWS					81.28	$P < 0.001$

The mean fecundity was similar in SWS and CWS populations (Table 2.3). The greatest number of eggs produced by a single SWS female was 5214. The equivalent for CWS was 4304 eggs. There was a large range of mean egg production per adult for both species among the orchards. SWS eggs were significantly smaller than those of CWS. There was a significant difference in egg sizes amongst orchards for SWS, but not for CWS. Of the 60 calibrated volume estimates of egg numbers, 95% were within ±9% of the actual number of eggs.

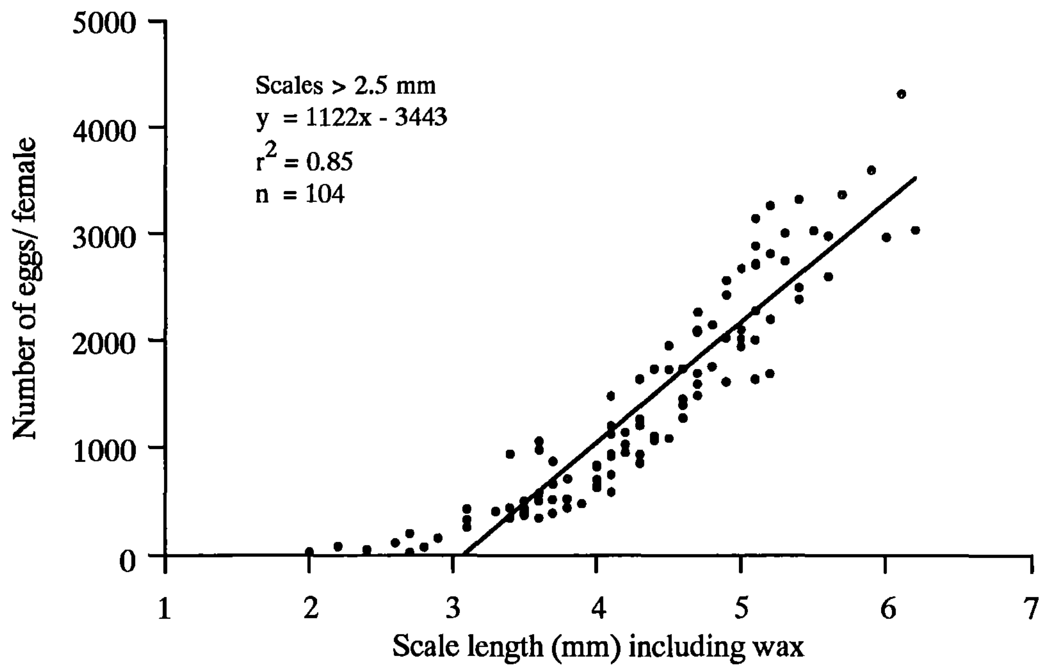
There were significant ($P < 0.001$) linear regressions between scale size and fecundity (Fig. 2.2). Every 0.1 mm increase in mean size increased the number of eggs produced per scale by 115 for SWS (Fig. 2.2a) and 112 for CWS (Fig. 2.2b).

Figure 2.2 Regressions between scale size and fecundity of wax scales on citrus.

A: Soft wax scale
Six orchards, Kerikeri 1990-92



B: Chinese wax scale
Four orchards, Kerikeri & Whangarei 1992-93



The proportion of SWS eggs hatching and emerging averaged 80% in 1992 and 45% in 1993. An average of 76% of CWS eggs emerged in 1992 and 1993 combined. There were insufficient data to compare years for CWS. Less than 0.5% of eggs were infertile for both species and in each year. From 317 SWS adults that had little or no emergence of crawlers, mites were present in 53%, disease in 8%, 10% had been cut open and 29% had no obvious cause of death. The respective figures for 175 CWS were mites 78%, disease 1% and unknown 21%.

Discussion

The maximum fecundity for SWS of 5200 eggs was greater than previously reported. Smith (1970) and Beattie (1988) recorded maxima of 3000 and 3321 eggs respectively. The mean fecundity of 3000 eggs reported by Zeck (1934) was considerably higher than in this study, whereas Newman *et al.* (1929) averaged 900-1000 eggs per scale. The maximum fecundity of CWS in this study was less than the 5475 eggs reported by Beattie (1988). The mean fecundity was also lower than the 2000 and 2121 eggs recorded by Silvestri (1920, cited in Sankaran 1959) and Snowball (1970) respectively. The methods used by other authors to sample scale to calculate the mean fecundity were usually not stated, so the figures may not be strictly comparable with this study. The linear regression between size and fecundity meant that the different maximum and average egg production values in each study presumably reflect the size of SWS or CWS examined. SWS and CWS are moderately productive compared with other *Ceroplastes* species; the maximum number of eggs laid ranges from under 800 in pink wax scale (Smith 1974), to over 10800 in *C. pseudoceriferus* Green (Sankaran 1959).

The range of scale sizes amongst orchards may be due to varying nutrient levels in the trees resulting from different levels of fertilisation. Beattie *et al.* (1990) found that SWS and CWS on citrus trees with high levels of nitrogen were larger than those on trees with low levels of nitrogen, whereas the levels of other nutrients had no effect. The survival, growth rate and fecundity of sap sucking insects are generally favoured by an increase in soluble nitrogen within their host plant (McClure 1990). Citrus orchards in Kerikeri commonly have excessive levels of nitrogen (Mooney *et al.* 1991), which besides being wasteful and possibly harmful to the trees, is also likely to exacerbate problems with scale insects.

The slopes of the regression equations between scale size and fecundity were considerably steeper than those calculated for Florida wax scale (*Ceroplastes floridensis* Comstock) by Podoler *et al.* (1981). The steep slopes meant that the range of mean sizes amongst orchards corresponded to large differences in egg production. The total number of young produced by scale populations is a function of both scale size and scale density. Growers may be able to reduce a scale problem simply by ensuring that they do not overfertilise their orchards resulting in excessive nitrogen levels and larger scales.

Counting eggs manually was accurate but slow. Estimating numbers of eggs from their volume was a faster method, and the calibrations showed it was reasonably accurate. An automatic counter that measured the area of a plate covered by eggs was tried, but the results it gave were much more variable than the volume method.

Under most adults, either virtually all the eggs hatched or they all died. Since a negligible proportion was infertile, this suggests that egg mortality was due to external factors such as mites or disease. Mites (*Tyrophagus perniciosus*) were present under a large proportion of adults whose eggs had failed to hatch. They are saprophytic feeders (G. Ramsey pers. comm.) and it was not known definitely whether they killed live eggs or attacked those which had died from another cause. However, they appeared to feed on live SWS eggs in the laboratory (pers. obs.). A greater infestation of mites in 1993 than in 1992 coincided with a higher mortality of SWS eggs.

The body shell of some adults had been cut open and the eggs removed. This was attributed to an unidentified predator. There was no evidence of predation on CWS eggs, which may have been protected by the harder wax covering the adults. Disease was a minor mortality factor for both species. The organisms responsible were not identified, but Beattie (1988) found a fungal pathogen *Fusarium* spp. associated with egg mortality in SWS and CWS. *Fusarium* spp. were isolated from diseased scales (Section 3.3).

2.5 Survival of scale populations

Objective

To monitor the change in numbers of SWS and CWS on branches in orchards with high and low populations of ladybirds.

Methods

The survival of SWS and CWS cohorts was followed on seven orchards used in phenological studies (Section 2.3). Six populations were monitored for varying lengths of time between January 1992 and March 1993, and two further populations from December 1992 to March and December 1993. Branches with wood up to two years old and a high density (Section 2.2) of scale were selected, and each leaf was numbered. Petroleum grease was applied below the two-year-old growth flush to prevent immigration from other branches. Emigration of crawlers from the leaves of labelled branches to neighbouring ones was not measured and was assumed to equal immigration. Eight branches per orchard were used at five sites. At Hellberg's orchard, two populations, each with four branches, based on the level of predation by ladybirds (see below) were analysed separately. At Strang's orchard, counts started at the third instar stage on 20 branches.

The number of adults present at the start of each generation was counted, and their production of eggs estimated from fecundity data (Section 2.4). The number of scale settling and surviving to third instar and adults was determined by counting the scales present on leaves and wood. During scale settlement, branches were examined weekly. Newly settled scales (since the previous count) were distinguished by the absence of wax or just the central pad without marginal rays (Section 1.3). This was checked against the development of new scale on leaves which were cleared of scale at the previous assessment. Once re-settlement on the wood was completed, counts were made approximately monthly. Finally, the numbers of breeding adults on the branches were assessed after the crawlers had emerged.

Survivorship curves of the reduction in numbers with time (Southwood 1978) were plotted for two groups, each with three SWS populations and one of CWS. The groups were subjected to either high or low levels of predation by ladybirds. The level of predation at each site was determined by the number of ladybirds recorded by 10 min visual counts (Section 4.2), and the presence or absence of evidence of predation in the form of wax fragments and damaged scale bodies remaining on leaves.

Results

At all four sites where predation pressure was low, the scale populations survived to breed the next season (Fig. 2.3, Appendix 5). Where predation was high, few scales reached the third instar. At Hellberg's and Hibbert-Foy's orchards, only one and two scales survived to reproduce, while the other two populations died out before the adult stage.

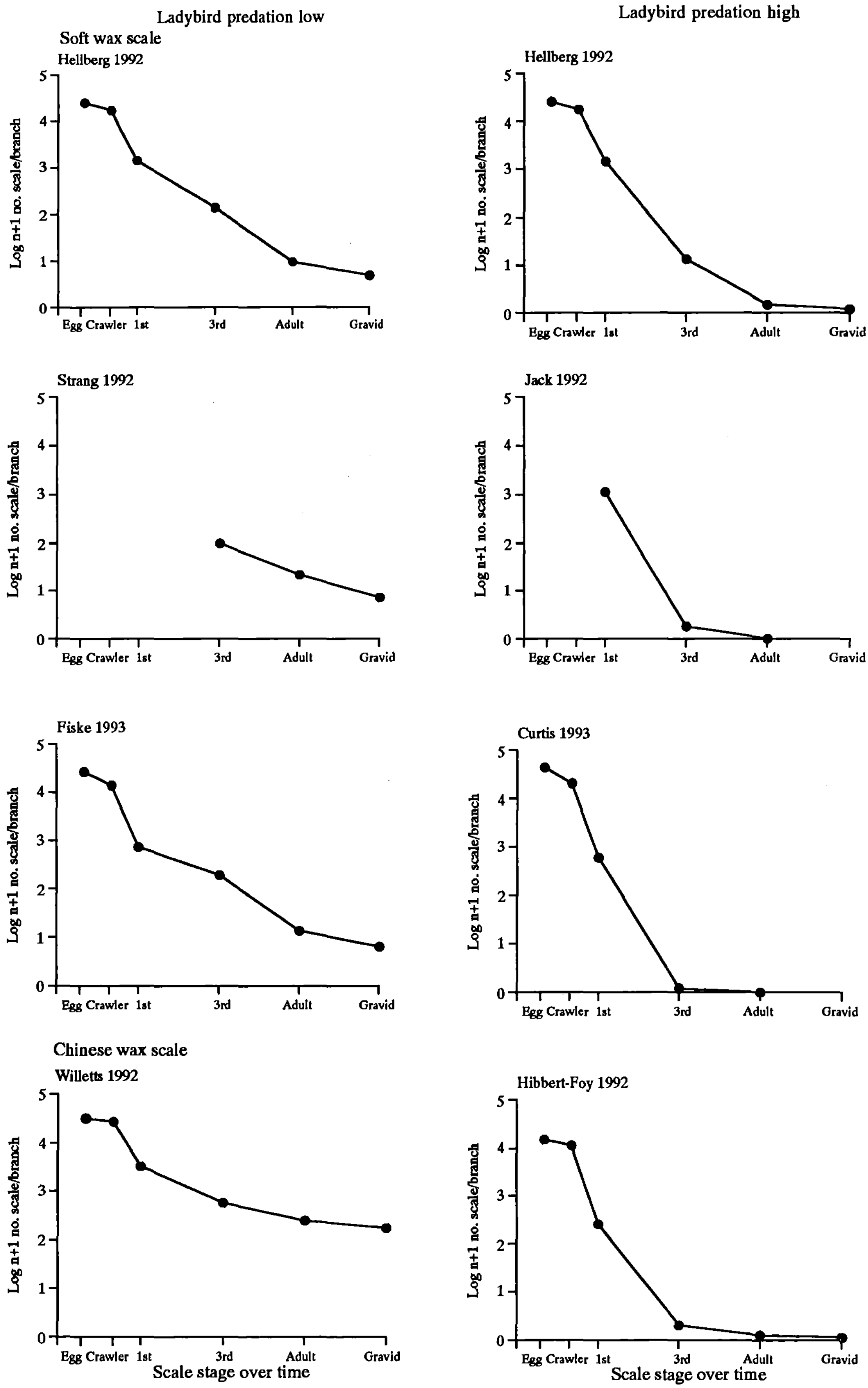
The mean numbers (and standard deviation) of ladybirds per assessment at the two groups of orchards were as follows: Low predation pressure - Hellberg 15.0 (4.2), Fiske 0.1 (0.4), Willetts 4.5 (2.6), Strang (not counted); High predation pressure - Jack 70 (one sample), Curtis 48.1 (13.4) and Hibbert-Foy 75.1 (40.4).

Discussion

The survivorship curves of both scale species followed a pattern typical of most insects, with the greatest mortality on the young stages. The monitoring of scales on orchards showed that some populations were under effective biological control while others were not. The critical difference between these populations appeared to be the number of ladybirds present. At the four orchards with high levels of ladybird predation, few scales survived past the second instar. There was lower mortality of first and second instar scales on orchards with few ladybirds. Although only the two populations at Hellberg's orchard were strictly comparable, the same pattern between orchards with high and low numbers of ladybirds occurred in both seasons and with both species of scale. The higher mortality of first and second instar scale corresponded with the stages predated by ladybirds (Section 4.3).

The Hellberg site was unusual because most of the scales were on a single row of small plants. Ladybirds gradually moved along the row so scales at one end were heavily predated while those at the other end largely escaped. Consequently, separate survivorship curves were compiled for two populations with low and high predation pressure from the same block.

Figure 2.3 Survivorship curves, expressed as mean number of scales per branch, for soft and Chinese wax scale on orchards with low and high levels of ladybird predation. SEMs were less than 0.22 (Appendix 5).



2.6 Life tables

Objectives

To compare the fate of scale cohorts on orchards with high and low numbers of ladybirds, recording the numbers of scale that survived to reach successive stages and to quantify the effects of mortality factors where possible.

Methods

Life tables for SWS and CWS were compiled from repeated counts of scale cohorts on labelled branches (Southwood 1978, Beattie 1988). Data were incorporated from Sections 2.3, 2.4 and 2.5 for four orchards. SWS was monitored on two orchards (Fiske and Curtis), in 1993 while CWS was studied at the orchards of Willetts and Hibbert-Foy during 1992. Sites where ladybirds were scarce (Fiske and Willetts) were contrasted with those where they were abundant (Curtis and Hibbert-Foy), to examine the effect of the absence or presence of a natural enemy (Bellows *et al.* 1992).

The potential and actual starting populations (number of eggs laid and number of crawlers emerging) per branch at each orchard were calculated for a known number of adults from data in Appendix 4. Mean crawler emergence for CWS was used at Hibbert-Foy. The number of crawlers falling from branches was estimated from grease traps at each orchard except Hibbert-Foy where data from Willetts was used. One 85 mm diameter Petri dish was smeared with petroleum jelly and hung beneath each branch. They were replaced weekly and the number of crawlers counted. The area under each branch was measured and divided by the area of the Petri dish. This value was multiplied by the total number of crawlers trapped to estimate the number of crawlers being blown or falling off branches (Appendix 6).

The number of scales settling on the leaves (first instars) and reaching third, adult and mature adult (egg laying) stages were counted on labelled branches (Section 2.5). Numbers entering successive stages on the eight branches per site were averaged for each site. The main mortality factors of third instars and adults were determined from samples of leaves and wood (Section 2.3). The maximum monthly percentage mortality for a factor was used as an estimate of the generational mortality due to that factor (Section 3.4).

Data were analysed by the life table approach of Varley & Gradwell (1960). The logarithm of n_x+1, where n_x= the mean number of scale at stage x, was calculated for each branch and averaged for each site. This number was subtracted from log n_x to determine the *k*-value for stage x. Summing the individual *k*-values gave the total generation mortality (K).

<u>Results</u>

The populations of SWS on the labelled branches at Fiske's orchard were reduced by over 80%, while at Curtis's orchard they declined to extinction before the adult stage (Table 2.4). Mortality of SWS eggs and crawlers before they emerged was about 50% at both orchards. This appeared to be largely due to mites, with smaller losses from disease and predation (Section 2.4). Of the crawlers that emerged, about 96% failed to settle. The *k*-value for this stage was slightly higher at Curtis's orchard. Few crawlers were collected in grease traps (Appendix 6) compared with those which disappeared.

Of first instar scale, over 25% survived to the third instars at Fiske's orchard, but virtually none survived at Curtis's orchard. First and second instar scale were killed by similar mortality factors as crawlers. Parasitism of third instar scale was low (<6%), while disease levels were slightly higher (<11%) (Section 3.4). No predation of third instars was recorded, but a few adults were predated. Disease was a major mortality factor of adult SWS.

CWS numbers increased over seven-fold at Willetts's orchard, whereas at Hibbert-Foy's orchard only two scales reached maturity (Table 2.5). Mortality of eggs was lower than for SWS, with mites also commonly found inside adults with dead eggs. A higher percentage of crawlers was estimated to have been collected in grease traps from Willetts's orchard than from the two orchards with SWS. At Willetts's orchard, 89% of crawlers failed to settle compared with 96% at Hibbert-Foy's orchard, resulting in a larger *k*-value at Hibbert-Foy.

Approximately 83% of first instars died at Willetts's orchard compared with 98% at Hibbert-Foy's orchard. Parasitism of third instar CWS was higher than in SWS whereas disease levels were lower (Section 3.4). Parasitism was the main mortality factor identified for adults. Disease levels were low for this stage and no predation was recorded.

Table 2.4 Life tables for soft wax scale on citrus at two orchards with low and high densities of ladybirds in Kerikeri, 1993.

Scale stage	Fiske[1]					Curtis[2]					
Mortality factor	lx[3]	dx[4]	% dx	log lx+1	k-value	lx	dx	% dx	log lx+1	k-value	
Fecund adults	100					100					
Potential eggs	80670			4.91		126640			5.10		
infertile		160	0.2				250	0.2			
mites		14120	17.5				36980	29.2			
disease		3030	3.8				4180	3.3			
predation		12130	15.0				1770	1.4			
other		9600	11.9				23300	18.4			
total		39040	48.4				66480	52.5			
Crawlers	41630			4.62	0.29	60160			4.78	0.32	*k*1
fall or blown off		4950	11.9				3970	6.6			
predation + other							54200	90.1			
other		34470	82.8								
total		39420	94.7				58150	96.7			
1st&2nd instars	2210			3.34	1.28	2010			3.30	1.48	*k*2
predation + other							2009	99.9			
other		1615	73.1								
total		1615	73.1				2009	99.9			
3rd instars	595			2.78	0.56	1			0.30	3.00	*k*3
parasitism		26	4.3								
disease		133	22.3								
other		386	64.8								
total		545	91.4				1	100			
Adults	50			1.71	1.07	0			0.00	0.30	*k*4
predation		12	24.9								
disease		6	11.9								
other		10	19.4								
total		28	56.2								
Mature adults	22			1.36	0.35				0.00	0.00	*k*5
Total K					3.55					5.10	

1 Low density of ladybirds

2 High density of ladybirds

3 lx Number entering stage

4 dx Number dying within stage

Table 2.5 Life tables for Chinese wax scale on citrus at two orchards with low and high densities of ladybirds in Kerikeri and Whangarei, 1992.

Scale stage	Willetts[1]					Hibbert-Foy[2]					
Mortality factor	lx[3]	dx[4]	% dx	log lx+1	k-value	lx	dx	% dx	log lx+1	k-value	
Fecund adults	100					100					
Potential eggs	150160			5.18		174960			5.24		
infertile		1050	0.7				520	0.3			
mites		17160	11.4				33240	19.0			
other		2660	1.8				8930	5.1			
total		20870	13.9				42690	24.4			
Crawlers	129290			5.11	0.07	132270			5.12	0.12	*k*1
fall or blown off		46940	36.3				48010	36.3			
predation + other							80070	60.5			
other		67880	52.5								
total		114820	88.8				128080	96.8			
1st&2nd instars	14470			4.16	0.95	4190			3.62	1.50	*k*2
predation + other							3910	93.4			
leaf abscission		720	5.0				210	5.0			
other		11240	77.6								
total		11960	82.6				4120	98.4			
3rd instars	2510			3.40	0.76	70			1.84	1.78	*k*3
parasitism		110	4.5				7	10.4			
disease		20	0.8				4	6.0			
leaf abscission		40	1.5				1	1.5			
other		1270	50.6				50	72.0			
total		1440	57.4				63	89.9			
Adults	1070			3.03	0.37	7			0.90	0.94	*k*4
parasitism		243	22.7				1.3	18.7			
disease		3	0.3				0.4	5.6			
leaf abscission		2	0.2				0	0.2			
other		53	5.0				2.4	34.9			
total		301	28.2				4.2	59.4			
Mature adults	769			2.89	0.14	3			0.58	0.32	*k*5
Total K					2.29					4.66	

1 Low density of ladybirds

2 High density of ladybirds

3 lx Number entering stage

4 dx Number dying within stage

Discussion

None of the four populations were stable in terms of the numbers of adult scales over the generation studied, with three populations decreasing and one increasing. However, as discussed in Section 2.4, an assessment of population changes needs to take into account both the number of adults and the change in egg production. At Willetts's orchard, there were 7.7 times more scale per branch in 1993 than in 1992. This coincided with a reduction in mean size of scale between years (Section 2.4), which meant that they produced 2.2 times as many eggs. In contrast, at both orchards where ladybirds were abundant, virtually no scale survived to reproduce. At Fiske's orchard the number of scales decreased between the 1992/93 and 1993/94 seasons but the average size was similar because larger scales were predated in the latter season. Consequently, egg production declined even though few ladybirds were present.

The mortality of SWS eggs was high in 1993 compared with 1992, which was similar to the mortality measured by Beattie (1988) in Australia. Predation by mites appeared to be the main mortality factor (Section 2.4). At all four orchards there was a high mortality of crawlers. Similar losses were recorded for the same scale species by Beattie (1988). Scale crawlers are especially susceptible to adverse environmental conditions. For example, *Icerya seychellarum* Westwood crawlers had a mean survival of three days under sheltered conditions, but less than eight hours under exposed conditions (Hill 1980). A temperature of 29^{0}C killed black scale *Saissetia oleae* (Olivier) crawlers within 24 hours and their longevity was reduced at lower temperatures by humidities below 80% (Mendel *et al.* 1984b). Most crawlers of *Ceroplastes brevicauda* Hall settled or died within 24 hours of emergence (Cilliers 1967). Many crawlers probably failed to find a suitable settling site and succumbed to desiccation. Weather during crawler emergence and settlement is likely to be of great importance to the establishment of scale populations.

Crawlers that disappeared may have been predated by ladybirds (Section 4.3), blown off the branches or washed off by rain. Dispersal by wind has been demonstrated in several species of scale (Willard 1976, Hill 1980, Podoler *et al.* 1981, Mendel *et al.* 1984b) including SWS (Hely 1960). The grease traps collected only crawlers which fell downwards. Willard (1976) found that 18% of California red scale *Aonidiella aurantii* (Maskell) crawlers in a lemon grove were dispersed downwards compared with 75% that were blown horizontally and 7% upwards. *Ceroplastes* crawlers are positively phototactic (Cilliers 1967) and this behaviour would draw them to the ends of branches where they were exposed to wind.

Much of the high mortality of first and second instar scale was probably due to weather. All larval stages of SWS are vulnerable to high temperatures (Smith & Ironside 1974, Milne 1981, Hely *et al.* 1982). A further source of mortality was losses occurring during the migration from leaves to wood. Beattie (1988) suggested that a failure to reinsert their mouthparts may constitute much of the undetermined mortality in this stage.

An important difference amongst the orchards was the level of predation of first and second instar scales. Where ladybirds were abundant at the Curtis and Hibbert-Foy orchards, the additional mortality from predation resulted in the overall decrease of these populations. This contrasted with Willetts's orchard where an absence of ladybirds contributed to the increase in the scale population. Compared with crawlers, there was a much greater difference in the *k*-values for first and second instars at the orchards of Curtis and Hibbert-Foy than at Fiske and Willetts. This suggests that predation had a relatively greater effect on these stages than on crawlers. The effect of ladybirds is discussed more extensively in Chapter 4.

The low levels of parasitism of third instar SWS and CWS did not significantly reduce the numbers of this stage. Beattie (1988) similarly found higher levels of disease in SWS than CWS. Disease levels were probably underestimated because some diseased scales were probably included with undetermined mortality. The level of mortality caused by parasites and disease is discussed more fully in Chapter 3. The loss of scale on abscised leaves was a mortality factor found in CWS but not SWS because of the longer period spent on leaves by CWS (Section 2.3).

Adult scales were less vulnerable to adverse environmental conditions than immature stages. Therefore, the presence of effective natural enemies becomes critical if numbers are to be reduced. The absence of parasitism in SWS and the small amount of predation indicated that biological control of adults may be reliant on disease. In the majority of cases where mortality of adult SWS was attributed to predation, a hole had been made through the wax and the body was punctured. This was possibly caused by predatory insect larvae or birds. Cilliers (1967) recorded three species of moth larvae attacking adult SWS. Several bird species including silvereyes *Zosterops lateralis* (Latham) have been observed feeding on SWS (Hely *et al.* 1982). Silvereyes were common on the orchards used in this study, although it was not confirmed whether they were responsible for predating adult scale. Adult CWS have a much harder wax cover than SWS and no predation of this scale was observed.

The method of sampling scale populations adopted in this study and by Beattie (1988) was based on successive counts of scales on the same selected branches with the size of the sample unit determined by growth flushes of the tree. This approach differed slightly from studies of other *Ceroplastes* spp. Itioka & Inoue (1991) similarly took a census of scale from the same branches, but only from several 50 mm long segments. Other studies counted scale on different randomly selected branches on successive occasions either in situ (e.g., Podoler *et al.* 1979, Podoler *et al.* 1981), or from cut samples (e.g., Argov *et al.* 1992). The advantage of counting scales in situ on the same branches is that the same population is sampled each time.

By taking a census of the whole branch (< 2 years old) the fate of virtually an entire cohort was determined. Samples of scales were taken from wood up to two years old because very few SWS or CWS settled on older twigs (unpubl. data). Itioka & Inoue (1991) similarly found that pink and Indian wax scale preferred to settle on wood under three years old, where their survival was significantly higher than on older wood.

The sampling of scale populations to determine the abundance of different instars and causes of mortality was initially made by randomly cutting branches from trees. However, the highly clumped distribution of the scales (unpubl. data) meant that this method was inefficient and therefore a change was made to selecting branches with a range of scale densities. These two methods were compared by Schneider *et al.* (1988) who found that non-random sampling of high host densities was the most efficient method for determining the percent parasitism, and that the results were consistent with those obtained by random sampling.

2.7 Key factors and density-dependent mortality

Objectives

To identify which mortality factor was most responsible for changes in the populations for which life tables were compiled and to determine whether any factor operated in a density-dependent manner.

Methods

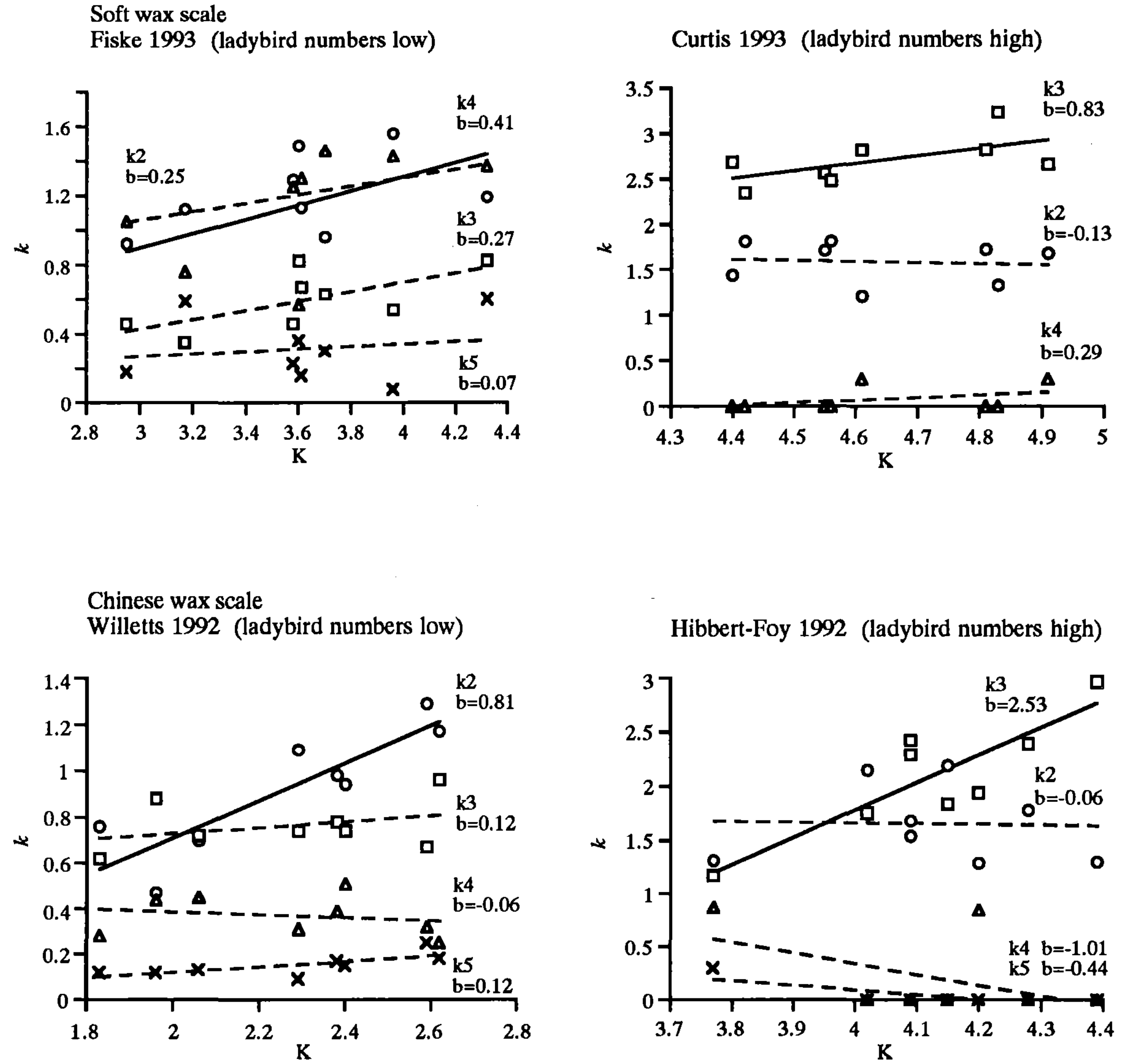
Key-factor analysis compares the contribution of each separate mortality factor to the overall generation mortality (Varley *et al.* 1973). The key factor is the submortality that was most responsible for changes in population density. They were identified by plotting *k*-values (Section 2.6) against the log of total mortality (K) where the *k*-value with the greatest slope (*b*) was the key factor (Podoler & Rogers 1975). Usually data from several successive generations or from several different populations are plotted, however, scales on the different branches at the four orchards used in life tables were treated as being separate populations for this analysis.

The relationship between scale density and major mortality factors was examined by plotting each *k*-value against the log of the density on which it acted (Varley & Gradwell 1960). Direct or inverse density dependence is suggested by a positive or a negative slope respectively. Density-independent factors produce slopes close to $b = 0$. Because *k*-values are derived from the density, the two variables are not independent and the independent variable was subject to sampling errors which invalidates the usual regression analysis (Varley & Gradwell 1968). Instead, proof of density dependence is given if log x+1 plotted against log x and the reverse, produce a significant correlation and both slopes of the regression coefficient are significantly different from $b = 1$ and are on the same side of this line (Varley & Gradwell 1968).

Results

Different key factors were identified from orchards with high and low numbers of ladybirds (Fig. 2.4). Where ladybirds were abundant (Curtis and Hibbert-Foy), mortality of settled first and second instar scale (*k*3) was the key factor. Mortality of adult SWS (*k*4) and the failure of CWS crawlers to settle (*k*2) contributed most to fluctuations in population density at the orchards with few ladybirds.

Figure 2.4 Graphical key factor analysis with *k*-values (*k*) plotted against total generation mortality (K), for populations of soft and Chinese wax scale. *k*2: crawlers, *k*3: settled first and second instars, *k*4: third instars, *k*5: adults.



A positive relationship suggesting direct density dependence between *k*-values and density were found only for *k*2 at the orchards of Fiske and Willetts (Fig. 2.5). The positive linear relationship (except on two branches) for *k*3 at Curtis's and Hibbert-Foy's orchards resulted from the extinction of the populations on those branches, therefore the *k*-value equalled the density. There were no significant correlations between the log of the number of first instars and the log of the number of crawlers at Fiske's and Willetts's orchards (Fig. 2.6). Therefore, the indication of density dependence for *k*2 at these orchards was not proven.

Figure 2.5 Density-dependent relationships for *k2*: crawlers, *k3*: settled first and second instars, *k4*: third instars, and *k5*: adults, of four populations of wax scales.

