THE BIOLOGY AND ECOLOGY OF CALIFORNIA RED SCALE, *Aonidiella aurantii* (Mask.) (Hemiptera:Diaspididae), AND ITS NATURAL ENEMY, *Aphytis melinus* DeBach (Hymenoptera:Aphelinidae).

by

Zhao Jing-wei

B. Ag. Sc. (Entomology),

M. Ag. Sc. (Fujian Agricultural College, China)

A thesis submitted for the degree of Doctor of Philosophy in the Faculty of Agricultural Science to the University of Adelaide.

Department of Entomology,

Waite Agricultural Research Institute,

The University of Adelaide.

August, 1987

TO

MY PARENTS

TABLE OF CONTENTS

	Page.
SUMMARY	I
DECLARATION	III
ACKNOWLEDGEMENTS	IV
CHAPTER 1. INTRODUCTION AND OBJECTIVES	1
1.1. Aonidiella aurantii (Mask.)	1
1.2. Aphytis melinus DeBach	2
1.3. Studies of Red Scale and its Aphytis Parasites	2
1.4. Studies on Red Scale and its Parasites in Australia	4
CHAPTER 2. RECORDING EXTREMES OF TEMPERATURES IN THE ORCHARD	10
2.1. In Winter	11
2.1.1. Method	11
2.1.2. Results	11
2.2. In Summer and Autumn	13
2.3. Discussion	15
CHAPTER 3. CULTURE OF EXPERIMENTAL INSECTS AND SPECIAL EQUIPMENT	19
3.1. California Red Scale	19
3.1.1. Culture of red scale	19
3.1.2. Mortality of red scale due to the method of transferring	22
3.1.2.1. Introduction	22
3.1.2.2. Experiment 1	22
3.1.2.3. Experiment 2	28
3.2. Mass Culture of A. melinus	28
3.2.1. Collection of one-day-old Aphytis wasps	32
3.3. Special Equipment	33
3.3.1. Collection tube for wasps of A. melinus	33
3.3.2. Constant humidity cage	33
3.3.3. Citrus fruit cage	33
3.3.4. Head lens	33
3.3.5. Microscope	37
3.3.6. Photographic equipment	40
CHAPTER 4. INFLUENCE OF TEMPERATURE ON THE BIOLOGY OF CALIFORNIA RED SCALE	44
4.1. Introduction	44
4.2. Mortality of Red Scale Cohorts on Trees	44
~~4.2.1. Introduction~~	44
4.2.1. Methods and materials	45
4.2.1.1. Starting experimental cohorts of red scales	45
4.2.1.2. Use of a photographic method to observe the survival and growth of red scale	47
4.2.1.3. Ambient temperature during the year	47

4.2.2 Results 51
4.2.2.1 The survival-rate of adult scales 53
4.2.2.2 The relationship between HD > 10°C and survival of adult red scales 58
4.2.2.3 The relationship between H.D. > 40°C and the survival of 1st instar scales 63
4.2.2.4 The drop-off rate of dead 1st instar scales 67
(i) Introduction 67
(ii) Methods 69
(iii) Results 70
(iv) Discussion 79
4.2.2.5 The drop-off rate of dead scales of other stages. 79-E
4.2.3 General discussion 79-

4.3. Mortality of Red Scale and the Durations of Temperatures 80
4.3.1. Mortality of red scale 80
4.3.1.1. Methods and materials 80
4.3.1.2. Results 80
4.3.2. Reproduction of treated adult female scales 83
4.3.2.1. Methods 85
4.3.2.2. Results 87
4.4. Mortality of Red Scale in the Sun 87
4.4.1. Experiment 1: Measurement of mortality on the tree 87
4.4.1.1. Methods and Materials 89
4.4.1.2. Results and discussion 90
4.4.2. Experiment 2: Mortality on lemons in the sun but off the tree 96
4.4.2.1. Methods and materials 97
4.4.2.2. Results and discussion 97
4.5. Mortality of Cohorts of Red Scale Responding to Low Temperature 99
4.5.1. Introduction 99
4.5.2. Methods and materials 99
4.5.3. Results and discussion 101

CHAPTER 5. BIOLOGY AND ECOLOGY OF Aphytis melinus DeBach 106

5.1. Host-Feeding of Female Adult of A. melinus 106
5.1.1. Experiments and results 107
5.1.2. Discussion 127
5.2. Longevity of Female Adults of A. melinus 129
5.2.1. Part 1: Laboratory experiments: Longevity of A. melinus wasps on different foods at constant temperatures 129
5.2.2. Part 2: Field experiments: Test of longevity of female adults of A. melinus on orange on the tree 136
5.3. Influence of Duration of High Temperature on Mortality of A. melinus Pupa 142
5.3.1. Methods and materials 142
5.3.2. Results and discussion 144
5.4. Searching Efficiency of Female Wasps of A. melinus in Cages at 25°C and 60% R.H. 146
5.4.1. Review and design of the present experiment 146
5.4.1.1. Introduction 146
5.4.1.2. What is "searching efficiency" ? 147
5.4.1.3. Design of the present experiment 150

Page.

5.4.2. Methods and materials 150
5.4.2.1. Treatments 150
5.4.2.2. Materials 150
5.4.3. Experiments 152
5.4.4. Results and discussion 154
5.4.4.1. General results 154
5.4.4.2. One female wasp 154
5.4.4.3. Interaction among parasites 161
5.4.4.4. Variation among densities of host scales and replications in each experiment 161
5.5. Development of A. melinus at Constant Temperature of 25°C and Constant 75% R.H. 164
5.5.1. Methods and materials 165
5.5.2. Results and discussion 166

CHAPTER 6. GROWTH OF Phacelia sp. AND ITS INFLUENCE ON Aphytis melinus DeBach 175

6.1. Growth of Phacelia sp. 175
6.2. Influence of Nectar on Female Wasps of A. melinus 185
6.2.1. On longevity 185
6.2.2. On searching efficiency of wasps 188

CHAPTER 7. SEASONAL ABUNDANCE OF CALIFORNIA RED SCALE 192

7.1. Introduction 192
7.2. Study Orchard and Sampling Method 194
7.2.1. Study orchard 194
7.2.2. Sampling method 194
7.2.2.1. Distribution of red scale on lemon trees 194
7.2.2.2. Subsampling method 195
7.2.2.3. Results of the sampling experiment 195
7.3. Field Sample of Red Scale 197
7.3.1. Sampling techniques 197
7.3.2. Results and discussion 201
7.3.2.1. Establishment of annual generations of red scale 201
7.3.2.2. The seasonal fluctuation of numbers of red scale 204
7.3.2.3. Growth of the population of red scale 219
7.3.2.3.1. In relation to parasitoid, A. melinus 219
7.3.2.3.2. In relation to daily mean ambient temperature 221

CHAPTER 8. GENERAL DISCUSSION

8.1. On the Population Regulation of Red Scale 232
8.2. On the Estimation of the Influence of Aphytis on the Natural Control of Red Scale 235
8.3. Control Strategies of Aphytis on Red Scale 238

APPENDIXES 241

SUMMARY

Studies of biology of California red scale, Aonidiella aurantii (Mask.), and its natural enemy, Aphytis melinus DeBach, were conducted at the Waite Agricultural Research Institute (W.A.R.I.), South Australia.

Field and laboratory experiments showed that survival and reproductive ability of female wasps of A. melinus are functions of a carbohydrate source, i.e., honey or flower-nectar. By contrast, host-feeding of female wasps has little effect on survival time and reproductive ability. The host-feeding can cause only little mortality of red scale of growing stages if the wasps have no access to a carbohydrate source.

A patchy population of red scale was constructed to test the searching efficiency of one-day-old female wasps of A. melinus. This population comprised several densities of red scale; different numbers of host citrus fruits were used to maintain the same total number of red scale in each of the densities. Results showed that wasps gave a "frequency response" instead of the classical Holling's functional response: the mortality of red scale was not aggregated in high densities of host scales. The wasps' searching efficiency varied greatly with the availability of carbohydrate.

Field and laboratory experiments tested the influence of extreme temperature on the mortality of red scale. Mortality was influenced not only by the values of the extremes but also by their durations. Similar results were obtained for pupae of A. melinus at 45°C.

Orchard experiments were conducted to measure the temperature 1 mm. above and 5 mm. under the skin of lemons in the sunlight. In summer, scales in the sunlight on lemons could experience a temperature 15°C higher than ambient (in a Stevenson Screen). Also in the orchard, cohorts of red scales were exposed to the sun in summer to measure the effect of extreme temperatures in the sunlight on mortality. The drop-off rate of a cohort in relation to extreme temperatures was also measured. The drop-off rate was not a function of extreme temperatures but a function of the duration after the cohort had been started.

From May 1984 to March 1986, the population dynamics of red scales on lemons were studied in the W.A.R.I. orchard. Samples were taken with an interval of about 95 day-degrees, greater than 12°C. After overwintering, the population of red scale started to grow in early November (mid spring) and stopped in late March (late summer) of the following year. A mathematical analysis indicated a threshold growth of the red scale population occurred at the mean of about 18.5°C for an observation period with 95 day-degrees greater than 12°C. The positive trend of the growth of the population during this period was not reversed by the extremely high temperatures in summer. The daily minima below 8.5°C could cause a significant mortality of red scale (young stages). The parasitoid, A. melinus, showed a poor ability to regulate the population of red scale.

Also detected or measured were (1) the influence of methods of transferring crawlers on the mortality of red scale, (2) the identification of stages of the development of A. melinus at 25°C and 75% R.H., and (3) the growth of Phacelia sp. at constant temperatures.

For field experiments, a special microscope system was constructed.

DECLARATION

The work presented in this thesis is my own, unless otherwise acknowledged, and has not been previously published or submitted to any university for the award of any degree or diploma. This thesis may be made available for loan or photocopying provided that an acknowledgement is made in the instance of any reference to this work.