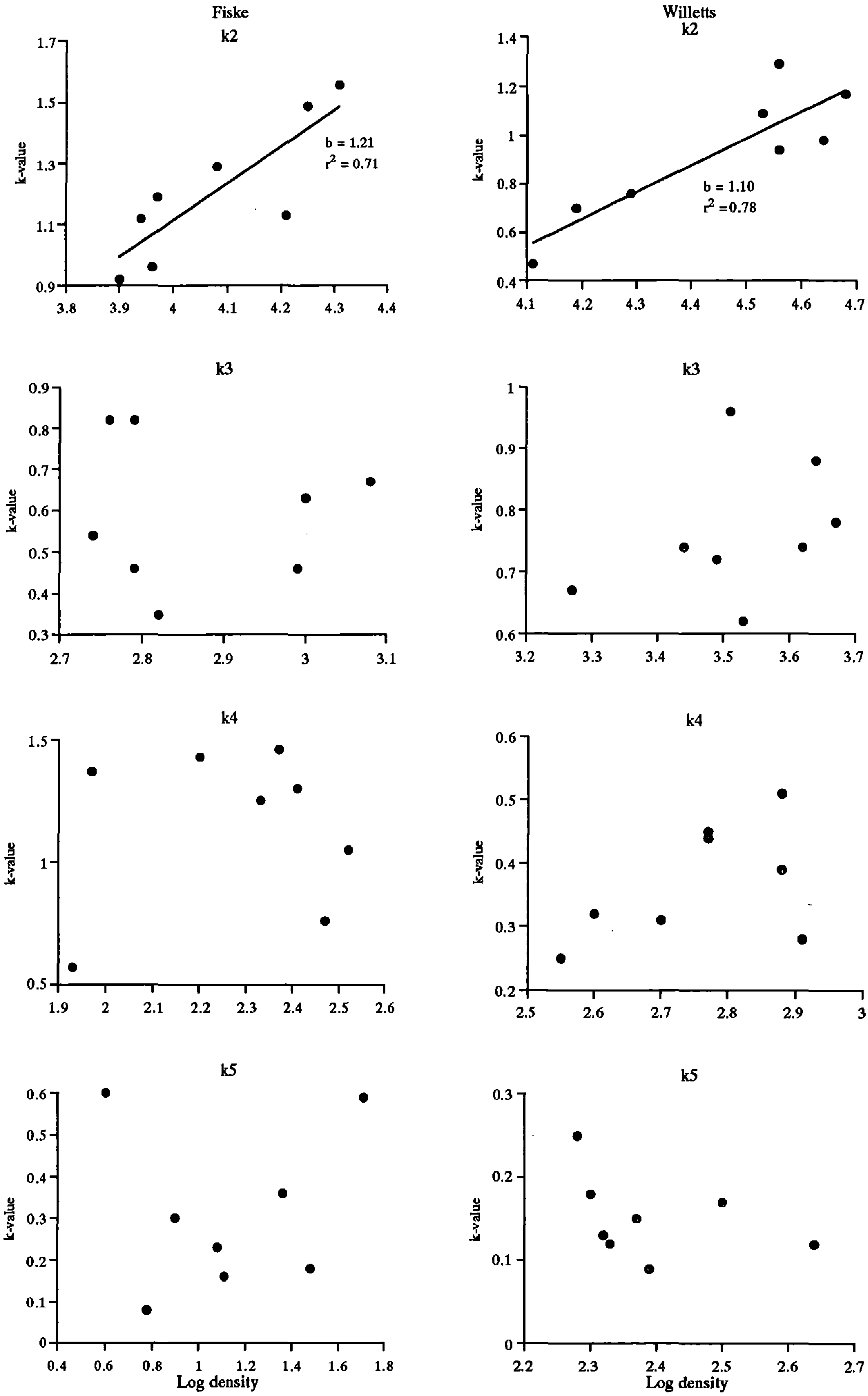


Figure 2.5 continued

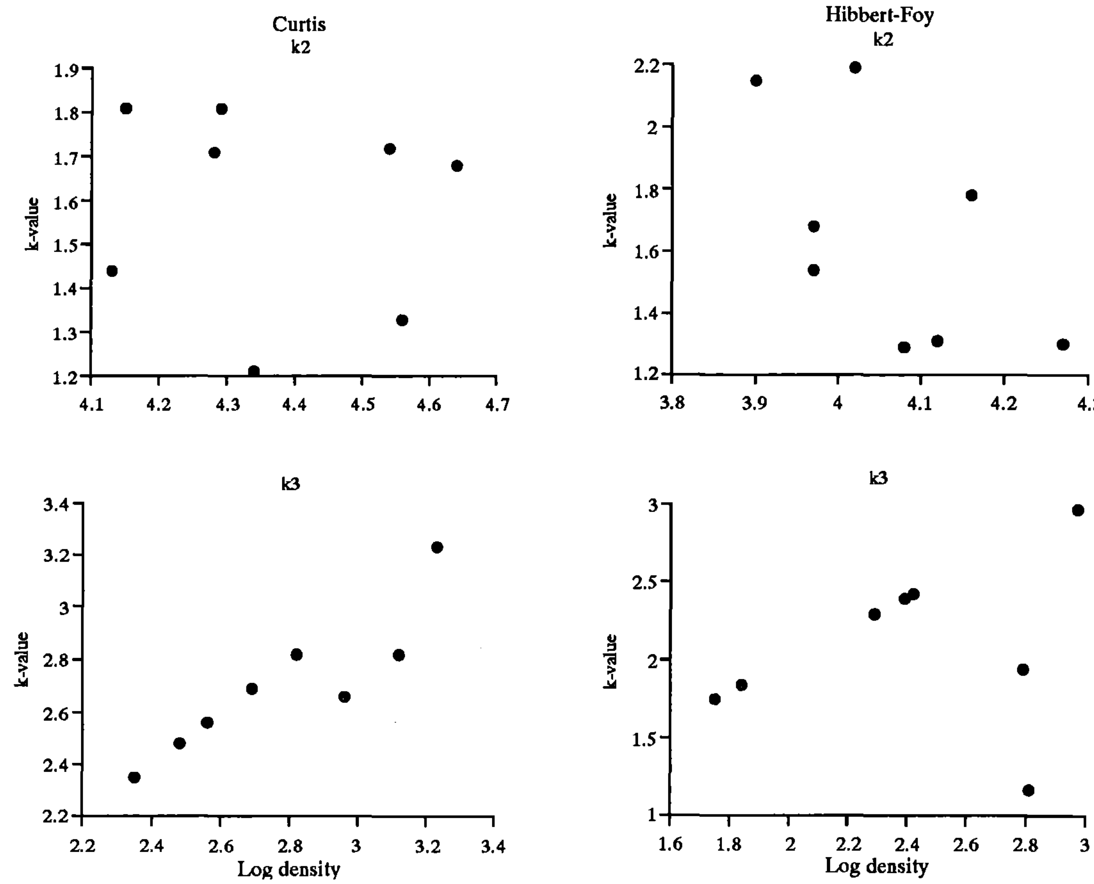
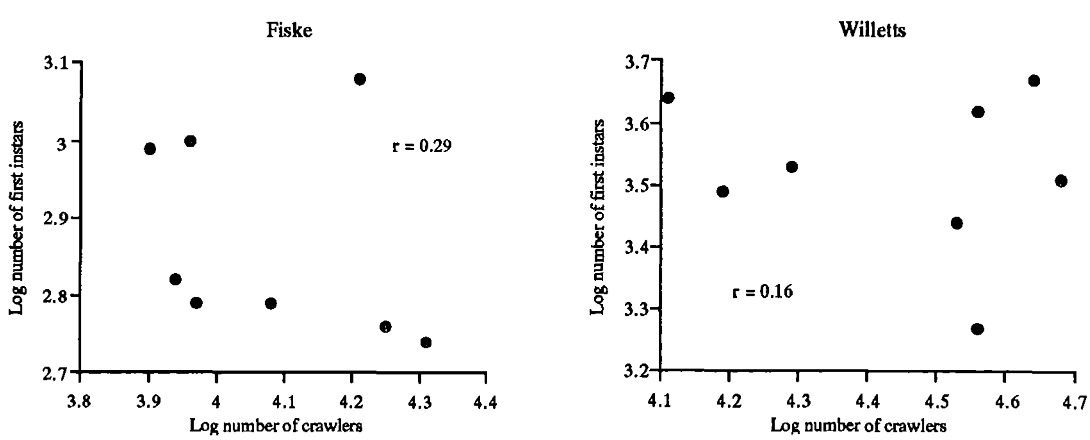


Figure 2.6 Plot of log number of crawlers against log number of first instars to test for proof of a density-dependent relationship for k2 (crawler mortality).



Discussion

Natural enemies, particularly predators and parasites were the most common key factors in 49 entomological studies reviewed by Stiling (1988). The identification of the same key factor on the two orchards with high numbers of ladybirds, and different key factors where there were few ladybirds, provided good evidence that these predators were contributing to a reduction in scale populations. Key factor mortality for Florida wax scale occurred in first and second instar larvae and pre-ovipositional adult females (Schneider *et al.* 1987, Argov *et al.* 1992). Mortality of first and second instar Florida wax scale was mainly due to climatic factors and predation by *Chilocorus bipustulatus* (L.), whereas young females were subject to mortality from several parasitoids (Podoler *et al.* 1981).

The determination of whether a natural enemy is acting in a directly density-dependent manner is important because this demonstrates its potential to regulate a pest population around some equilibrium density (DeBach & Rosen 1991). In this study, however, density-dependent mortality was not confirmed. One reason was that populations of scale on individual branches at Curtis's and Hibbert-Foy's orchards were reduced to extinction irrespective of their density. Schneider *et al.* (1987) and Argov *et al.* (1992) similarly failed to detect density-dependent mortality operating on Florida wax scale in Israel. Life table studies are usually conducted over several generations, but in this study data were available for only one generation from each of four populations. Increasing the number of generations studied increases the likelihood of finding density-dependent mortality (Hassell *et al.* 1989).

2.8 Summary

- The population dynamics of SWS and CWS were studied through regular destructive sampling of leaves and wood, and repeated non-destructive counts of scale cohorts.
- SWS was more abundant than CWS around Kerikeri, but was absent from Whangarei.
- CWS was more widespread than SWS, but it rarely reached densities that caused sooty mould contamination of fruit.
- Both species were univoltine.

- Egg hatching began about two months earlier in SWS than in CWS, and the development of successive instars of SWS remained a similar period ahead of CWS.
- The starting date of SWS crawler emergence varied by about seven weeks over six years, and corresponded with the accumulated number of degree-days.
- First and second instar SWS were present for approximately three months compared with eight months for CWS.
- There was a linear relationship between body size and fecundity for both species.
- Total egg production per branch was a function of mean scale size and of scale density, both of which varied widely amongst orchards.
- Survivorship curves and life tables of scale populations were compared between orchards with high and low numbers of ladybirds.
- There was a high mortality of crawlers at both groups of orchards, which was largely due to adverse environmental conditions.
- On orchards with abundant ladybirds, predation combined with weather meant that few scales survived to the third instar stage and mortality of first and second instar scale was the key factor.
- In contrast, where few ladybirds were present sufficient scale survived to produce breeding adults.
- Disease was a major mortality factor in third instar and adult SWS, whereas parasitism was more important in CWS.
- A density-dependent mortality factor that regulated scale populations was not demonstrated.

Chapter 3 PARASITOIDS AND DISEASE OF SOFT AND CHINESE WAX SCALE

3.1 Introduction

SWS in its native South Africa rarely reaches densities where it becomes a pest (Snowball 1969). This contrasts with the present situation in New Zealand and its former status in Australia. In South Africa, SWS is attacked by over 20 hymenopteran parasitoids from the superfamily Chalcidoidea, and the predacious larvae of three moths (Cilliers 1967, Snowball 1969). CWS is attacked by several chalcidoids in Australia (Snowball 1970, Sands 1984), although they have little impact on its abundance (Snowball 1970).

In Australia, SWS was a major pest of citrus prior to the early 1970's (Hely *et al.* 1982, Smith & Papacek 1985). Seven species of parasitic Hymenoptera and a predatory moth were introduced to Australia to control SWS between 1968 and 1973 (Sands *et al.* 1986). The establishment of two encyrtids, in particular *Paraceraptrocerus nyasicus* (Compere) and *Anicetus communis* (Annecke), is believed to have been responsible for reducing densities of SWS to the extent that it has since been uncommon or only a minor pest (Smith & Papacek 1985, Sands *et al.* 1986).

Pathogenic microorganisms are another potentially important natural enemy of scale insects. The biological control potential of entomopathogenic fungi has been recognised for over a century, and the search for alternatives to chemical pesticides has led to renewed interest in microbial pathogens. For example, the fungus *Verticillium lecanii* (Zimmermann) Viegas causes epizootics amongst scales and aphids in tropical and sub-tropical regions, and two strains have been developed into commercial insecticides against aphids and whiteflies (Hall 1981).

It is necessary to assess the levels of parasitism and disease existing in New Zealand populations of wax scales, before strategies of IPM such as the introduction of parasites can be considered. Scale insects have several advantages that enable the generational level of parasitism (or disease) to be determined relatively easily (Van Driesche 1983). Since they are largely sessile and leave evidence of past mortality, unparasitised hosts that develop to the next instar and parasitised scales from which parasites have emerged, do not disappear from the sample population and can be incorporated in calculations of the level of parasitism. A further advantage is the lack of bias in sampling parasitised or unparasitised insects. Behavioural differences between parasitised and unparasitised scale, which could affect sample percentage parasitism values, do not occur as in other insects.

Predators were identified in Chapter 2 as being important natural enemies of wax scales. Research in this chapter was concerned with identifying parasitoids (Section 3.2) and pathogens (Section 3.3), and determining their levels of mortality and whether they showed density dependence (Section 3.4). Results are discussed in Section 3.5.

3.2 Parasitoids

Objectives

To identify the parasitoids of SWS and CWS and determine their phenology.

Methods

Parasitoids were collected from SWS and CWS that were sampled while gathering data on population dynamics (Section 2.3). Scales were examined under a stereomicroscope and parasitoids could be observed through the ventral body surface. Parasitoid larvae were white and pupae were black or brown. Adult parasitoids emerged from the dorsal surface leaving a circular hole. Small parasitoid larvae could not be detected externally, but where a parasitoid was suspected from the dull appearance of the wax covering, the scale was dissected. Parasitised scales were removed from twigs and leaves and incubated in vials at 23^{0}C. Adult parasitoids were collected as they emerged. Parasitoids were identified by J. Berry (Landcare Research, Auckland, N.Z.). The proportion of each parasitoid species and male and female parasitoids was compared between seasons for SWS and CWS by Chi-square tests. The phenology of parasitoids with respect to each scale species is expressed graphically.

Parasitised scales were randomly selected to determine the scale instar. Scales were prepared for slide mounting using a technique developed for armoured scale (Lo & Blank 1989), which was based on a procedure described by Sandlant (1978). Scales were placed in Essig's fluid, stained with acid fuchsin and heated for 1-2 min in a microwave oven. Instars were identified from the number of spiracular setae, following Cilliers (1967) and Pollet (1972), for SWS and CWS respectively.

Results

Two species of hymenopteran parasitoids, *Euxanthellus philippiae* Silvestri (Aphelinidae) and *Coccidoctonus dubius* (Girault) (Encyrtidae) were recorded from SWS and CWS (Table 3.1, Appendix 7). In 1992 and 1993 when samples were collected for the whole season, approximately 23% of the parasitoids were *C. dubius* in both SWS and CWS. The seasonal proportions of the two parasitoids differed in both SWS ($\chi^2 = 43.8$, df=3, $P < 0.001$) and CWS ($\chi^2 = 242.7$, df=3, $P < 0.001$). In SWS, 1.2% of the *E. philippiae* were males compared with 10.3% in CWS ($\chi^2 = 41.0$, df=1, $P < 0.001$). The percentage of male *E. philippiae* in CWS increased from winter (2.4%), through spring (10.5%), to summer (22.0%) and autumn (18.6%) ($\chi^2 = 54.1$, df=3, $P < 0.001$). Two specimens of an unidentified parasitoid were also found in CWS.

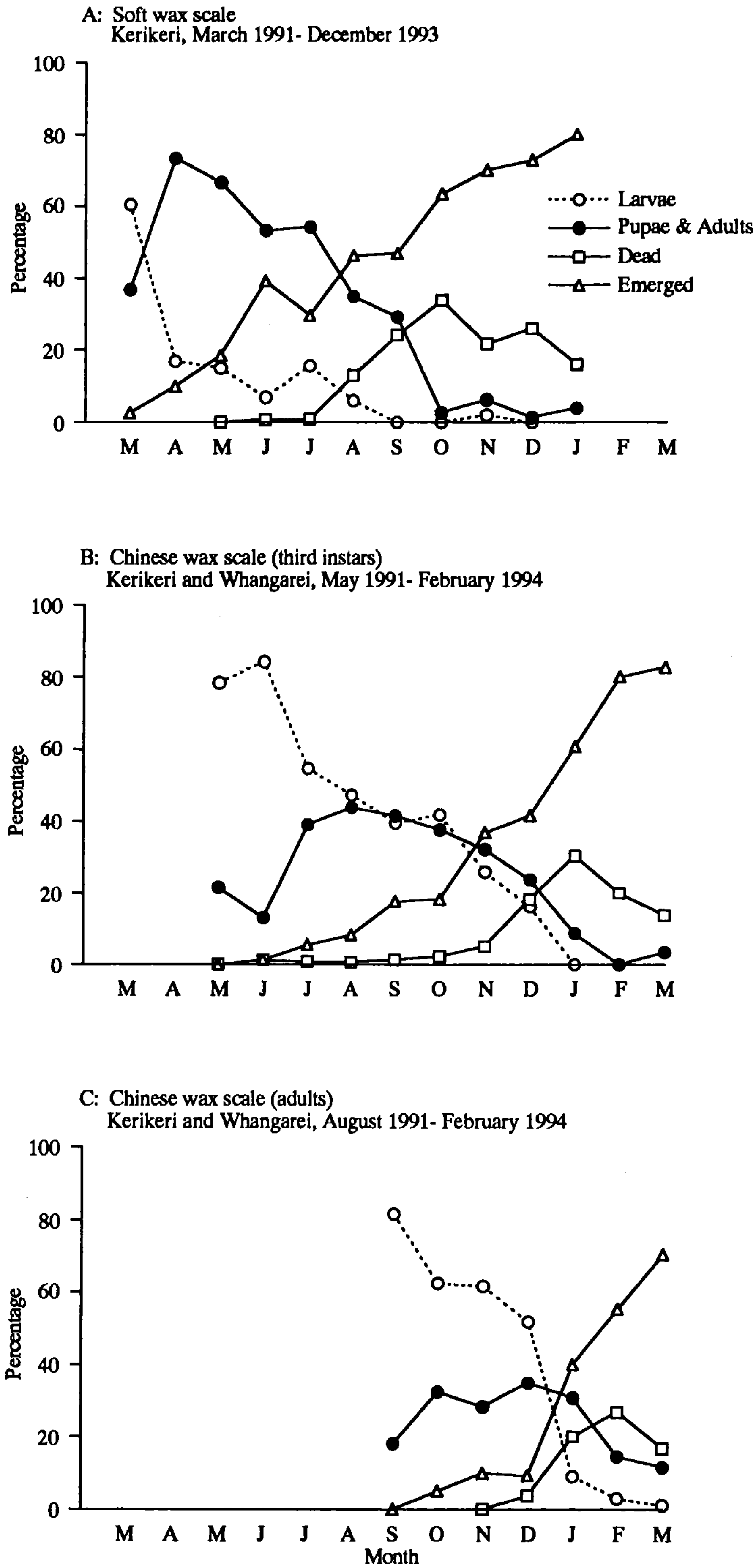
Table 3.1 Number of parasitoids and percentage of each species in soft and Chinese wax scales collected in Northland, March 1991-February 1994.

Scale			% parasitoid species	
Species	Sampled	n	*E. philippiae*	*C. dubius*
Soft	Mar-May	234	82.5	17.5
	Jun-Aug	372	59.4	40.6
	Sep-Nov	102	79.4	20.6
	Dec-Feb	24	83.3	16.7
	Total	732		
Chinese	Jun-Aug	342	98.5	1.5
	Sep-Nov	642	92.4	7.6
	Dec-Feb	292	63.7	36.3
	Mar-May	78	55.1	44.9
	Total	1354		

Both third instar and adult CWS were parasitised. Out of 226 parasitised scale, 178 were third instars and 48 were adults. In contrast, out of 220 parasitised SWS, there were 218 third instars and 2 adults.

In SWS, the great majority of live parasitoids were found in samples from March to September (Fig. 3.1a, Appendix 8). By August, over 50% of live parasitoids had emerged, and this increased to 96% in October. In third instar CWS, parasitoid larvae were common from May until November (Fig. 3.1b, Appendix 9). The proportion of emerged parasitoids increased throughout these months as in SWS, and few live parasitoids remained after December. In adult CWS (Fig. 3.1c, Appendix 9), few live parasitoids were present after January, when the majority had emerged.

Figure 3.1 Monthly percentage of parasitoid stages in soft and Chinese wax scales.



3.3 Disease

Objective

To identify and determine the incidence of pathogenic microorganisms in SWS and CWS.

Methods

Branches with high densities of scales were selectively cut from five Kerikeri orchards in August 1991, and May and August 1992. The scales were examined under a stereomicroscope and collected into separate vials based on the following four categories: Healthy - scales with a normal reddish-pink colour; Unhealthy - body an abnormal yellow colour; Diseased - white fungal hyphae present around the base and underside of the body which was yellow or brown; Dead - body brown and dry but hyphae not evident.

Scales were kept in a refrigerator for up to a week until they were processed. The scales were plated out in a laminar flow cabinet. They were dipped in a 20% sodium hypochlorite (Janola) solution for 1 min to sterilise their outer surfaces, and then washed in distilled water to remove the bleach. Scales were transferred to potato dextrose agar plates with five scales per plate. The plates were sealed and incubated at 20^0 C in a 12 h light:dark cycle for three weeks. Fungi were identified by H. Goh (HortResearch, Ruakura, N.Z.).

Results

Two pathogenic fungi *Verticillium lecanii* and *Fusarium* spp. were identified from both SWS and CWS (Table 3.2). *V. lecanii* was not isolated from any 'healthy' scales but some had *Fusarium* spp. present. The status of the 'unhealthy' and 'diseased' scale categories was confirmed by the culture of fungi from a large percentage of these specimens. Fungal colonies were grown from half of the dead scale. A few scales had both types of fungi present.

Table 3.2 Percentages of soft and Chinese wax scale infected with pathogenic fungi.

Scale		n	*Verticillium lecanii* (%)	*Fusarium* spp. (%)	Total diseased (%)
Species	Category				
Soft	Healthy	61	0	26.2	26.2
	Unhealthy	134	26.1	43.3	69.4
	Diseased	151	75.5	21.2	92.1
	Dead	98	13.3	40.8	50.0
Chinese	Diseased	24	70.8	8.3	75.0

3.4 Levels of mortality and density dependence

Objectives

To measure the levels of mortality caused by parasitoids and diseases in populations of SWS and CWS, and to determine whether there was a relationship between these mortality factors and scale density.

Methods

The cause of death in samples of scale collected from leaves and wood (Section 2.3) was identified where possible. Identification procedures are described in Sections 3.2 and 3.3. Data for predation of adult SWS and unidentified mortality are also presented here for completeness. Some adult SWS had been pierced, leaving a hole through the wax and puncturing the body, or the body had been removed leaving a ring of wax. This was attributed to predation. If the cause of death could not be determined, the mortality factor was recorded as 'unknown'. The percentage mortality was calculated separately for third instar and adult scales. The number of third instars assessed included adult scales since these had successfully passed through the third instar stage. The individual percentage mortalities from different orchards were averaged for each season. The overall percentage mortality for each factor in each month was the mean of three seasons' (1991-1993) data.

Because the percentage mortalities on leaves and wood were different for CWS, to calculate the overall mortality each month, the percentages were weighted according to the proportion of scale on each substrate (Appendix 10). These proportions were estimated from counts of scale on labelled branches (Section 2.5) and from samples of leaves and wood (Section 2.3).

Mortality from parasitism and disease was examined for density dependence by correlating the percentage mortality for each factor against scale density on individual branches (Varley *et al.* 1973). This was examined for five populations of SWS and two of CWS sampled in the 1992 and 1993 seasons. The density was calculated by dividing the total number of scale by the area of wood on the branch. Each twig was assumed to have the area of a cylinder with a diameter measured at the mid point of the growth flush. The areas of the two growth flushes were calculated separately and added together for each branch.

Results

In SWS populations, disease was the main identifiable cause of mortality, particularly for adults (Fig. 3.2, Appendix 11). Parasitism was low in third instars and not recorded from adult scale. In third instars, however, the cause of death of most scales could not be identified. A small percentage of adults was predated. In contrast, parasitism was more important than disease in CWS, especially in adults (Fig. 3.3, Appendix 12). The levels of disease were similar for both third instar and adult CWS.

The correlations between scale density and the percentages of parasitised and diseased scale produced coefficients within $r \pm 0.3$ except for two populations (Table 3.3). There were no significant positive correlations at the 5% level for either parasitism or disease. The only significant negative correlation was for parasitism of CWS at Fiske's orchard in 1992/93.

Table 3.3 Correlation coefficients (r) for relationships between scale density and the percentages of parasitised and diseased scale on individual branches. * = $P < 0.001$

Orchard	Year	Parasitism		Disease	
		n	r	n	r
Soft wax scale					
Curtis	1992	62	-0.23	62	0.10
	1993	66	-0.17	76	0.01
Fiske	1992	24	0	24	-0.25
	1993	60	0.16	60	-0.13
Hellberg	1992	0	-	35	0.22
Ritchie	1992	71	-0.04	71	0.05
Strang	1992	100	-0.07	81	0.05
Chinese wax scale					
Fiske	1992/93	42	-0.59*	42	0.02
	1993/94	46	-0.26	66	-0.04
Willetts	1992/93	16	-0.41	0	-
	1993/94	15	-0.17	40	-0.12

Figure 3.2 Mean percentage mortality of soft wax scale, November 1990-December 1993.

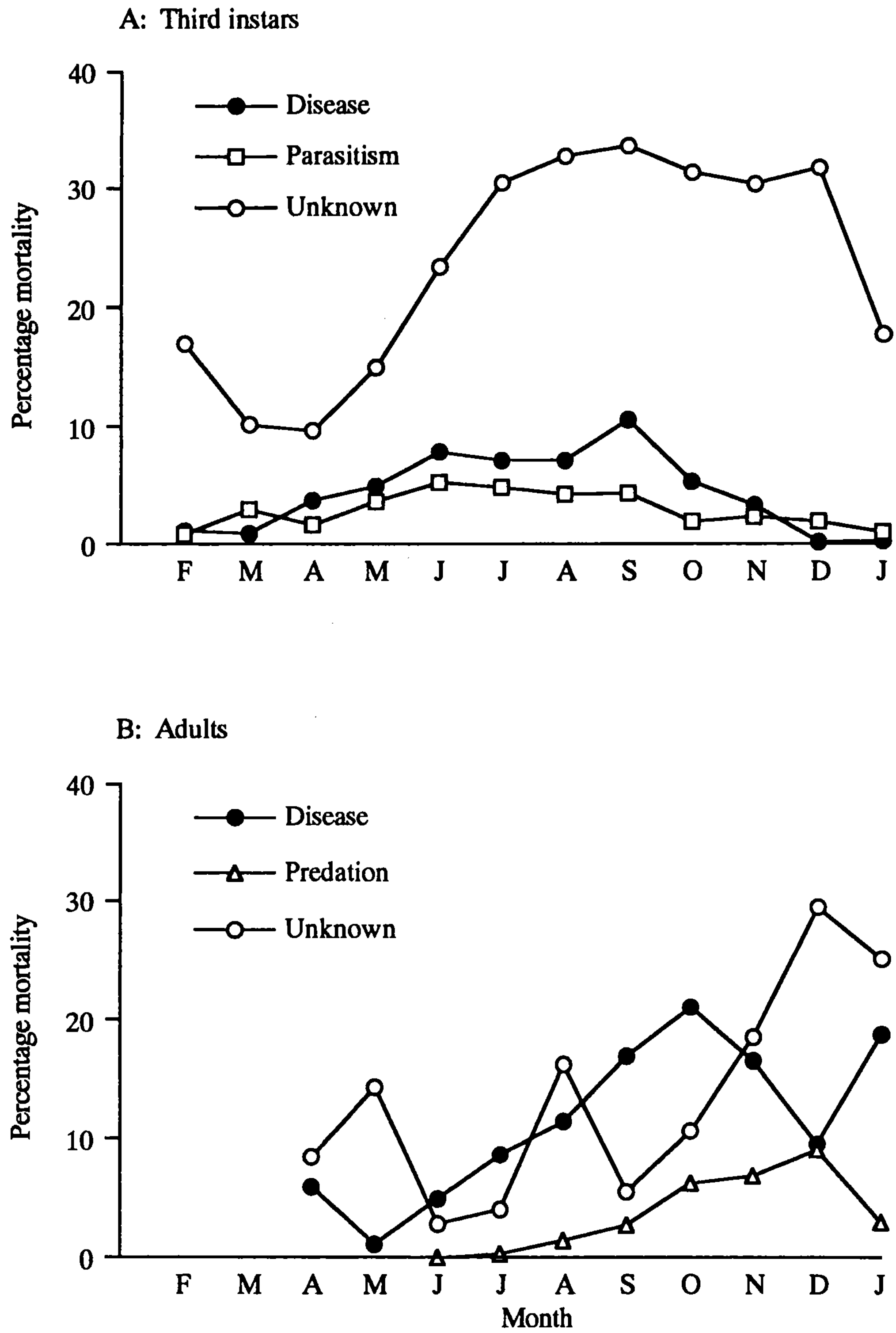
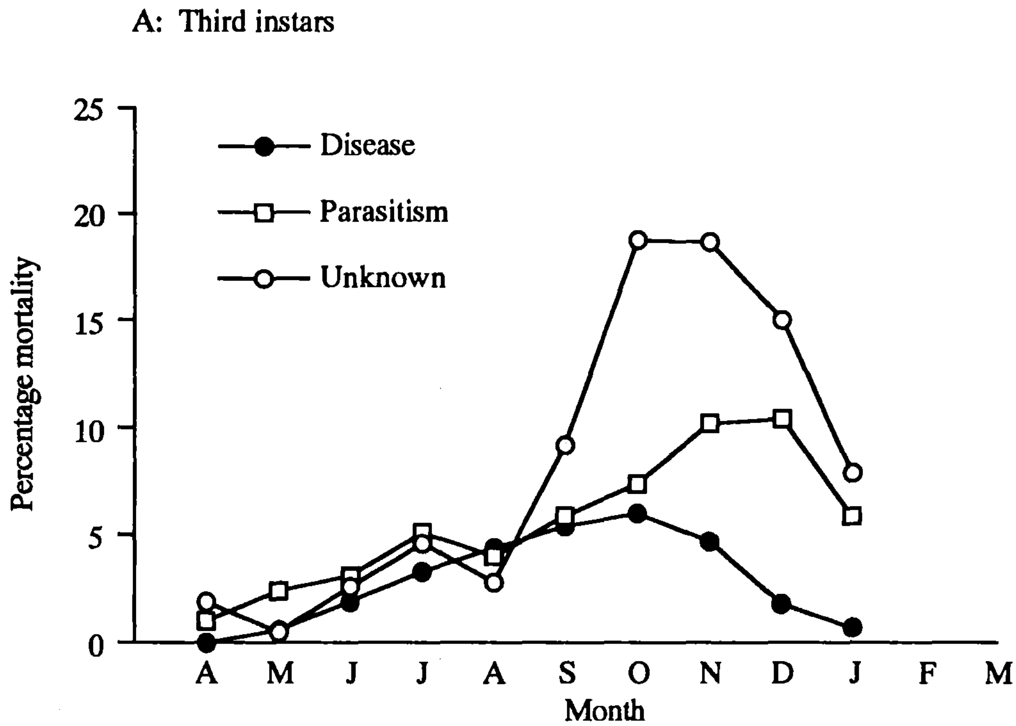
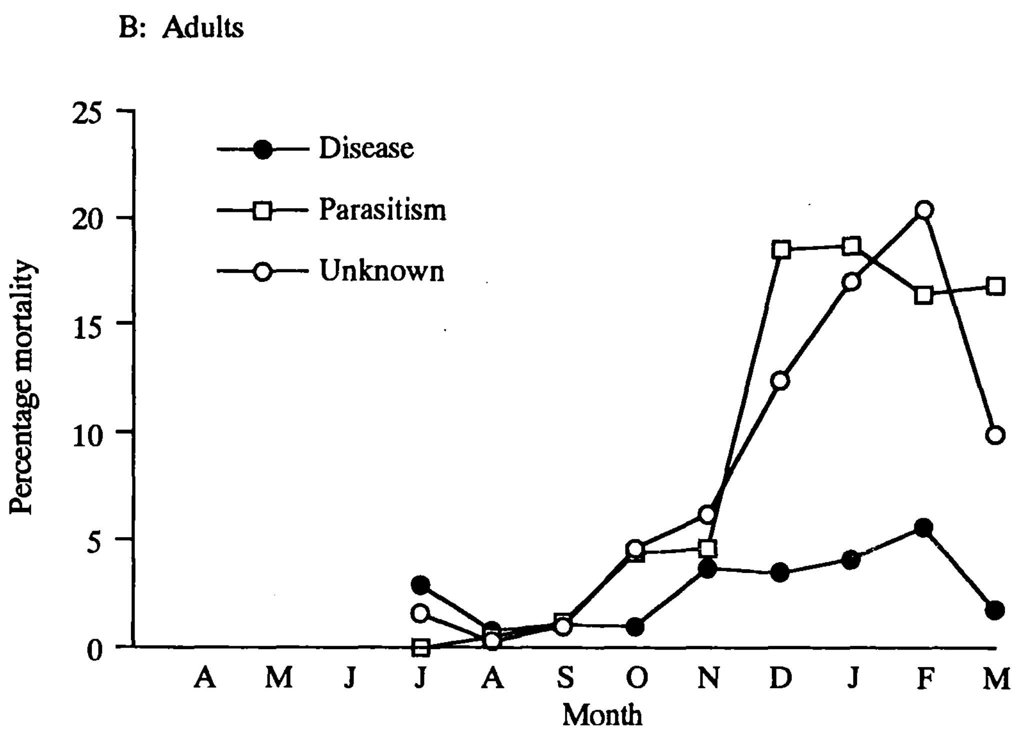


Figure 3.3 Mean percentage mortality of Chinese wax scale, April 1991-February 1994.





3.5 Discussion

E. philippiae appears to have been a fortuitous arrival in New Zealand with its coccid hosts, since there is no record of it having been introduced. It parasitises several coccids besides SWS and CWS, including black scale and soft brown scale (*Coccus hesperidum* L.) (Valentine & Walker 1991). These latter two species were also present on citrus orchards, and may be useful as alternative hosts when suitable stages of SWS and CWS are absent. SWS in South Africa is parasitised by *E. philippiae* and *E. adustus* (Annecke & Prinsloo 1976). The finding that *E. philippiae* almost exclusively parasitises third instar SWS contrasts with Sands *et al.* (1986) who recorded only adult scales being attacked.

Several genera of Aphelinidae, including *Euxanthellus*, are highly unusual because the sexes have a divergent ontogeny (Doutt 1959, Noyes & Valentine 1989). Unmated females oviposit only hyperparasitically in an insect already parasitised by the same or similar species, and these eggs develop into males (Doutt 1959). Diploid eggs that develop into females are laid in immature and adult stages of various Homoptera. Consequently, female *E. philippiae* are primary endoparasitoids, while males are secondary ectoparasitoids of primary endoparasitic hymenopterous larvae, including the larvae of their own species (Valentine & Walker 1991).

C. dubius is native to Australia (Noyes 1988) and was introduced to New Zealand in the mistaken belief that it was a primary parasitoid of black scale (Valentine 1967). It is actually a secondary parasitoid of *E. philippiae* and other chalcidoids (Valentine & Walker 1991). In this study some male *E. philippiae* were reared from the pupae of *C. dubius*, which would make them secondary and tertiary parasitoids. The hyperparasitic biology of *C. dubius* and male *E. philippiae* means that they tended to emerge after female *E. philippiae* (unpubl. data). This may explain their increasing proportions in CWS later in the season. Another Aphelinid parasitoid *Encarsia citrina* (Craw) has also been recorded from CWS in New Zealand (Noyes & Valentine 1989), but it principally parasitises armoured scales and was not found in this study.

Van Driesche (1983) discussed models where the peak percentage parasitism for a series of samples could be lower than, the same as, or higher than the generational percent parasitism, depending on the respective phenologies of hosts and parasitoids. In this study, the peak percentage parasitism was used as an estimate of the generational level of parasitism because the recruitment of hosts into the susceptible stage had finished, while the development of scales and emergence of parasitoids were accounted for in samples. At the times of peak percent parasitism, a small proportion (<10%) of parasitoids was still in the larval stage. Since there is a delay between parasitoid oviposition and the development of larvae to a size that could be detected, the peak percentage parasitism from the monthly samples probably slightly underestimated the generational levels of parasitism.

The levels of parasitism of both SWS and CWS were generally lower in this study, than those observed in other *Ceroplastes* species. In Australia, Beattie (1988) recorded parasitism levels of over 60% in SWS, which is consistent with the importance placed on parasitoids in reducing SWS populations by Milne (1981) and Sands *et al.* (1986). Peak parasitism levels of up to 70-80% in pink wax scale (Smith 1986) and 80% in Florida wax scale (Argov *et al.* 1992) were considered to make a significant contribution to reducing populations of these species. Parasitism was regarded as a minor mortality factor in two other studies of Florida wax scale where peak parasitism levels reached approximately 30-50% (Podoler *et al.* 1981, Schneider *et al.* 1988).

This study showed that more CWS than SWS were parasitised by *E. philippiae*. Several factors could account for the different rates of parasitism. Both third instar and adult CWS were parasitised, whereas parasitism of SWS was virtually restricted to third instars. The asynchronous phenologies of SWS and CWS (Section 2.3) may have favoured parasitism of CWS because from autumn to spring when parasitoids emerged from SWS, there were third instar and adult CWS available to be parasitised. In contrast, most parasitoids emerged from CWS during spring and summer when the great majority of SWS were adults or first and second instars, and not vulnerable to *E. philippiae*. By February, when the next generation of third instar SWS had developed, few *E. philippiae* were still emerging from CWS. *E. philippiae* may also have preferred CWS to SWS as a host but this was not examined here.

As discussed in Chapter 2, mortality factors which act in a directly density-dependent way have the potential to regulate the host population. However, the incidence of both parasitism and disease were highly variable at all scale densities. Neither increased with increasing scale densities and in fact parasitism tended to have an inverse correlation with density. An inverse relationship could arise if the parasitoid laid a similar number of eggs per branch irrespective of scale density. Schneider *et al.* (1988) and Itioka & Inoue (1991) similarly failed to demonstrate density dependence between percentage parasitism and the density of Florida wax scale, and pink and Indian wax scale respectively.

The two fungal entomopathogens found in SWS and CWS are commonly found in several insect orders. *V. lecanii* is a cosmopolitan organism that is most frequently recorded from scale insects and aphids (Hall 1981). It has successfully controlled these insects outdoors in tropical and sub-tropical regions, but in temperate climates, large reductions of insect populations due to *V. lecanii* have generally occurred only inside greenhouses where high levels of humidity can be maintained (Hall 1981). Russo *et al.* (1989) demonstrated on orange trees in Sicily, that *V. lecanii* was an effective biological control agent of black scale, but epidemic infections occurred only with high moisture levels and high scale densities. *V. lecanii* requires a relative humidity of over 90% for germination and disease transmission (Gillespie 1988).

The level of disease reached 60% in one sample of adult SWS, but was highly variable all scale densities. The average relative humidity at Kerikeri and Whangarei varies between 70-90% during the year (Anon. 1973), so epidemic levels of infection may only occur during a prolonged period of warm moist conditions. The greater incidence of disease in SWS than CWS may have been at least partly due to the moist consistency of the wax of SWS. This may have provided a higher level of humidity than the drier wax of CWS. The incidence of *V. lecanii* and *Fusarium* spp. cultured from 'dead' and 'unhealthy' scale showed some of the "unknown" mortality was due to disease. Therefore the level of mortality caused by pathogens was underestimated. Moribund scales can remain attached to branches for several months and as the interval between death and sampling increased, it became more difficult to distinguish accurately scales that appeared to have been killed by disease.

3.6 Summary

- This chapter identified the agents responsible for parasitism and disease of soft and Chinese wax scale and assessed their resulting levels of scale mortality.
- Two hymenopteran parasitoids, one primary (*Euxanthellus philippiae*) and one secondary (*Coccidoctonus dubius*), were found in both soft and Chinese wax scale.
- *E. philippiae* attacked third instar and adult Chinese wax scale, but only third instar soft wax scale.
- Two fungal pathogens (*Verticillium lecanii* and *Fusarium* spp.) were identified from both soft and Chinese wax scale.
- The culturing of fungi from 'unhealthy' and dead scales showed that the levels of disease were underestimated.
- Disease was an important mortality factor of soft wax scale, whereas parasitism contributed little to reducing numbers of, .
- Chinese wax scale had a higher level of parasitism than soft wax scale, whereas the opposite applied to diseases.
- There was no evidence that mortality from parasitism or disease acted in a directly density-dependent manner on either SWS or CWS.

Chapter 4 IMPACT OF PREDATION BY LADYBIRDS, PARTICULARLY THE STEELBLUE LADYBIRD, ON SCALE POPULATIONS

4.1 Introduction

Ladybirds have been successfully used as biological control agents of scale insects around the world (Drea & Gordon 1990). Their potential has been recognised since the successful introduction a century ago of the vedalia ladybird *Rodolia cardinalis* (Mulsant) against cottony cushion scale *Icerya purchasi* Maskell on citrus in California (Doutt 1964).

Six ladybird species have been recorded predating SWS in Australia (Smith 1970, Beattie 1988). Five of these species were imported to New Zealand as predators for other scales, mealy bugs and aphids (Cameron *et al.* 1987). Three species, *Halmus chalybeus* (Boisduval) (steelblue ladybird, SBL) (Fig. 4.1), *Cryptolaemus montrouzieri* Mulsant and *Rhyzobius forestieri* (Mulsant) became established (Cameron *et al.* 1987).

Australian studies of SWS and CWS have produced conflicting statements on the importance of ladybirds in controlling these pests. Smith (1970) and Snowball (1972) reported that the SBL was an important predator of SWS, without indicating the level of control exerted by this species. Hely *et al.* (1982) stated that predators reduced, but did not control, SWS populations. However, they also attributed a resurgence in SWS populations following insecticide applications to the elimination of ladybirds. In contrast, Beattie (1988) regarded coccinellids as having no influence on the population dynamics of SWS or CWS.

The analysis of scale insect life tables (Section 2.6) indicated that predation by ladybirds was more important than parasitism or disease in reducing scale populations. However, a weakness of life table studies is that they cannot distinguish between cause and effect. Only the experimental evaluation of biological control can demonstrate the efficacy of natural enemies, especially when supplemented by other methods such as population sampling (Luck *et al.* 1988, DeBach & Rosen 1991).

Figure 4.1 Larval and adult (4 mm long) steelblue ladybirds feeding on first and second instar Chinese wax scales.

The objective of research described in this chapter was to measure, by population sampling and experimentally, the impact of ladybirds and SBL in particular, on populations of SWS and CWS. Seasonal changes in ladybird populations were monitored on orchards (Section 4.2), and their abundance compared with densities of scale populations (Section 4.4). Experiments were conducted to determine which scale instars were vulnerable to ladybirds (Section 4.3), the feeding rate of ladybirds (Section 4.5) and the reduction in scale populations from different ladybird densities (Section 4.6).

4.2 Ladybird species and their seasonal abundance

Objectives

To identify the species of ladybirds on orchards, monitor their seasonal abundance and compare two methods of assessing ladybird populations.

Methods

The number of ladybirds was assessed by searching trees while walking slowly through an orchard block. The foliage was not disturbed. Because trees differed in size, they were searched at a constant speed instead of walking over a fixed distance. Approximately 20 trees per block were assessed. All stages and species seen in 10 min were recorded. Counts were made only on fine days between 0900-1900 hours.

Three unsprayed blocks in Kerikeri were visited regularly to assess seasonal changes in coccinellid populations. Intervals between visits varied from 1-3 weeks between December and April, when ladybirds were abundant, up to several months at other times. Monthly changes in ladybird numbers were plotted with counts made in the same month averaged. Occasional counts of ladybirds were made in a similar manner on another 12 orchards around Kerikeri and Whangarei.

Manual searches for ladybirds were made on three occasions at two orchards to compare the numbers and stages recorded by visual searches. In manual searches, leaves and branches throughout whole or half trees were examined closely with the aim of finding all ladybird stages present. The amount of time spent searching varied between about 40-80 min per tree, depending on the size and denseness of trees and on the number of ladybirds present. Searches were repeated up to four times over three weeks where necessary to remove all the ladybirds. The trees were covered (Section 4.6) between searches to prevent re-invasion. Manual and visual searches were conducted at the same time to allow direct comparisons. At Hendl's orchard, 18 of the same trees that were manually searched, were scanned for 1 min per tree. The visual searches at Curtis's orchard were based on examining 20 trees in the same block for a total of 10 min.

<u>Results</u>

Seven ladybird species were recorded by visual and manual searches, but the SBL was the dominant species at all orchards and throughout the year (Appendix 13). They comprised 98.1% of the total number and were followed by *R. forestieri* (1.5%), *R. cardinalis* (0.2%) and *C. montrouzieri* (0.2%).

Ladybirds were found by visual searches throughout the year, being most abundant on the 15 orchards assessed between January and May, and least numerous in winter (Appendix 13). The highest numbers recorded in visual searches at three orchards with SWS occurred in January (Rhodes in 1991 and Curtis in 1992/93), and March (Strang in 1991) (Fig 4.2). Adult ladybirds were the most common stage found, with the highest proportion of larvae and pupae recorded during December and January (Table 4.1).

Figure 4.2 Mean number of ladybirds recorded by visual searches on three Kerikeri citrus orchards with soft wax scale.

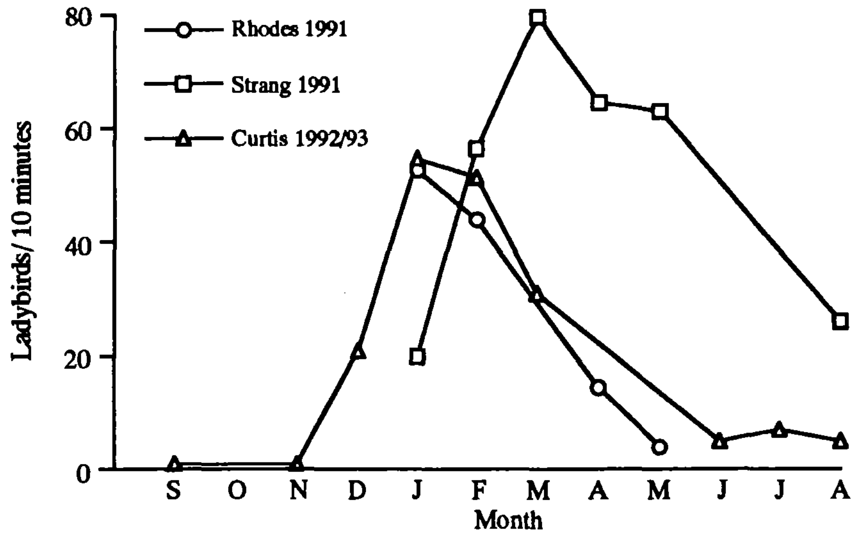


Table 4.1 Percentage of larvae, pupae and adult ladybirds recorded on citrus orchards by visual searches, Northland, January 1991 - February 1994.

Period	n	Larvae&Pupae (%)	Adult (%)
August-September	362	0.0	100.0
October-November	225	1.8	98.2
December-January	1351	10.1	89.9
February-March	3871	2.7	97.3
April-May	913	1.9	98.1
June-July	126	1.6	98.4
Total	6848	3.9	96.1

Early in the season, manual searches found that larvae comprised about 80% and adults 10% of the ladybird population (Table 4.2). By February, the proportion of adults had increased to 95%. Much higher numbers of ladybirds were recorded compared with visual searches, particularly of immature stages. The numbers of adults in visual searches ranged from 3.6 - 5.4% of those found by manual searches.

Table 4.2 Comparison between number of ladybirds per tree recorded by manual and visual searches, and percentage of manual totals seen by visual searches.

Orchard (Date)	Ladybird stage	Manual Mean	Manual SEM	Visual Mean	Visual SEM	Visual/Manual (%)
Hendl	Egg batches	6.2	0.7	0	-	0
(Nov/Dec 1991)	Larvae	118.8	7.2	0.1	0.1	0
	Pupae	14.0	2.2	0.1	0.1	0.4
	Adults	13.9	0.8	0.7	0.2	5.2
	Total (excl. eggs)	146.7	8.3	0.8	0.2	0.6
Curtis	Egg batches	0.3	0.1	0	-	0
(Dec 1992)	Larvae	10.9	0.9	0.3	-	2.7
	Pupae	4.6	0.6	0.1	-	1.3
	Adults	6.5	1.0	0.2	-	3.6
	Total (excl. eggs)	22.1	1.8	0.6	-	2.5
Curtis	Egg batches	0	-	0	-	-
(Feb 1993)	Larvae	3.0	1.3	0	-	0
	Pupae	0.3	0.3	0	-	0
	Adults	59.3	10.1	3.2	-	5.4
	Total	62.7	10.6	3.2	-	5.1

Discussion

The brighter colour and larger size of larval and adult SBL made them as or more conspicuous than the larvae and adults of the other ladybird species that predate SWS. While this may have biased the species recordings slightly, SBL was clearly the most abundant coccinellid on orchards and the species with the greatest potential to have an impact on scale populations. Breeding of SBL and their peak abundance occurred about early summer, which coincided with the emergence and settlement of SWS (Section 2.3). The synchronisation of life cycles between natural enemies and pests is one of several important attributes for a natural enemy to be an effective biological control agent (Huffaker & Rosen 1990).

The year-round presence of SBL on orchards could also be advantageous for IPM if they can respond quickly to an increase in pest populations. The majority of coccinellids that are of economic importance on orchards migrate and hibernate elsewhere (Hodek 1973). These species may be vulnerable to adverse conditions in other habitats, and because they must reestablish themselves on orchards each year they may not always be closely synchronised with their prey.

Visual searches had the advantages of being a simple, precise and rapid technique. They provided good relative estimates of adult ladybird numbers. Successive weekly counts from the same orchard usually gave similar numbers of ladybirds (unpubl. data), indicating that this method gave repeatable or precise results. This enables estimates made over a season or between different orchards to be compared. Adults were the most visible stage, hence the percentage of the ladybird population seen, increased later in the season as the proportion of larvae decreased. Since totals of adults recorded by visual searches were approximately 4-5% of those found in manual searches, visual counts could be multiplied by 20-25 times to estimate the approximate numbers of adult ladybirds.

Manual searches showed, however, that visual counts were unsuitable for estimating the abundance of immature ladybirds, especially in spring and early summer when these stages predominated. Egg batches were detected manually but not by visual searches because they were usually laid on the underside of leaves inside the tree canopy. Larvae and pupae were harder to observe than adults because larvae are smaller and more cryptically coloured, while pupae are dull coloured and stationary. Although manual searches were more accurate than visual counts for estimating actual population levels, this method has a major disadvantage in being extremely labour intensive.

Alternative sampling methods such as sweepnetting, suction sampling and beating (Southwood 1978) were initially tested but caught few beetles. Sweepnetting and suction sampling were difficult amongst the three-dimensional environment and woody vegetation of citrus trees. Michels & Behle (1992) found visual counts were more precise than sweepnetting or beating for sampling coccinellids in grain sorghum *Sorghum bicolor* Moench. Beating was ineffective because unlike *C. montrouzieri*, *R. forestieri* and other coccinellids, SBL did not drop readily when disturbed.

4.3 Vulnerability of scale instars to ladybird predation

Objective

To determine which scale instars were vulnerable to predation by ladybirds.

Methods

Experiments were based on the exclusion technique described by DeBach & Huffaker (1971). Changes in pest populations were compared in the presence and absence of the natural enemy. The use of cages to exclude natural enemies is particularly suitable for insects like scales that have low powers of dispersal.

Terylene voile bags, approximately 40 x 60 cm, were used as a physical barrier on tangelo trees to protect or expose scale to predators. Branches of similar size with similar densities of the desired scale stage (first, second or third instars) were covered and ladybirds were either included or excluded. Other potential predators were removed. Individual trees were regarded as blocks and treatments were randomly assigned to each branch. Scale numbers were counted at the start and end of each experiment. Three successive experiments were conducted that corresponded with the crawler, settled first and second instar or third instar stages.

Crawlers

This experiment examined the effect of predation on the settlement of SWS crawlers. Ladybirds were excluded from five closed bags. One or two adult SBL were accidentally included inside the other five closed bags, providing a further treatment, i.e., 'Bags closed with ladybirds'. Two control treatments, each with 10 branches, had either 'No bags' or 'Bags open'. The latter were attached to branches at the proximal end with the distal end left open as a control for the effect of the bags. Numbers of live and dead adult scale were assessed on 11 December 1990. The number of scale crawlers that settled on the leaves was counted four and seven weeks later. The means of the two 'Bag closed' treatments were adjusted for the five missing values. Numbers of ladybirds in the same block were assessed five times during the experiment using 10 min visual searches (Section 4.2).

Settled first and second instars

The survival of first and second instar scales on bagged branches from which ladybirds were excluded was compared with unbagged branches where scales were exposed to predators. Because the 'Open bag' treatment had the same effect as the 'No bag' treatment in the previous experiment, it was subsequently deleted. Branches with 11-23 leaves and 300-800 scale were selected. Dead and damaged scales on the leaves and all scales on the wood were first removed. This experiment was conducted at two sites. At Orchard A, SWS was predominant, there were high numbers of ladybirds and six replicates were used. The experiment ran for eight weeks from 1 February - 27 March 1991. Orchard B had only CWS, ladybirds were scarce and eight replicates were used. The experiment lasted seven weeks from 5 April 1991. Numbers of ladybirds were estimated approximately fortnightly by 10 min visual searches.

Third instars

Numbers of third instar SWS on bagged branches were compared four weeks after 0, 2, or 8 adult SBL per bag were introduced. Branches had 80-140 scale and were checked to ensure that the bags were free of ladybirds at the start. This experiment began on 11 April 1991 and six replicates were used.

In each experiment, the homogeneity of means was tested by the variance ratio test (Zar 1984). Where necessary, the numbers of scale per leaf were transformed ($\sqrt{x}$) and analysed by ANOVA, with a significance level of 5%.

Results

Crawlers

There were approximately 12 times more scale settled on branches that were protected from predators (treatment 1) compared with exposed branches (treatments 2, 3, 4) (Table 4.3). There was no difference in the numbers of immature scale on treatments 2, 3 and 4. Results were similar after seven weeks. No scale survived through to third instar on exposed branches, unlike protected treatments. Branches of treatment 1 had more adult scale than the other treatments. The number of ladybirds averaged 52.8 (SEM 2.5) per 10 min count.

Table 4.3 Initial number of adult soft wax scale and effect of protection or exposure to predation on number of first instar scale settled after four and seven weeks.

Treatment	Adults/100cm^2 wood		First instars/leaf					
	11.12.90		8.1.91			31.1.91		
	Mean	SEM	Mean	√x	SEM	Mean	√x	SEM
1 Bag closed - ladybirds	36.5	8.2	26.2	4.9	0.9	22.2	4.5	0.7
2 Bag closed + ladybirds	22.3	6.4	2.2	1.0	0.4	0.9	0.8	0.3
3 Bag open	25.0	3.6	4.7	1.6	0.5	0.0	0.1	0.1
4 No bag	25.6	3.6	0.5	0.6	0.1	0.0	0.1	0
SED	5.7			0.6			0.4	
ANOVA								
Trt. 1 vs 2, 3, 4	$P<0.05$			$P<0.001$			$P<0.001$	
Trt. 2 vs 3, 4	ns			ns			ns	
Trt. 3 vs 4	ns			ns			ns	

Settled first and second instars

At Orchard A, 51.3% of scale disappeared from exposed branches compared with 10.4% on protected ones (Table 4.4). Scales did not disappear uniformly from the exposed branches, but disappeared earlier from some leaves and branches than others (unpubl. data). At Orchard B in contrast, there was a similar disappearance of scale on exposed (21.6%) and protected (16.2%) branches. Orchard A averaged 70.4 (SEM 11.0) ladybirds per 10 min count compared with 3.7 (SEM 0.3) ladybirds at Orchard B.

Table 4.4 Initial number of first and second instar scale and number disappeared after eight and seven weeks respectively, at two orchards with high (A) and low (B) numbers of ladybirds.

Orchard	Treatment	Mean no. scale/ branch			
		Start	SEM	Disappeared	SEM
Orchard A		1.2.91		27.3.91	
Soft wax scale	Bag closed - ladybirds	504.7	61.1	54.0	11.8
	No bag	593.3	41.0	308.8	38.0
	ANOVA	ns		$P<0.001$	
Orchard B		5.4.91		24.5.91	
Chinese wax scale	Bag closed - ladybirds	420.6	51.7	73.3	25.2
	No bag	431.4	74.8	98.0	26.1
	ANOVA	ns		ns	

Third instars

The presence of up to eight ladybirds per bag had no effect on the loss of third instar scale (Table 4.5). The three treatments averaged between 3.5-5.6% fewer scales after four weeks. One replicate in the 0-ladybird treatment had a loss of 54%. The cause was unknown, but since there were no ladybirds inside the bag, this datum was excluded from the analysis.

Table 4.5 Initial number of third instar scale and number disappeared after four weeks exposure to two densities of steelblue ladybirds.

Treatment (No. ladybirds)	Mean no. scale /branch 11.4.91	SEM	Mean no. disappeared/branch 8.5.91	SEM
0	120.5	6.5	6.0	2.5
2	104.2	6.0	3.7	1.5
8	112.3	6.3	6.3	2.1
ANOVA	ns		ns	

Discussion

The three experiments showed that first and second instar scale, but not third instars were predated by ladybirds. This agrees with the observations of Milne (1981) and Beattie (1988). Presumably the beetles were deterred by the larger size or thicker layer of wax secreted by third instars. Adult scales which have much thicker wax were not tested. Adult SBL were observed feeding on third instar CWS in the field, but this appears to be uncommon. Some ladybirds will predate the later instars of wax scales, as Richards (1981) found for larvae of *R. forestieri* feeding on *Ceroplastes rubens*.

In the crawler experiment, although the protected branches had about 1.5 times more adult scale than other treatments, this alone did not explain the 12 times higher number of settled scale on these branches compared with exposed ones. The similar density of settled scale amongst exposed treatments suggests that predators were responsible for the difference. This experiment did not distinguish between predation on crawlers and settled scale. Both scale stages were predated by larval and adult SBL in the laboratory (pers. obs.).

At the two orchards where predation on first and second instar scales was tested, the contrasting results suggest that the greater disappearance of scales from exposed branches at

Orchard A was due to the higher number of ladybirds than at Orchard B. This was supported by other evidence. Predation by ladybirds was evident from the remains of wax fragments left on leaves. The disproportionate disappearance of scale among leaves and among branches indicated that mortality acted unevenly on the population. If environmental factors were the main cause, they would be expected to affect all scale reasonably equally, and the losses should have been more evenly distributed in time and space. Settled scale killed by environmental factors would also remain on the leaves and this did not occur. CWS was used at Orchard B because SWS had passed the second instar stage by this time and was no longer vulnerable to predation by ladybirds.

4.4 Comparison between the densities of scales and ladybirds

Objective

To examine the relationship between the densities of adult and immature scales, and between ladybirds and immature scales.

Methods

The densities of adult and immature SWS were assessed on twelve blocks of mandarins, oranges and tangelos on nine orchards. Sampling was conducted between 16 January and 1 February 1991, after scale crawlers had settled on the leaves (Section 2.3). Scales on the outer canopy at a height of 1-2 m were sampled once or twice per block. Each sample comprised 20 randomly selected branches (1 per tree) consisting of wood up to two-years-old, and 50 randomly sampled leaves, which were assessed in the laboratory. Adult and immature scales were assessed on wood and leaves respectively. Both live and dead scales were included. The length and average diameter of twigs were measured to calculate the density of adult scale per 100 cm^2 of wood.

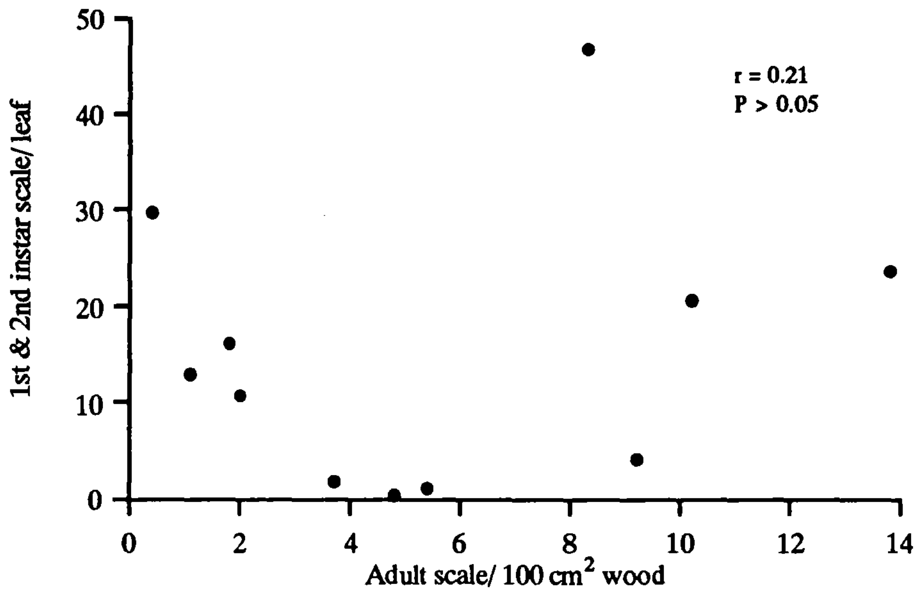
The total number of larval, pupal and adult ladybirds was recorded during visual searches of orchards as described in Section 4.2. Ladybirds were assessed two or three times from the same blocks and during the same period as scale samples were collected. Correlations between the mean densities of adult and immature scale on each orchard, and between the density of first and second instar scale and the mean number of ladybirds were calculated.

Results

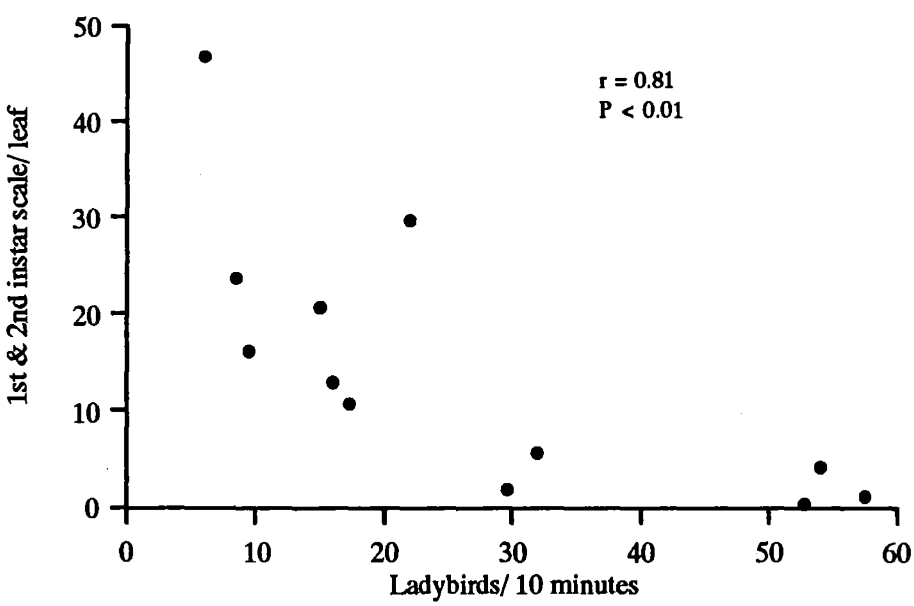
There was no clear relationship between the density of adult scale and the resulting scale settlement (Fig. 4.3a). However, the density of first and second instar scale was inversely correlated with numbers of ladybirds (Fig. 4.3b). Blocks with more than about 30 ladybirds per 10 min search had less than six first and second instar scale per leaf.

Figure 4.3 Correlations between (A) the mean densities of adult and immature soft wax scale, and (B) immature soft wax scale and the mean number of ladybirds on citrus orchards in Kerikeri, January-February 1991.

A: Adult scale versus first and second instar scale



B: Ladybirds versus first and second instar scale



Discussion

There should be a positive correlation between the number of adult SWS and the number of crawlers produced, as Yardeni & Ravid (1984) found for Florida wax scale. The numbers of adults and settled scale should have a similar relationship unless a mortality factor acted unequally on the different populations. Although scale crawlers are highly vulnerable to environmental conditions (Section 2.6), these factors will act in a largely density-independent manner on all orchards and were therefore unlikely to cause the observed pattern.

The inverse correlation between scale settlement and the abundance of ladybirds could account for the lack of a relationship between adult and settled scales. If predation by ladybirds was important in determining the survival of settled scale, then the absence of ladybirds should allow a relatively higher settlement of scale compared with orchards where ladybirds were abundant.

Rhodes's orchard had a moderately high density of adult scale compared with the other orchards, but the lowest density of settled scale. Virtually no scale survived to the third instar stage on this block, except on branches protected by bags from which ladybirds were excluded (Section 4.3). The relatively high number of ladybirds at this orchard (53/10 min) was apparently sufficient to reduce the scale to these low densities.

4.5 Ladybird feeding rates

Objectives

To determine which of the most common species of ladybirds on citrus orchards would feed on SWS, and to measure their feeding rate under laboratory and field conditions.

Methods

Feeding rates on SWS of the four most common species of ladybird (Section 4.2) were measured in the laboratory on individual tangelo leaves or tangelo twigs (Table 4.6). In both experiments, first and second instar scales were counted after any obviously dead scale had been removed. Each leaf was placed in an 8 cm diameter plastic container and each twig in a pottle of water inside a 4 l plastic container with a porous fabric lid. One larval or adult ladybird was introduced into each container which were kept at 20±1°C under natural daylight.

The leaves initially had 44-148 scales which were recounted after 24 h. This experiment was conducted from 10 January to 14 February 1991. The twigs had 6-16 leaves with 230-590 scale and were assessed after six days. The experiment began on 8 February 1991. Four controls were used in both the leaf and twig experiments. The reduction in numbers of scale, in containers with ladybirds, was adjusted by the change in numbers on the controls to calculate the mean reduction in number of scale per day per ladybird.

The feeding rates of SBL and *R. forestieri* on SWS, were also tested in the field between 23 February and 14 March 1991. Branches with 7-23 leaves and 150-650 first and second instar scale were covered with voile bags and two adult ladybirds were included. Ladybirds were collected from the orchard and immediately placed in the bags. The number of scale was counted at the start of the experiment and reassessed after seven or 12 days. The number of scale disappearing per day per ladybird was calculated and analysed as above.