(Zhao Jing-wei)

August, 1987

ACKNOWLEDGEMENTS

I wish to express my deep appreciation to my supervisors, Dr. Derek Maelzer and Dr. Roger Laughlin, for their untiring and continued guidance, advice, assistance and critical discussions in the preparation of this thesis.

Thanks are also due to Professor T. O. Browning, formerly professor, Department of Entomology, Waite Agricultural Research Institute, for allowing me to commence this study in his department.

I am indebted to members of Entomology Department, Waite Institute, all of whom have helped me in various ways. I wish to thank Miss Rachel Perry for her help in printing this thesis.

I would like to thank the Chinese Government for awarding me the scholarship for making this study possible. I am grateful to the Fujian Agricultural College for granting me the period of leave required to carry out this study and for helping me in various ways.

Finally, thanks are due to my parents and other members of my family for their constant encouragement; thanks are also due to my wife and two daughters for their patience and encouragement during my study period.

CHAPTER 1.

INTRODUCTION AND OBJECTIVES

CHAPTER 1. INTRODUCTION AND OBJECTIVES

My study was designed to allow a better understanding of the population dynamics of California red scale, Aonidiella aurantii (Mask.), in the experimental orchard of the Waite Institute in Adelaide, South Australia. In particular the study involved the quantification of the seasonal abundance of red scale on lemons and a series of experiments in the laboratory and in the field which were designed to quantify

(1) the influence of the duration (hours or days) of extreme temperatures on survival or reproduction of red scale and/or A. melinus and

(2) the searching efficiency of A. melinus on red scale in relation to differences of food supplies (for parasite).

1.1. Aonidiella aurantii (Mask.)

California red scale is one of the most important pests of citrus in California, Australia, South Africa, and northwestern Mexico; it is a major pest of citrus in the eastern Mediterranean Basin, North Africa, and parts of South America; as well in China (Quayle 1938; Ebeling 1959; U.S. Dept. Agri. 1978). As a major pest of citrus, it is known mainly in subtropical areas, generally between the latitudes 25 and 40 degree north and south (DeBach 1960).

California red scale can infest all the above-ground parts of citrus trees. Heavy infestations may severely set back or even kill the tree (Ebeling 1951). The life history of red scale was worked out as early as the 1910's (Quayle 1911). It's biology was further investigated by Nel (1933) in a comparative study of the red and the yellow scale. Later, Dickson and Lindgren (1947) and others made a field study of its seasonal history.

The stages of development of red scale have been classified in different ways. In the 1950's they were described as: crawler, white-cap, nipple, first moult, second moult, gray adult and adult stage in order (Ebeling 1951). Later, Abdelrahman (1973a) divided development into the stages: crawler, 1st instar, 1st moult, 2nd instar, female 2nd moult (also male prepupa), female 3rd instar (also male pupa to adult) and female adult stage. He divided all the stages into two categories according to the sexes of scale insects. From the crawler stage to the second instar were considered as the sex-indistinguishable stages and from second moult (female) and prepupa (male) to adult were the sex-distinguishable stages. By contrast, researchers in California University (1984) believed that

development of the female and male scales is the same only until the first moult ends (one stage earlier than Abdelrahman's).

A field study by Atkinson (1977) established a threshold temperature of 12°C for the development of red scale and, for the completion of one generation, a requirement of 580 day-degrees above 12°C. By comparison, McLaren (1971) estimated a threshold of 15°C for the growth of a population of red scale in the field.

1.2. *Aphytis melinus* DeBach

This parasite has been known for many years as a good agent for the biological control of red scale in California. It was introduced into California in 1956-1957 from India and Pakistan and soon proved to be the most effective known natural enemy of red scale. Since 1959, *A. melinus* has been transferred from California to numerous other countries (Rosen and DeBach 1979).

1.3. Studies of Red Scale and its *Aphytis* Parasites

Many studies have been done world wide but especially, from the 1950's, by DeBach and his colleagues in U.S.A. who have been interested in the broad spectrum of the biology of red scale (DeBach 1946, 1958, 1965; DeBach, Hendrickson and Rose 1978) and its parasitoids, especially *Aphytis* spp. (DeBach 1954, 1957, 1959, 1966; DeBach, Fisher and Landi 1955; DeBach and Sisojevic 1960). They have also studied at length the biological and chemical control of red scale (DeBach 1950, 1951, 1952, 1960; DeBach and Bartlett 1951; DeBach and Landi 1961; DeBach, Land and White 1962; DeBach and Arguriou 1967; DeBach, Rosen and Kennett 1971) and experimental methods, e.g., for the cultural control of red scales or for the assessment of the role of the parasites (DeBach and Erickson 1952; DeBach 1955; DeBach and White 1960; DeBach and Huffaker 1973).

The influence of *Aphytis* parasites on the population regulation of red scale has been thought to be affected mainly by various biotic factors, namely,

(1) the availability of the host scale insects and especially the influence of the different development stages of scale on the fecundity of adult *Aphytis* (DeBach 1969; Baker 1976, Luck and Podoler 1985, Opp an Luck 1986),

(2) host plant, which affects the fecundity and efficiency of *Aphytis*,

(3) a food for the adult parasite, namely, carbohydrate and proteinaceous food (DeBach and White 1960; van den Bosch and Telford 1964),

(4) honeydew-seeking ants, which affect the numbers of Aphytis mainly by interference with the adult parasite (DeBach, Dietrick and Fleschmer 1951; DeBach 1958, 1966; Steyn 1958).

The influence of physical factors affecting Aphytis in the population regulation of red scale were mainly considered as (1) temperature extremes (Lord and MacPhee 1953; DeBach, Fisher and Landi 1955; Kfir and Podoler 1983), causing high mortality and reducing searching efficiency of Aphytis adult wasps and (2) low humidity, combined with high temperature, which could seriously reduce the numbers of egg laid by adults of Aphytis (DeBach, Fisher and Landi 1955). Other factors which have also been considered to influence the role of Aphytis are airborne dust (Bartlett 1951) and light (photoperiod and/or intensity) (DeBach, Fisher and Landi 1955; DeBach and White 1960); and so on.

Chemical treatment used to control red scale has also been a factor in the interaction of red scale and its parasites. DeBach (1965) reported that all insecticides, i.e. DDT, tosaphene, endrin, and dieldrin, eventually caused host population increases of 40-60 fold in the inland areas. In the coastal area only DDT caused impressive increases but these were over 200-fold. After application of DDT, a period as long as 3 years was needed for a population of red scale, upset as a result of DDT decimating A. melinus, to fall again to the economic injury threshold (DeBach, Rosen and Kennett 1971).

Since the 1970's, some intensive investigations on the population dynamics of red scale have been made. For example, the influence of natural enemies and environmental factors on the population fluctuation of red scale in S. Africa were discussed by Atkinson (1983a, b) and a mathematical model was built on the searching efficiency of Aphytis on red scale by Luck, Allen and Baasch (1980).

However, the role of Aphytis sp. in the population regulation of red scale is difficult to evaluate because of the subtle influence of other factors, e.g. weather and the availability of food for the adult parasites.

1.4. Studies on Red Scale and its Parasites in Australia

Research work was started as early as 1897 (Quinn 1897) but the intensive studies were not made until the 1970's (McLaren and Buchanan 1973; Maelzer 1979). Maelzer (1979) pointed out that red scale mostly occurs in two climatic zones in Australia in which the citrus industry is concentrated; they were, namely, (1) the inland semi-arid zone involving irrigated regions along the River Murray in South Australia, Victoria and New South Wales, and along the Murrumbidgee River in New South Wales and (2) the non-irrigated humid coastal regions of New South Wales and south-eastern Queensland. A. melinus was introduced into the inland citrus regions in the early 1960's and soon established relatively good biological control of red scale. Because of the efficiency of such control, 75% of growers in South Australia did not apply chemicals for the control of red scale (Furness 1973).

However, much of the research on red scale and its parasites in Australia has been confined to laboratory studies. Initially, attention was first given to the essential biology of red scale and its parasites, e.g. the development and reproduction of red scale (Willard 1972), the growth and development of A. melinus (Abdelrahman 1974b), behaviour of Aphytis adult wasps (McLaren, Ph.D. thesis) and ovipositional behaviour of A. melinus (Abdelrahman 1974c). Further studies involved processes relevant to the ecology of red scale in the field. Thus Abdelrahman (1974a) studied the influence of extremes of temperature, both high and low, on the mortality of both red scale and A. melinus and he suggested that, in summer in South Australia, extremes of high temperatures are not high enough to cause a high mortality of red scale. Earlier, however, an understanding of the influence of high temperature on mortality of red scale had been used to develop a method of heat treatment of citrus for control of red scale (Martin and Black 1960).

The toxicity of chemical insecticides to red scale and A. melinus was also studied by Abdelrahman (1973a, b); he concluded that integration of malathion and biological control (by A. melinus) of red scale in S. Australia did not seem possible. A similar conclusion was reached from a study of biological control of red scale in Queensland (Smith 1978). Other studies done in Australia towards an understanding of the population regulation of red scale have been: the population growth of red scale (McLaren 1971; McLaren and Buchanan 1973), the population growth of red scale as influenced by the dispersion of crawlers by wind (Willard 1968),

the colonization of A. melinus in orchards (Campbell 1976) and the aggregation of A. melinus and the density-independence of parasitism in the field (Smith and Maelzer 1986). Maelzer (unpublished) also developed a sampling method for red scale on orange trees in S. Australia.

REFERENCES

Abdelrahman, I. (1973a). Toxicity of malathion to California red scale, Aonidiella aurantii (Mask.) (Hemipera:Diaspididae). Aust. J. Agric. Res., 24:111-118.

Abdelrahman, I. (1973b). Toxicity of malathion to the natural enemies of California red scale, Aonidiella aurantii (Mask.) (Hemiptera:Diaspididae). Aust. J. Agri. Res., 24:119-133.

Abdelrahman, I. (1973c). A laboratory spraying apparatus. Aust. J. Agric. Res., 24:135-142.