A second experiment at another orchard determined the feeding rate of SBL on CWS from 28 March to 3 April 1992. A higher density of scale was used, with branches having 8-16 leaves and 1100-1800 scale. This experiment used eight adult ladybirds per branch. Control branches were bagged to exclude ladybirds. Six and two control branches were used for the SWS and CWS experiments respectively.

Results

In the laboratory, all four species of ladybird tested consumed some SWS (Table 4.6). SBL had the highest feeding rates on leaves, although results varied between 2-138 and 2-64 scale per day for larvae and adults respectively. On twigs, adult SBL and *R. forestieri* consumed 21-24 scale per day. An average of 1.0 and 0.5 scale per day disappeared from control leaves and twigs respectively. Under field conditions on bagged branches, feeding rates of about 16 scale per day were obtained for adult SBL and *R. forestieri* predating SWS

(Table 4.7). SBL fed at a similar rate on CWS. On control branches, the change in number of scale per day was -0.9 and 2.3 respectively.

Table 4.6 Feeding rates (mean loss of scale per day per ladybird) of larval and adult ladybirds on soft wax scale on leaves and twigs in the laboratory.

Ladybird species	Leaves			Twigs		
	Reps	Feeding rate	SEM	Reps	Feeding rate	SEM
H. chalybeus (larvae)	7	54.0	23.1	5	2.2	1.1
H. chalybeus (adults)	9	27.0	7.9	5	20.7	6.5
R. forestieri (l)	-			2	7.3	7.6
R. forestieri (a)	9	15.0	2.8	5	24.0	8.3
C. montrouzieri (a)	2	25.0	4.0	2	8.1	5.3
R. cardinalis (a)	2	0		4	7.4	4.5

Table 4.7 Feeding rates of adult ladybirds on soft and Chinese wax scale on bagged branches in the field.

Species		Reps	Mean loss of scale	
Ladybird	Scale		/day/ladybird	SEM
H. chalybeus	Soft	4	15.6	3.8
R. forestieri	Soft	4	15.5	2.7
H. chalybeus	Chinese	8	13.3	2.6

Discussion

Predacious coccinellids accept a wide range of food, but have a narrower range of preferred prey (Hodek 1973). The degree of specialisation is likely to determine how readily they will accept SWS and CWS. Both scale species were readily consumed by SBL, although whether they prefer SWS or CWS was not tested. SBL are generalist predators of insects and mites (Beattie & Gellatley 1983), including several diaspid scales (Drea & Gordon 1990). They were imported to New Zealand as a predator of black scale (Dumbleton 1936). *R. forestieri* is also polyphagous and feeds readily on *Ceroplastes rubens* (Richards 1981). The larvae of *R. forestieri* were also observed feeding on SWS and CWS. *C. montrouzieri* and *R. cardinalis* appear to be more specialised predators. *C. montrouzieri* is primarily a predator of mealy bugs (Babu & Azam 1987), while the principal prey of *R. cardinalis* is cottony-cushion scale (Rosen 1990).

The data from leaves showed that both larval and adult SBL could be voracious predators of SWS. These rates are likely to be artificially high, because confining predators within small areas probably increases predation rates since they repeatedly search areas previously searched (Luck *et al.* 1988). However, these results indicate the potential of SBL to reduce scale populations when taking into account the large numbers of ladybirds that can be present on citrus trees (Section 4.2). Predation rates of SBL larvae were higher than adults on leaves but lower on twigs. This was at least partly due to the larvae spending a large proportion of time on the walls or lid of the twig containers instead of feeding.

Feeding rates derived from bagged branches in the field should be a more realistic estimate than those from twigs in the laboratory. The bagged branches were larger and exposed to field conditions. These results indicate the feeding rate of ladybirds over a relatively short period and it may vary seasonally depending on the metabolic requirements and physiological state of the beetles.

4.6 Do ladybirds reduce scale populations?

Objective

To measure the reduction in density of SWS caused by a range of densities of SBL.

Methods

Two experiments were conducted on tangelo trees with bagged branches or covered trees to test the effect of a range of ladybird densities on scale populations. The first experiment began on 3 March 1992 at the start of scale crawler production. Branches with two densities of adult CWS (Table 4.8) were covered with voile bags. Ladybird treatments (0, 2, 4 or 8 adult SBL) were randomly assigned to branches within each scale density. There were six replicates of each treatment for each scale density. The numbers of breeding adults and settled first and second instar scales were counted after twelve weeks when crawler production had ceased.

A larger experiment was carried out using whole tangelo trees (2.2-2.6 m high) infested with SWS. The trees were searched manually twice (Section 4.2) on 21 and 23 December

1992 to remove larval and adult ladybirds. They were covered with 1.2 mm mesh insect netting after the first search. SBL were collected from several orchards and introduced to the caged trees on 23 and 24 December, before the emergence of scale crawlers. Ladybirds were reintroduced to the covered trees at six rates (Fig. 4.4), in the same ratio of 1 larva to 3 adults that they were collected. Trees with a high density (Section 2.2) of scales were used, and they were visually subdivided into 'high' and 'low' density groups. There were two replicates in each category, and the six treatments were randomly assigned to each replicate.

First and second instar scales on the leaves were assessed by randomly picking 25 outer canopy leaves per tree (100/ treatment). A preliminary sample from control trees was made on 6 January 1993 to determine the level of settlement. Full assessments began on 11 January and were repeated at about eight day intervals until 22 February, when few settled scales were present in all trees. At this time the trees were searched again for ladybirds. An automatic data logger (Infologger, HortResearch) recorded temperature and humidity from within the canopy of a covered and an adjacent uncovered tree. No sprays were applied during the trial, but one copper fungicide was used two months before the experiment started.

Data from both experiments were analysed by two-way ANOVA. For the branch experiment the numbers of rays were transformed ($\sqrt{x}$) before analysis to stabilise the variances. In the tree experiment, each sampling date was analysed separately and the first four full samples were combined for further analysis. The total number of live ladybirds at the end of the trial was similarly analysed.

Results

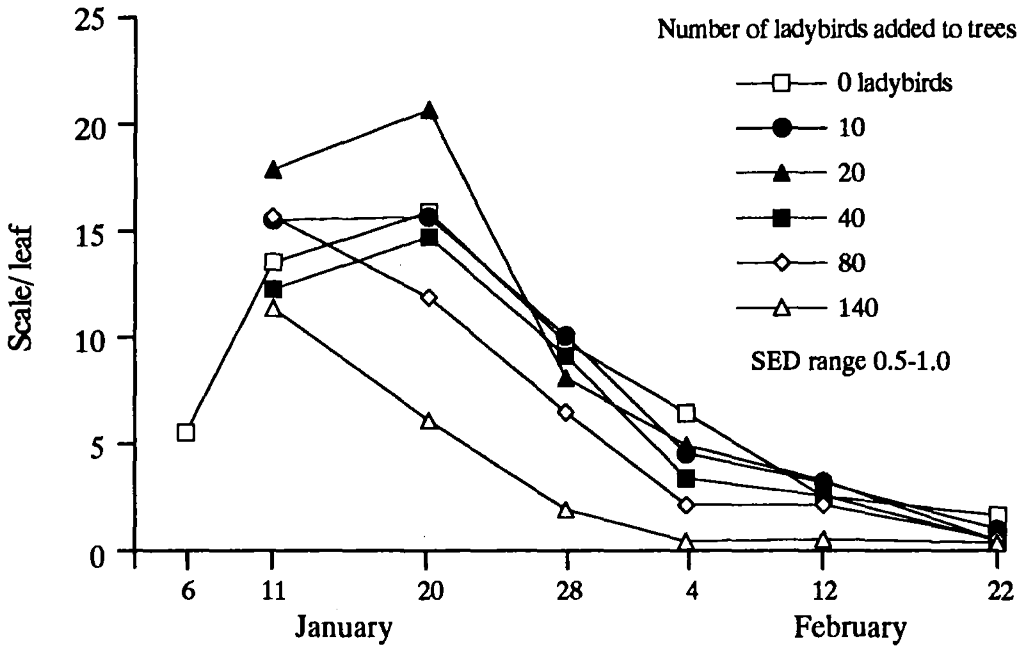
In the bagged branch experiment, there was no difference in the initial density of adult scale amongst treatments (Table 4.8). All three ladybird densities significantly reduced the numbers of settled scale compared to controls at both densities of adult scale. The difference in numbers of scale surviving between branches with 0 and 2 ladybirds averaged 790 and 540 scale per branch at 'low' and 'high' adult scale densities respectively. There was a linear reduction in the density of settled scale with increasing ladybird densities. The density of settled scale was similar between branches with a 'low' or 'high' density of adult scale within each treatment, except on control branches. There was a significantly larger difference between treatments with and without ladybirds at 'low' scale densities than at 'high' scale density. The trend for larger numbers of ladybirds to have a greater effect, occurred irrespective of adult scale density.

Table 4.8 Effect of adult steelblue ladybirds on scale settlement after 12 weeks in bagged branches with low and high densities of adult soft wax scale.

Treatment	Adult scale density	Breeding adults/branch		Live scale settled/breeding adult		
		Mean	SEM	Mean	√x	SEM
1: 0 ladybirds	Low	18.6	1.9	46.2	6.7	0.6
2: 2 "		18.0	2.3	1.9	1.0	0.4
3: 4 "		16.0	0.7	2.0	0.8	0.5
4: 8 "		19.3	1.4	0.1	0.2	0.1
1: 0 ladybirds	High	40.0	2.7	19.0	4.3	0.2
2: 2 "		37.5	2.5	4.9	1.7	0.6
3: 4 "		34.5	4.1	5.6	1.7	0.8
4: 8 "		30.7	3.6	0.7	0.6	0.2
ANOVA						
Among treatments		ns			$P<0.001$	
Between scale densities		$P<0.001$			ns	
Trts 1 vs 2, 3, 4		ns			$P<0.001$	
Linear trend Trts 2, 3, 4		ns			$P<0.05$	
Interaction Trt byScale density		ns			$P<0.01$	
Trt 1 vs 2, 3, 4 by Scale density		ns			$P<0.001$	
Linear trend by Scale density		ns			ns	

In the experiment with covered trees, on each sampling date there were no significant differences among treatments. When the the first four full samples were combined, the number of scale declined linearly ($P < 0.05$) with increasing density of ladybirds (Fig. 4.4). The number of settled scale declined soonest on trees with the two highest ladybird densities. However, scale numbers eventually declined to below three per leaf in all treatments including the control. The mean number of ladybirds at the end of the trial was not significantly different amongst treatments (range 102-132 per tree). Temperature and mean daily humidity inside covered and uncovered trees were within ±0.4^{0}C and ±9% R.H of each other.

Figure 4.4 Mean number (backtransformed data) of first and second instar soft wax scale on tangelo trees with different initial densities of steelblue ladybirds.



Discussion

These experiments demonstrate that SBL can reduce scale populations. Two ladybirds per branch were sufficient to reduce the number of scale settling at both low and high densities of adult scale. The difference in numbers of scale settling between branches with and without ladybirds was less than 800, and this number can be accounted for by the estimated feeding rate of SBL from branches (Section 4.5). Assuming a constant feeding rate of 15.5 scale per day, two ladybirds would consume approximately 2700 scale (31 scale x 87 days) during the experiment. Why the control branches with a low density of adult scale had more settled scale than the high density branches is unknown.

On the covered trees, the disappearance of settled scale from all treatments was not due to scale migrating onto the wood since virtually none survived to the third instar, but was almost certainly due to predation by ladybirds. It was expected that the ladybird populations would reproduce in response to the available food and hence eventually obscure some of the initial distinction between treatments. However, the initial searches must have overlooked many small larvae on the control trees as well as on the treatment trees. As a result there was no difference in the final ladybird populations amongst the trees.

By the end of the trial all the trees had a minimum of about 100 ladybirds and this was sufficient to reduce the scale populations virtually to extinction. However, because of the high numbers of ladybirds in all treatments, the experiment did not determine what was the minimum ladybird density that would result in this low scale density. It is possible to speculate what the minimum might be, because a similar decline in the scale population was observed on adjacent uncovered trees (Sections 2.5 and 2.6). If visual counts of ladybirds in this block were multiplied by 20-25 times (Section 4.2), this gives an estimate of approximately 54-67 ladybirds per tree.

Manual removal as a means of assessing the effectiveness of natural enemies has the advantage over other methods of changing only one variable, in this case the number of ladybirds. A mechanical rather than a chemical means of removing ladybirds was used to avoid the possibility of any confounding effects of residual toxicity against scale crawlers and ladybirds. The "insecticidal check" method can introduce several other biases such as pesticide-related sublethal effects on pests and natural enemies, and pesticide-induced physiological changes in the plant (Luck *et al.* 1988). With hindsight, however, manual searches were too inefficient to remove all ladybirds from trees of the size used. Despite the potential complications of applying an insecticide, this method would probably have been a more effective means of excluding ladybirds than hand removal.

4.7 Summary

- The main objective of this chapter was to evaluate the importance of coccinellids, particularly steelblue ladybirds, in reducing populations of soft and Chinese wax scale.
- Steelblue ladybirds comprised 98% of the ladybirds found on orchards.
- Immature ladybirds were most abundant in summer, while adults remained numerous through to autumn.

- Visual counts of ladybirds were suitable for relative estimates of adults, while manual searches gave a better estimate of the actual abundance of ladybirds, especially larvae.
- There was no relationship between the densities of adult and immature scale on 11 orchards, but a strong inverse correlation existed between scale settlement and the number of ladybirds.
- The larvae and adults of SBL and *R. forestieri* fed on first and second instar soft and Chinese wax scale.
- Steelblue ladybirds did not predate third instar soft wax scale, third instar Chinese wax scale were not tested.
- Fewer scales survived to third instar on branches that were exposed to predators than on protected branches where ladybirds were abundant.
- A feeding rate of about 15 soft or Chinese wax scale per day per ladybird was calculated for two species of ladybird in the field.
- This feeding rate could account for the difference in scale settlement between branches with and without ladybirds.
- Covered trees with approximately 100 ladybirds per tree had virtually no scale surviving to third instars.
- Steelblue ladybirds can control wax scales.

Chapter 5 EFFECTS OF PESTICIDES ON STEELBLUE LADYBIRDS

5.1 Introduction

Both larval and adult SBL are important predators of immature SWS and CWS in New Zealand citrus orchards (Chapter 4). A medium or high density of SWS occurred on the majority of orchards where insecticides had been used, whereas most unsprayed orchards had low populations of SWS (Section 2.2). It was speculated that pesticides could be disrupting biological control agents, resulting in higher numbers of scales. The outbreak of primary and secondary pests due to the destruction of their natural enemies is a common side effect of insecticides (Croft 1990, DeBach & Rosen 1991).

Organophosphates and mineral oils are currently the most widely used insecticides in citrus orchards. Three organophosphates were recommended in the N.Z. Ministry of Agriculture and Fisheries citrus export spray programme (Sale 1988). Public concern over the hazards of broad spectrum pesticides such as organophosphates, has led to a search for alternative chemicals. These include selective insecticides that have a low toxicity to mammals such as insect growth regulators (IGRs) (Coats 1994) and fatty acid salts (potassium soaps) (Osborne 1984).

In addition to insecticides, citrus may also require regular applications of fungicides. In New Zealand, citrus is susceptible to four main fungal diseases, verrucosis (*Elsinoe fawcetti* Bitanc. & Jenk.), botrytis (*Botrytis cinerea* Pers.), melanose (*Diaporthe citri* Wolf) and alternaria (*Alternaria citri* Ellis & Pierce), which may require spraying at about 3 week intervals from spring to autumn (Sale 1990). Protectant copper-based fungicides, such as copper oxychloride and cupric hydroxide, have been the traditional means of disease control. This is likely to continue, particularly since the most effective eradicant fungicide, difolatan, is now unavailable.

To develop an integrated pest and disease management (IPDM) programme for citrus in New Zealand, it is necessary to assess which pesticides have the least harmful effects on biological control agents. A full evaluation of pesticides should include the mortality caused by direct contact and post-treatment residues to both the target pest and beneficial organisms (Bellows & Morse 1988). In addition to direct mortality, pesticides also have a wide variety of sublethal effects on the physiology and behaviour of natural enemies (Messing & Croft 1990).

In this study, research on pesticides was limited to examining their disruptive effects on ladybirds. This chapter describes three experiments that measured some direct and indirect impacts of pesticides on SBL. In two laboratory experiments, a range of fungicides and insecticides were screened for their toxicity to SBL (Section 5.2), and for their disruption to predation of SWS by SBL (Section 5.3). The effect of three fungicides, applied at different frequencies, on densities of SBL in an orchard was also investigated (Section 5.4).

5.2 Toxicity of pesticides to adult steelblue ladybirds

Objective

To determine the toxicity of 10 fungicides and 10 insecticides to adult SBL.

Methods

The toxicity of each chemical was tested at the recommended label rate, at 0.1x and at 3x this rate and compared with a water control (Table 5.1). The rates of active ingredients and trade names are given in Appendix 14. Each chemical was made into a 1 litre solution at the highest concentration tested and then diluted. Ladybirds were stuck on their back onto glass microscope slides with double-sided sellotape. The slides were immersed for 10 seconds into one of the solutions which was kept agitated. Excess fluid was blotted off and the slides were allowed to dry before being placed in Petri dishes and kept at 21±1^{0}C under natural daylight.

Each treatment was tested once, using 20 ladybirds on two slides with 10 ladybirds per slide. Because of the time needed to run the experiment, tests with different treatments were conducted on five occasions between 25 February and 19 March 1993. A fresh control with 20 ladybirds was used each time, giving a total of 100 control ladybirds. There was an unexpected difference in results between the two organophosphates, so they were retested at label rates with a further 30 ladybirds each on 19 March. Ladybirds were collected from orchards and held for up to 5 days in a refrigerator prior to testing. They were acclimatised for 24 hours at 21 ± 1^0C before being dipped.

Preliminary results showed that mortality increased in some treatments up to 72 hours after dipping. Subsequent changes in mortality were ≤5%, so this interval was used to assess all treatments. The ladybirds were assessed as being either alive or dead; those classified as dead were motionless when prodded or unable to walk across the 9 cm dish. All the ladybirds that were unable to walk normally eventually died.

Data were analysed by comparing the mean percentage mortality of different groups of chemicals using independent and paired sample *t* tests (Zar 1984). Mortality caused by the two organophosphates was compared using a Chi-square test with Yates' correction (Zar 1984). The significance level was $P \leq 0.05$.

Results

Insecticides killed twice as many ladybirds as fungicides at 3x label rates, and three times as many at 1x label rates, but there was no significant difference in mortality at 0.1x label rates (Tables 5.1, 5.2). Amongst fungicides, the copper-based ones killed five times more ladybirds than non-copper fungicides at three times label rates, but were not significantly more toxic at the other two rates. The toxicity of copper fungicides increased significantly between 1x-3x label rates, but not from 0.1-1x. There was no difference amongst mortality levels of the three rates of non-copper fungicides.

Mineral oils killed almost a third fewer ladybirds than synthetic pyrethroids and organophosphates at label rates. The synthetic pyrethroid killed all ladybirds at both concentrations tested. Both organophosphates caused a similar low mortality at 0.1x label rates ($\chi^2 = 0.3$, df=1, ns), but diazinon was more toxic than chlorpyrifos at label rates ($\chi^2 = 10.8$, df=1, $P < 0.01$). This difference was confirmed by the repeated test when dipping in diazinon resulted in 100% mortality compared with 17% for chlorpyrifos ($\chi^2 = 39.5$, df=1, $P < 0.001$). Of the remaining pesticides, the IGR caused little mortality whereas the potassium salts were highly toxic at label and 3x label rates. The organotin miticide was moderately toxic in comparison with these two insecticides.

Table 5.1 Toxicity of fungicides and insecticides at 0.1x, 1x and 3x label rates, to adult steelblue ladybirds 72 hours after being dipped.

Chemical group	Treatment	Percentage mortality		
		0.1x	1x	3x
Fungicides				
Copper	cupric hydroxide (Kocide)	5	10	45
	cupric hydroxide (Champ)	5	25	55
	copper oxychloride	0	30	50
	copper sulphate + lime	5	15	60
	copper sulphate pentahydrate	0	55	75
Non-copper	iprodione	25	20	10
	triforine	10	10	15
	chlorothalonil	10	0	0
	mancozeb	15	15	25
	benomyl	0	10	0
Insecticides				
Mineral oil	Sunspray	10	40	35
	DC Tron	30	50	90
	Ultrafine	0	5	30
Synthetic pyrethroid	taufluvalinate	100	100	-
SP/OP	permethrin + pirimiphosmethyl	40	100	-
Organophosphate	diazinon	5	100	-
	chlorpyrifos	15	50	-
Potassium salts	C12-C18 fatty acids	5	80	95
IGR	buprofezin	-	5	5
Organotin	azocyclotin	5	35	85
Water	control		1	

Table 5.2 Results of independent and paired sample *t* tests between the mean percentage mortality of groups of pesticides (from Table 5.1) at 0.1x, 1x and 3x label rates.

Comparison	Mean percentage mortality					
	0.1x	SEM	1x	SEM	3x	SEM
All fungicides	7.5	2.5	19.0	4.8	33.5	8.5
All insecticides	21.5	9.6	56.5	11.7	69.0	11.3
Independent sample *t*	-1.41	ns	-2.96	$P<0.05$	-2.52	$P<0.05$
Copper fungicides	3.0	1.2	27.0	7.8	57.0	5.1
Paired sample *t*		2.71 ns		6.32 $P<0.01$		
Non-copper fungicides	12.0	4.1	11.0	3.3	10.0	4.7
Paired sample *t*		-0.30 ns		-0.25 ns		
Independent sample *t*	-2.12	ns	1.88	ns	6.71	$P<0.001$
Mineral oils	13.3	8.8	31.7	13.6	51.7	19.2
Synthetic pyrethroids & Organophosphates	40.0	21.3	87.5	12.5	-	
Independent sample *t*	-1.16	ns	-3.02	$P<0.05$		

5.3 Pesticide disruption to predation of soft wax scale by steelblue ladybirds

Objective

To screen 10 fungicides, five insecticides and a surfactant for their effect on predation of SWS by SBL.

Methods

Three laboratory experiments were conducted (Table 5.3) (Lo & Blank 1992). Each pesticide was tested at recommended label rates (see Appendix 14 for rates of active ingredients and trade names), and compared to water-treated controls. First and second instar SWS on *Citrus trifoliata* leaves were counted after removing dead scale. After being treated, each leaf was allowed to dry and placed separately in Petri dishes which were kept at 21±1^{0}C. Ladybirds were collected from the field and held overnight without food before being added to the dishes. The numbers of scale remaining were assessed after 24 hours. Ladybird survival was assessed after 12 and 24 hours, and also after 4 days in Experiment 3.

Table 5.3 Details of procedures used in the three predation disruption experiments.

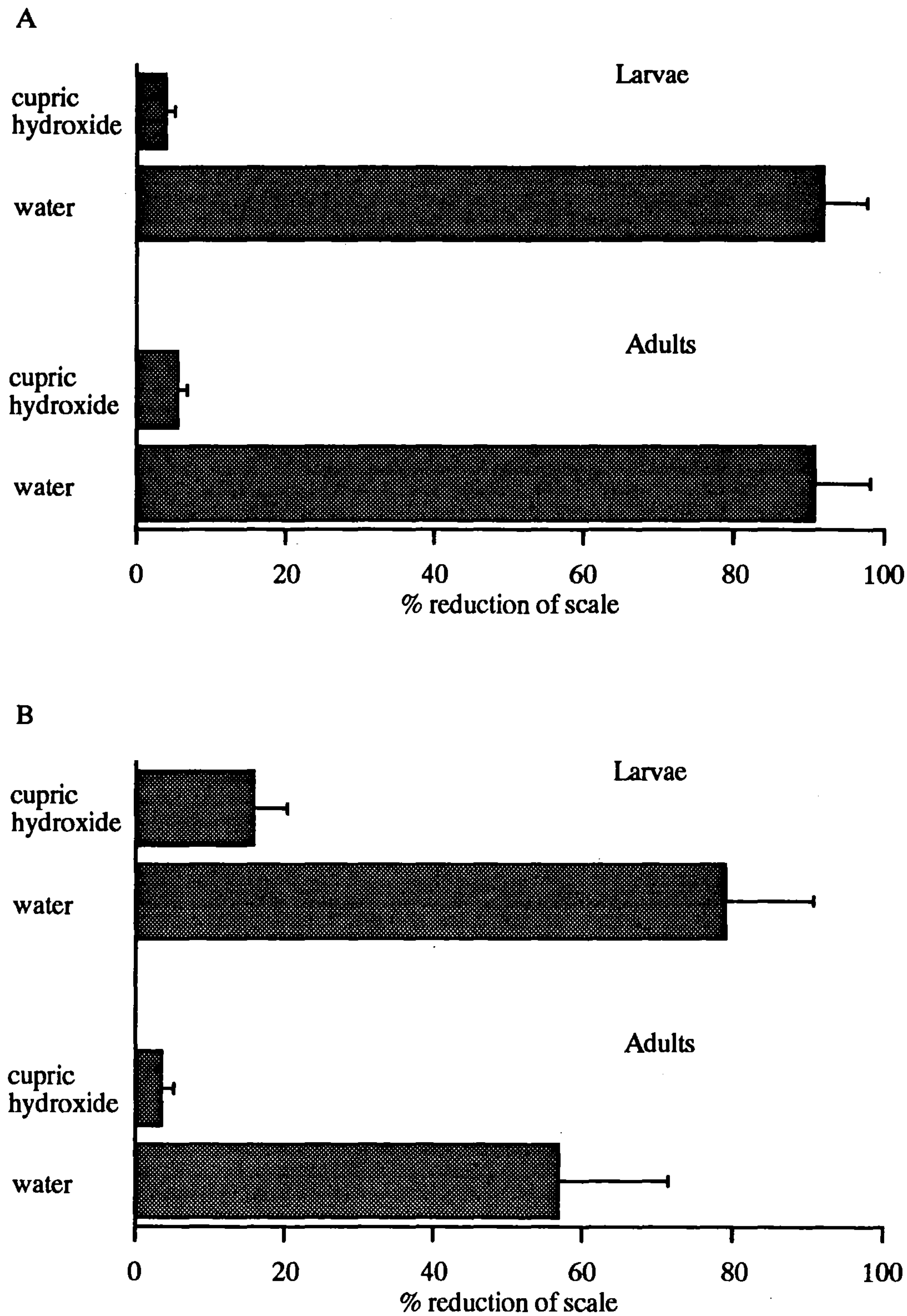
	Experiment 1 No-choice	Choice	2	3
Chemicals tested	1 fungicide		9 fungicides	5 insecticides, 1 surfactant
Initial number of scale/ leaf	100-200		100-160	130-160
Method of treating leaves	Hand sprayed to runoff		Dipped for 10 seconds into 1 litre aqueous suspensions	
Treatments given separately	Yes	No - choice of treated and control leaves	Yes	Yes
No. ladybirds/ dish	6 larvae or 6 adults		6 adults	6 adults
No. replicates	6 & 6	6 & 6	4	4

Results were expressed as the percentage reduction of scale. An arcsine transformation was performed on square root transformed data and analysed by ANOVA . In Experiment 2, a Scott-Knott cluster analysis (Scott & Knott 1974), was used to compare groups of fungicides, excluding triforine and control. Tukey's test (Zar 1984) was used to determine significant differences between pairs of treatments.

Results

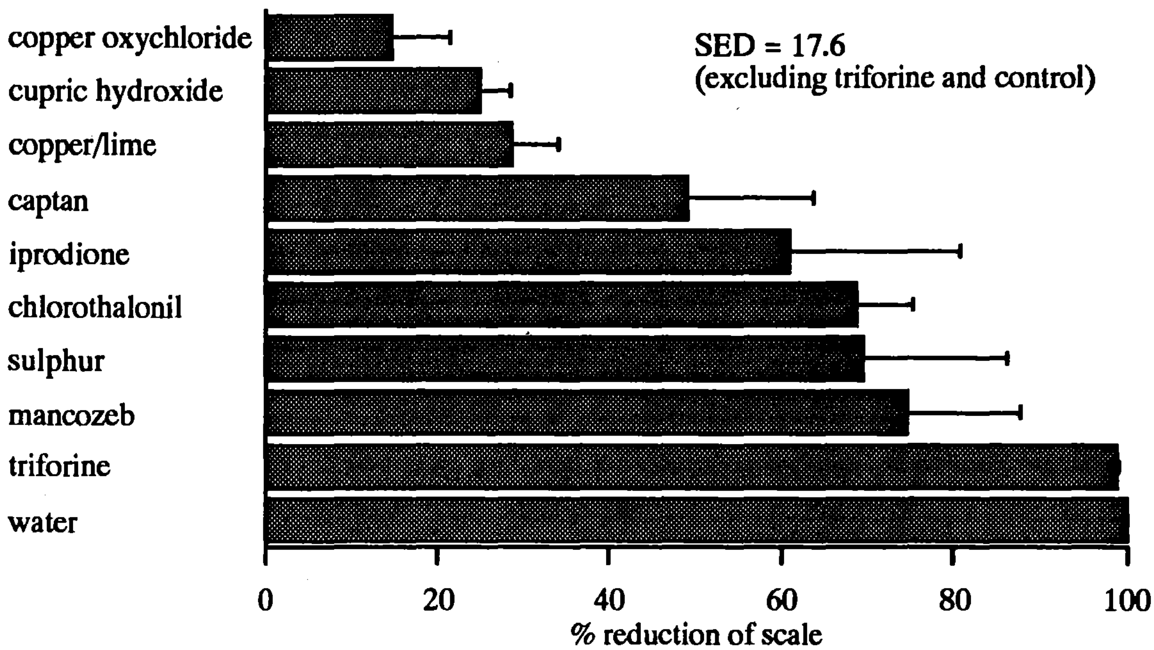
In Experiment 1, predation (as shown by the percentage reduction of scale) by both larval and adult ladybirds was significantly ($P < 0.001$) reduced on cupric hydroxide-treated leaves compared with untreated leaves. This occurred in both the no-choice (Fig. 5.1a) and choice experiments (Fig. 5.1b). Larvae ate significantly ($P < 0.05$) more scale than adults in the choice experiment, but there was no interaction effect between ladybird stage and treatment. There was no mortality of ladybirds within 24 hours.

Figure 5.1 Mean percentage (±SEM) reduction of soft wax scale by larval and adult steelblue ladybirds on cupric hydroxide (Kocide 101 WP) and water-treated citrus leaves. A: No-choice (SED = 6.5); B: Choice (SED = 11.8).



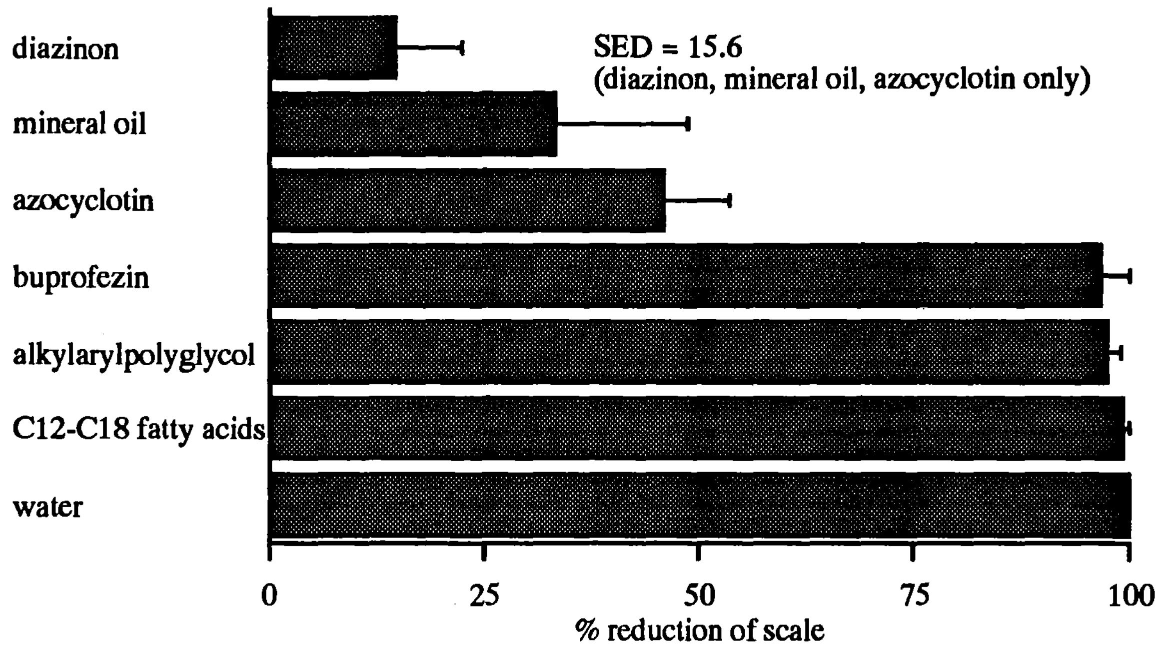
In Experiment 2, there was significantly less ($P < 0.05$) predation on scales treated with the three copper-based fungicides compared with those treated with captan, iprodione, chlorothalonil, sulphur and mancozeb (Fig. 5.2). No mortality of ladybirds occurred within 24 hours.

Figure 5.2 Effect of fungicides on the mean percentage (±SEM) reduction of soft wax scale by adult steelblue ladybirds on citrus leaves.



In Experiment 3, diazinon, mineral oil and azocyclotin caused similar reductions in numbers of scale (Fig. 5.3). These treatments significantly ($P < 0.001$) reduced predation compared with the buprofezin, insecticidal soap (fatty acids), surfactant and water-treated control treatments. There was no mortality of ladybirds within four days, except in the diazinon treatment. After 12 hours, 63% of the ladybirds in the diazinon treatment were dying or dead and by 24 hours this had increased to 92%.

Figure 5.3 Effect of insecticides, a miticide and a surfactant on mean percentage (±SEM) predation of soft wax scale by adult steelblue ladybirds on citrus leaves.



5.4 Effect of field applications of fungicides on numbers of steelblue ladybirds

Objective

To determine the effects of three fungicides applied in five spray programmes on numbers of SBL in an orchard.

Methods

An experiment was conducted in a commercial orchard at Glenbervie near Whangarei, on a block of 12-year-old, 4 m high tangelo trees. Plots comprised 3 or 4 adjacent trees with no unsprayed buffer trees between plots. The 5 fungicide treatments and an unsprayed control were assigned to plots using a randomised block design with 4 replicates.

Cupric hydroxide (Champ) at 45 g ai/100 litres and chlorothalonil (Bravo 500F) at 150 g ai/100 litres were both applied at moderate (5 sprays) and high (9) frequencies. Copper sulphate plus hydrated lime (Bordeaux mixture) at 600 & 800 g ai/100 litres was applied once.

Application dates are shown in Figure 5.4. The moderate-frequency plots received the first 3 sprays before monitoring of ladybirds began on 20 February. There was a 2 month interval between the third application and the start of monitoring. High-frequency plots received their first 5 sprays up to 3 weeks before 20 February. Fungicides were applied with a hand gun and hydraulic sprayer operating at 1200 kPa. Each tree received approximately 4 litres of spray (12-16 litres per plot), equivalent to 2700 litres per ha. No other sprays were applied to the trees during the experiment.

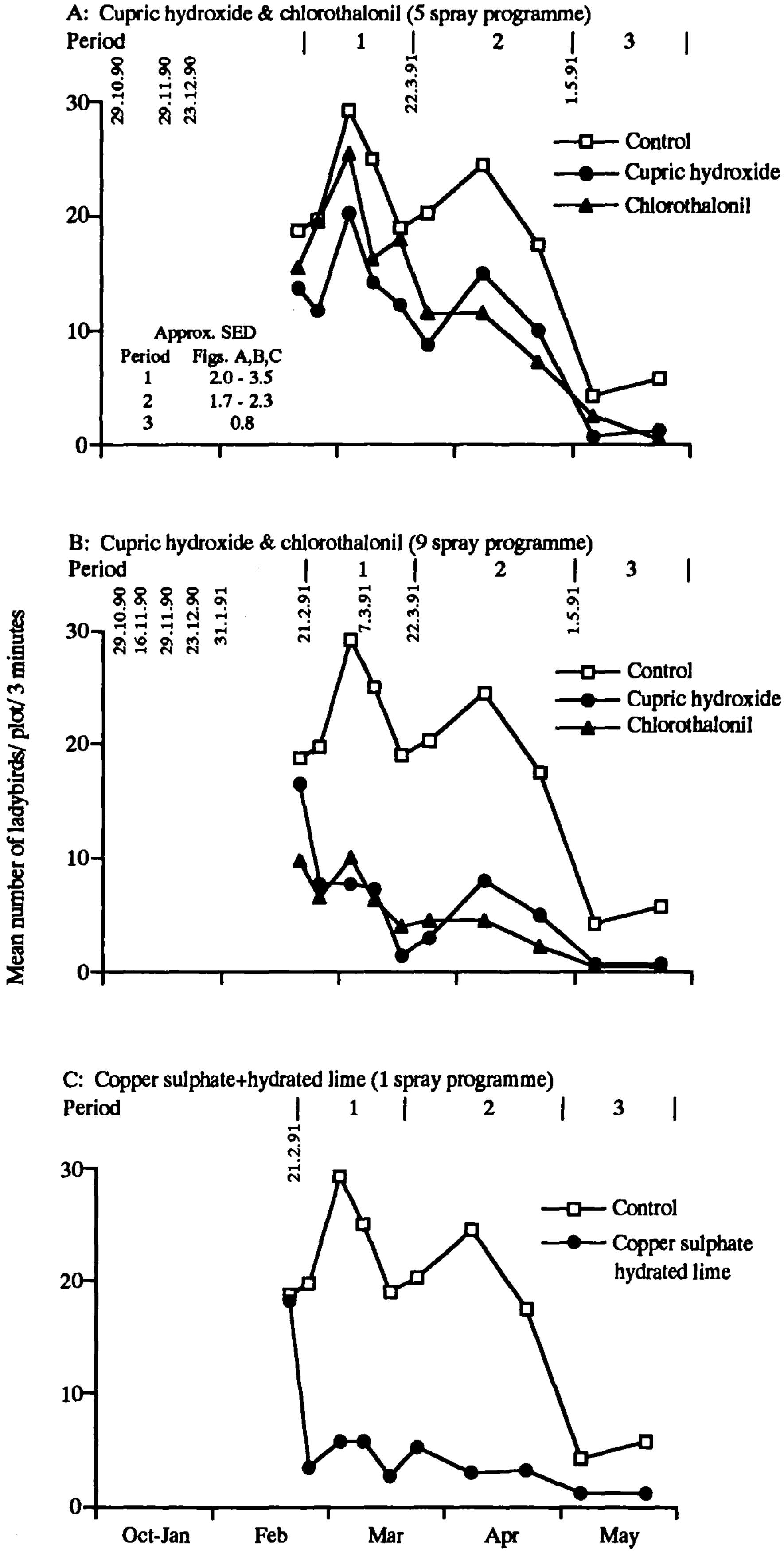
Numbers of ladybirds were assessed at weekly intervals from 20 February until 25 March, and then fortnightly until numbers on the unsprayed plots declined in late May. Counts were made between 1100-1500 hours. Each plot was visually searched for 3 minutes, 1.5 minutes each side of the row, recording all live larvae, pupae and adult SBL. Areas within half a tree of plot boundaries were not assessed, to avoid any treatment edge effects.

The assessments were divided into three periods for analysis: 1) 20 February - 18 March; 2) 25 March - 22 April; 3) 6 - 23 May. These periods corresponded to intervals between fungicide applications on 22 March and 1 May. Mean ladybird numbers on each sampling date were transformed ($\sqrt{x}$) and ANOVA was used to compare the effects of fungicides and spray frequencies over the whole experiment and for each period separately. The numbers of immature ladybirds on treated and untreated plots were compared using a Mann-Whitney test with the normal approximation (Zar 1984). Rainfall data were obtained from the Northland Regional Council meteorological station at Glenbervie forest.

<u>Results</u>

Overall, the two 5-spray programmes significantly ($P < 0.01$) reduced numbers of ladybirds by 41% for cupric hydroxide and 31% for chlorothalonil compared with unsprayed trees (Fig. 5.4a). During Period 1, numbers of ladybirds on chlorothalonil-treated and untreated plots were similar, and significantly ($P < 0.05$) greater than on cupric hydroxide-treated plots. This was 8.5-12.5 weeks after the third fungicide application. After the fungicide applications on 22 March (Periods 2 & 3), both treatments had less ($P < 0.01$) ladybirds than on untreated plots, but were not significantly different from each other.

Figure 5.4 Effect of different spray programmes of three fungicides on mean numbers of steelblue ladybirds (untransformed data).



The 9-spray programmes of cupric hydroxide and chlorothalonil significantly ($P < 0.001$) reduced ladybird densities by 68% and 75% respectively, compared with unsprayed trees (Fig. 5.4b). There was no significant ($P > 0.05$) difference in ladybird densities between plots receiving either of the two 9-spray programmes. Over the three periods, numbers of ladybirds were significantly ($P < 0.001$) lower on trees sprayed 9 times compared with 5 times.

Prior to the single application of copper sulphate/hydrated lime, trees in the treatment plots had a similar density of ladybirds as untreated trees (Fig. 5.4c). Spraying resulted in a sustained, significant ($P < 0.001$) reduction in ladybird densities of 81% over the full 3 month monitoring period. Ladybird densities in this treatment were significantly ($P < 0.001$) different from the 5-spray programmes of cupric hydroxide and chlorothalonil, but not different from the two 9-spray programmes.

Larvae and pupae comprised 1% of the total number of ladybirds recorded. Immature ladybirds were observed from 20 February to 25 March. There were significantly ($P < 0.05$) more larvae and pupae on untreated trees (0.54 per plot per 3 min) than on fungicide treated trees (0.11 per plot per 3 min) during this time. Rainfall during the trial (29.10.90 - 23.5.91) was 414 mm.

5.5 Discussion

In general, insecticides are highly toxic to natural enemies whereas fungicides have a relatively low direct toxicity (Theiling & Croft 1988). This also applied to SBL, but the high densities of SWS encountered in sprayed orchards (Section 2.2) may not be just the result of the secondary effects of insecticides. The detrimental effects of fungicides, particularly copper-based ones, of suppressing ladybird populations and reducing predation of sprayed scales, are also likely to reduce the ability of SBL to regulate wax scale populations.

Fungicide applications could affect biological control of SWS because the time of most frequent spraying coincides with the presence of the scale stages that are vulnerable to predation by ladybirds. The most important period for disease control of tangelo fruit is the 3-5 months following fruit set (Olson *et al.* 1992), which occurs about November. SBL feed on first and second instar SWS (Section 4.3), which are present from about December to March (Section 2.3, Olson *et al.* 1993). These experiments suggest that the use of copper fungicides should be avoided from about November to February, to minimise disruption to ladybird predation of the vulnerable scale stages.

Bordeaux mixture was highly disruptive to field populations of SBL, with one application being equivalent to several of cupric hydroxide or chlorothalonil. This corroborates a study (cited by Hely *et al.* 1982), which reported an outbreak of SWS in the season after citrus trees were sprayed with Bordeaux mixture. This outbreak was attributed to reduced ladybird predation. Bordeaux mixture has been largely superseded by newer copper fungicides such as cupric hydroxide. Unfortunately this appears to be just as disruptive to ladybirds when used in multiple applications.

Chlorothalonil suppressed ladybird numbers for a shorter period than cupric hydroxide, and was less disruptive to SBL predation than copper fungicides. However, the field experiment showed that multiple applications of chlorothalonil will still reduce numbers to an extent similar to cupric hydroxide. Neither fungicide could be used in a typical spray programme without severely reducing ladybird populations within the orchard. Cupric hydroxide residues are long lasting on foliage (Anon. 1993b), and the longevity of fungicide residues in the field experiment may have been enhanced by drier than normal weather. Rainfall during the experiment was 58% lower than the 30 year average.

The large reduction in ladybird densities following fungicide applications was probably due to some repellent effect, since the laboratory experiments indicated that mortality was likely to have been low. This effect was greater with an increased spraying frequency. Hely *et al.* (1982) also concluded that SBL were repelled by heavy deposits of Bordeaux mixture. The lower number of immature ladybirds on fungicide-treated trees may simply reflect the lower numbers of adult ladybirds present, or it could have resulted from increased larval mortality. The direct toxicity of fungicides to larvae was not tested, but predation by larvae was reduced by a similar amount to predation by adults.

The laboratory experiments identified mineral oils, the IGR and the potassium soap as potentially causing less disruption to SBL than organophosphates and synthetic pyrethroids. The IGR buprofezin, had the least overall effect on SBL of all the insecticides tested. Buprofezin is effective against *C. floridensis* (Dreishpoun *et al.* 1990, cited by Mendel *et al.* 1991), several other scale insects, whiteflies and planthoppers (Yarom *et al.* 1988). It acts mainly on juvenile stages, preventing chitin synthesis, but can also reduce the longevity, fecundity and fertility of adults (Smith & Papacek 1990, Mendel *et al.* 1991).

The three mineral oils had a relatively low direct toxicity to SBL, but 'Sunspray' substantially disrupted predation by ladybirds. The laboratory experiments were assessed after 24 hours and longer term effects on predation need to be investigated. The fatty acid product was not disruptive and had no residual toxicity to SBL in the experiment on predation, but caused high mortality when ladybirds were dipped. Dipping gave the ladybirds a much higher exposure to the chemical, which probably accounts for the difference in toxicity between experiments. This product needs to be tested on ladybirds in an orchard to determine whether it will disrupt biological control of SWS and CWS. It may be possible to minimise direct toxicity by applying at times of day when ladybirds are relatively inactive.

The high toxicity of organophosphates and synthetic pyrethroids to natural enemies reported by Theiling & Croft (1988) was confirmed for SBL, although Croft & Whalon (1982) noted that synthetic pyrethroids caused a range of toxicity levels among coccinellid species. These insecticides are likely to be highly disruptive to scale predation by ladybirds. In addition, organophosphates may interfere with parasites of scale and predatory mites. Based on its lower toxicity to SBL, chlorpyrifos may be preferable to diazinon for use against SWS and CWS. The organotin miticide, azocyclotin, was less toxic to ladybirds than diazinon. It did interfere with predation, however, and could have a disruptive influence on ladybirds. The surfactant can be regarded as non-disruptive to SBL.

5.6 Summary

- Fungicides and insecticides were bioassayed on citrus leaves, to determine their toxicity to steelblue ladybirds and their effect on predation of soft wax scale by these ladybirds.
- Copper-based fungicides were more toxic than non-copper fungicides at three times label rates.
- Feeding by both larval and adult ladybirds was greatly reduced by a copper fungicide.
- Three copper-based fungicides, cupric hydroxide, copper oxychloride and copper sulphate/hydrated lime, significantly reduced predation by adult ladybirds by 71-85%.
- Six non-copper fungicides were less disruptive.
- Mineral oils had a relatively low toxicity, while chlorpyrifos was the less toxic of the two organophosphates tested.
- The insecticides diazinon, mineral oil and the miticide, azocyclotin, reduced predation by 54-85%.
- Buprofezin caused little mortality to steelblue ladybirds and did not interfere with their predation of SWS.
- An insecticidal soap did not affect predation but was relatively toxic.
- Steelblue ladybirds were monitored for 11 weeks on citrus trees sprayed with 3 fungicides under different spray regimes.
- Cupric hydroxide and chlorothalonil significantly reduced ladybird densities by 41% and 31% respectively under a 5-spray programme, and by 68% and 75% respectively in a 9-spray programme compared with unsprayed plots.
- There was no significant difference in ladybird densities between fungicides for either the 9- or 5-spray programmes.
- Both fungicides suppressed ladybird densities for several weeks after application.
- Copper sulphate/ hydrated lime was highly disruptive, with a single application reducing ladybird densities by 81%.
- Disruption to the activity of ladybirds caused by fungicides could affect biological control of soft wax scale because the presence of scale stages that are preyed on by steelblue ladybirds coincides with when citrus fruit are most susceptible to fungal diseases.

Chapter 6 SYNTHESIS AND DISCUSSION

This study examined the feasibility of changing from the present means of controlling wax scales by relying on insecticides, to methods which adopt the principles of IPM and place the emphasis on biological control. The first objective of this research was to study and compare the population dynamics of SWS and CWS. The different phenology of the two species helped to explain why SWS was more abundant than CWS around Kerikeri. SWS eggs hatched over a shorter period and the scales developed through to third instars several months quicker than CWS. This was probably because SWS eggs hatched in early summer, two months before those of CWS, whose first and second instars developed during autumn and winter. Consequently, these stages that have the least wax protection, were vulnerable to adverse environmental conditions and predation for longer in CWS than in SWS.

A second objective of this study was to determine the major mortality factors of SWS and CWS. Life tables were compiled at two orchards with few ladybirds, where adverse environmental conditions were probably responsible for most of the 89-95% mortality of crawlers, and the 73-83% mortality of settled first and second instars. Immature scales are particularly vulnerable to desiccation from extremes of temperature and low humidities (Mendel *et al.* 1984b). In addition to these two factors, Beattie (1988) also identified the failure to insert mouthparts and crowding as major causes of mortality of first and second instar SWS and CWS in Australia.

Among natural enemies, ladybirds, which preyed on first and second instar scales, were relatively more important than mortality caused by parasitoids and fungal pathogens in reducing scale populations. At four orchards with abundant ladybirds, mortality of settled first and second instar scales was approximately 99%. In contrast to this study, however, Beattie (1988) concluded that predation had no effect on the population dynamics of either SWS or CWS, although he recorded that several species of coccinellids, including SBL, preyed on first and second instar scales. This difference in the significance of predation may have been related to the different scale and ladybird faunas on New Zealand and Australian orchards. SBL may have had a more preferred prey available, or been less abundant at Beattie's study area. Other

Australian studies, however, for example Smith (1970), Snowball (1972), Milne (1981) and Hely *et al.* (1982) have stated that coccinellid predators were important in reducing populations of SWS. Life table studies of Florida wax scale (Podoler *et al.* 1981) and black scale (Podoler *et al.* 1979, Mendel *et al.* 1984a) also found that predation by the ladybird *Chilocorus bipustulatus* was a major mortality factor of larval scale.

Overall mortality of third instar and adult scales was about 80% and 50% respectively. Once scales reached the third instar, they were less vulnerable to the weather. Mortality of third instar and adult SWS from parasites and predators was less than 10%. The levels of parasitism observed in this study were unlikely to reduce populations of SWS significantly compared with other forms of mortality. The percentage parasitism of SWS was low partly because only one primary parasitoid species, *Euxanthellus philippiae*, was found and it did not attack adult SWS. Disease killed approximately 20% of adult SWS, although the proportion varied greatly among samples. The laboratory culture of pathogens from dead scale showed that the level of disease was underestimated. Some scales were sampled months after they had died, and the visual assessment could not attribute the cause to disease with certainty. Parasitism reached about 10% in third instar CWS and 20% in adults. It was suggested that the invulnerability of adult SWS and the asynchronous phenologies of the two scale species may have contributed to a higher percentage of parasitism than in SWS. Parasitoids emerging from SWS had vulnerable stages of CWS available to parasitise but not vice versa. Mortality due to disease was about 5% in third instar and adult CWS which was lower than occurred in SWS.

Compared with SWS and CWS in Australia (Beattie 1988), in this study parasitism was lower for SWS but higher in CWS. The level of disease was lower in both species. In Australia, SWS has been controlled by the successful introduction of parasitoids (Smith & Papacek 1985, Sands *et al.* 1986), so a relatively high level of parasitism was expected. In contrast, CWS, which probably became established in Australia in the early 1960s (Snowball 1970), is becoming an increasing problem due to a lack of biological control (Beattie 1988). Although it is attacked by several parasitoids and an egg predator, these are considered to have little impact on reducing its numbers (Snowball 1970). The densities of CWS encountered during this study indicated that the level of biological control was generally sufficient to prevent pest problems. Following the arrival of CWS in New Zealand and its subsequent population explosion, *E. philippiae* was largely responsible for the reduction in scale density on mangroves (*Avicennia marina* Forster) (Cumber 1972). *E. philippiae* was introduced to Australia from New Zealand but it failed to become established (Sands *et al.* 1986).

Mortality factors may simply reduce populations or they can also regulate numbers around some equilibrium density if they operate in a directly density-dependent manner. Some mortality factors such as weather act in a density-independent fashion, whereas others such as natural enemies are capable of regulation (DeBach & Rosen 1991). In this study, however, mortality from ladybirds, parasitoids or disease was not shown to act in a density-dependent manner. No density-dependent mortality factors were found in approximately half of 58 entomological studies reviewed by Stiling (1988). This does not necessarily mean that density-dependent mortality was absent. Hassell *et al.* (1989) in a critique of Stiling's review, pointed out that the likelihood of demonstrating density-dependent mortality increased with the number of generations studied. Alternatively key factor analysis may fail to detect regulatory processes operating at a different level from the mean population size. Southwood & Reader (1976) did not detect any density-dependent mechanisms over 11 generations of the viburnum whitefly, *Aleurotrachelus jelinekii* (Frauenfeld). Part of this data was reanalysed and density dependence was identified on a leaf-to-leaf basis (Hassell *et al.* 1987, Southwood *et al.* 1989). Density dependence acting between generations can thus be obscured by within-generation random heterogeneity (Hassell *et al.* 1987).

It seems likely that a combination of factors, environmental, natural enemies and competition, was responsible for regulating populations of SWS and CWS. Density-dependent mortality arising through intra-specific competition was not specifically investigated as part of this study, but is potentially an important regulatory factor. Scales compete for space and nutrients, and at Willetts' orchard between 1992 and 1993, the mean scale size and hence egg production, decreased with an increase in scale density. Thus competition could act in a density-dependent way. Beattie (1988) stated that competition among crawlers had a regulatory effect at high densities of SWS and CWS. Competition can also have longer term effects on scale populations. Itioka & Inoue (1991) found that a high density of pink and Indian wax scales greatly reduced the survival of the subsequent generation of scales settling on the same twigs. McClure (1980) similarly found that elongate hemlock scale had a lower survival and fecundity, and longer development time in the generation following a high density of infestation. These effects were due to a reduction in the availability of foliar nitrogen (McClure 1980).

The third major objective of this study was to quantify the importance of ladybirds. Population monitoring and field experiments confirmed that ladybirds (predominantly SBL) could reduce local scale populations to the point of extinction, and predation was shown to be the key mortality factor causing population changes where ladybirds were abundant. Field experiments compared the disappearance of scale on bagged branches with and without ladybirds. The increased loss of scales in the presence of ladybirds was accounted for by the feeding rate of larval and adult SBL. Currently biological control of SWS and CWS depends on having sufficient numbers of SBL present while the vulnerable first and second instar stages are present.

One way to reduce the reliance on SBL is to adopt the classical approach to biological control and import additional natural enemies. There are numerous examples overseas where armoured and wax scale insects have been successfully brought under control by this method (DeBach & Rosen 1991). In southern California, for example, six species of scale that are serious pests elsewhere, are completely controlled by their natural enemies (DeBach & Rosen 1991). In Queensland, pink wax scale was successfully controlled within four years of the release of *Anicetus beneficus* Ishii & Yasumatsu (Smith 1986). The decline of SWS in New South Wales was largely due to *A. communis* (Milne 1981, Sands *et al.* 1986, Beattie 1988) while *P. nyasicus* had a similar effect on SWS in Queensland (Smith & Papacek 1985, Sands *et al.* 1986) and Papua New Guinea (Williams 1986). Several importations of natural enemies have been made against scale pests in New Zealand, but not for SWS or CWS (Cameron *et al.* 1989).

The susceptibility of third instar and adult SWS to natural enemies needs to be increased to improve the existing level of biological control. Besides *P. nyasicus* and *A. communis*, two other potential natural enemies that could be evaluated for introduction to New Zealand are *Scutellista cyanea* Motschulsky (Hymenoptera: Pteromalidae) and *Tetrastichus ceroplastae* (Girault) (Hymenoptera: Eulophidae). Both of these latter two species were also successfully established in Australia (Sands *et al.* 1986). Except for *S. cyanea*, they attack third instar and adult scales (Sands *et al.* 1986). *S. cyanea* is an egg predator and facultative ectoparasite of SWS (Snowball 1969), CWS (Beattie 1988) and Florida wax scale (Podoler *et al.* 1981). It was released in New Zealand against black scale but it failed to become established (Cameron *et al.* 1987). Other potential natural enemies of wax scales include the polyphagous ladybirds of the genus *Chilocorus*. Three species including *C. bipustulatus* were introduced to New Zealand between 1987 and 1989 as predators of armoured scales, but they have apparently not become established (Hill *et al.* 1993).

Fungal entomopathogens have much potential as biocontrol agents and have several advantages over chemicals as pesticides. They are generally more specific, safer, long-lasting, compatible with other natural enemies and less likely to induce pest resistance (Hall 1981, Quinlan 1988). Their effectiveness, however, especially in temperate zones, is limited by their requirement for high humidities (Hall 1981). The mortality caused by pathogens also depends on the rate of transmission, virulence of the numerous strains and the susceptibility of the hosts (Dempster 1975). This susceptibility can itself vary according to stress factors such as population density and environmental conditions. Because the effects of disease are dependent on several variables, the occurrence of epizootics is often sporadic. The variable incidence of disease found in this study fits this pattern.

The natural occurrence of *Verticillium lecanii* and *Fusarium* spp. in SWS and CWS is encouraging for biological control, but considerable development is required before pathogenic fungi could be actively used as a method of controlling these pests. Their pathogenicity to SWS, CWS and beneficial insects, and levels of inoculation still need to be experimentally tested. Another problem is that the maintenance of the necessary high humidities for entomopathogenic fungi, is incompatible with the need to reduce the incidence of fungal plant diseases. Many broad spectrum fungicides used to control these diseases are also toxic to entomopathogens such as *V. lecanii* (Quinlan 1988). Also the levels of humidity found in New

Zealand are relatively low for the transmission and development of entomopathogens such as *V. lecanii.* These factors mean that fungal pathogens are likely to be a less effective means of improving biological control of wax scales than the importation of parasitoids.

Breeding of SBL was synchronised more closely with that of SWS than CWS, and therefore ladybirds were more abundant when first instar SWS were emerging and settling. Since ladybirds are an important predator, why did SWS reach high densities on more orchards than CWS? It was speculated that biological control of SWS was disrupted by pesticides. Fungicides and insecticides are likely to be applied most frequently during spring and summer when fruit are most susceptible to plant pathogens and insect populations are increasing. This would cause more interference with ladybird predation of SWS than CWS because of their respective phenologies.

Fungicides and insecticides are currently essential means of controlling plant pathogens and pests such as thrips and mites on citrus orchards in New Zealand. The fourth major objective of this study was to assess the suitability of various pesticides for an IPDM programme. The main finding was that non-copper fungicides appear to be more compatible with SBL than copper-based types for an IPDM programme where biological control of wax scales is a priority. In laboratory experiments, non-copper fungicides were less toxic to SBL and less disruptive to ladybird predation than copper-based types. In an orchard, however, numbers of ladybirds were reduced by both copper and non-copper fungicides.

The disruptive effects of copper fungicides are important because the period when fruit are most susceptible to fungal diseases (and hence require more frequent spraying) coincides with when SWS populations are usually most vulnerable to SBL. Copper is an essential trace element for citrus (Mooney *et al.* 1991) so copper sprays have both fungicidal and nutritional properties. Thompson (1939) found that the increased vigour of citrus trees following copper and zinc treatments led to increased densities of two diaspid scales. The substitution of copper fungicides with less disruptive chemicals could therefore have dual benefits. Orchardists should avoid or reduce applications of copper-based fungicides during spring and summer to minimise disruption to predation by ladybirds. However, once SWS have developed to third instars, copper fungicides may be preferable to broad spectrum fungicides which are toxic to fungal pathogens. Any replacements should not compromise disease control, and at present insufficient information is available to recommend a specific alternative.

This study identified several insecticides that are potentially compatible with SBL. However, their efficacy against SWS is unknown. Smith & Ironside (1977) screened a range of insecticides for toxicity towards SWS, but these did not include the mineral oils, insect growth regulator and potassium salts which were the least disruptive to SBL. Mineral oils are widely used against citrus scales in IPDM programmes because of their low residual toxicity to natural enemies (Anon. 1991). While three oils were not toxic to SBL, the one mineral oil tested disrupted predation. Potassium salts of fatty acids (insecticidal soaps) are effective against several arthropod pests such as whitefly (Puritch *et al.* 1982) and mites (Osborne 1984), but do not appear to have been commonly used against scales.

Buprofezin was the least disruptive of the insecticides screened. Its efficacy has not been tested on SWS, but six other IGRs tested by Peleg (1982, 1988) and Eisa *et al.* (1991) inhibited the development of Florida wax scale. IGRs including buprofezin have a low toxicity towards some parasites (Peleg 1983b, Smith & Papacek 1990) and it is this selectivity which makes them attractive as potential components of IPM programmes. However, IGRs increased the mortality of some coccinellids. Although buprofezin was non-toxic to adult *Cryptolaemus montrouzieri*, it increased the mortality of juveniles (Smith & Papacek 1990). Four other IGRs tested against *Chilocorus bipustulatus* (Peleg 1983a) and *Rodolia cardinalis* (Loia & Viggiani in press) killed the larvae or inhibited their pupation and adults laid non-viable eggs.

Insecticides are generally most effective against the younger instars of scale insects which are less well protected than older stages. First and second instar SWS and pink wax scale are the stages most susceptible to insecticides (Smith 1970, 1976). Mobile stages like crawlers are susceptible to both direct contact from sprays and spray residues, while the later sessile instars have a thicker covering which protects them from direct contact with insecticides. Chemical control of SWS and CWS is simplified by their univoltine life cycle because the most vulnerable stages can be targeted at one time of year. For SWS populations, this "window of vulnerability" extends over approximately three months.

The precise timing of insecticide applications is critical to the effective control of scale insects (Walker *et al.* 1990). Recommendations for the timing of insecticides against SWS and CWS in New Zealand are based on the time of year when first and second instars are usually present (Helson 1973, Sale 1977, 1988). However, the seven week variation in the appearance of SWS crawlers over the past six years means that orchardists cannot rely on the calendar application of insecticides to target first and second instar scales accurately. The period when insecticides are most effective needs to be defined more precisely. For example, the optimal timing of insecticides to control two diaspid scales was at the peak of crawler emergence (Rice & Jones 1988, Walker *et al.* 1990). With data from more seasons, degree-day records should be useful for predicting the start and peak of crawler emergence in New Zealand and may help to improve the timing of insecticide applications.

Ladybirds cannot be relied on to be sufficiently abundant at the right time of year to achieve control of wax scales with current spray programmes, particularly those involving highly toxic organophosphate and synthetic pyrethroid insecticides. DeBach & Rosen (1991) outlined various methods of conserving and augmenting natural enemies. The use of selective pesticides at the least injurious time and only when absolutely necessary is paramount. Other strategies that may be appropriate for SBL include the provision of refuges, for example in shelterbelts or by spraying alternate rows on different occasions to reduce the impact of pesticides. This should not affect the control of a sessile pest such as scale insects. Since SBL are polyphagous it may be possible to increase their populations by providing another food source, for example by planting a shelter species which supports a scale that is not a pest of citrus. The captive breeding and release of predators and parasites are commonly used overseas, but although SBL were successfully reared on an artificial diet (unpubl. data), the small size of the citrus industry in New Zealand is likely to make the costs of artificial rearing prohibitive.

Orchardists need simple, fast and precise means of assessing scale and ladybird populations for an IPM programme. Populations of first and second instar scales are easily monitored by randomly sampling leaves. Visual counts meet the requirements for sampling ladybirds except when the majority of the population are immature. This method could be supplemented by hand searching a 3-dimensional quadrat area of foliage during spring.

There are several priorities for further progress towards an IPM programme for wax scales. Control action thresholds need to be developed, in conjunction with the establishment of ratios of scale and ladybird densities that prevent scale populations from increasing above economic injury levels. A range of additional natural enemies should be evaluated for importation into New Zealand. The introduction of parasitoids or predators that attack third instar and adult scales would complement the existing biological control from SBL. It is critical to develop spray programmes which are compatible with SBL and other natural enemies. The efficacy against citrus diseases and SWS, of the less disruptive fungicides and insecticides and their optimum timing, need to be tested. The longer term effects on SBL of these insecticides, particularly mineral oils and IGRs, also need to be evaluated before recommendations can be made regarding the best pesticides for an IPDM programme.

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Appendix 1: Overall percentage of live Chinese wax scale in each instar. Calculated from percentage live in samples of leaves and wood, weighted according to proportions of scale on each substrate.