Abdelrahman, I. (1974a). The effect of extreme temperatures on California red scale, Aonidiella aurantii (Mask.) (Hemiptera:Diaspididae), and its natural enemies. Aust. J. Zool., 22:203-212.

Abdelrahman, I. (1974b). Growth, development and innate capacity for increase in Aphytis chrysomphali Mercet and A. melinus DeBach, parasites of California red scale, Aonidiella aurantii (Mask.), in relation to temperature. Aust. J. Zool., 22:213-230.

Abdelrahman, I. (1974c). Studies in ovipositional behaviour and control of sex in Aphytis melinus DeBach, a parasite of California red scale, Aonidiella aurantii (Mask.). Aust. J. Zool., 22:231-247.

Atkinson, P. R. (1977). Preliminary analysis of a field population of citrus red scale, Aonidiella aurantii (Mask.), and the measurement and expression of stage duration and reproduction for life tables. Bull. Entom. Res., 67:65-87

Atkinson, P. R. (1983a). Environmental factors associated with fluctuation in the numbers of natural enemies of a population of citrus scale, Aonidiella aurantii (Hemiptera:Homoptera:diaspididae). Bull. Entom. Res., 73:417-426.

Atkinson, P. R. (1983b). Estimates of natural mortality related to environmental factors in a population of citrus red scale, Aonidiella aurantii (Hemiptera:Homoptera:Diaspididae). Bull. Entom. Res., 73:239-258.

Baker, J. L. (1976). Determinants of host selection for species of Aphytis (Hymenoptera:Aphelinidae), parasites of diaspine scales. Hilgardia, 44:1-25

Bartlett, B. R. (1951). The action of certain "inert" dust materials on parasitic Hymenoptera. J. Econ. Entom., 44:891-986.

Campbell, M. M. (1976). Colonization of Aphytis melinus DeBach (Hymenoptera:Aphelinidae) in Aonidiella aurantii (Mask.) (Hemiptera:Coccidae) on citrus in South Australia. Bull. Entom. Res., 65:659-668.

DeBach, P. (1946). An insecticidal check method for measuring the effecacy of entomophagous insects. J. Econ. Entom., 39:695-697.

DeBach, P. (1950). Natural control of citrus pests in Texas and Florida. Calif. Citrog., 35:410-434.

DeBach, P. (1951). Possibilities in biological control of citrus pests. 5th Ann. Rio Grande Val. Hort. Inst. Proc. :77-80.

DeBach, P. (1952). Biological control of red scale in San Diego county. Calif. Citrog., 37:136-137, 158-160.

DeBach, P. (1954). Relative effecacy of the red scale parasites Aphytis chrysomphali (Mercet) and Aphytis "A" on citrus trees in southern California. Boll. Lab. Zool. Gen. Agr. "Filippo Silvestri", Portici, 33:135-151.

DeBach, P. (1955). Validity of the insecticidal check method as a measure of the effectiveness of natural enemies of diaspine scale insects. J. Econ. Entom., 48:584-588.

DeBach, P. (1957). New natural enemies of citrus pests imported. Calif. Citrog., 42:414-424.

DeBach, P. (1958). The role of weather and entomophagous species in the natural control of insect populations. J. Econ. Entom., 51:474-484.

DeBach, P. (1959). New species and strains of Aphytis (Hymenoptera:Eulophidae) parasitic on the California red scale, Aonidiella aurantii (Mask.) in the Orient. Ann. Entom. Soc. Amer., 52:354-362.

DeBach, P. (1960). Biological control of the California red scale, Aonidiella aurantii (Mask.), on citrus around the world. XI. Int. Cong. Ent. Proc., 2:749-7532

DeBach, P. (1965). Weather and the success of parasites in population regulation. Canad. Entom., 97:848-863.

DeBach, P. (1966). The competitive displacement and coexistence principles. Ann. Rev. Entom., 11:183-212.

DeBach, P. (1969). Biological control of diaspine scale insects on citrus in California. Proc. 1st Interna. Citrus Symp.(Riverside,1986), 2:801-822.

DeBach, P. and Arguriou, L. C. (1967). The colonization and success in Greece of some imported Aphytis spp. (Hym.:Aphelinidae) parasitic on citrus scale insects (Hom., Diaspididae). Entomophaga, 12:325-342.

DeBach, P. and Bartlett, B.R. (1951). Effects of insecticides on biological control of insect pest on citrus. J. Econ. Entom., 44:372-383.

DeBach, P., Dietrick, E. J. and Fleschner, C. A. (1951). Ants vs. biological control of citrus pests. Calif. Citrog., 36:312, 347-348.

DeBach, P. and Erickson, L. (1952). Roots lemon fruits for citrus pest studies. J. Econ. Entom., 45:1097-1098.

DeBach, P., Fisher, T. W. and Landi, J. (1955). Some effects of meteorological factors on all stages of Aphytis lingnanensis, a parasite of the California red scale. Ecology, 36:743-753.

DeBach, P., Hendrickson, R.M. and Rose, M. (1978). Competitive displacement: Extinction of the yellow scale, Aonidiella citrina (Coq.) (Homoptera:Diaspididae), by its ecological homologue, the California red scale, A. aurantii (Mask.) in Southern California. Hilgardia, 46:1-35

DeBach, P. and Huffaker, C. B. (1973). Experimental techniques for evaluation of the effectiveness of natural enemies. in C. B. Huffaker (Editor), Biological Control. Plenum Press, N. Y., pp.113-139.

DeBach, P. and Landi, J. (1961). The introduced purple scale parasite, Aphytis lepidosaphes, and a method of integrating chemical with biological control. Hilgardia, 31:459-497.

DeBach, P., Land, J. and White, E. B. (1962). Biological control of California red scale. Calif. Citrog., 47:453-459; 48:16-20.

DeBach, P., Rosen, D. and Kennett, C. E. (1971). Biological control of coccids by introduced natural enemies. in C. B. Huffaker (ed.), "Biological Control", Plenum Press, N. Y., pp.165-194.

DeBach, P. and Sisojevic, P. (1960). Some effects of temperature and competition on the distribution and relative abundance of Aphytis lingnanensis and A. chrysomphali (Hymenoptera:Aphelinidae). Ecology, 41:153-160.

DeBach, P. and White, E. B. (1960). Biological control of red scale. Calif. Citrog., 40:254, 271-272.

Dickson, R.C. and Lindgren, D.L. (1947). The California red scale. Calif. Citrograph, 32:524, 542-544

Ebeling, W. (1951). Subtropical Entomology. Lithotype Process Co., Calif., U.S.A. 747 pp.

Ebeling, W. (1959). Subtropical fruit pests. Uni. of Cal., Division of Agricultural Science, Los Angeles, 436 pp.

Furness, G. O. (1973). Integrated control of red scale. Dept. Agriculture, S. Australia. Extension Bulletin, 27.73.

Kfir, R. and Podoler, H. (1983). Effect of temperature and parasite density on three species of Aphytis (Hymenoptera:Aphelinidae), parasitising California red scale. Res. Popul. Ecol., 25:69-80.

Lord, F. T. and MacPhee, A. W. (1953). The influence and the natural control of the oystershell scale, Lepidosaphes ulmi (L.) (Homoptera:Coccidae). Canad. Entom., 85:282-291.

Luck, R. F., Allen, J. C. and Baasch, D. (1980). California red scale/Aphytis models. in C. B. Huffaker (ed.), "New Technology of Pest Control", pp. 379-393, A Wiley-Interscience Publication.

Luck, R. F. and Podoler, H. (1985). The potential role of host size in the competitive exclusion of Aphytis lingnanensis by A. melinus. Ecology, 66:904-913.

Maelzer, D. A. (1979). Concepts and innovations in biological control of insects. Australian Applied Entomological Conference, 1979.

Martin, B. H. and Black, R. F. (1960). Heat treatment of citrus for control of red scale. Aust. J. Agric. Res., 11:197-207. Nel, R.G. (1933). A comparison of Aonidiella aurantii and A. citrina, including a study of the internal anatomy of the latter. Hilgardia, 7:417-466

McLaren, I.W. (1971). A comparison of the population growth potential in California red scale, Aonidiella aurantii (Mask.), and yellow scale, A. citrina (Coq.), on citrus. Aust. J. Zool., 19:189-204

McLaren, I. W. (1976). a behavioural study of Aphytis chrysomphali (Mercet) and A. melinus DeBach (Hymenoptera:aphelinidae) parasitic on California red scale, Aonidiella aurantii (Mask.) (Homoptera:diaspididae). Ph.D. thesis of Latrobe University.

McLaren, I. W. and Buchanan, G. A. (1973). Parasitism by Aphytis chrysomphali (Mercet) and A. melinus DeBach of California red scale Aonidiella aurantii (Mask.), in relation to seasonal availability of suitable stages of the scale. Aust. J. Zool., 21:111-117.

Opp, S. B. and Luck, R. F. (1986). Effects of host size on selected fitness components of Aphytis melinus and A. lingnanensis (Hymenoptera:Aphelinidae). Ann. Ent. Soc. Ame., 79:700-704.

Quayle, H.J. (1911). Locomotion of certain young scale insects. J. Eco. Entom., 4:301-306

Quinn, G. (1897). The hydrocyanic acid gas treatment for destroying scale insects. J. Agric. Ind. S. Aust., 1:351-357.

Quayle, H.J. (1938). Insects of Citrus and other subtropical fruits. Comstock Publishing Co., Ihtaca, N.Y.

Rosen, D. and DeBach, P. (1979). Species of Aphytis of the world (Hymenoptera:Aphelinidae). Keter Publishing House Jerusalem, Ltd., 801 pp.

Smith, A. D. M. and Maelzer, D. A. (1986). Aggregation of parasitoids and density-independence of parasitism in field populations of the wasps Aphytis melinus and its host, the red scale Aonidiella aurantii. Ecol. Entom., 11:425-434.

Smith, D. (1978). Biological control of scale insects on citrus in southeastern Queensland: I. Control of red scale, Aonidiella aurantii (Mask.). J. Aust. Entom. Soc., 17:367-371.

Steyn, J. J. (1958). The effect of ants on citrus scales at Leteba, South Africa. Proc. 10th Interna. Congr. Entom. (Montreal, 1956), 4:589-594.

Uni. of California. (1984). Integrated pest management for citrus. Uni. of California. Publication 3303, 1984

U.S. Dept. Agri. (1978). California red scale (Aonidiella aurantii (Mask.)). in "Introduced Parasites and Predators of Arthropoda Pests and Weeds: A World Review, Agriculture Handbook No.480, pp.79-93". ed: Curtis P. Clausen., Washington, D.C.

van den Bosch, R. and Telford, A. D. (1964). Environmental modification and biological control. Chapter 16 in P. DeBach (ed.), "Biological control of insect pests and weeds", Chapman and Hall, London, pp.459-488.

Willard, J. R. (1968). Dispersal of red scale (Aonidiella aurantii (Mask.)) by wind in South Australia. Ph. D. thesis, Waite Agricultural Research Institute, University of Adelaide, 397 pp.

Willard, J. R. (1972). Studies on rates of development and reproduction of California red scale, Aonidiella aurantii (Mask.) (Homoptera: Diaspididae). Aust. J. Zool., 20:37-47.

CHAPTER 2.

RECORDING EXTREMES OF TEMPERATURES IN THE ORCHARD

CHAPTER 2. RECORDING EXTREMES OF TEMPERATURES IN THE ORCHARD

Munger (1948) developed a method of estimating the body-temperature of red scale by use of a thermocouple made of wire 0.001 inch (0.025mm) in diameter. He also used a thermocouple made of wire 0.013 inch (0.33mm) in diameter to measure the temperatures of hosts of red scale. All his temperature measurements were made on the mature females. As he said, the pliability of the wire made it necessary to puncture the integument of the scale with a sharp needle before inserting the thermocouple to measure the scale's body-temperature. However, some of his results (converted to °C) were as follows:

(1) in the shade, the scale's body-temperature was close to that of its host, the greatest deviations being +0.7°C and -0.8°C and

(2) in the sunlight, when air temperatures ranged from 23.6°C to 36.0°C, the greatest deviation of the scale's body-temperature from the air temperature was +10.3°C when the air was 30.5°C; the body-temperature was 1.3°C lower than the temperature of the host of lemon. He concluded that (a) in natural shade there was close agreement between air, hosts of scales, and scales while (b) in the sun there was somewhat less agreement between the temperatures of scale and host and both rose well above the air temperature and (c) the greatest deviation of the body-temperature from the air temperature was +11.9°C when the air temperature was 28.9°C.

In Munger's work (ibid), it was obvious that the thermal capacity of the so-called "sharp needle" was not considered as a fact which might have influenced the real body-temperature of the scale insects. Besides, since the tested scales had already been punctured, I believe the so-called body-temperature could only be regarded as the temperature of a dead scale and not the body-temperature of a live insect.

Since it is almost impossible to measure a real body-temperature of live scales and even more difficult to get a continuous reading of such temperature, one has to use some indirect method for estimating the temperature of a scale insect. The obvious method is to use the measurement of the plant surface since the Munger's measurements of temperature within the scale was never different from that of the host by more than 3°C.

The following experiments were therefore conducted to measure the surface temperature of a lemon, assuming that such a temperature would be little different from that of a scale insect on the surface of the lemon.

2.1. In Winter

2.1.1. Methods

8 sensors were placed on 4 lemons on a tree in the orchard in the 8 combinations of the following 3 pairs of alternatives: East and west of the canopy; 1mm above and 5mm under the skin of the lemon; on the shady side or the sunny side of the lemon [Table 2.1 (1)]. Sensors on the sunny side were exposed to the sun for only part of the day; sensors on the shady side were never in direct sunlight; all the experimental lemons were in the sunlight for part of the day.

Each sensor was made of copper-constantan thermocouple wire 0.5mm in diameter and about 4-5mm in length.

In the following description, the temperature under the skin of a lemon is called the "in-skin temperature" and the temperature above the skin is called the "above-skin temperature".

2.1.2. Results

The pattern of sensor-temperatures obtained in late autumn, on 19/6/83, are plotted against time in Fig.2.1 (1) to 2.1 (4); for the comparison, also plotted in these figures are the ambient temperatures obtained from a Stevenson Screen. The plot started about one hour after sunrise when the whole orchard was still in the shade of a hill. All the in-skin and above-skin temperatures were 2 or 3°C lower than the ambient temperature. After 0900h, when only parts of the tree were exposed to the sun, temperatures were quite variable.

On the eastern side of the canopy: In-skin and above-skin temperatures in the sunlight rose rapidly [Fig.2.1 (1)]. At noon, They reached the maximum values of about 27°C. By contrast, the ambient temperature was 11°C lower, about 16°C. After noon, both "skin" temperatures dropped rapidly after the eastern part of the canopy was shaded from the sun. At 1500h, deviations between skin temperatures and the ambient temperature were zero. Then the skin temperatures fluctuated around the ambient temperatures with a range of 1-2°C until sunrise next day. However, as shown in Figure 2.1 (1), during the period 0800-1900h, the difference between the in-skin and above-skin temperatures was always smaller than 1°C.

Table 2.1 (1). Thermocouple sensors on lemons on the tree during the winter period of 16/6-10/8, 1983.

No. of sensor	Aspect	Treatments to sensors:	Height (m.)
	East--in the sunlight		
S1		1 mm above the skin	0.95
S2		5 mm in the skin	0.95
	East--shaded*		
S3		1 mm above the skin	1.20
S4		5 mm in the skin	1.20
	West--in the sunlight		
S5		1 mm above the skin	1.15
S6		5 mm in the skin	1.15
	West--shaded*		
S7		1 mm above the skin	1.35
S8		5 mm in the skin	1.35

*: the sensors were shaded by each lemon itself but this lemon was in the sunlight.

By contrast, the in-skin and above-skin temperatures from the sensors on the shady part of the lemon did not vary so much as that from the sensors in the sun [Fig.2.1 (2)]. At 1100h, they reached maximum values of about 18°C , which was only about 3°C higher than the ambient temperature. Then, both "skin" temperatures fell to about the ambient temperature and after about 1500h, when this part of the canopy was in natural shade, the "skin" temperatures, again, fluctuated around the ambient temperatures with a range of 1-2°C. On the shady part of the lemon, the in-skin and above-skin temperatures never differed by more than 1°C.

On the western side of the canopy: In-skin and above-skin temperatures in the sunlight rose rapidly [Fig.2.1 (3)]. They reached the maximum values at 1400h. The above-skin temperature was about 30°C and the in-skin temperature was about 28°C, about 11-13°C higher than the ambient temperature (17°C). After 1400h, both "skin" temperatures dropped rapidly. At 1700h, the difference between skin temperatures was zero. Then, again, both "skin" temperature fluctuated around the ambient temperatures with a range of 1-2°C until sunrise next day. During the period 1400-1600h, the difference between the in-skin and above-skin temperature was always smaller than 2°C.

As shown in Fig.2.1 (4), obtained from the sensors on the shady part of the lemon, the difference between "skin" temperatures and the ambient temperature was never bigger than 2°C at any time throughout the day.

Above and below the skin: Within each pair of "skin" temperatures, the difference between the two temperatures was never bigger than 3°C. And by comparison with Munger's measurements, I thought that a sensor 1mm above the lemon skin could be used to measure a temperature which was very close to the in-skin temperature but would not cause any damage to lemons. It could thus be used for the long term measurement of the temperatures of lemon surfaces. These temperatures are used instead of body-temperatures of red scale in my experiments.

2.2. In Summer and Autumn

A similar experiment to the above was run in the same orchard of the Waite Institute in summer and in autumn but for convenience, only the fluctuations resulting from above-skin sensors on a typical summer day will be described.

Figure 2.1 (1). On 19/6/1983, on the east-part of the canopy, the ambient temperature (from the Stevenson Screen) and the sensor-temperature on the sunny side of a lemon. (A.: ambient temperature; S1: above-skin temperature; S2: in-skin temperature)

Figure 2.1 (2). On 19/6/1983, on the east-part of the canopy, the ambient temperature (from the Stevenson Screen) and the sensor-temperature on the shady side of a lemon. (A.: ambient temperature; S3: above-skin temperature; S4: in-skin temperature)

Figure 2.1 (3). On 19/6/1983, on the west-part of the canopy, the ambient temperature (from the Stevenson Screen) and the sensor-temperature on the sunny side of a lemon. (A.: ambient temperature; S5: above-skin temperature; S6: in-skin temperature)

Figure 2.1 (4). On 19/6/1983, on the west-part of the canopy, the ambient temperature (from the Stevenson Screen) and the sensor-temperature on the shady side of a lemon. (A.: ambient temperature; S7: above-skin temperature; S8: in-skin temperature)