Month		% total number	% of each instar 1&2	3	4
Boon 1991					
November	leaves	57.1	0.0	3.3	96.7
	wood	42.9	0.0	2.6	97.4
	overall		*0.0*	*3.0*	*97.0*
Hibbert-Foy 1991					
November	leaves	13.8	0.0	21.1	78.9
	wood	86.2	0.0	5.3	94.7
	overall		*0.0*	*7.5*	*92.5*
Irvine 1991					
November	leaves	69.2	0.0	5.7	94.3
	wood	30.8	0.0	8.1	91.9
	overall		*0.0*	*6.4*	*93.6*
Willetts 1991					
November	leaves	22.0	0.0	43.6	56.4
(est.)	wood	78.0	0.0	17.9	82.1
	overall		*0.0*	*23.6*	*76.4*
Strang 1992					
October	leaves	34.0	2.8	88.9	8.3
(est.)	wood	66.0	0.0	60.0	40.0
	overall		*1.0*	*69.8*	*29.2*
Strang 1992					
November	leaves	22.0	0.0	37.3	62.7
(est.)	wood	78.0	0.0	33.3	66.7
	overall		*0.0*	*34.2*	*65.8*
Fiske 1992					
November	leaves	17.1	0.0	52.4	47.6
	wood	82.9	0.0	12.4	87.6
	overall		*0.0*	*19.2*	*80.8*

Month	Sample	Willetts 1992 % live scale	% of each instar 1&2	3	4	Willetts 1993 % total number	% of each instar 1&2	3	4	Fiske 1993 % total number	% of each instar 1&2	3	4
April	leaves	98.6	95.8	4.2	0.0								
	wood	1.4	73.8	26.2	0.0								
	overall		*95.5*	*4.5*	*0.0*								
May	leaves	96.9	82.0	18.0	0.0					95.0	69.8	30.2	0.0
	wood	3.1	49.0	51.0	0.0					5.0	17.2	67.2	15.6
	overall		*81.0*	*19.0*	*0.0*						*67.2*	*32.1*	*0.8*
June	leaves	90.4	68.8	31.2	0.0	97.9	61.9	37.9	0.2	81.8	55.2	44.4	0.4
	wood	9.6	72.4	27.6	0.0	2.1	56.0	44.0	0.0	18.2	31.1	67.0	1.9
	overall		*69.1*	*30.9*	*0.0*		*61.8*	*38.0*	*0.2*		*50.8*	*48.5*	*0.7*
July	leaves	84.0	75.6	24.4	0.0	95.6	48.3	51.7	0.0	70.4	37.8	62.2	0.0
	wood	16.0	46.7	52.6	0.7	4.4	27.6	55.2	17.2	29.6	19.3	72.7	8.0
	overall		*71.0*	*28.9*	*0.1*		*47.4*	*51.9*	*0.8*		*32.3*	*65.3*	*2.4*
August	leaves	74.0	65.1	34.9	0.0	88.1	28.7	71.3	0.0	62.9	31.3	67.3	1.5
	wood	26.0	18.0	74.1	7.8	11.9	19.3	76.0	4.8	37.1	8.7	66.6	24.7
	overall		*52.9*	*45.1*	*2.0*		*27.6*	*71.9*	*0.6*		*22.9*	*67.0*	*10.1*
September	leaves	63.9	40.8	59.2	0.0	87.4	7.9	88.7	3.3	47.9	5.9	87.2	6.9
	wood	36.1	4.6	65.4	30.0	12.6	0.7	61.8	37.5	52.1	0.5	39.1	60.4
	overall		*27.7*	*61.4*	*10.8*		*7.0*	*85.3*	*7.6*		*3.1*	*62.1*	*34.8*
October	leaves	34.4	15.2	78.4	6.4	42.7	0.0	72.6	27.4	40.9	1.3	93.8	5.0
	wood	65.6	1.6	64.1	34.3	57.3	0.6	47.2	52.1	59.1	0.0	16.2	83.8
	overall		*6.3*	*69.0*	*24.7*		*0.3*	*58.0*	*41.6*		*0.5*	*47.9*	*51.6*
November	leaves	26.0	1.6	66.1	32.3	36.0	0.0	30.5	69.5	3.7		50.0	50.0
	wood	74.0	0.2	41.8	58.0	64.0	0.0	26.4	73.6	96.3		6.0	94.0
	overall		*0.6*	*48.1*	*51.3*		*0.0*	*27.9*	*72.1*		*0.0*	*7.6*	*92.4*
December	leaves	14.5	0.0	0.0	100	16.5	0.0	11.5	88.5	3.1		25.0	75.0
	wood	85.5	0.0	0.4	99.6	83.5	0.0	8.0	92.0	96.9		0.5	99.5
	overall		*0.0*	*0.3*	*99.7*		*0.0*	*8.6*	*91.4*		*0.0*	*1.3*	*98.7*
January						11.6	0.0	1.5	98.5	2.5			100.0
						88.4	0.0	0.0	100.0	97.5			100.0
							0.0	*0.2*	*99.8*		*0.0*	*0.0*	*100.0*
February						15.7			100.0				
						84.3			100.0	100.0			100.0
							0.0	*0.0*	*100.0*		*0.0*	*0.0*	*100.0*

Appendix 2: Numbers of live female soft wax scale and percentage in each stage, from field samples November 1990 - December 1993.

Year Orchard	Instar	December n	December %	January n	January %	February n	February %	March n	March %	April n	April %	May n	May %	June n	June %	July n	July %	August n	August %	September n	September %	October n	October %	November n	November %	December n	December %	January n	January %
1990				Jan 91																									
Rhodes	1st&2nd			39	*100.0*																				*0.0*		*0.0*		*0.0*
	3rd				*0.0*																				*0.0*		*0.0*		*0.0*
	Adult				*0.0*																			69	*100.0*	41	*100.0*	81	*100.0*
	Total	0		39		0		0		0		0		0		0		0		0		0		69		41		81	
1991																													
Birchall	1st&2nd			4675	*100.0*	21	*18.8*				*0.0*				*0.0*														
	3rd				*0.0*	91	*81.3*			570	*95.0*			316	*65.8*														
	Adult				*0.0*		*0.0*			30	*5.0*			164	*34.2*														
	Total	0		4675		112		0		600		0		480		0		0		0		0		0		0		0	
Hellberg	1st&2nd										*0.0*				*0.0*														*0.0*
	3rd									619	*81.9*			185	*33.3*														*0.0*
	Adult									137	*18.1*			370	*66.7*													102	*100.0*
	Total	0		0		0		0		756		0		555		0		0		0		0		0		0		102	
Hendl	1st&2nd			1029	*100.0*	78	*24.1*		*0.0*		*0.0*				*0.0*				*0.0*				*0.0*		*0.0*				*0.0*
	3rd				*0.0*	246	*75.9*	57	*87.7*	299	*84.0*			66	*16.8*			10	*13.9*			4	*4.7*		*0.0*				*0.0*
	Adult				*0.0*		*0.0*	8	*12.3*	57	*16.0*			326	*83.2*			62	*86.1*			81	*95.3*	50	*100.0*			30	*100.0*
	Total	0		1029		324		65		356		0		392		0		72		0		85		50		0		30	
Hume	1st&2nd			233	*100.0*	424	*92.0*				*0.0*				*0.0*				*0.0*										
	3rd				*0.0*	37	*8.0*			482	*99.4*			99	*24.4*			1	*0.8*										
	Adult				*0.0*		*0.0*			3	*0.6*			306	*75.6*			119	*99.2*										
	Total	0		233		461		0		485		0		405		0		120		0		0		0		0		0	
Ritchie	1st&2nd			1058	*100.0*	241	*80.3*				*0.0*				*0.0*				*0.0*										
	3rd				*0.0*	59	*19.7*			725	*92.0*			109	*30.3*			23	*35.4*										
	Adult				*0.0*		*0.0*			63	*8.0*			251	*69.7*			42	*64.6*										
	Total	0		1058		300		0		788		0		360		0		65		0		0		0		0		0	
Strang	1st&2nd			2961	*100.0*	1207	*59.8*	4	*0.5*		*0.0*				*0.0*				*0.0*				*0.0*		*0.0*				
	3rd				*0.0*	813	*40.2*	824	*99.2*	661	*97.1*			102	*35.9*			9	*20.0*			2	*1.3*		*0.0*				
	Adult				*0.0*		*0.0*	3	*0.4*	20	*2.9*			182	*64.1*			36	*80.0*			147	*98.7*	71	*100.0*				
	Total	0		2961		2020		831		681		0		284		0		45		0		149		71		0		0	
Total n	**Mean %**																												
	1st&2nd			9995	*100.0*	1971	*55.0*	4	*0.2*	0	*0.0*			0	*0.0*			0	*0.0*			0	*0.0*	0	*0.0*	0	*0.0*	0	*0.0*
	3rd			0	*0.0*	1246	*45.0*	881	*93.4*	3356	*91.6*			877	*34.4*			43	*17.5*			6	*3.0*	0	*0.0*	0	*0.0*	0	*0.0*
	Adult			0	*0.0*	0	*0.0*	11	*6.3*	310	*8.4*			1599	*65.6*			259	*82.5*			228	*97.0*	190	*100.0*	41	*100.0*	213	*100.0*
	Total	0		9995		3217		896		3666		0		2476		0		302		0		234		190		41		213	

Appendix 2: continued

Year Orchard	Instar	December n	December %	January n	January %	February n	February %	March n	March %	April n	April %	May n	May %	June n	June %	July n	July %	August n	August %	September n	September %	October n	October %	November n	November %	December n	December %	January n	January %
1992																													
Curtis	1st&2nd												0.0		0.0		0.0		0.0		0.0		0.0		0.0		0.0		0.0
	3rd											344	93.0	124	55.1	61	46.2	4	2.6	20	11.8		0.0		0.0		0.0		0.0
	Adult											26	7.0	101	44.9	71	53.8	149	97.4	149	88.2	159	100.0	182	100.0	138	100.0	168	100.0
	Total	0		0		0		0		0		370		225		132		153		169		159		182		138		168	
Fiske	1st&2nd																								0.0		0.0		0.0
	3rd																								0.0		0.0		0.0
	Adult																							155	100.0	93	100.0	102	100.0
	Total	0		0		0		0		0		0		0		0		0		0		0		155		93		102	
Hellberg	1st&2nd					1128	100.0	949	87.8	66	20.7		0.0		0.0		0.0		0.0		0.0		0.0		0.0		0.0		0.0
	3rd						0.0	132	12.2	249	78.1	324	99.4	201	96.6	213	90.3	59	66.3	28	43.8	2	3.3		0.0		0.0		0.0
	Adult						0.0		0.0	4	1.3	2	0.6	7	3.4	23	9.7	30	33.7	36	56.3	59	96.7	30	100.0	30	100.0	26	100.0
	Total	0		0		1128		1081		319		326		208		236		89		64		61		30		30		26	
Jack	1st&2nd			740	100.0	94	87.0																						
	3rd				0.0	14	13.0																						
	Adult				0.0		0.0																						
	Total	0		740		108		0		0		0		0		0		0		0		0		0		0		0	
Ritchie	1st&2nd												0.0		0.0		0.0		0.0		0.0		0.0		0.0		0.0		0.0
	3rd											27	73.0	211	66.4	188	67.6	33	13.5	12	7.1	7	13.0		0.0		0.0		0.0
	Adult											10	27.0	107	33.6	90	32.4	211	86.5	157	92.9	47	87.0	155	100.0	121	100.0	113	100.0
	Total	0		0		0		0		0		37		318		278		244		169		54		155		121		113	
Strang	1st&2nd							5	2.7		0.0		0.0		0.0		0.0		0.0		0.0		0.0		0.0		0.0		0.0
	3rd							179	97.3	333	99.4	270	92.8	174	74.4	93	38.3	22	51.2	9	6.8	3	2.2	1	0.7		0.0		0.0
	Adult								0.0	2	0.6	21	7.2	60	25.6	150	61.7	21	48.8	124	93.2	131	97.8	133	99.3	89	100.0	48	100.0
	Total	0		0		0		184		335		291		234		243		43		133		134		134		89		48	
Total n	**Mean %**																												
	1st&2nd			740	100.0	1222	93.5	954	45.3	66	10.3	0	0.0	0	0.0	0	0.0	0	0.0	0	0.0	0	0.0	0	0.0	0	0.0	0	0.0
	3rd			0	0.0	14	6.5	311	54.7	582	88.7	965	89.5	710	73.1	555	60.6	118	33.4	69	17.4	12	4.6	1	0.1	0	0.0	0	0.0
	Adult			0	0.0	0	0.0	0	0.0	6	0.9	59	10.5	275	26.9	334	39.4	411	66.6	466	82.6	396	95.4	655	99.9	471	100.0	457	100.0
	Total	0		740		1236		1265		654		1024		985		889		529		535		408		656		471		457	

Appendix 2: continued

Year Orchard	Instar	December n	December %	January n	January %	February n	February %	March n	March %	April n	April %	May n	May %	June n	June %	July n	July %	August n	August %	September n	September %	October n	October %	November n	November %	December n	December %	January n	January %
1993																													
Curtis	1st&2nd	85	100.0	414	100.0	258	100.0	104	28.3		0.0		0.0		0.0		0.0		0.0		0.0		0.0		0.0		0.0		
	3rd		0.0		0.0		0.0	263	71.7	119	100.0	206	85.5	174	59.6	55	37.7	28	16.0	7	4.7	5	3.1		0.0		0.0		
	Adult		0.0		0.0		0.0		0.0		0.0	35	14.5	118	40.4	91	62.3	147	84.0	143	95.3	156	96.9	104	100.0	72	100.0		
	Total	85		414		258		367		119		241		292		146		175		150		161		104		72		0	
Fiske	1st&2nd	58	100.0	286	100.0	361	100.0	98	21.3		0.0		0.0		0.0		0.0		0.0		0.0		0.0		0.0		0.0		
	3rd		0.0		0.0		0.0	363	78.7	256	99.2	242	91.0	201	90.5	176	58.9	119	47.6	37	16.0	20	7.6		0.0		0.0		
	Adult		0.0		0.0		0.0		0.0	2	0.8	24	9.0	21	9.5	123	41.1	131	52.4	194	84.0	242	92.4	191	100.0	137	100.0		
	Total	58		286		361		461		258		266		222		299		250		231		262		191		137		0	
Total n	**Mean %**																												
	1st&2nd	143	100.0	700	100.0	619	100.0	202	24.8	0	0.0	0	0.0	0	0.0	0	0.0	0	0.0	0	0.0	0	0.0	0	0.0	0	0.0		
	3rd	0	0.0	0	0.0	0	0.0	626	75.2	375	99.6	448	88.2	375	75.1	231	48.3	147	31.8	44	10.3	25	5.4	0	0.0	0	0.0		
	Adult	0	0.0	0	0.0	0	0.0	0	0.0	2	0.4	59	11.8	139	24.9	214	51.7	278	68.2	337	89.7	398	94.6	295	100.0	209	100.0		
	Total	143		700		619		828		377		507		514		445		425		381		423		295		209		0	
1990-1993																													
Total n	**Mean %**																												
	1st&2nd	143	100.0	11435	100.0	3812	82.8	1160	23.4	66	3.4	0	0.0	0	0.0	0	0.0	0	0.0	0	0.0	0	0.0	0	0.0	0	0.0	0	0.0
	3rd	0	0.0	0	0.0	1260	17.2	1818	74.5	4313	93.3	1413	88.9	1962	60.9	786	54.4	308	27.6	113	13.9	43	4.3	1	0.0	0	0.0	0	0.0
	Adult	0	0.0	0	0.0	0	0.0	11	2.1	318	3.3	118	11.1	2013	39.1	548	45.6	948	72.4	803	86.1	1022	95.7	1140	100.0	721	100.0	670	100.0
	Total	143		11435		5072		2989		4697		1531		3975		1334		1256		916		1065		1141		721		670	

Appendix 3: Numbers of live female Chinese wax scale and percentage in each stage, from field samples March 1991 - February 1994.

Year Orchard	Instar	February		March		April		May		June		July		August		September		October		November		December		January		February		March	
		n	%	n	%	n	%	n	%	n	%	n	%	n	%	n	%	n	%	n	%	n	%	n	%	n	%	n	%
1991/92																					*								
Boon	1st&2nd							33	*19.8*	37	*14.3*	11	*7.0*	72	*26.4*	0	*0.0*	0	*0.0*		*0.0*								
	3rd							134	*80.2*	222	*85.7*	144	*91.1*	199	*72.9*	200	*90.9*	44	*47.8*	3	*3.0*								
	Adult								*0.0*		*0.0*	3	*1.9*	2	*0.7*	20	*9.1*	48	*52.2*	96	*97.0*								
	Total	0		0		0		167		259		158		273		220		92		99		0		0		0			
																					*								
Hibbert-Foy	1st&2nd			245	*93.9*	277	*73.1*	167	*38.3*			44	*19.1*	13	*6.2*	2	*2.1*		*0.0*		*0.0*				*0.0*				
	3rd			16	*6.1*	102	*26.9*	269	*61.7*			182	*79.1*	196	*93.8*	85	*90.4*	35	*33.3*	13	*7.7*				*0.0*				
	Adult				*0.0*		*0.0*		*0.0*			4	*1.7*		*0.0*	7	*7.4*	70	*66.7*	156	*92.3*			135	*100.0*				
	Total	0		261		379		436		0		230		209		94		105		169		0		135		0			
																					*								
Irvine	1st&2nd							5	*2.0*	15	*5.2*	2	*1.5*	1	*0.7*		*0.0*		*0.0*		*0.0*								
	3rd							250	*98.0*	268	*93.1*	105	*77.8*	83	*59.3*	141	*70.1*	21	*22.6*	9	*6.3*								
	Adult								*0.0*	5	*1.7*	28	*20.7*	56	*40.0*	60	*29.9*	72	*77.4*	133	*93.7*								
	Total	0		0		0		255		288		135		140		201		93		142		0		0		0			
																					*								
Willetts	1st&2nd																				*0.0*								*0.0*
	3rd																			53	*23.8*								*0.0*
	Adult																			170	*76.2*							154	*100.0*
	Total	0		0		0		0		0		0		0		0		0		223		0		0		0		154	
Total n	**Mean %**																												
	1st&2nd			245	*93.9*	277	*73.1*	205	*20.0*	52	*9.7*	57	*9.2*	86	*11.1*	2	*0.7*	0	*0.0*	0	*0.0*			0	*0.0*			0	*0.0*
	3rd			16	*6.1*	102	*26.9*	653	*80.0*	490	*89.4*	431	*82.7*	478	*75.3*	426	*83.8*	100	*34.6*	78	*10.2*			0	*0.0*			0	*0.0*
	Adult			0	*0.0*	0	*0.0*	0	*0.0*	5	*0.9*	35	*8.1*	58	*13.6*	87	*15.5*	190	*65.4*	555	*89.8*			135	*100.0*			154	*100.0*
	Total	0		261		379		858		547		523		622		515		290		633		0		135		0		154	
1992/93																					*								
Fiske	1st&2nd																				*0.0*		*0.0*		*0.0*		*0.0*		*0.0*
	3rd																			69	*19.2*		*0.0*		*0.0*		*0.0*		*0.0*
	Adult																			290	*80.8*	139	*100.0*	77	*100.0*	89	*100.0*	88	*100.0*
	Total	0		0		0		0		0		0		0		0		0		359		139		77		89		88	
Hibbert-Foy	1st&2nd	37	*100.0*	469	*100.0*			159	*100.0*			117	*97.5*								*0.0*								
	3rd		*0.0*		*0.0*				*0.0*			3	*2.5*								*0.0*								
	Adult		*0.0*		*0.0*				*0.0*				*0.0*							21	*100.0*								
	Total	37		469		0		159		0		120		0		0		0		21		0		0		0		0	

Appendix 3: continued

Year Orchard	Instar	February n	%	March n	%	April n	%	May n	%	June n	%	July n	%	August n	%	September n	%	October n	%	November n	%	December n	%	January n	%	February n	%	March n	%
1992/93																		*		*									
Strang	1st&2nd											15	*50.0*					2	*1.4*		*0.0*		*0.0*		*0.0*		*0.0*		*0.0*
	3rd											15	*50.0*					96	*69.6*	24	*33.8*		*0.0*		*0.0*		*0.0*		*0.0*
	Adult												*0.0*					40	*29.0*	47	*66.2*	10	*100.0*	15	*100.0*	20	*100.0*	42	*100.0*
	Total	0		0		0		0		0		30		0		0		138		71		10		15		20		42	
						*		*		*		*		*		*		*		*		*							
Willetts	1st&2nd	1227	*100.0*	4464	*100.0*	345	*95.6*	122	*80.8*	438	*69.1*	565	*71.0*	280	*52.9*	192	*27.8*	43	*6.3*	3	*0.5*		*0.0*		*0.0*		*0.0*		*0.0*
	3rd		*0.0*	1	*0.0*	16	*4.4*	29	*19.2*	196	*30.9*	230	*28.9*	239	*45.2*	424	*61.4*	471	*69.1*	280	*48.1*	1	*0.4*		*0.0*		*0.0*		*0.0*
	Adult		*0.0*		*0.0*		*0.0*		*0.0*		*0.0*	1	*0.1*	10	*1.9*	75	*10.9*	168	*24.6*	299	*51.4*	266	*99.6*	251	*100.0*	203	*100.0*	306	*100.0*
	Total	1227		4465		361		151		634		796		529		691		682		582		267		251		203		306	
Total n	**Mean %**																												
	1st&2nd	1264	*100.0*	4933	*100.0*	345	*95.6*	281	*90.4*	438	*69.1*	697	*72.8*	280	*52.9*	192	*27.8*	45	*3.9*	3	*0.1*	0	*0.0*	0	*0.0*	0	*0.0*	0	*0.0*
	3rd	0	*0.0*	1	*0.0*	16	*4.4*	29	*9.6*	196	*30.9*	248	*27.1*	239	*45.2*	424	*61.4*	567	*69.3*	373	*25.3*	1	*0.1*	0	*0.0*	0	*0.0*	0	*0.0*
	Adult	0	*0.0*	0	*0.0*	0	*0.0*	0	*0.0*	0	*0.0*	1	*0.0*	10	*1.9*	75	*10.9*	208	*26.8*	657	*74.6*	415	*99.9*	343	*100.0*	312	*100.0*	436	*100.0*
	Total	1264		4934		361		310		634		946		529		691		820		1033		416		343		312		436	
1993/94								*		*		*		*		*		*		*		*		*					
Fiske	1st&2nd	278	*100.0*	360	*99.7*	153	*72.2*	245	*67.1*	247	*50.7*	227	*32.3*	172	*22.9*	17	*3.1*	1	*0.4*		*0.0*		*0.0*		*0.0*		*0.0*		
	3rd		*0.0*	1	*0.3*	59	*27.8*	117	*32.1*	236	*48.5*	458	*65.2*	504	*67.0*	345	*62.2*	136	*47.9*	18	*7.6*	3	*1.3*		*0.0*		*0.0*		
	Adult		*0.0*		*0.0*		*0.0*	3	*0.8*	4	*0.8*	17	*2.4*	76	*10.1*	193	*34.8*	147	*51.8*	220	*92.4*	226	*98.7*	227	*100.0*	157	*100.0*		
	Total	278		361		212		365		487		702		752		555		284		238		229		227		157			
										*		*		*		*		*		*		*		*		*			
Willetts	1st&2nd	497	*100.0*	434	*100.0*	281	*100.0*	490	*79.2*	435	*61.9*	347	*47.3*	187	*27.6*	38	*7.0*	2	*0.4*		*0.0*		*0.0*		*0.0*		*0.0*		
	3rd		*0.0*		*0.0*		*0.0*	129	*20.8*	267	*38.0*	380	*51.8*	487	*71.8*	461	*85.4*	261	*58.0*	97	*27.8*	33	*8.7*	1	*0.3*		*0.0*		
	Adult		*0.0*		*0.0*		*0.0*		*0.0*	1	*0.1*	6	*0.8*	4	*0.6*	41	*7.6*	187	*41.6*	252	*72.2*	345	*91.3*	298	*99.7*	303	*100.0*		
	Total	497		434		281		619		703		733		678		540		450		349		378		299		303			
Total n	**Mean %**																												
	1st&2nd	775	*100.0*	794	*99.9*	434	*86.1*	735	*73.1*	682	*56.3*	574	*39.8*	359	*25.2*	55	*5.1*	3	*0.4*	0	*0.0*	0	*0.0*	0	*0.0*	0	*0.0*		
	3rd	0	*0.0*	1	*0.1*	59	*13.9*	246	*26.4*	503	*43.2*	838	*58.5*	991	*69.4*	806	*73.8*	397	*52.9*	115	*17.7*	36	*5.0*	1	*0.2*	0	*0.0*		
	Adult	0	*0.0*	0	*0.0*	0	*0.0*	3	*0.4*	5	*0.5*	23	*1.6*	80	*5.3*	234	*21.2*	334	*46.7*	472	*82.3*	571	*95.0*	525	*99.8*	460	*100.0*		
	Total	775		795		493		984		1190		1435		1430		1095		734		587		607		526		460			
1991-1994	**Total n Mean %**																												
	1st&2nd	2039	*100.0*	5972	*97.9*	1056	*84.9*	1221	*61.2*	1172	*45.0*	1328	*40.6*	725	*29.8*	249	*11.2*	48	*1.4*	3	*0.0*	0	*0.0*	0	*0.0*	0	*0.0*	0	*0.0*
	3rd	0	*0.0*	18	*2.1*	177	*15.1*	928	*38.7*	1189	*54.5*	1517	*56.1*	1708	*63.3*	1656	*73.0*	1064	*52.3*	566	*17.7*	37	*2.6*	1	*0.1*	0	*0.0*	0	*0.0*
	Adult	0	*0.0*	0	*0.0*	0	*0.0*	3	*0.1*	10	*0.4*	59	*3.3*	148	*6.9*	396	*15.8*	732	*46.3*	1684	*82.2*	986	*97.4*	1003	*99.9*	772	*100.0*	590	*100.0*
	Total	2039		5990		1233		2152		2371		2904		2581		2301		1844		2253		1023		1004		772		590	

* % weighted according to proportions of scale on leaves and wood

Appendix 4: Scale size, fecundity, egg size and fertility from individual orchards.

Year	Orchard	Variety	Date collected	Scale size n	Scale size Mean (mm)	Fecundity n	Regression equation X coeff.	Regression equation constant	r2	Mean no. eggs by site	Mean no. eggs all>2.1mm	Egg size n	Egg size Mean (no./mm)	Fertility % eggs infertile	Fertility n	Fertility % emergence	
Soft wax scale																	
1990-91	Rhodes	Tangelo	29.11.90	35	4.21	35	1416.3	-4208.4	0.89	1748.6	1913.5	-		0.4	-		
1991-92	Curtis	Yen Ben	5.2.92	35	4.63	-					2401.9			-	31	86.3	
	Hellberg	Harward	15.1.92	69	3.30	27	785.4	-1564.7	0.87	1027.9		3	370.7	1.2	10	68.0	
	>2.1 mm			65	3.39	23	980.1	-2241.0	0.89	1079.3	973.0						
	Hendl	Harward	5.12.91	33	3.69	10	542.3	-1092.9	0.66	910.4	1325.0	3	327.9	0.4	-		
	Jack	Harward	5.12.91	55	4.02	26	1311.6	-3703.5	0.88	1562.6	1693.9	8	331.9	0.2	83	85.1	
	Strang	Tangelo	1.5.92	80	3.93	-					1591.7			-	-	Mean	79.8
1992-93	Curtis	Tangelo	21.12.92	56	3.64	21	1183.2	-2861.5	0.80	1448.9	1266.4	4	336.1	0.2	170	47.5	
	Fiske	Clementine	31.12.92	53	3.24	24	1094.8	-2587.1	0.76	963.3	806.7	9	366.8	0.2	107	51.6	
	Ritchie	Navel	28.1.93	50	3.62	-					1237.7				100	40.4	
	Strang	Tangelo	28.1.93	50	3.89	-					1544.5				46	42.2	
1993-94	Fiske	Clementine	13.1.94	59	3.20	-					753.8					Mean	45.4
Total (all scale)				575	3.76	143	1084.2	-2652.3	0.83	1424.2		27	346.7		547		
Total (>2.1mm)				571	3.77	139	1149.3	-2920.5	0.84		1409.8						
Mean														0.4			62.6
Chinese wax scale											all >2.5 mm						
1992	Hibbert-Foy	Tangelo	6.2.92	72	4.63	40	1282.0	-4011.0	0.89	1921.8	1749.3	10	291.6	0.3	-		
	Willetts	Tangelo	17.2.92	59	4.41	27	934.7	-2665.8	0.89	1453.2	1501.4	6	302.7	0.7	240	86.1	
1993	Fiske	Tangelo	12.2.93	58	4.05	26	892.7	-2552.3	0.84	1060.1		11	297.3	0.1	107	65.4	
	>2.5 mm			57	4.08	25	984.6	-2967.2	0.85	1045.5	1129.6						
	Strang	Tangelo	2.3.93	50	4.08	14	656.6	-1614.4	0.72	1061.9		6	310.7	0.1	42	88.6	
	>2.5 mm			48	4.16	12	1037.4	-3243.4	0.76	1070.5	1222.6						
	Willetts	Tangelo	22.2.93	50	3.45	-					430.2			-	80	62.3	
Total (all scale)				289	4.12	107	1039.2	-3057.2	0.84	1226.2		33	300.6		469		
Total (>2.5 mm)				286	4.14	104	1121.9	-3442.6	0.86		1206.6						
Mean														0.3		75.6	

Appendix 5: Numbers of different soft and Chinese wax scale stages on labelled branches of seven orchards with low and high levels of predation by ladybirds.

Orchard Hellberg
Year 1992
Scale species Soft
Ladybird predation Low

Scale stage	Branch 1	2	3	8	4	5	6	7	Mean	SEM	No./100 adults
Breeding adults	59	26	47	28	11	21	43	27	32.8		100
Eggs*	51525	22706	41045	24452	9606.3	18339	37552	23579	28601		87330
Log n+1	*4.71*	*4.36*	*4.61*	*4.39*	*3.98*	*4.26*	*4.57*	*4.37*	***4.41***	0.08	*4.94*
Crawlers*	35037	15440	27911	16628	6532.3	12471	25535	16034	19448		59384.4
Log n+1	*4.54*	*4.19*	*4.45*	*4.22*	*3.82*	*4.10*	*4.41*	*4.21*	***4.24***	0.08	*4.77*
k value	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	**0.17**		0.17 k1
% crawlers/eggs									68.0		
Settled 1st instars	2232	1894	2298	1006	907	1223	838	2006	1550.5		4734.4
Log n+1	*3.35*	*3.28*	*3.36*	*3.00*	*2.96*	*3.09*	*2.92*	*3.30*	***3.16***	0.07	*3.68*
k value	1.20	0.91	1.08	1.22	0.86	1.01	1.48	0.90	**1.08**		1.10 k2
% 1st/crawlers	6.4	12.3	8.2	6.1	13.9	9.8	3.3	12.5	9.1		
3rd instars	131	129	187	120					141.8		432.8
Log n+1	*2.12*	*2.11*	*2.27*	*2.08*					***2.15***	0.03	*2.64*
k value	1.23	1.16	1.09	0.92					**1.10**		1.04 k3
% 3rd/1st	5.9	6.8	8.1	11.9					8.2		
Adults	11	10	6	8					8.8		26.7
Log n+1	*1.08*	*1.04*	*0.85*	*0.95*					***0.98***	0.04	*1.44*
k value	1.04	1.07	1.43	1.13					**1.17**		1.19 k4
% adults/3rd	8.4	7.8	3.2	6.7					6.5		
Mature adults	6	3	2	5					4.0		12.2
Log n+1	*0.85*	*0.60*	*0.48*	*0.78*					***0.68***	0.06	*1.12*
k value	0.23	0.44	0.37	0.18					**0.30**		0.32 k5
% mature/ adults	54.5	30.0	33.3	62.5					45.1		
Total k	3.87	3.75	4.14	3.61					**3.84**		3.82

Orchard Hellberg
Year 1992
Scale species Soft
Ladybird predation High

Scale stage	Branch 1	2	3	8	4	5	6	7	Mean	SEM	No./100 adults
Breeding adults	59	26	47	28	11	21	43	27	32.8		100
Eggs*	51525	22706	41045	24452	9606.3	18339	37552	23579	28601		87330
Log n+1	*4.71*	*4.36*	*4.61*	*4.39*	*3.98*	*4.26*	*4.57*	*4.37*	***4.41***	0.08	*4.94*
Crawlers*	35037	15440	27911	16628	6532.3	12471	25535	16034	19448		59384
Log n+1	*4.54*	*4.19*	*4.45*	*4.22*	*3.82*	*4.10*	*4.41*	*4.21*	***4.24***	0.08	*4.77*
k value	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	**0.17**		0.17 k1
% crawlers/eggs									68.0		
Settled 1st instars	2232	1894	2298	1006	907	1223	838	2006	1550.5		4734.4
Log n+1	*3.35*	*3.28*	*3.36*	*3.00*	*2.96*	*3.09*	*2.92*	*3.30*	***3.16***	0.07	*3.68*
k value	1.20	0.91	1.08	1.22	0.86	1.01	1.48	0.90	**1.08**		1.10 k2
% 1st/crawlers	6.4	12.3	8.2	6.1	13.9	9.8	3.3	12.5	9.1		
3rd instars					10	39	4	14	16.8		51.1
Log n+1					*1.04*	*1.60*	*0.70*	*1.18*	***1.13***	0.13	*1.72*
k value					1.92	1.49	2.22	2.13	**1.94**		1.96 k3
% 3rd/1st					1.1	3.2	0.5	0.7	1.4		
Adults					0	0	0	4	1.0		3.1
Log n+1					*0.00*	*0.00*	*0.00*	*0.70*	***0.17***	0.12	*0.61*
k value					1.04	1.60	0.70	0.48	**0.95**		1.11 k4
% adults/3rd					0.0	0.0	0.0	28.6	7.1		
Mature adults					0	0	0	1	0.3		0.8
Log n+1					*0.00*	*0.00*	*0.00*	*0.30*	***0.08***	0.05	*0.25*
k value					0.00	0.00	0.00	0.40	**0.10**		0.36 k5
% mature/ adults								25.0	25.0		
Total k					3.98	4.26	4.57	4.07	**4.22**		4.69

Appendix 5: continued

Orchard	Jack
Year	1992
Scale species	Soft
Ladybird predation	High

	Branch										No./100
Scale stage	1	2	3	4	5	6	7	8	Mean	SEM	adults
Breeding adults	-	-	-	-	-	-	-	-	-		
Eggs*	-	-	-	-	-	-	-	-	-		
Log n+1											
Crawlers*	-	-	-	-	-	-	-	-	-		
Log n+1											
k value											
% crawlers/eggs											
Settled 1st instars	1718	2212	825	1425	870	1064	598	1078	1223.8		
Log n+1	*3.24*	*3.34*	*2.92*	*3.15*	*2.94*	*3.03*	*2.78*	*3.03*	***3.05***	0.07	
k value											
% 1st/crawlers											
3rd instars	6	0	0	1	0	1	3	0	1.4		
Log n+1	*0.85*	*0.00*	*0.00*	*0.30*	*0.00*	*0.30*	*0.60*	*0.00*	***0.26***	0.11	
k value	2.39	3.34	2.92	2.85	2.94	2.73	2.18	3.03	**2.80**		
% 3rd/1st	0.3	0.0	0.0	0.1	0.0	0.1	0.5	0.0	0.1		
Adults	0	0	0	0	0	0	0	0	0.0		
Log n+1	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	***0.00***	0.00	
k value	0.85	0.00	0.00	0.30	0.00	0.30	0.60	0.00	**0.26**		
% adults/3rd											
Mature adults											
Log n+1											
k value											
% mature/ adults											
Total k											

* Number of eggs per adult estimated from data on scale size in Appendix 4.

* Number of crawlers per branch estimated from data on percentage emergence in Appendix 4.

Appendix 5: continued

Orchard	Strang
Year	1992
Scale species	Soft
Ladybird predation	Low

	Branch																						
Scale stage	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	Mean	SEM	
Breeding adults	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-			
Eggs*	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-			
Log n+1																							
Crawlers*	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-			
Log n+1																							
k value																							
% crawlers/eggs																							
Settled 1st instars	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-			
Log n+1																							
k value																							
% 1st/crawlers																							
3rd instars	35	107	78	139	77	101	59	144	88	79	186	206	130	89	169	79	53	113	79	159	108.5		
Log n+1	*1.56*	*2.03*	*1.90*	*2.15*	*1.89*	*2.01*	*1.78*	*2.16*	*1.95*	*1.90*	*2.27*	*2.32*	*2.12*	*1.95*	*2.23*	*1.90*	*1.73*	*2.06*	*1.90*	*2.20*	***2.00***	0.04	
k value																							
% 3rd/1st																							
Adults	14	31	14	69	18	4	19	22	26	23	64	54	27	34	18	20	2	17	16	35	26.4		
Log n+1	*1.18*	*1.51*	*1.18*	*1.85*	*1.28*	*0.70*	*1.30*	*1.36*	*1.43*	*1.38*	*1.81*	*1.74*	*1.45*	*1.54*	*1.28*	*1.32*	*0.48*	*1.26*	*1.23*	*1.56*	***1.34***	0.07	
k value	0.38	0.53	0.72	0.30	0.61	1.31	0.48	0.80	0.52	0.52	0.46	0.58	0.67	0.41	0.95	0.58	1.26	0.80	0.67	0.65	**0.66**		k4
% adults/3rd	40.0	29.0	17.9	49.6	23.4	4.0	32.2	15.3	29.5	29.1	34.4	26.2	20.8	38.2	10.7	25.3	3.8	15.0	20.3	22.0	24.3		
Mature adults	3	13	6	15	4	3	7	2	8	10	31	15	2	15	3	11	1	8	4	3	8.2		
Log n+1	*0.60*	*1.15*	*0.85*	*1.20*	*0.70*	*0.60*	*0.90*	*0.48*	*0.95*	*1.04*	*1.51*	*1.20*	*0.48*	*1.20*	*0.60*	*1.08*	*0.30*	*0.95*	*0.70*	*0.60*	***0.86***	0.07	
k value	0.57	0.36	0.33	0.64	0.58	0.10	0.40	0.88	0.48	0.34	0.31	0.54	0.97	0.34	0.68	0.24	0.18	0.30	0.53	0.95	**0.49**		k5
% mature/ adults	21.4	41.9	42.9	21.7	22.2	75.0	36.8	9.1	30.8	43.5	48.4	27.8	7.4	44.1	16.7	55.0	50.0	47.1	25.0	8.6	33.8		
Total k																							

Appendix 5: continued

Orchard	Fiske	Curtis
Year	1993	1993
Scale species	Soft	Soft
Ladybird predation	Low	High

Fiske

Scale stage	Branch 1	2	3	4	5	6	7	8	Mean	SEM	No./100 adults
Breeding adults	49	56	33	26	45	25	22	24	35.0		100
Eggs*	39528	45175	26621	20974	36302	20168	17747	19361	28235		80670
Log n+1	*4.60*	*4.65*	*4.43*	*4.32*	*4.56*	*4.30*	*4.25*	*4.29*	*4.42*	0.06	*4.91*
Crawlers*	20397	23310	13736	10823	18732	10406	9158	9990	14569		41626
Log n+1	*4.31*	*4.37*	*4.14*	*4.03*	*4.27*	*4.02*	*3.96*	*4.00*	*4.14*	0.06	*4.62*
k value	0.29	0.29	0.29	0.29	0.29	0.29	0.29	0.29	0.29		0.29 k1
% crawlers/eggs									51.6		
Settled 1st instars	570	553	611	615	1208	1004	967	662	773.8		2210.7
Log n+1	*2.76*	*2.74*	*2.79*	*2.79*	*3.08*	*3.00*	*2.99*	*2.82*	*2.87*	0.05	*3.34*
k value	1.55	1.62	1.35	1.24	1.19	1.02	0.98	1.18	1.27		1.27 k2
% 1st/crawlers	2.8	2.4	4.4	5.7	6.4	9.6	10.6	6.6	6.1		
3rd instars	85	159	211	93	259	232	332	295	208.3		595.0
Log n+1	*1.93*	*2.20*	*2.33*	*1.97*	*2.41*	*2.37*	*2.52*	*2.47*	*2.28*	0.08	*2.78*
k value	0.82	0.54	0.46	0.82	0.67	0.63	0.46	0.35	0.59		0.57 k3
% 3rd/1st	14.9	28.8	34.5	15.1	21.4	23.1	34.3	44.6	27.1		
Adults	22	5	11	3	12	7	29	50	17.4		49.6
Log n+1	*1.36*	*0.78*	*1.08*	*0.60*	*1.11*	*0.90*	*1.48*	*1.71*	*1.13*	0.13	*1.70*
k value	0.57	1.43	1.25	1.37	1.30	1.46	1.05	0.76	1.15		1.07 k4
% adults/3rd	25.9	3.1	5.2	3.2	4.6	3.0	8.7	16.9	8.9		
Mature adults	9	4	6	0	8	3	19	12	7.6		21.8
Log n+1	*1.00*	*0.70*	*0.85*	*0.00*	*0.95*	*0.60*	*1.30*	*1.11*	*0.81*	0.14	*1.36*
k value	0.36	0.08	0.23	0.60	0.16	0.30	0.18	0.59	0.31		0.35 k5
% mature/ adults	40.9	80.0	54.5	0.0	66.7	42.9	65.5	24.0	46.8		
Total k	3.60	3.96	3.58	4.32	3.61	3.70	2.95	3.17	3.61		3.55

Curtis

Scale stage	Branch 1	2	3	4	5	6	7	8	Mean	SEM	No./100 adults
Breeding adults	54	32	20	28	51	21	64	29	37.4		100
Eggs*	68386	40525	25328	35459	64586	26594	81050	36726	47332		126640
Log n+1	*4.83*	*4.61*	*4.40*	*4.55*	*4.81*	*4.42*	*4.91*	*4.56*	*4.64*	0.07	*5.10*
Crawlers*	32483	19249	12031	16843	30679	12632	38499	17445	22483		60154
Log n+1	*4.51*	*4.28*	*4.08*	*4.23*	*4.49*	*4.10*	*4.59*	*4.24*	*4.31*	0.07	*4.78*
k value	0.32	0.32	0.32	0.32	0.32	0.32	0.32	0.32	0.32		0.32 k1
% crawlers/eggs									47.5		
Settled 1st instars	1711	1330	491	366	665	221	917	301	750.3		2007.4
Log n+1	*3.23*	*3.12*	*2.69*	*2.56*	*2.82*	*2.35*	*2.96*	*2.48*	*2.78*	0.11	*3.30*
k value	1.28	1.16	1.39	1.66	1.66	1.76	1.62	1.76	1.54		1.48 k2
% 1st/crawlers	5.3	6.9	4.1	2.2	2.2	1.7	2.4	1.7	3.3		
3rd instars	0	1	0	0	0	0	1	0	0.3		0.7
Log n+1	*0.00*	*0.30*	*0.00*	*0.00*	*0.00*	*0.00*	*0.30*	*0.00*	*0.08*	0.05	*0.22*
k value	3.23	2.82	2.69	2.56	2.82	2.35	2.66	2.48	2.70		3.08 k3
% 3rd/1st	0.0	0.1	0.0	0.0	0.0	0.0	0.1	0.0	0.0		
Adults	0	0	0	0	0	0	0	0	0.0		0.0
Log n+1	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	0.00	*0.00*
k value	0.00	0.30	0.00	0.00	0.00	0.00	0.30	0.00	0.08		0.22 k4
% adults/3rd		0.0					0.0		0.0		
Mature adults											0.0
Log n+1											*0.00*
k value											0.00 k5
% mature/ adults											
Total k	4.83	4.61	4.40	4.55	4.81	4.42	4.91	4.56	4.64		5.10

Appendix 5: continued

Orchard	Willetts										
Year	1992										
Scale species	Chinese										
Ladybird predation	Low										
	Branch										No./100
Scale stage	1	2	3	4	5	6	7	8	Mean	SEM	adults
Breeding adults	10	12	37	34	28	28	26	15	23.8		100
Eggs*	15016	18019	55559	51054	42045	42045	39042	22524	35663		150160
Log n+1	*4.18*	*4.26*	*4.74*	*4.71*	*4.62*	*4.62*	*4.59*	*4.35*	*4.51*	0.08	*5.18*
Crawlers*	12929	15515	47836	43958	36201	36201	33615	19393	30706		129288
Log n+1	*4.11*	*4.19*	*4.68*	*4.64*	*4.56*	*4.56*	*4.53*	*4.29*	*4.44*	0.08	*5.11*
k value	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06	**0.06**		0.06 k1
% crawlers/eggs									86.1		
Settled 1st instars	4382	3097	3234	4641	1843	4133	2763	3395	3436.0		14467.4
Log n+1	*3.64*	*3.49*	*3.51*	*3.67*	*3.27*	*3.62*	*3.44*	*3.53*	*3.52*	0.05	*4.16*
k value	0.47	0.70	1.17	0.98	1.29	0.94	1.09	0.76	**0.92**		0.95 k2
% 1st/crawlers	33.9	20.0	6.8	10.6	5.1	11.4	8.2	17.5	14.2		
3rd instars	582	594	356	766	395	756	504	820	596.6		2512.1
Log n+1	*2.77*	*2.77*	*2.55*	*2.88*	*2.60*	*2.88*	*2.70*	*2.91*	*2.76*	0.05	*3.40*
k value	0.88	0.72	0.96	0.78	0.67	0.74	0.74	0.62	**0.76**		0.76 k3
% 3rd/1st	13.3	19.2	11.0	16.5	21.4	18.3	18.2	24.2	17.8		
Adults	212	209	200	313	190	233	245	433	254.4		1071.1
Log n+1	*2.33*	*2.32*	*2.30*	*2.50*	*2.28*	*2.37*	*2.39*	*2.64*	*2.39*	0.04	*3.03*
k value	0.44	0.45	0.25	0.39	0.32	0.51	0.31	0.28	**0.37**		0.37 k4
% adults/3rd	36.4	35.2	56.2	40.9	48.1	30.8	48.6	52.8	43.6		
Mature adults	162	156	132	211	107	165	198	331	182.8		769.5
Log n+1	*2.21*	*2.20*	*2.12*	*2.33*	*2.03*	*2.22*	*2.30*	*2.52*	*2.24*	0.05	*2.89*
k value	0.12	0.13	0.18	0.17	0.25	0.15	0.09	0.12	**0.15**		0.14 k5
% mature/ adults	76.4	74.6	66.0	67.4	56.3	70.8	80.8	76.4	71.1		
Total k	1.96	2.06	2.62	2.38	2.59	2.40	2.29	1.83	**2.27**		2.29

Orchard	Hibbert-Foy										
Year	1992										
Scale species	Chinese										
Ladybird predation	High										
	Branch										No./100
Scale stage	1	2	3	4	5	6	7	8	Mean	SEM	adults
Breeding adults	7	9	10	11	7	6	8	14	9.0		100
Eggs*	12247	15746	17496	19246	12247	10498	13997	24494	15746		174960
Log n+1	*4.09*	*4.20*	*4.24*	*4.28*	*4.09*	*4.02*	*4.15*	*4.39*	*4.18*	0.04	*5.24*
Crawlers*	9258.9	11904	13227	14550	9258.9	7936.2	10582	18518	11904		132270
Log n+1	*3.97*	*4.08*	*4.12*	*4.16*	*3.97*	*3.90*	*4.02*	*4.27*	*4.06*	0.04	*5.12*
k value	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	**0.12**		0.12 k1
% crawlers/eggs									75.6		
Settled 1st instars	194	614	648	242	265	55	68	932	377.3		4191.7
Log n+1	*2.29*	*2.79*	*2.81*	*2.39*	*2.42*	*1.75*	*1.84*	*2.97*	*2.41*	0.16	*3.62*
k value	1.68	1.29	1.31	1.78	1.54	2.15	2.19	1.30	**1.65**		1.50 k2
% 1st/crawlers	2.1	5.2	4.9	1.7	2.9	0.7	0.6	5.0	2.9		
3rd instars	0	6	43	0	0	0	0	0	6.1		68.1
Log n+1	*0.00*	*0.85*	*1.64*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.31*	0.22	*1.84*
k value	2.29	1.94	1.17	2.39	2.42	1.75	1.84	2.97	**2.10**		1.78 k3
% 3rd/1st	0.0	1.0	6.6	0.0	0.0	0.0	0.0	0.0	1.0		
Adults	0	0	5	0	0	0	0	0	0.6		6.9
Log n+1	*0.00*	*0.00*	*0.78*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.10*	0.10	*0.90*
k value	0.00	0.85	0.87	0.00	0.00	0.00	0.00	0.00	**0.21**		0.94 k4
% adults/3rd		0.0	11.6						5.8		
Mature adults	0	0	2	0	0	0	0	0	0.3		2.8
Log n+1	*0.00*	*0.00*	*0.48*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.06*	0.06	*0.58*
k value	0.00	0.00	0.30	0.00	0.00	0.00	0.00	0.00	**0.04**		0.32 k5
% mature/ adults			40.0						40.0		
Total k	4.09	4.20	3.77	4.28	4.09	4.02	4.15	4.39	**4.12**		4.67

Appendix 6: Numbers of scale crawlers collected in grease traps under labelled branches, compared with estimated emergence of crawlers.

Orchard Curtis
Scale species Soft
Date 10.12.92 - 4.2.93

	Branch 1	2	3	4	5	6	7	8	Mean
Total breeding adults	54	32	20	28	51	21	64	29	37.4

Appendix 4: Est. no. eggs/adult 1266.4
Est. % crawler emergence 47.5

	1	2	3	4	5	6	7	8	Mean
Est. crawlers produced (No. eggs*emergence)	32483	19249	12031	16843	30679	12632	38499	17445	
Total crawlers collected in grease traps	505	307	145	576	265	228	432	120	
Area under branch (cm2)	300	300	220	180	200	180	180	500	258

Area of petri dish = 60 cm2 Branch area/catching area = 258/60=4.3

	1	2	3	4	5	6	7	8	Mean
Estimated no. falling (no. in trap *4.3)	2172	1320	624	2477	1140	980	1858	516	
% falling off	6.7	6.9	5.2	14.7	3.7	7.8	4.8	3.0	6.6

Orchard Fiske
Scale species Soft
Date 10.12.92 - 4.2.93

	Branch 1	2	3	4	5	6	7	8	Mean
Total breeding adults	49	56	33	26	45	25	22	24	35.0

Appendix 4: Est. no. eggs/adult 806.7
Est. % crawler emergence 51.6

	1	2	3	4	5	6	7	8	Mean
Est. crawlers produced (No. eggs*emergence)	20397	23310	13736	10823	18732	10406	9158	9990	
Total crawlers collected in grease traps	851	154	275	114	253	210	227	213	
Area under branch (cm2)	450	350	330	180	450	375	350	400	361

Area of petri dish = 60 cm2 Branch area/catching area = 361/60=6.0

	1	2	3	4	5	6	7	8	Mean
Estimated no. falling (no. in trap *4.3)	5106	924	1650	684	1518	1260	1362	1278	
% falling off	25.0	4.0	12.0	6.3	8.1	12.1	14.9	12.8	11.9

Orchard Willetts
Scale species Chinese
Date 27.2.92 - 1.5.92

	Branch 1	2	3	4	5	6	7	8	Mean
Total breeding adults	10	12	37	34	28	28	26	15	23.8

Appendix 4: Est. no. eggs/adult 1501.6
Est. % crawler emergence 86.1

	1	2	3	4	5	6	7	8	Mean
Est. crawlers produced (No. eggs*emergence)	12929	15515	47836	43958	36201	36201	33615	19393	
Total crawlers collected in grease traps	1028	1044	1189	2141	1203	2142	2914	1058	
Area under branch (cm2)	375	300	375	300	450	450	375	450	384

Area of petri dish = 60 cm2 Branch area/catching area = 384/60=6.4

	1	2	3	4	5	6	7	8	Mean
Estimated no. falling (no. in trap *6.4)	6579	6682	7610	13702	7699	13709	18650	6771	
% falling off	50.9	43.1	15.9	31.2	21.3	37.9	55.5	34.9	36.3

Appendix 7: Numbers of parasitoids (Euxanthellus philippiae and Coccidotonus dubius), collected from monthly scale samples.

Soft wax scale

Month	1991/92 E. philippiae F	M	T	C. dubius	1992/93 E. philippiae F	M	T	C. dubius	1993/94 E. philippiae F	M	T	C. dubius	1991-94 E. philippiae Female	Male	Total	C. dubius	Total
March	7		7		4		4	11			0		11	0	11	11	22
April	75		75	21	23	1	24	0	5		5		103	1	104	21	125
May			0		74		74	9	4		4		78	0	78	9	87
Total	82	0	82	21	101	1	102	20	9	0	9	0	192	1	193	41	234
%	*100.0*	*0.0*	*79.6*	*20.4*	*99.0*	*1.0*	*83.6*	*16.4*	*100.0*	*0.0*	*100.0*	*0.0*	*99.5*	*0.5*	*82.5*	*17.5*	
June	52	1	53	74	73	1	74	24	6		6		131	2	133	98	231
July			0		45	2	47	13	5		5	10	50	2	52	23	75
August	9		9	15	27	0	27	14			0	1	36	0	36	30	66
Total	61	1	62	89	145	3	148	51	11	0	11	11	217	4	221	151	372
%	*98.4*	*1.6*	*41.1*	*58.9*	*98.0*	*2.0*	*74.4*	*25.6*	*100.0*	*0.0*	*50.0*	*50.0*	*98.2*	*1.8*	*59.4*	*40.6*	
September					24		24	16	11		11		35	0	35	16	51
October					25		25	2	1		1		26	0	26	2	28
November					13		13	3	7		7		20	0	20	3	23
Total	0	0	0	0	62	0	62	21	19	0	19	0	81	0	81	21	102
%					*100.0*	*0.0*	*74.7*	*25.3*	*100.0*	*0.0*	*100.0*	*0.0*	*100.0*	*0.0*	*79.4*	*20.6*	
December					13	1	14	1	3		3	1	16	1	17	2	19
January					3		3	2			0		3	0	3	2	5
February							0	0			0		0	0	0	0	0
Total	0	0	0	0	16	1	17	3	3	0	3	1	19	1	20	4	24
%					*94.1*	*5.9*	*85.0*	*15.0*	*100.0*	*0.0*	*75.0*	*25.0*	*95.0*	*5.0*	*83.3*	*16.7*	
Total	143	1	144	110	324	5	329	95	42	0	42	12	509	6	515	217	732
%	*99.3*	*0.7*	*56.7*	*43.3*	*98.5*	*1.5*	*77.6*	*22.4*	*100.0*	*0.0*	*77.8*	*22.2*	*98.8*	*1.2*	*70.4*	*29.6*	

Chinese wax scale

Month	1991 E.p. F	M	T	C.d.	1992/93 E.p. F	M	T	C.d.	1993/94 E.p. F	M	T	C.d.	1991-94 E.p. Female	Male	Total	C.d.	Total
June	68	1	69		1		1		8		8	1	77	1	78	1	79
July	141	1	142	1	10		10				0		151	1	152	1	153
August	87	3	90	3	8	1	9		6	2	8		101	6	107	3	110
Total	296	5	301	4	19	1	20	0	14	2	16	1	329	8	337	5	342
%	*98.3*	*1.7*	*98.7*	*1.3*	*95.0*	*5.0*	*100.0*	*0.0*	*87.5*	*12.5*	*94.1*	*5.9*	*97.6*	*2.4*	*98.5*	*1.5*	
September	129	9	138	2	19	1	20		24	1	25		172	11	183	2	185
October	78	12	90	6	43	8	51		18	3	21		139	23	162	6	168
November	136	16	152	16	58	10	68	20	26	2	28	5	220	28	248	41	289
Total	343	37	380	24	120	19	139	20	68	6	74	5	531	62	593	49	642
%	*90.3*	*9.7*	*94.1*	*5.9*	*86.3*	*13.7*	*87.4*	*12.6*	*91.9*	*8.1*	*93.7*	*6.3*	*89.5*	*10.5*	*92.4*	*7.6*	
December					47	3	50	8	40	12	52	19	87	15	102	27	129
January					25	10	35	37	19	8	27	19	44	18	62	56	118
February					4	4	8	14	10	4	14	9	14	8	22	23	45
Total	0	0	0	0	76	17	93	59	69	24	93	47	145	41	186	106	292
%					*81.7*	*18.3*	*61.2*	*38.8*	*74.2*	*25.8*	*66.4*	*33.6*	*78.0*	*22.0*	*63.7*	*36.3*	
March	1		1	3	16	4	20	26					17	4	21	29	50
April	1		1				0	3					1	0	1	3	4
May	17	4	21	1			0	2					17	4	21	3	24
Total	19	4	23	4	16	4	20	31	0	0	0	0	35	8	43	35	78
%	*82.6*	*17.4*	*85.2*	*14.8*	*80.0*	*20.0*	*39.2*	*60.8*					*81.4*	*18.6*	*55.1*	*44.9*	
Total	658	46	704	32	231	41	272	110	151	32	183	53	1040	119	1159	195	1354
%	*93.5*	*6.5*	*95.7*	*4.3*	*84.9*	*15.1*	*71.2*	*28.8*	*82.5*	*17.5*	*77.5*	*22.5*	*89.7*	*10.3*	*85.6*	*14.4*	

Appendix 8: Phenology of parasitoids in soft wax scale. Number of parasitoids collected from monthly scale samples.

Month Year	Orchard	Larvae	Pupae	Adults	Dead	Emerged	Total
February							
1991	Hendl		1				
	Ritchie		3				
March							
1991	Strang	8		7			
1992	Strang	15	3			1	
	Total	23	7	7	0	1	38
	%	*60.5*	*18.4*	*18.4*	*0.0*	*2.6*	
April							
1991	Birchall	7	17			6	
	Hellberg	2	4	21		5	
	Hendl	3	14	4		3	
	Hume	4	25				
	Ritchie	4	30	2		2	
	Strang	3	3	3		1	
1992	Strang	2	3				
1993	Fiske	4	1				
	Total	29	97	30	0	17	173
	%	*16.8*	*56.1*	*17.3*	*0.0*	*9.8*	
May							
1992	Curtis	9	37	11		15	
	Hellberg		1				
	Ritchie		8	1			
	Strang	5	14			5	
1993	Fiske	3	2	2		1	
	Total	17	62	14	0	21	114
	%	*14.9*	*54.4*	*12.3*	*0.0*	*18.4*	
June							
1991	Birchall	3	25	1		6	
	Hellberg		7	2		13	
	Hendl		4	2		10	
	Hume		29	3		36	
	Ritchie	7	49	8		50	
	Strang	1	3			6	
1992	Curtis	3	33	3		23	
	Ritchie	10	21	4		7	
	Strang	2	19			6	
1993	Curtis			1		1	
	Fiske	2	4		3	2	
	Total	28	194	24	3	160	409
	%	*6.8*	*47.4*	*5.9*	*0.7*	*39.1*	
July							
1992	Curtis	3	14	3		11	
	Ritchie	5	10	7		19	
	Strang	7	19	1		2	
1993	Curtis	4	7	1		1	
	Fiske	1	7	1	1	5	
	Total	20	57	13	1	38	129
	%	*15.5*	*44.2*	*10.1*	*0.8*	*29.5*	
August							
1991	Hendl		1			2	
	Hume		8			6	
	Ritchie	4	8	1		2	
	Strang		1			2	
1992	Curtis	2	17		9	39	
	Ritchie		3		4	13	
	Strang	2	11	1	3	4	
1993	Curtis	1			2		
	Fiske		1		1	1	
	Total	9	50	2	19	69	149
	%	*6.0*	*33.6*	*1.3*	*12.8*	*46.3*	

Month Year	Orchard	Larvae	Pupae	Adults	Dead	Emerged	Total
September							
1992	Curtis		3		9	18	
	Hellberg		1			1	
	Ritchie		2		7	8	
	Strang		15	1	5	17	
1993	Curtis		5	1	3	3	
	Fiske		1	5	4	8	
	Total	0	27	7	28	55	117
	%	*0.0*	*23.1*	*6.0*	*23.9*	*47.0*	
October							
1991	Hendl					2	
	Strang					5	
1992	Curtis				6	13	
	Ritchie		1		11	5	
	Strang		1		7	15	
1993	Curtis				1	2	
	Fiske					5	
	Total	0	2	0	25	47	74
	%	*0.0*	*2.7*	*0.0*	*33.8*	*63.5*	
November							
1991	Hendl		1		1	8	
	Strang					6	
1992	Curtis		2		5	13	
	Fiske	1	1		5	18	
	Hellberg					2	
	Ritchie		1		3	5	
	Strang				1	13	
1993	Curtis				6	1	
	Fiske	1	1			2	
	Total	2	6	0	21	68	97
	%	*2.1*	*6.2*	*0.0*	*21.6*	*70.1*	
December							
1992	Curtis				4	16	
	Fiske				8	26	
	Ritchie		1		3	4	
	Strang				1	7	
1993	Curtis				5	1	
	Fiske					5	
	Total	0	1	0	21	59	81
	%	*0.0*	*1.2*	*0.0*	*25.9*	*72.8*	
January							
1992	Curtis					5	
	Fiske				1	7	
	Hellberg		2			2	
	Ritchie					1	
	Strang				11	43	
1994	Fiske		1				
February							
1991	Willetts					2	
	Total	0	3	0	12	60	75
	%	*0.0*	*4.0*	*0.0*	*16.0*	*80.0*	

Appendix 9: Phenology of parasitoids in Chinese wax scale. Number of parasitoids collected from monthly scale samples.

Third instar scale

Month		Parasite stage					
Year	Orchard	Larvae	Pupae	Adults	Dead	Emerged	Total
April							
1991	Hibbert-Foy	2					
May							
1991	Boon		1				
	Hibbert-Foy	9					
	Irvine	17	7				
1993	Willetts	1					
	Total	29	8	0	0	0	37
	%	*78.4*	*21.6*	*0.0*	*0.0*	*0.0*	
June							
1991	Blank	1					
	Boon	2					
	Irvine	47	7			1	
	Kwan	2	1				
1993	Fiske	9	2		1		
	Willetts	3					
	Total	64	10	0	1	1	76
	%	84.2	13.2	0.0	1.3	1.3	
July							
1991	Boon		1				
	Hibbert-Foy	24	3				
	Irvine	39	42	3		7	
1992	Strang	1					
	Willetts	2					
1993	Fiske	2	1		1		
	Willetts	2					
	Total	70	47	3	1	7	128
	%	54.7	36.7	2.3	0.8	5.5	
August							
1991	Hibbert-Foy	28	11				
	Irvine	31	48	3		12	
1993	Fiske	9	1		1		
	Total	68	60	3	1	12	144
	%	47.2	41.7	2.1	0.7	8.3	
September							
1991	Boon		1			1	
	Hibbert-Foy	33	26	2		8	
	Irvine	27	36	4		23	
1992	Willetts	2	6				
1993	Fiske	15	3		2	3	
	Willetts	8	9	2	1	3	
	Total	85	81	8	3	38	215
	%	39.5	37.7	3.7	1.4	17.7	
October							
1991	Blank	3	4			1	
	Boon	3	2				
	Curtis	19	11			7	
	Hibbert-Foy	27	21	6		4	
	Irvine	9	13	4		32	
1992	Strang	27	5				
	Tyson	3	11			3	
	Willetts	8	5				
1993	Fiske	9	13		5	1	
	Willetts	3	4	1	1	1	
	Total	111	89	11	6	49	266
	%	41.7	33.5	4.1	2.3	18.4	

Month		Parasite stage					
Year	Orchard	Larvae	Pupae	Adults	Dead	Emerged	Total
November							
1991	Boon	1	6	1		5	
	Hibbert-Foy	15	33	9		37	
	Irvine	5	11	3		52	
	Bellingham	2	9	2		9	
	Strang	35	10			9	
	Riley	3	6	2		8	
	Cottage	4	4	1		2	
	Fiske	6	14	3		10	
	Willetts	14	8			11	
1992	Fiske	30	23	5	16	28	
	Hibbert-Foy					2	
	Strang	8	6			2	
	Willetts	5	5	1	1	7	
1993	Fiske	10	8	2	8	9	
	Willetts	1			2	5	
	Total	139	143	29	27	196	534
	%	26.0	26.8	5.4	5.1	36.7	
December							
1992	Fiske	1	8		13	27	
	Strang	3	7		4	19	
	Willetts	1	3	1	2	9	
1993	Fiske	10	11		7	3	
	Willetts	9	5		1	3	
	Total	24	34	1	27	61	147
	%	16.3	23.1	0.7	18.4	41.5	
January							
1993	Fiske		2		10	20	
	Strang		6		10	26	
	Willetts		1		8	9	
1994	Fiske				2	6	
	Willetts				1	1	
	Total	0	9	0	31	62	102
	%	0.0	8.8	0.0	30.4	60.8	
February							
1993	Strang				2	8	
1994	Willetts				2	8	
	Total	0	0	0	4	16	20
	%	0.0	0.0	0.0	20.0	80.0	
March							
1993	Fiske				1	8	
	Strang		1		3	15	
	Willetts					1	
	Total	0	1	0	4	24	29
	%	0.0	3.4	0.0	13.8	82.8	

Appendix 9: continued

Adult scale

Month Year	Orchard	Larvae	Pupae	Adults	Dead	Emerged	Total
		Parasite stage					
August							
1991	Hibbert-Foy	1					
1993	Fiske	2					
September							
1991	Hibbert-Foy	1	1				
	Irvine		1				
1993	Fiske	3					
	Willetts	2					
	Total	9	2	0	0	0	11
	%	81.8	18.2	0.0	0.0	0.0	
October							
1991	Curtis		1				
	Hibbert-Foy	2	2				
	Irvine		2				
1992	Strang	19					
	Tyson		1	1		2	
	Willetts	1	3				
1993	Fiske	3	2				
	Willetts		1				
	Total	25	12	1	0	2	40
	%	62.5	30.0	2.5	0.0	5.0	
November							
1991	Boon	2	2				
	Hibbert-Foy	5	1			3	
	Irvine	3	1			1	
	Riley	1	4			3	
	Fiske	1					
	Willetts	4	1	1			
1992	Fiske	5	8			1	
	Strang	7	1				
	Willetts	4	2				
1993	Fiske	8	2				
	Willetts	10					
	Total	50	22	1	0	8	81
	%	61.7	27.2	1.2	0.0	9.9	
December							
1992	Fiske	12	29	1	3	16	
	Strang	1	3			3	
	Willetts	57	26			3	
1993	Fiske	8	7		4		
	Willetts	46	18		2		
	Total	124	83	1	9	22	239
	%	51.9	34.7	0.4	3.8	9.2	
January							
1993	Fiske		3		6	17	
	Strang		22	1	3	15	
	Willetts	4	27		8	21	
1994	Fiske	4	8		20	29	
	Willetts	16	19	2	16	24	
	Total	24	79	3	53	106	265
	%	9.1	29.8	1.1	20.0	40.0	
February							
1993	Fiske		1	1	12	37	
	Strang					6	
	Willetts	2	9	4	6	34	
1994	Fiske		3		8	12	
	Willetts	5	16		37	40	
	Total	7	29	5	63	129	233
	%	3.0	12.4	2.1	27.0	55.4	
March							
1992	Willetts			4		24	
1993	Fiske				9	20	
	Strang				1	10	
	Willetts	2	14	2	19	68	
	Total	2	14	6	29	122	173
	%	1.2	8.1	3.5	16.8	70.5	
April							
1992	Willetts					29	
	Total	0	0	0	0	29	29
	%	0.0	0.0	0.0	0.0	100.0	

Appendix 10: Percentage mortality of third instar and adult Chinese wax scale, weighted according to proportions of scale on leaves and wood.