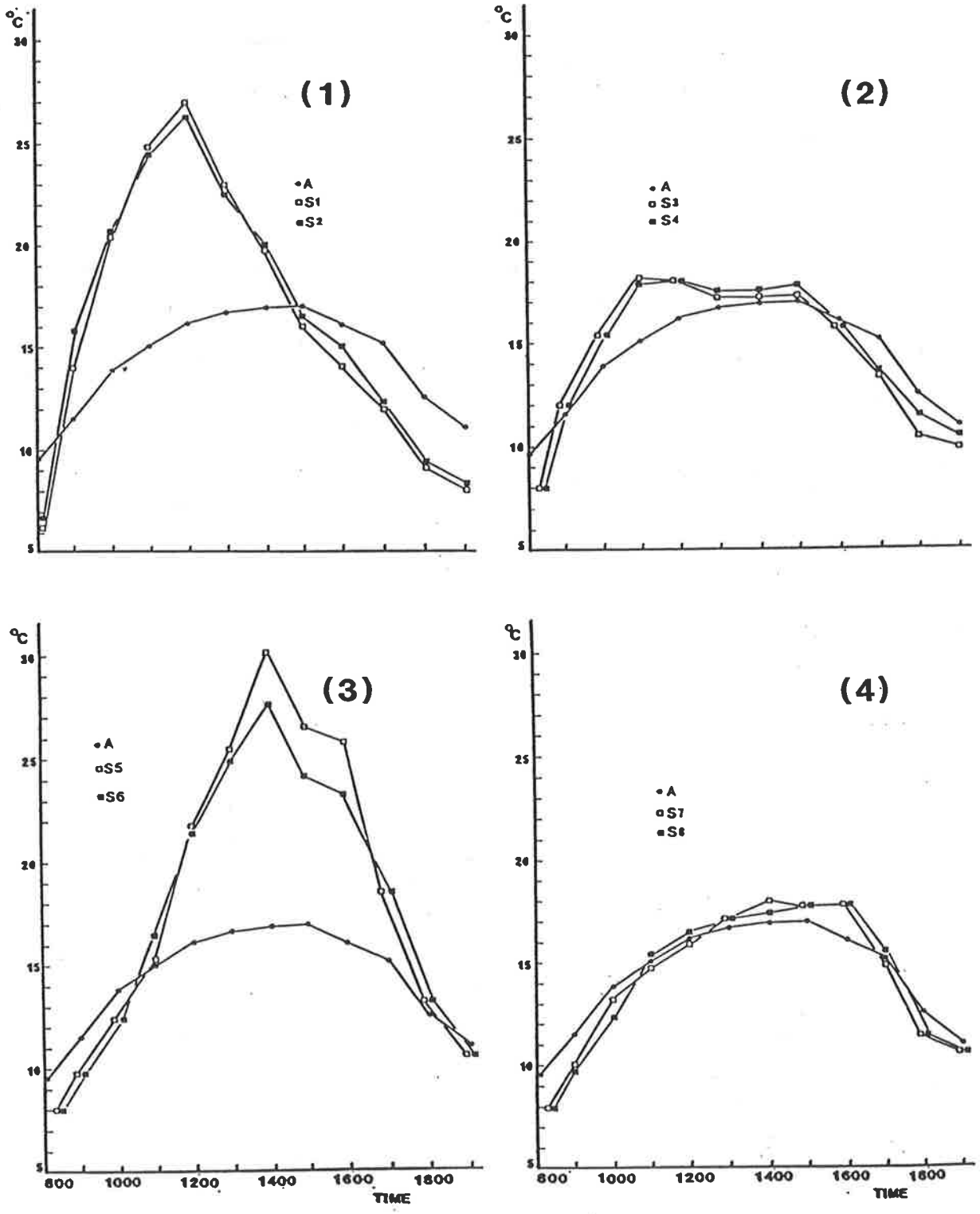


Figure 2.1 (1) - 2.1 (4)

Above-skin temperatures were measured on 4/2/83 on lemons on the east and the west of a tree canopy. The above-skin temperatures and ambient temperatures are given in Appendix Table 2.2 (1); they are plotted against time in Fig.2.2 (1). In the sunlight, the above-skin temperatures were very high and distinctly different from the ambient temperatures.

On the eastern side of the canopy: From 0700h, one hour after the orchard had been in the sunlight, the above-skin temperature increased rapidly. At 1000h it reached a value of 38°C, about 15°C higher than the ambient temperature and 16.0°C higher than the above-skin temperature on the western side. It reached a maximum value of 41°C at noon when the ambient temperature was about 26.0°C, a difference of 15°C. The difference between above-skin temperatures on east and west was also 15°C. From 1400h, the above-skin temperature on the eastern side decreased rapidly as the lemon was naturally shaded. Finally, as in late autumn and winter, the above-skin temperature went down and fluctuated around the ambient temperatures with a range of 1-2°C throughout the whole night till sunrise next day.

The very high above-skin temperature, >40°C, lasted about 2 hours.

On the western side of the canopy: As may be expected, fluctuation of the above-skin temperature was not much different to that on the east in shape but it differed in time of occurrence [Fig.2.2 (1)]. 1400h was the turning point; before this point the above-skin temperature was little different from the ambient temperature because this part of canopy was still in natural shade. After 1400h this part of canopy was in the sunlight and above-skin temperatures were greatly different from the ambient temperature. It increased rapidly to a peak of about 43.8°C at 1800h [App.Tab.2.2 (1)]. It was 12.8°C higher than the ambient temperature and 15.5°C higher than the above-skin temperature on the eastern side. Subsequently it dropped rapidly down to 26.5°C at 2000h, about 1°C lower than the ambient temperature.

2.3. Discussion

Above-skin temperatures of the sort described above were recorded continuously on a Honeywell thermocouple recorder for the period between 1983 and 1985. During this period, the highest above-skin temperature in the sunlight that was recorded was 52°C at 1700h on western side of the

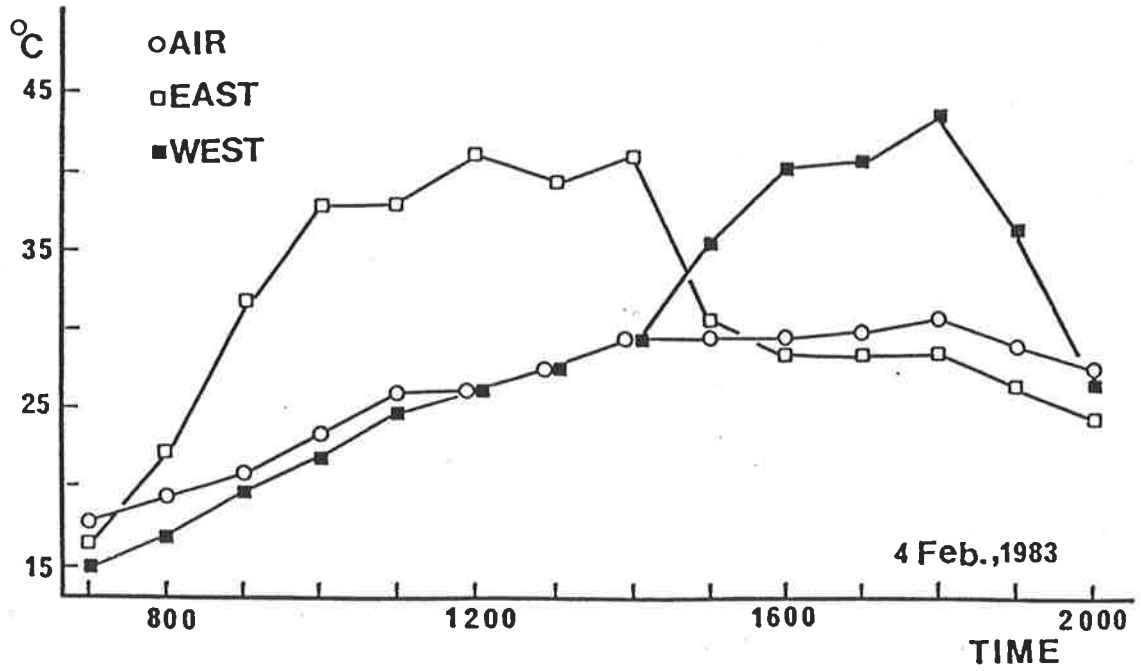


Figure 2.2 (1). Fluctuations of ambient temperatures and above-skin temperatures on lemons on the eastern and western side of the canopy of a lemon tree on a typical summer day. The above-skin temperature was given by a sensor placed 1mm above the skin of a lemon.

lemon tree canopy when the ambient temperature of the orchard was 38°C in February (mid summer); the difference between these temperatures was 14°C. In winter, after sunset and/or during night time, I never recorded an above-skin temperature which was more than 3°C lower than the ambient temperature. These maximum and minimum differences allow estimates to be made from standard recording of ambient temperatures of the extreme high and low temperatures in the sun or at night likely to occur on lemon trees at the Waite Institute. The highest and lowest standard ambient temperatures recorded at the Waite Inst. between 1925 and 1983 are 44°C and 0.9°C respectively (Waite Inst.; Biennial Report 1982-83). Hence, it can be estimated that in the orchard of the Waite Institute, red scale and its parasitoid enemy, Aphytis melinus, on lemon trees could experience extreme temperatures not higher than 44+14=58 (°C) in summer and not lower than 0.9-3=(-2.1) (°C) in winter.

It is now of interest to use these estimates of extreme high and low temperatures along with the temperature-mortality data of Abdelrahman (1974) to estimate the mortality that may occur for both red scale and Aphytis in summer and in winter. These comparisons suggested:

(1) in summer, a high mortality could occur in scale insects exposed to the sun because the above-skin extreme temperature of 58°C is 10°C higher than the LD50's temperature estimated by Abdelrahman (ibid),

(2) in winter, a high mortality could possibly occur in moult stages of red scale, as well in the larva stage of A. melinus, because their expected LD50's temperature was about 3 or 8°C higher than the estimated extremely low temperature of -2°C and

(3) since the estimated extremely low temperature of -2.1°C was similar to the "low" LD50's temperature, no high mortality was expected to occur in the growing stages of red scale, namely, first instar, 2nd instar, 3rd instar and young-adult stage. Similarly, no high mortality should be expected of all but the larval stages of A. melinus.

However, Abdelrahman's estimates of LD50 were obtained in the laboratory from insects which may not have been adequately acclimatized. I therefore conducted further experiments to measure the mortality of red scale in the field in relation to temperature. These experiments are described in following chapters.

REFERENCES

Munger, F. (1948). Body-temperature measurements of the California red scale. J. Econ. Entom., 41:422-423.

Abdelrahman, I. (1974). The effect of extreme temperatures on California red scale, Aonidiella aurantii (Mask.) (Hemiptera:Diaspididae), and its natural enemies. Aust. J. Zool., 22:203-212

CHAPTER 3.

CULTURE OF EXPERIMENTAL INSECTS AND SPECIAL EQUIPMENT

CHAPTER 3. CULTURE OF EXPERIMENTAL INSECTS AND SPECIAL EQUIPMENT

3.1. California Red Scale

3.1.1. Culture of red scale

Mass culture of scales is often desired for two major purposes: for experiments and for the mass culture of parasitoids for inoculative release in biological control programs.

California red scale is able to survive on a large number of host plants (Quayle 1938; Bodenheimer 1951) and methods of culture on some of these hosts were reported by Bliss et al (1931), Henderson et al (1943), Yust and Munger (1943), Mathis (1947), Tashiro (1966) and others.

Flanders (1951) perhaps was the first to use a mass culture of red scale on potatoes for the culture of parasitoids. Both cultures were maintained at 27.8°C and 60% relative humidity. Crawlers were transferred to new potatoes by a compressed air brush. Some years later, DeBach and White (1960) used the Oleander scale (uniparental strain), Aspidiotus hederae (Vallot), as host for the commercial culture of A. lingnanensis. The scale insects were cultured on banana squash, Cucurbita maima. They also tested several kinds of host, namely, the citron or cow melon, Citrullus vulgaris; the butternut pumpkin, Cucurbita moschata; potatoes and citrus fruits, etc. On the basis of year-round availability and cost alone, they suggested that only banana squashes and potatoes could meet the requirement of a commercial mass-culture, even though the scale insects preferred citrus fruits. On the other hand, Bartlett and Fisher (1950) suggested that banana squash was an unsuitable host because they could not be used at relative humidities in excess of 40%, and they believed such a humidity was too low for satisfactory parasitoid culture.

By contrast to Bartlett and Fisher's (1950) observations, mass cultures of red scale have been successfully carried out at the Waite Agricultural Research Institute on butternut pumpkins since the 1970's. This host has year-round availability in South Australia. It also lasts sufficiently long at 50-70% R.H. and gives a sufficiently high survival of scales for the successful culture of red scale and Aphytis spp. (D.A.Maelzer, pers. comm.).

So I used butternut pumpkins to maintain a red scale culture. The culture was maintained in an insectary room kept at 25-27°C and about 60% R.H. The photoperiod was natural and depended on the light from a window.

The aim of the culture was to produce a sufficient number of crawlers for experiments at any time.

Experience confirmed that butternut pumpkins were ideal for red scale culture under these conditions. In the culture room, they could last 3-4 months or even longer.

Before being placed in the culture room, pumpkins were washed throughly in running tap water and then left to dry. In order to avoid any influence of chemicals on the biology of scales, the pumpkins were not treated with any fungicide. To reduce fungus rot, however, it was necessary to choose completely mature pumpkins with undamaged skin. To maintain the culture, fresh pumpkins were placed in the culture room at intervals of 3-4 weeks. They were simply mixed with the "already infested" pumpkins.

Culture for experiments: Methods of culture of red scale can be divided into two major categories, namely, those using fruits and those using leaves of host plants. For instance, Abdelrahman (1974a, b) did his studies in the early 1970's with scales cultured on lemon fruits. DeBach and Erickson (1952) used a method of "rooted lemon fruits for citrus pest studies". Such rooted fruits may remain in a turgid healthy condition for as long as six months under glasshouse conditions. Willard (1976), on the other hand, mainly used a leaf disc method for experiments with red scale.

For convenience I used butternut pumpkins, lemons and oranges at different times for cultures of experimental red scale. The citrus fruits were used whenever possible so that the results of the experiments could be extrapolated to the field.

Citrus fruits to be used in experiments were picked, sterilized at the "stem end" and then covered with paraffin wax [Fig.3.1 (1)] within six hours. The "stem end" was sterilized by soaking in 75% alcohol for 5-10 seconds and leaving to dry. Except for an experimental area, 2.5 cm in diameter, the whole fruit was then covered with paraffin wax, to reduce water loss by evaporation. The fruit would then last long enough for red scale to complete more than one generation. Beeswax was not used for covering the experimental host fruits because its high sugar content allowed diseases to develop rapidly in the fruits. Fruits covered with beeswax could only last for about half a generation of red scale in the culture room.

Figure 3.1 (1). Waxing experimental lemons for a culture of California red scale.

Crawlers for experiments came from pumpkins in the culture room. A day or two before they were needed, these pumpkins were washed thoroughly in running tap water for a few seconds to remove any sticky secretions on the skins of the pumpkins as well as any newly formed white caps and 1st instar scales. The pumpkins were then gently dried by dabbing with an absorbent cloth, rather than by wiping. This process seemed to make the transferring of crawlers easier. The washing process also removed dirt and dead scales.

3.1.2. Mortality of red scale due to the method of transferring crawlers

3.1.2.1. Introduction

Flanders (1951) used four methods of transferring crawlers of red scale to new hosts. They were: (1) the contact method, involving the temporary placement of the new host on top of the infested host to allow crawlers to move from the old hosts to the new ones; (2) the drop method, involving the placement of new hosts beneath infested hosts, the crawlers dropping from the latter; (3) the brush method, involving brushing the crawlers from infested hosts with a very fine brush; and (4) the blowing method, involving the use of compressed air.

Methods 1, 2 and 4 could not be used to concentrate a required number of crawlers on a small experimental area so method 3 was used in most of my experiments. However, as Flanders pointed out, the "brush" method might injure many crawlers. So preliminary experiments were carried out to compare the mortality caused by the contact method with that caused by the brush method. Both pumpkins and citrus fruits were used in the comparison; in the first experiment, butternut pumpkins and lemons; in the second experiment, oranges.

3.1.2.2. Experiment 1

Method The experiment was conducted in the insectary in which the mass culture of red scale was kept (Section 3.1.1). There were four treatments comprising the combinations of 2 methods of transfer by 2 sorts of fruits, namely, lemons and butternut pumpkins.

Before the crawlers were transferred, the pumpkins and lemons were treated (washed, sterilized and waxed) by the methods described in Section 3.1.1.

Mortalities were measured when some red scales reached the pre-reproduction adult stage; each scale cover was then turned over under a x25 magnification microscope and the scale insect was then determined to be alive or dead.

Results The mortalities are given in Table 3.1 (1) for each stage of red scale up to the young adult stage (female). Total mortality ranged from 10.0 to 23.7% for the different treatments. These data were estimated as the "final mortality" of scales in this experiment.

A chi-square test was used to test the null hypothesis that the final percentage mortality was the same in each treatment. The expected numbers of dead in each treatment was based on the mean mortality of 17.2% over all treatments. The observed and expected numbers of dead and alive scale insects in each treatment are given in Table 3.1 (2). The chi-square value of 33.21 (d.f.= 3, $P<0.005$) indicates that the observed percentage mortality was not the same in each treatment so further analyses were conducted to assess whether there were differences between methods of transferring crawlers and/or differences between host fruits.

Testing differences between methods of transfer:

The numbers of dead and alive scales are re-arranged in Table 3.1 (3) to test the null hypothesis that there was no difference in mortality between methods of transfer. On pumpkins, 10.0% mortality occurred with the contact method and 13.5% with the brush method. On lemons, on the other hand, 17.2% mortality occurred with the contact method, and 23.7% with the brush method.

The 2 chi-square values (1.44 on pumpkins and 2.53 on lemons) lead to acceptance of the null hypothesis that the brush method of transferring crawlers did not cause a significantly higher mortality of red scale than the contact method. So either method can be used to start an experimental cohort of red scale on lemons or pumpkins.

Testing the difference between host fruits:

The data of Table 3.1 (2) may be re-arranged again, as in Table 3.1 (4), to test the null hypothesis that there is no difference in mortality between hosts. Using the contact method, 10.0% mortality occurred on pumpkins and 17.2% on lemons. Using the brush method, 13.5% mortality occurred on pumpkins and 23.7% on lemons.

Table 3.1 (1). Percent mortality of red scale observed for each of 2 methods of transferring crawlers to each of 2 kinds of hosts.

Stage of red scale	Brush method		Control method	
	pumpkins (1)	lemons (2)	pumpkins (3)	lemons (4)
white cap	3.9	5.5	3.4	4.8
1st instar	2.1	5.5	0.8	4.8
1st moult	5.3	10.4	2.8	6.9
2nd instar	1.1	0.7	0.8	0
2nd moult	0	0.5	0	0
3rd instar	1.1	0.2	2.2	0
young adult	0	0	0	0
2nd male	0	0.9	0	0.7
Total	13.5	23.7	10.0	17.2
Original numbers of red scale	283	565	358	146

Table 3.1 (2). The observed and expected numbers of dead and alive red scale in 2 methods of transferring crawlers to 2 kinds of host fruits. The chi-square value (3 d.f.) tests the null hypothesis of equal mortality in all treatments.

Host fruits	Methods of transferring crawlers	Numbers of red scale				
		Observed			Expected	
		alive	dead	total	alive	dead
pumpkin	brush	245	38	283	234	49
	contact	322	36	358	296	62
lemon	brush	431	134	565	468	97
	contact	121	25	146	121	25
total		1119	233	1352		
chi-square value						33.21
P						<0.005

Table 3.1 (3). Numbers, alive and dead, of red scale on host pumpkins and lemons; also given are chi-square values to test the null hypothesis there was no difference in percent mortality of red scale between methods of transferring crawlers for each of 2 kinds of host fruits.

Methods of transferring crawlers	On host pumpkins: Numbers of scales			On host lemons: Numbers of scales		
	Alive	Dead	Total	Alive	Dead	Total
Brush	245	38	283	431	134	565
contact	322	36	358	121	25	146
chi-square value			1.44			2.53
P			>0.05			>0.05

Table 3.1 (4). Numbers, alive and dead, of red scale observed in 2 methods of transferring crawlers; also given are chi-square values to test the null hypothesis, for each transference method separately, that there was no difference in percent mortality of scales on 2 kinds of host fruits.