Month	% of 3rd instars on			% mortality			% of adults on			% mortality		
Orchard	leaves	wood		parasite	disease	other	leaves	wood		parasite	disease	other
April												
Fiske 1993	100.0	0.0	leaves	1.0	0.0	1.9						
			wood	0.0	0.0	2.2						
Mean	*100.0*	*0.0*	overall	*1.0*	*0.0*	*1.9*						
May												
Willetts 1993	100.0	0.0	leaves	2.4	0.6	0.5						
			wood	0.0	0.0	5.3						
Mean	*100.0*	*0.0*	overall	*2.4*	*0.6*	*0.5*						
June												
Willetts 1993	97.4	2.6	leaves	3.5	1.8	2.0						
Fiske 1993	75.5	24.5	wood	0.2	2.2	6.5						
Mean	*86.5*	*13.6*	overall	*3.1*	*1.9*	*2.6*						
July												
Willetts 1992	73.6	26.4					17.6	82.4				
Willetts 1993	94.1	5.9	leaves	6.7	3.0	4.7	0.0	100.0	leaves	0.0	0.0	3.4
Fiske 1993	59.2	40.8	wood	0.2	4.2	4.4	0.0	100.0	wood	0.0	3.1	1.5
Mean	*75.6*	*24.4*	overall	*5.1*	*3.3*	*4.6*	*5.9*	*94.1*	overall	*0.0*	*2.9*	*1.6*
August												
Willetts 1993	87.8	12.2	leaves	5.3	5.1	3.3	0.0	100.0	leaves	0.0	0.0	1.8
Fiske 1993	64.2	35.8	wood	0.0	2.1	1.4	11.4	88.6	wood	0.5	0.9	0.2
Mean	*76.0*	*24.0*	overall	*4.0*	*4.4*	*2.8*	*5.7*	*94.3*	overall	*0.5*	*0.8*	*0.3*
September												
Willetts 1992	57.1	42.9					6.1	93.9				
Willetts 1993	86.4	13.6	leaves	8.7	6.1	10.8	38.5	61.5	leaves	4.0	0.4	0.4
Fiske 1993	51.5	48.5	wood	0.8	4.1	6.1	9.5	90.5	wood	0.6	1.3	1.1
Mean	*65.0*	*35.0*	overall	*5.9*	*5.4*	*9.2*	*18.0*	*82.0*	overall	*1.2*	*1.1*	*1.0*
October												
Willetts 1992	29.8	70.2					10.7	89.3				
Willetts 1993	75.1	24.9	leaves	13.3	7.9	23.9	39.6	60.4	leaves	14.4	1.2	0.0
Fiske 1993	49.0	51.0	wood	1.2	3.9	13.5	4.8	95.2	wood	2.2	0.9	5.6
Mean	*51.3*	*48.7*	overall	*7.4*	*6.0*	*18.8*	*18.4*	*81.6*	overall	*4.4*	*1.0*	*4.6*
November												
Willetts 1992	22.9	77.1					11.4	88.6				
Willetts 1993	56.7	43.3	leaves	19.9	6.1	35.2	36.8	63.2	leaves	8.4	2.2	5.9
Fiske 1993	42.0	57.0	wood	3.6	3.7	7.5	2.8	97.2	wood	3.8	4.0	6.3
Mean	*40.5*	*59.5*	overall	*10.2*	*4.7*	*18.7*	*17.0*	*83.0*	overall	*4.6*	*3.7*	*6.2*
December												
Willetts 1992	14.5	85.5					10.9	89.1				
Willetts 1993	42.2	57.8	leaves	23.8	3.4	40.0	20.2	79.8	leaves	22.0	2.1	20.2
Fiske 1993	12.2	87.8	wood	6.4	1.3	7.5	5.0	95.0	wood	18.0	3.7	11.3
Mean	*23.0*	*77.0*	overall	*10.4*	*1.8*	*15.0*	*12.0*	*88.0*	overall	*18.5*	*3.5*	*12.4*
January												
Willetts 1993	26.7	73.3	leaves	23.4	3.9	33.6	12.7	87.3	leaves	41.6	1.3	15.6
Fiske 1993	10.9	89.1	wood	1.8	0.0	1.9	5.7	94.3	wood	16.4	4.4	17.1
Mean	*18.8*	*81.2*	overall	*5.9*	*0.7*	*7.9*	*9.2*	*90.8*	overall	*18.7*	*4.1*	*17.0*
February												
Willetts 1993							23.3	76.7	leaves	21.6	5.2	32.7
Fiske 1993							0.0	100.0	wood	15.7	5.6	18.8
Mean							*11.7*	*88.4*	overall	*16.4*	*5.6*	*20.4*
March												
Willetts 1992							5.8	94.2	leaves	17.4	0.0	7.5
									wood	16.8	1.9	10.1
Mean							*5.8*	*94.2*	overall	*16.8*	*1.8*	*9.9*

Appendix 11: Number of third instar and adult soft wax scale assessed from wood samples, and percentage mortality (for samples with >20 scale), November 1990 - December 1993.

3RD INSTARS

Total number of scales assessed

Year	Orchard	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Total
1990	Rhodes										159	128	155	
1991	Birchall	125		817		750								
	Hellberg			820		641							172	
	Hendl	359	74	822		944		173		348	364		354	
	Hume	40		782		588		190						
	Ritchie	79		1021		681		236						
	Strang	835	994	876		1006		252		543	196			
1992	Curtis				554	457	409	431	503	440	477	380	342	
	Fiske										480	409	288	
	Hellberg			275	369	331	397	298	315	258	214	46	139	
	Ritchie				223	438	470	442	427	385	398	271	201	
	Strang		239	382	372	368	425	205	437	318	302	198	99	
1993	Curtis		267	120	270	412	285	402	351	402	381	351		
	Fiske		363	299	348	403	494	442	417	405	359	375		
Total	1990&1991	1438	1068	5138	0	4610	0	851	0	891	719	128	681	15524
	1992	0	239	657	1518	1594	1701	1376	1682	1401	1871	1304	1069	14412
	1993	0	630	419	618	815	779	844	768	807	740	726	0	7146
	1991-1993	1438	1937	6214	2136	7019	2480	3071	2450	3099	3330	2158	1750	37082

% parasitism

Year	Orchard	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan
1990	Rhodes										0.0	0.0	0.0
1991	Birchall	0.0		3.7		4.7							
	Hellberg			3.9		3.4							0.6
	Hendl	0.3	0.0	2.9		1.7		1.7		0.6	2.7		0.0
	Hume	0.0		3.7		11.6		7.4					
	Ritchie	3.8		3.7		16.7		6.4					
	Strang	0.0	1.4	1.1		1.0		1.2		0.9	3.1		
1992	Curtis				13.0	13.6	7.6	15.5	6.0	4.3	4.2	5.3	1.5
	Fiske										5.0	8.3	2.8
	Hellberg			0.0	0.8	0.0	0.0	0.0	0.6	0.0	0.9	0.0	1.4
	Ritchie				4.0	9.6	8.7	4.5	4.0	4.4	2.3	3.0	0.5
	Strang		7.9	1.3	6.5	7.3	6.8	10.2	8.7	7.2	4.6	4.0	3.0
1993	Curtis		0.0	0.0	0.0	0.5	4.6	1.0	3.4	0.7	1.8	1.7	
	Fiske		0.0	2.0	2.3	2.7	3.0	0.7	4.3	1.2	1.1	1.3	
Mean	1990&1991	0.8	0.7	3.2		6.5		4.2		0.8	1.9	0.0	0.2
	1992		7.9	0.7	6.1	7.6	5.8	7.6	4.8	4.0	3.4	4.1	1.8
	1993		0.0	1.0	1.2	1.6	3.8	0.9	3.9	1.0	1.5	1.5	
	1991-1993	0.8	2.9	1.6	3.6	5.2	4.8	4.2	4.3	1.9	2.3	1.9	1.0

% disease

Year	Orchard	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan
1990	Rhodes										0.0	0.0	0.0
1991	Birchall	0.0		3.7		8.1							
	Hellberg			1.3		0.6							0.0
	Hendl	5.6	4.1	26.6		20.6		4.0		0.6	2.2		0.0
	Hume	0.0		0.6		3.1		0.0					
	Ritchie	0.0		3.0		4.6		1.3					
	Strang	0.0	0.8	1.0		1.9		7.9		0.0	0.0		
1992	Curtis				1.4	2.8	6.4	5.3	10.9	6.4	4.8	1.6	0.3
	Fiske										8.1	0.7	1.0
	Hellberg			4.4	2.7	14.2	20.4	35.9	33.7	28.7	12.6	0.0	0.0
	Ritchie				2.2	4.3	7.9	7.9	11.9	3.6	10.8	0.4	0.0
	Strang		0.0	1.0	2.4	0.5	0.5	0.0	7.1	9.1	1.7	0.5	2.0
1993	Curtis		0.4	0.0	5.9	0.7	2.1	4.2	4.0	2.7	1.6	0.0	
	Fiske		0.0	5.0	9.5	22.3	8.5	7.0	6.2	4.4	1.4	0.0	
Mean	1990&1991	1.1	2.5	6.0		6.5		3.3		0.3	0.7	0.0	0.0
	1992		0.0	2.7	2.2	5.5	8.8	12.3	15.9	12.0	7.6	0.6	0.7
	1993		0.2	2.5	7.7	11.5	5.3	5.6	5.1	3.6	1.5	0.0	
	1991-1993	1.1	0.9	3.7	4.9	7.8	7.1	7.1	10.5	5.3	3.3	0.2	0.3

Appendix 11: continued

% other mortality

Year	Orchard	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan
1990	Rhodes										30.8	42.2	14.2
1991	Birchall	27.2		18.8		18.8							
	Hellberg			2.6		7.5							5.8
	Hendl	25.6	8.1	18.6		11.7		17.3		3.4	11.8		0.0
	Hume	7.5		33.6		12.4		11.6					
	Ritchie	21.5		15.6		21.1		28.8					
	Strang	2.6	17.0	20.1		65.7		37.7		43.5	40.8		
1992	Curtis				18.8	34.1	51.8	28.8	44.1	32.0	28.3	28.9	22.8
	Fiske										48.3	52.1	17.0
	Hellberg			3.6	8.1	23.0	18.6	33.2	31.7	39.5	68.7	4.3	70.5
	Ritchie				46.2	12.1	23.2	22.9	26.7	76.6	34.4	22.1	17.9
	Strang		17.2	9.9	12.6	28.3	30.4	66.8	49.2	27.7	27.2	14.6	15.2
1993	Curtis		1.1	0.8	4.8	26.2	33.3	42.0	29.3	35.8	24.1	29.6	
	Fiske		0.0	6.7	11.8	19.6	26.5	31.2	29.7	17.8	20.1	28.0	
Mean	1990&1991	16.9	12.6	18.2		22.9		23.9		23.5	27.8	42.2	6.7
	1992		17.2	6.8	21.4	24.4	31.0	37.9	37.9	44.0	41.4	24.4	28.7
	1993		0.6	3.8	8.3	22.9	29.9	36.6	29.5	26.8	22.1	28.8	
	1991-1993	16.9	10.1	9.6	14.9	23.4	30.5	32.8	33.7	31.4	30.4	31.8	17.7

ADULTS

Total number of scales assessed

Year	Orchard	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Total
1990	Rhodes										110	74	133	
1991	Birchall			33		197								
	Hellberg			137		382							161	
	Hendl			127		558		123		328	303		354	
	Hume					330		153						
	Ritchie			68		283		127						
	Strang			20		214		125		300	110			
1992	Curtis				26	102	79	213	176	252	299	244	258	
	Fiske										185	159	228	
	Hellberg						29	33	79	80	38	44	39	
	Ritchie				79	113	95	253	233	52	209	202	164	
	Strang				22	61	172	25	144	175	200	160	79	
1993	Curtis				35	125	116	184	215	239	276	241		
	Fiske				24	22	130	151	212	290	278	265		
Total	1990&1991	0	0	385	0	1964	0	528	0	628	523	74	648	4750
	1992	0	0	0	127	276	375	524	632	559	931	809	768	5001
	1993	0	0	0	59	147	246	335	427	529	554	506	0	2803
	1991-1993	0	0	385	186	2387	621	1387	1059	1716	2008	1389	1416	12554

% disease

Year	Orchard	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan
1990	Rhodes										1.8	5.4	0.0
1991	Birchall			3.0		13.2							
	Hellberg			0.0		0.0							16.8
	Hendl			25.2		32.0		27.6		41.2	35.6		60.2
	Hume					4.2		7.2					
	Ritchie			1.5		4.2		2.4					
	Strang			0.0		3.7		35.2		31.7	21.8		
1992	Curtis				0.0	1.0	5.1	10.8	14.2	24.6	21.1	17.6	10.5
	Fiske										8.1	10.7	23.2
	Hellberg						13.8	3.0	51.9	17.5	7.9	6.8	10.3
	Ritchie				6.3	5.3	5.3	10.7	19.7	7.7	17.2	10.4	8.5
	Strang				0.0	0.0	7.0	4.0	4.2	19.4	11.0	9.4	6.3
1993	Curtis				0.0	1.6	16.4	11.4	15.3	7.5	21.7	16.6	
	Fiske				0.0	4.5	2.3	6.6	7.1	10.7	11.9	7.5	
Mean	1990&1991			5.9		9.6		18.1		36.5	19.7	5.4	25.7
	1992				2.1	2.1	7.8	7.1	22.5	17.3	13.1	11.0	11.8
	1993				0.0	3.1	9.4	9.0	11.2	9.1	16.8	12.1	
	1991-1993			5.9	1.1	4.9	8.6	11.4	16.9	21.0	16.5	9.5	18.7

Appendix 11: continued

% predation

Year	Orchard	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan
1990	Rhodes										0.0	0.0	0.0
1991	Birchall			0.0		0.0							
	Hellberg			0.0		0.0							0.0
	Hendl			0.0		0.5		3.3		13.4	9.9		7.3
	Hume					0.0		0.0					
	Ritchie			0.0		0.0		1.6					
	Strang			0.0		0.0		0.0		0.0	0.0		
1992	Curtis				0.0	0.0	2.5	5.2	0.0	0.8	5.0	4.5	1.2
	Fiske										1.1	13.8	6.6
	Hellberg						0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Ritchie				0.0	0.0	0.0	0.4	0.0	0.0	1.9	4.5	3.0
	Strang				0.0	0.0	0.0	0.0	4.9	0.0	6.5	10.6	6.3
1993	Curtis				0.0	0.0	0.0	3.3	8.4	19.7	17.4	15.8	
	Fiske				0.0	0.0	0.0	0.0	0.0	3.4	11.2	24.9	
Mean	1990&1991			0.0		0.1		1.2		6.7	3.3	0.0	2.4
	1992				0.0	0.0	0.6	1.4	1.2	0.2	2.9	6.7	3.4
	1993				0.0	0.0	0.0	1.7	4.2	11.6	14.3	20.4	
	1991-1993			0.0	0.0	0.0	0.3	1.4	2.7	6.2	6.8	9.0	2.9

% other mortality

Year	Orchard	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan
1990	Rhodes										35.5	39.2	39.1
1991	Birchall			6.1		3.6							
	Hellberg			0.0		3.1							19.9
	Hendl			29.9		7.0		18.7		20.7	38.0		24.0
	Hume					3.0		15.0					
	Ritchie			5.9		7.1		63.0					
	Strang			0.0		11.2		36.0		19.3	12.7		
1992	Curtis				0.0	0.0	2.5	14.1	1.1	11.5	13.0	21.3	23.3
	Fiske										6.5	17.0	25.4
	Hellberg						6.9	6.1	2.5	8.8	13.2	25.0	17.9
	Ritchie				81.0	0.0	0.0	5.5	12.9	1.9	6.7	25.2	19.5
	Strang				4.5	1.6	5.8	12.0	4.9	5.7	16.0	24.4	26.6
1993	Curtis				0.0	4.0	5.2	5.4	9.8	7.5	23.2	37.8	
	Fiske				0.0	0.0	3.1	6.6	1.4	2.4	8.3	15.8	
Mean	1990&1991			8.4		5.8		33.2		20.0	28.7	39.2	27.7
	1992				28.5	0.5	3.8	9.4	5.4	7.0	11.1	22.6	22.5
	1993				0.0	2.0	4.2	6.0	5.6	5.0	15.8	26.8	
	1991-1993			8.4	14.3	2.8	4.0	16.2	5.5	10.6	18.5	29.5	25.1

Appendix 12: Mortality of third instar and adult Chinese wax scale from leaf and wood samples (for samples with >10 scale), April 1991 - February 1994.

3rd instars

Leaf samples

Total number of scales assessed

Year	Orchard	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Total
1991	Boon		135	229	161	216	237	108	91			
	Hibbert-Foy	108	287		262	272	214	155	336			
	Irvine		278	330	243	280	374	196	255			
	Willetts								159			
1992	Fiske								126	101	53	
	Strang				17			157	106	65	136	
	Willetts			97	85	83	169	262	175	50	54	
1993	Fiske	59	92	139	228	263	255	245	156	53	42	
	Willetts		131	173	201	211	313	373	279	308	209	
Total	1991	108	700	559	666	768	825	459	841	0	0	4926
	1992	0	0	97	102	83	169	419	407	216	243	1736
	1993	59	223	312	429	474	568	618	435	361	251	3730
	1991-1993	167	923	968	1197	1325	1562	1496	1683	577	494	10392

% parasitism

Year	Orchard	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan
1991	Boon		0.7	0.9	0.6	0.0	0.8	3.7	8.8		
	Hibbert-Foy	1.9	3.1		9.9	14.0	31.8	36.1	26.5		
	Irvine		9.4	16.1	35.4	31.1	23.8	27.0	27.5		
	Willetts								17.6		
1992	Fiske								58.7	41.6	49.1
	Strang				5.9			19.7	12.3	43.1	27.9
	Willetts			0.0	2.4	0.0	2.4	4.6	9.7	28.0	33.3
1993	Fiske	0.0	0.0	2.2	1.3	1.9	5.9	8.2	22.4	15.1	19.0
	Willetts		0.8	1.7	0.0	0.0	3.8	2.7	2.9	4.9	1.0
Mean	1991	1.9	4.4	8.5	15.3	15.0	18.8	22.3	20.1		
	1992			0.0	4.2	0.0	2.4	12.2	26.9	37.6	36.8
	1993	0.0	0.4	2.0	0.7	1.0	4.9	5.5	12.7	10.0	10.0
	1991-1993	1.0	2.4	3.5	6.7	5.3	8.7	13.3	19.9	23.8	23.4

% disease

Year	Orchard	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan
1991	Boon		0.0	0.9	3.1	6.5	1.7	3.7	0.0		
	Hibbert-Foy	0.0	0.7		6.1	4.0	6.5	0.6	3.9		
	Irvine		0.0	0.0	1.6	9.6	8.0	7.1	8.2		
	Willetts								0.0		
1992	Fiske								0.0	1.0	1.9
	Strang				0.0			0.0	0.0	0.0	0.0
	Willetts			0.0	0.0	0.0	0.0	2.3	0.0	0.0	0.0
1993	Fiske	0.0	1.1	6.5	5.3	7.6	15.7	8.6	13.5	1.9	0.0
	Willetts		0.8	3.5	5.5	9.5	10.2	28.7	17.2	11.0	14.4
Mean	1991	0.0	0.2	0.5	3.6	6.7	5.4	3.8	3.0		
	1992			0.0	0.0	0.0	0.0	1.2	0.0	0.3	0.6
	1993	0.0	1.0	5.0	5.4	8.6	13.0	18.7	15.4	6.5	7.2
	1991-1993	0.0	0.6	1.8	3.0	5.1	6.1	7.9	6.1	3.4	3.9

% other mortality

Year	Orchard	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan
1991	Boon		0.0	1.3	5.0	0.5	4.6	7.4	23.1		
	Hibbert-Foy	3.7	2.4		13.0	9.6	17.8	45.2	54.2		
	Irvine		0.7	1.2	7.8	9.3	13.6	16.8	20.0		
	Willetts								44.0		
1992	Fiske								21.4	22.8	26.4
	Strang				5.9			1.3	23.6	38.5	57.4
	Willetts			2.1	1.2	1.2	8.3	11.1	14.9	30.0	13.0
1993	Fiske	0.0	0.0	1.4	0.9	1.9	8.6	49.8	59.0	47.2	31.0
	Willetts		0.0	4.0	3.0	2.4	15.3	35.1	41.9	51.9	38.8
Mean	1991	3.7	1.0	1.3	8.6	6.5	12.0	23.1	35.3		
	1992			2.1	3.6	1.2	8.3	6.2	20.0	30.4	32.3
	1993	0.0	0.0	2.7	2.0	2.2	12.0	42.5	50.5	49.6	34.9
	1991-1993	1.9	0.5	2.0	4.7	3.3	10.8	23.9	35.2	40.0	33.6

Appendix 12: continued

3rd instars
Wood samples
Total number of scales assessed

Year	Orchard	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Total
1991	Boon								61			
	Hibbert-Foy							110	197			
	Irvine								49			
	Willetts								191			
1992	Fiske								402	197	171	
	Strang							31	18	20	53	
	Willetts	46	86	101	246	245	435	444	477	403	303	
1993	Fiske		53	151	366	407	425	420	354	381	345	
	Willetts			144	326	354	405	418	365	421	400	
Total	1991	0	0	0	0	0	0	110	498	0	0	608
	1992	46	86	101	246	245	435	475	897	620	527	3678
	1993	0	53	295	692	761	830	838	719	802	745	5735
	1991-1993	46	139	396	938	1006	1265	1423	2114	1422	1272	10021

% parasitised

Year	Orchard	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan
1991	Boon								8.2		
	Hibbert-Foy							0.9	2.5		
	Irvine								0.0		
	Willetts								0.0		
1992	Fiske								7.0	3.6	3.5
	Strang							3.2	16.7	25.0	7.5
	Willetts	0.0	0.0	0.0	0.0	0.0	0.9	0.2	0.2	0.5	0.0
1993	Fiske		0.0	0.7	0.3	0.0	0.7	1.9	0.6	6.0	0.0
	Willetts			0.0	0.6	0.0	0.5	0.0	0.0	0.0	0.0
Mean	1991							0.9	2.7		
	1992	0.0	0.0	0.0	0.0	0.0	0.9	1.7	8.0	9.7	3.7
	1993		0.0	0.4	0.5	0.0	0.6	1.0	0.3	3.0	0.0
	1991-1993	0.0	0.0	0.2	0.2	0.0	0.8	1.2	3.6	6.4	1.8

% disease

Year	Orchard	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan
1991	Boon								4.9		
	Hibbert-Foy							8.2	0.5		
	Irvine								4.1		
	Willetts								0.0		
1992	Fiske								1.2	0.5	0.0
	Strang							0.0	0.0	0.0	0.0
	Willetts	0.0	0.0	0.0	0.0	0.8	0.0	0.2	0.0	0.0	0.0
1993	Fiske		0.0	3.3	11.7	4.4	6.4	4.3	5.4	2.4	0.0
	Willetts			5.6	5.2	2.3	9.9	2.6	11.0	2.4	0.0
Mean	1991							8.2	2.4		
	1992	0.0	0.0	0.0	0.0	0.8	0	0.1	0.4	0.2	0.0
	1993		0.0	4.5	8.5	3.4	8.2	3.5	8.2	2.4	0.0
	1991-1993	0.0	0.0	2.2	4.2	2.1	4.1	3.9	3.7	1.3	0.0

% other mortality

Year	Orchard	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan
1991	Boon								0.0		
	Hibbert-Foy							15.5	18.8		
	Irvine								12.2		
	Willetts								2.1		
1992	Fiske								4.0	1.0	2.3
	Strang							0.0	5.6	10.0	7.5
	Willetts	2.2	10.5	9.9	0.4	0.8	3.4	3.2	4.0	6.2	1.3
1993	Fiske		0.0	0.7	7.7	1.2	3.1	29.0	10.7	11.0	0.0
	Willetts			5.6	9.2	2.8	14.6	17.5	8.5	7.6	0.3
Mean	1991							15.5	8.3		
	1992	2.2	10.5	9.9	0.4	0.8	3.4	1.6	4.5	5.7	3.7
	1993		0.0	3.2	8.5	2.0	8.9	23.3	9.6	9.3	0.2
	1991-1993	2.2	5.3	6.5	4.4	1.4	6.1	13.5	7.5	7.5	1.9

Adults
Leaf samples
Total number of scale assessed

Year	Orchard	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Total
1991	Boon			20	48	60					
	Hibbert-Foy					44					
	Irvine	29	57	63	75	107					
	Willetts					33					
1992	Fiske					14	35	12			
	Strang				28	46	12	20	15	32	
	Willetts				19	48	21	29		85	
1993	Fiske			14			16	21			
	Willetts				35	77	90	95	134		
Total	1991	29	57	83	123	244	0	0	0	0	536
	1992				47	108	68	61	15	117	416
	1993			14	35	77	106	116	134		482
	1991-1993	29	57	97	205	429	174	177	149	117	1434

% parasitised

Year	Orchard	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar
1991	Boon			0.0	0.0	1.7				
	Hibbert-Foy					9.1				
	Irvine	0.0	0.0	1.6	2.7	3.7				
	Willetts					12.1				
1992	Fiske					28.6	37.1	58.3		
	Strang				67.9	15.2	16.7	75.0	20.0	21.9
	Willetts				15.8	8.3	38.1	31.0		12.9
1993	Fiske			7.1			12.5	38.1		
	Willetts				0.0	1.3	14.4	18.9	23.1	
Mean	1991	0.0	0.0	0.8	1.4	6.7				
	1992				41.9	17.4	30.6	54.8	20.0	17.4
	1993			7.1	0.0	1.3	13.5	28.5	23.1	
	1991-1993	0.0	0.0	4.0	14.4	8.4	22.0	41.6	21.6	17.4

% disease

Year	Orchard	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar
1991	Boon			0.0	0.0	0.0				
	Hibbert-Foy					0.0				
	Irvine	0.0	0.0	1.6	1.3	0.9				
	Willetts					0.0				
1992	Fiske					0.0	0.0	0.0		
	Strang				0.0	0.0	0.0	0.0	0.0	0.0
	Willetts				0.0	0.0	0.0	0.0		0.0
1993	Fiske			0.0			6.3	0.0		
	Willetts				2.9	6.5	2.2	5.3	10.4	
Mean	1991	0.0	0.0	0.8	0.7	0.2				
	1992				0.0	0.0	0.0	0.0	0.0	0.0
	1993			0.0	2.9	6.5	4.3	2.7	10.4	
	1991-1993	0.0	0.0	0.4	1.2	2.2	2.1	1.3	5.2	0.0

% other mortality

Year	Orchard	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar
1991	Boon			0.0	0.0	1.7				
	Hibbert-Foy					22.7				
	Irvine	3.4	1.8	1.6	0.0	2.8				
	Willetts					3.0				
1992	Fiske					0.0	14.3	16.7		
	Strang				0.0	4.3	50.0	5.0	40.0	3.1
	Willetts				0.0	6.3	9.5	3.4		11.8
1993	Fiske			0.0			25.0	38.1		
	Willetts				0.0	6.5	6.7	7.4	25.4	
Mean	1991	3.4	1.8	0.8	0.0	7.6				
	1992				0.0	3.5	24.6	8.4	40.0	7.5
	1993			0.0	0.0	6.5	15.9	22.8	25.4	
	1991-1993	3.4	1.8	0.4	0.0	5.9	20.2	15.6	32.7	7.5

Appendix 12: continued

Adults
Wood samples
Total number of scales assessed

Year	Orchard	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Total
1991	Boon					52					
	Hibbert-Foy				75	147		179			
	Irvine					38					
	Willetts					154				201	
1992	Fiske					311	187	161	205	146	
	Strang				12	10	13	45	22	23	
	Willetts		23	131	151	267	375	299	299	438	
1993	Fiske	30	109	239	239	281	306	345	236		
	Willetts	69	20	118	180	227	355	399	442		
Total	1991				75	391	0	179	0	201	846
	1992		23	131	163	588	575	505	526	607	3118
	1993	99	129	357	419	508	661	744	678		3595
	1991-1993	99	152	488	657	1487	1236	1428	1204	808	7559

% parasitised

Year	Orchard	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar
1991	Boon					5.8				
	Hibbert-Foy				5.3	3.4		7.3		
	Irvine					2.6				
	Willetts					1.3				13.9
1992	Fiske					3.2	25.7	11.8	24.9	19.9
	Strang				0.0	10.0	38.5	57.8	13.6	17.4
	Willetts		0.0	0.0	0.7	0.7	20.8	17.1	18.4	21.5
1993	Fiske	0.0	1.8	0.8	1.3	3.2	5.6	15.4	9.7	
	Willetts	0.0	0.0	1.7	0.6	4.0	9.9	10.8	15.2	
Mean	1991				5.3	3.3		7.3		13.9
	1992		0.0	0.0	0.4	4.6	28.3	28.9	19.0	19.6
	1993	0.0	0.9	1.3	1.0	3.6	7.8	13.1	12.5	
	1991-1993	0.0	0.5	0.6	2.2	3.8	18.0	16.4	15.7	16.8

% disease

Year	Orchard	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar
1991	Boon					13.5				
	Hibbert-Foy				0.0	4.1		3.9		
	Irvine					0.0				
	Willetts					0.0				2.0
1992	Fiske					0.6	1.1	9.3	6.8	4.8
	Strang				0.0	0.0	0.0	0.0	4.5	0.0
	Willetts		0.0	0.0	0.0	0.0	0.0	0.3	0.7	0.5
1993	Fiske	3.3	3.7	4.2	2.5	7.8	12.1	4.9	3.4	
	Willetts	2.9	0.0	0.8	2.8	7.0	2.0	7.5	11.1	
Mean	1991				0.0	4.4		3.9		2.0
	1992		0.0	0.0	0.0	0.2	0.4	3.2	4.0	1.8
	1993	3.1	1.9	2.5	2.7	7.4	7.1	6.2	7.3	
	1991-1993	3.1	0.9	1.3	0.9	4.0	3.7	4.4	5.6	1.9

% other mortality

Year	Orchard	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar
1991	Boon					7.7				
	Hibbert-Foy				2.7	8.2		13.4		
	Irvine					7.9				
	Willetts					0.6				7.5
1992	Fiske					1.0	8.0	32.9	24.9	11.0
	Strang				0.0	10.0	15.4	17.8	18.2	4.3
	Willetts		0.0	0.0	1.3	0.4	11.2	5.0	13.0	22.8
1993	Fiske	0.0	0.9	2.5	24.7	11.4	11.8	15.4	20.3	
	Willetts	2.9	0.0	1.7	2.2	6.6	10.4	23.3	17.6	
Mean	1991				2.7	6.1		13.4		7.5
	1992		0.0	0.0	0.7	3.8	11.5	18.6	18.7	12.7
	1993	1.5	0.5	2.1	13.5	9.0	11.1	19.4	19.0	
	1991-1993	1.5	0.2	1.1	5.6	6.3	11.3	17.1	18.8	10.1

Appendix 13: Number and species of ladybirds recorded in visual counts and manual searches, January 1991-February 1994.

Visual counts	Huanui 1991			1991			1991/92			1992/93			1993/94			Total			All	No. 10 min
	L	P	A	L	P	A	L	P	A	L	P	A	L	P	A	Larvae	Pupae	Adults	stages	counts
August	-	-	-	-	-	-	0	0	43	-	-	-	0	0	52	0	0	95	95	7
September	-	-	-	-	-	-	0	0	59	0	0	1	0	0	207	0	0	267	267	7
October	-	-	-	-	-	-	0	0	42	1	1	16	0	0	52	1	1	110	112	9
November	-	-	-	-	-	-	1	1	25	0	0	2	0	0	84	1	1	111	113	10
December	-	-	-	-	-	-	-	-	-	18	9	24	1	2	15	19	11	39	69	9
January	-	-	-	22	17	848	2	0	49	34	20	235	11	1	43	69	38	1175	1282	46
February	11	2	632	8	8	649	1	0	44	1	3	158	12	0	116	33	13	1599	1645	33
March	13	3	1120	23	10	391	4	3	579	2	1	77	-	-	-	42	17	2167	2226	31
April	0	0	447	10	7	270	-	-	-	-	-	-	-	-	-	10	7	717	734	13
May	0	0	80	0	0	99	-	-	-	-	-	-	-	-	-	0	0	179	179	6
June	-	-	-	-	-	-	0	0	5	1	1	40	-	-	-	1	1	45	47	4
July	-	-	-	-	-	-	0	0	43	0	0	36	-	-	-	0	0	79	79	5
Total	24	5	2279	63	42	2257	8	4	889	57	35	589	24	3	569	176	89	6583	6848	180

Manual searches	Total			All	%	
	Larvae	Pupae	Adults	stages	L&P	A
Hendl (Nov)	2851	336	333	3520	*90.5*	*9.5*
Curtis (Dec)	262	111	157	530	*70.4*	*29.6*
Curtis (Feb)	12	1	253	266	*4.9*	*95.1*

Species of ladybirds recorded in visual counts and manual searches

	Visual counts							Manual searches					Overall (Visual & Manual)	
Ladybird species	Huanui	1991	91/92	92/93	93/94	Total	%	Hendl (Nov)	Curtis (Dec)	Curtis (Feb)	Total	%	n	%
Halmus chalybeus	2285	2319	826	718	531	6679	*97.53*	3486		265	3751	*99.08*	10430	*98.08*
Rhyzobius forestieri	7	84	11	10	11	123	*1.80*	34		1	35	*0.92*	158	*1.49*
Cryptolaemus montrouzieri	2	8	4	2	2	18	*0.26*				0	*0.00*	18	*0.17*
Rodolia cardinalis	12	8	2	2	0	24	*0.35*				0	*0.00*	24	*0.23*
Other*	2	1	0	1	0	4	*0.06*				0	*0.00*	4	*0.04*
Total	2308	2420	843	733	544	6848	*100.0*	3520		266	3786	*100.0*	10634	*100.0*
Not recorded									530					

* Other species   *Adalia bipunctata, Harmonia conformis, Illeis galbula*

Appendix 14: Trade name and rate of active ingredient of pesticides used in experiments with steelblue ladybirds (Chapter 5).

Chemical	Trade name	Company	Rate (g ai/100 litres)
Fungicides			
copper oxychloride	Copper oxychloride 50WP	FruitFed	150
cupric hydroxide	Champ 18F	Yates	70
cupric hydroxide	Kocide 101WP	Shell	100
copper sulphate + lime	Bordeaux WP	Yates	600 + 800
copper sulphate pentahydrate	Phyton 27	Technology Biologicals	150
benomyl	Benlate DF	Du Pont	12.5
captan	Captan 80WP	Yates	160
chlorothalonil	Bravo 500F	Yates	150
iprodione	Rovral 250F	Rhone-Poulenc	50
mancozeb	Dithane M-45 80WP	Rohm & Haas	160
sulphur	Microsul 80WP	FruitFed	80
triforine	Saprol 19EC	Ispray	20
Insecticides			
mineral oil	Sunspray	Shell	1%
mineral oil	DC Tron	BASF	1%
mineral oil	Ultrafine		1%
taufluvalinate	Mavrik SC	Yates	4.8
permethrin + pirimiphosmethyl	Attack EC	ICI	2.5 + 47.5
diazinon	Diazinon 50WP	Nufarm	25
chlorpyrifos	Lorsban 50W	DowElanco	37.5
C12-C18 fatty acids	Defender 25SC	Yates	500
buprofezin	Applaud 25W	DowElanco	12.5
Other			
azocyclotin	Peropal 25WP	Bayer	19
alkylarylpolyglycol ether	Citowett	BASF	25