Host fruits	Contact method: Numbers of scale			Brush method: Numbers of scale		
	Alive	Dead	Total	Alive	Dead	Total
Pumpkins	322	36	358	245	38	283
Lemons	121	25	146	431	134	565
chi-square value			4.23			11.72
P			<0.05			<0.005

The 2 chi-square values (4.23, $P<0.05$ for the contact method and 11.72, $P<0.005$ for the brush method) indicate that the null hypothesis must be rejected. So a significantly higher mortality occurred on lemons than on pumpkins with both methods transfer.

3.1.2.3. Experiment 2

Method The experiment was conducted in the same insectary as experiment 1. There were only 2 treatments, namely, the two methods of transferring crawlers. The crawlers were transferred to oranges which had been treated (washed, sterilized and waxed) by the methods described in Section 3.1.1. Mortalities of red scale were measured by the method of Section 3.1.2.2 but observations were made when the scale reached the 3rd instar.

Results The percentage mortality of red scale of each stage is given in Table 3.1 (5); 6.6% mortality occurred with the contact method and 10.9% with the brush method.

The total numbers of red scale, alive and dead, are given in Table 3.1 (6). A chi-square test gave a value of 2.21 (d.f.=1, $P>0.05$) indicating that the brush method did not cause a significantly higher mortality of red scale than the contact method. And so, again, either method of transferring crawlers could be used to start experimental cohorts of red scale on oranges.

3.2. Mass Culture of *A. melinus*

Methods and techniques for the mass culture of *Aphytis* spp. have been developed in the U.S.A. since the 1940's, and especially in the 1950's and the beginning of the 1960's (Flanders 1943, 1947, 1951; DeBach and White 1960). California red scale and Oleander scale were used as hosts. Mass cultures were kept at about 27°C and 50% relative humidity. DeBach and Fisher (1956) believed that Oleander scale was a superior host for *Aphytis* spp. than California red scale. The comparison between the two scales is shown in Table 3.2 (1). Larger parasites emerge from Oleander scale, indicating that in any study of the biology of *Aphytis* spp., the survival and/or reproduction potential could be affected by the host scale species. However, in my experiments, California red scale was the only host used. The culture room for *A. melinus* was set up with a constant temperature of

Table 3.1 (5). The percent mortality of red scale observed in 2 methods (contact and brush) of transferring crawlers to oranges.

Stage of red scale	Contact method	Brush method
white cap	0.5	0.4
1st instar	0.9	1.2
1st moult	1.4	1.2
2nd instar	3.3	4.5
2nd moult	0.5	0.4
3rd instar	0	1.2
2nd male*	0	2.0
Total	6.6	10.9
Original numbers of scales	213	246

*: No males emerged during the experimental period.

Table 3.1 (6). Numbers, live and dead, of red scale following two methods of transferring crawlers to oranges; also given are the chi-square value to test the null hypothesis that there was no difference between methods.

Method of transferring crawlers	Number of red scale:		
	Alive	Dead	Total
Contact	199	14	213
Brush	219	27	246
Chi-square value			2.21
P			>0.05

Table 3.2 (1). Comparison between Oleander scale and California red scale in the mass culture of parasitoids (after DeBach and Fisher 1956)

Factors compared	Red scale	Oleander scale
unsuitable moult stage present	yes	no
relatively high degree of parasitization	no	yes
size of parasite progeny	small	large

about 25°C, 50% relative humidity and an artificially controlled photoperiod of L:D = 14:10 hours. Pumpkins with parasitized red scales were placed on a caged shelf and the shelf-cage was made of very fine gauze.

3.2.1. Collection of one-day-old *Aphytis* wasps

Two major methods are often used for collecting wasps, the "sucking" method and the CO2 method (Flanders, 1951; Baker, 1976). Flanders described the "sucking" method as follows: Adult parasites are collected by air suction into transparent plastic tubes, 8 inches in length. This length is needed to provide an air cushion to minimize injury to the parasites when they are sucked into the tube. Here, the word "minimize" used by Flanders might indicate that this method did cause some injury to wasps. Certainly, either of the above two methods could possibly cause either a physical (the "sucking" method) or a physiological (the CO2 method) injury to wasps. Since I wished to use undamaged wasps for experiments, I used a modified method, the "direct sucking" method for the collection of wasps. A small collection tube (see Section 3.3.1) whose bottom part was covered with very fine gauze and was directly fixed inside the "sucking tube"; then, under a x3 magnification head-lens, wasps were very gently sucked into the collection tube [see Fig. 3.3 (1)]. Using this method, wasps were sucked into each tube by the very gentle air flow and travelled only a very short distance (3-4cm) before being stopped on the "bottom gauze". After "sucking", all my experimental wasps were checked under x25 magnification microscope and I never found any damage that had been done to the experimental wasps by this process.

Wasps to be used for experiments were collected from the mass culture room of *A. melinus*. At 1000-1100h, one day before an experiment, wasps that had emerged from the parasitized red scales on pumpkins were carefully brushed away using a very fine brush. The pumpkins were then checked under a x3 magnification head-lens to ensure that no wasps still remained on them. Then they were put in an "emergence box", a cardboard box, 55 x 40 x 40cm. Next day, at 1000-1100h, wasps, about 20 wasps per tube, were sucked into collection tubes and kept in the tubes for an hour or two. These wasps were then considered to have mated but had not had any food except that which they might have got from some "host-feeding" on scales. These wasps, about one day old, were now ready to be randomized for experiments at noon.

3.3. Special Equipment

3.3.1. Collection tube for wasps of A. melinus

The collection tubes were made of transparent plastic. Each tube was about 4cm long; 5mm in diameter at one end and 7mm at the other. The 7mm end was covered with very fine gauze, fixed on with glue. Tubes were with a soft sucking tube, about 0.5m long [Fig. 3.3 (1)].

3.3.2. Constant humidity box

Each of the humidity boxes was a plastic container, 30cm long by 19cm wide and 14cm high. A saturated solution of salt (NaCl) in a container was used to produce a constant relative humidity of about 75% at constant temperatures from 10°C up to 30°C (Winston and Bates 1960).

3.3.3. Citrus fruit cage

The "citrus fruit cages" [Fig. 3.3 (2)-A] were cut from a semi-transparent plastic funnel. Two 7mm holes were covered with fine gauze. These two holes served as "vents" and were expected to maintain a good air circulation. As a result, no dew could form inside the cage at any time.

A third hole, about 5mm in diameter, was drilled on the side wall. This was a "releasing hole" for the collection tube of wasps (see Section 3.3.1). A collection tube with wasps could be fitted over this hole using modelling clay or melted paraffin wax [Fig. 3.3.(2)-B].

A ring of plastic foam sponge (2mm thickness) was placed between the cage and the fruit. The cage was then held on to the fruit by a rubber band. The ring filled any gaps through which the released wasps might have escaped.

Figure 3.3 (2)-C shows a cage on the tree, which was shaded from the sun.

3.3.4. Head lens

The x10 magnification head-lens was used for the purpose of roughly distinguishing stages of red scale. It freed the worker's hands and carried its own illumination system. The apparatus was constructed from a hand-lens and a head-frame. On the head-frame, a plastic plate was fitted to occlude the sight of the non-observing eye. Two bulbs (6V) formed an additional light source [Fig. 3.3 (3)].

Figure 3.3 (1). Collection tube for wasps of A.melinus.

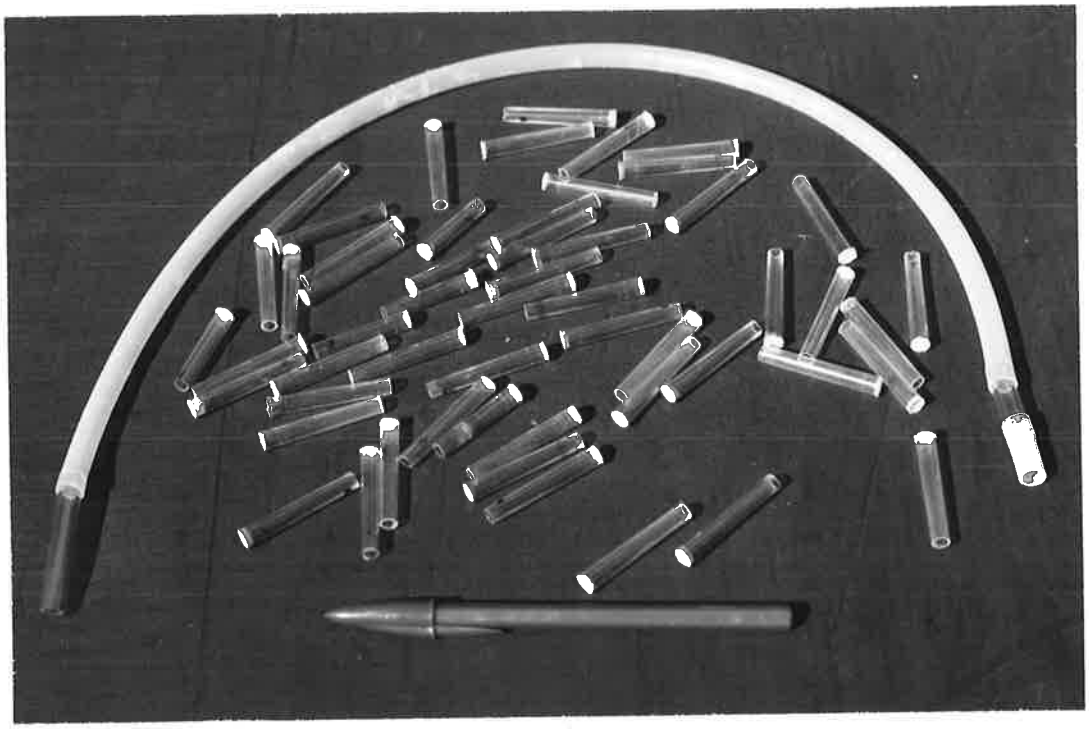


Figure 3.3 (2). Citrus fruit cage.

A: Cage.
B: Cage with collection tube for wasps of A. mulinus.
C: Cage on the tree.

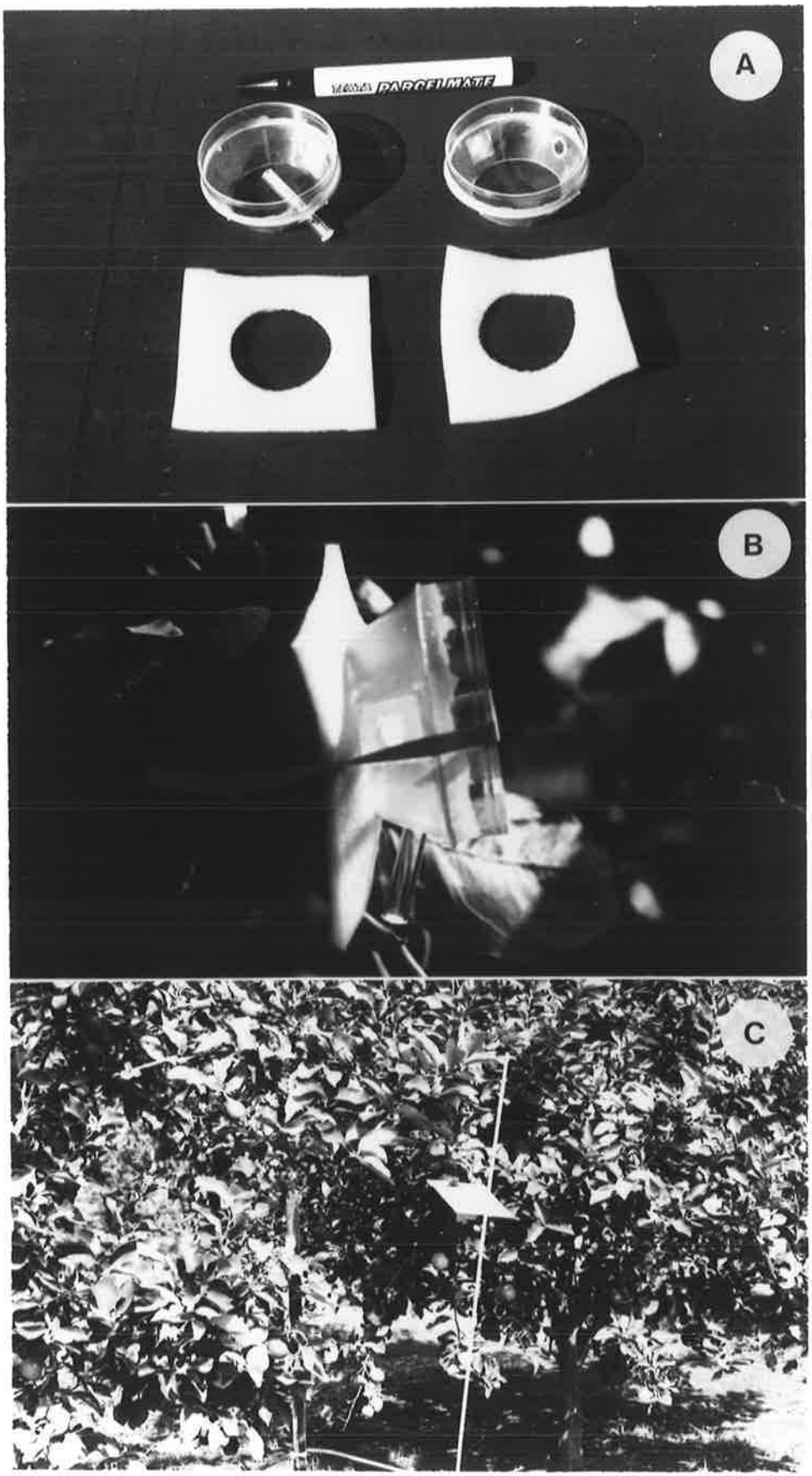
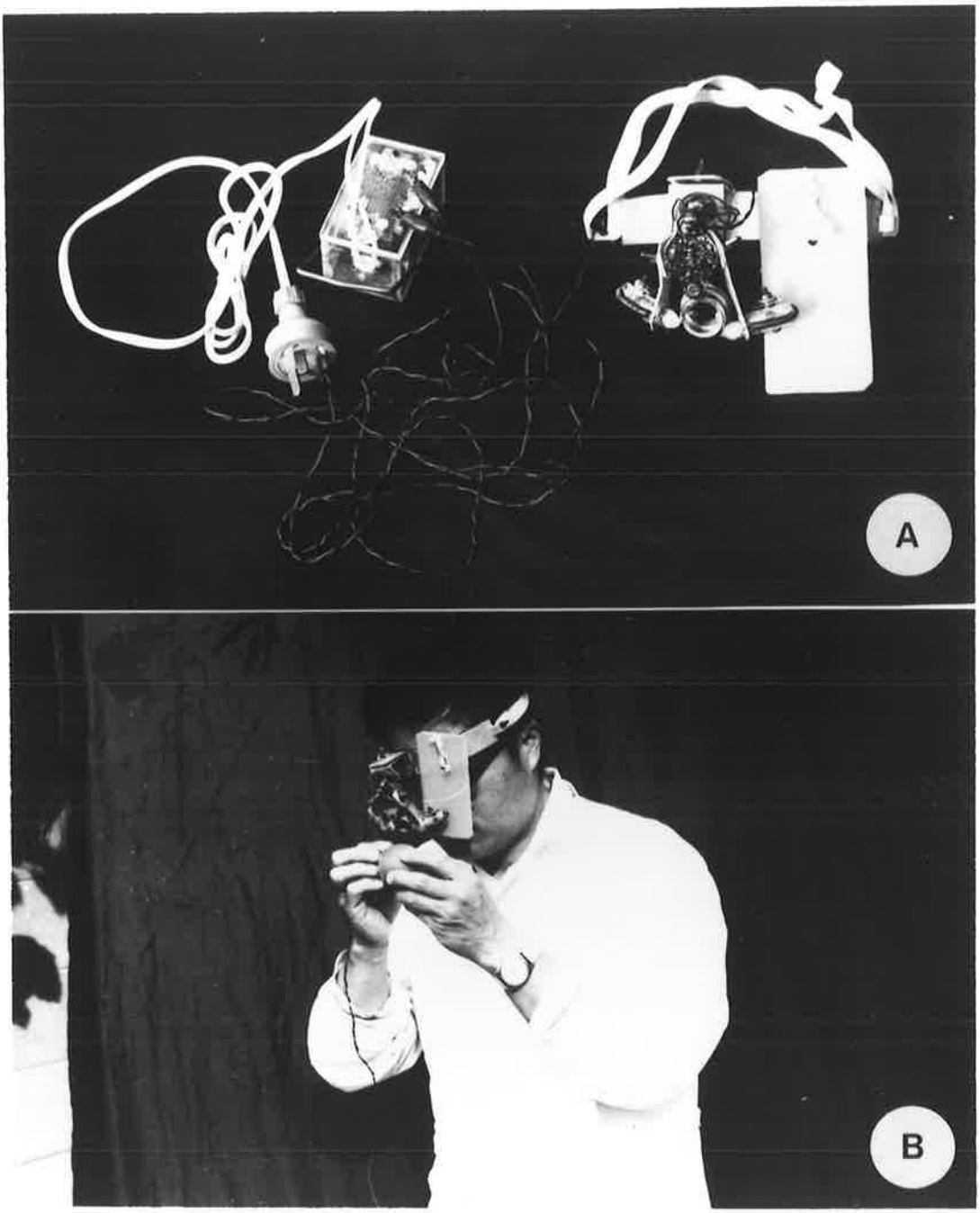

A
PARCELMATE
B
C

Figure 3.3 (3). x10 head lens.


A
B

3.3.5. Microscope

(1) Microscope-trolley: A small trolley was fitted with a bracket for a microscope. As shown in Fig.3.3 (4), this bracket comprised three poles, namely, the microscope pole I (about 17cm long), the support pole II (about 45cm long) and the main support pole III (about 150cm tall). The microscope was fitted on "pole I". This pole could be turned and moved horizontally on the support pole II, which itself could rotate horizontally and move up and down on the main support pole III. No doubt, each of the above mentioned lengths of poles could be varied to meet a special requirement for experiments. The light source, IV in Fig. 3.3 (4), a microscope lamp (50w, 15v/240v), was clipped on the microscope pole I.

(2) Shoulder-bracket for microscope: The shoulder bracket comprised three parts.

(i) Part 1, a flexible mono-support [M in Fig.3.3 (5), A], was an aluminium pole, about 200cm long and 1.5cm diameter. It was fitted with a triangular frame. This frame was made from 3 pieces of aluminium tube [Fig.3.3 (5), B]: tubes T1 and T3 were about 2cm in diameter but tube T2 was about 2.5cm in diameter in order to let the mono-support move smoothly up and down inside it. Between each two of the tubes, a sort of hinge joint was used. This kind of joint made the whole frame somewhat flexible and made observation with the microscope much more convenient. On the top part of T3, a large thick washer (W) was chained. When the triangular frame was moving upwards, this washer lay horizontally and let the mono-pole pass smoothly through but when the frame was moving downwards the washer turned and jammed on the mono-pole, stopping the frame from slipping downwards.

(ii) Part 2, the microscope support (MS) was made of angle iron. The whole structure looked like a reversed "L" [in Fig.3.3 (5), A]. It comprised 3 frames, namely, F1, F2 and F3. On F1, a microscope and a light source (50W, 15V/240V) were fitted (the light source could be also clipped on T3 of the triangular frame of the mono-support). For the sake of convenience and comfort one could vary the length of F2 and let F3, the so-called "abdomen frame", always remain at the level of the belly button.

(iii) Part 3, comprising two pieces of shoulder-carrier (SC) made from curved aluminium tubes about 1.5cm in diameter [in Fig.3.3 (5), A]. These two shoulder-carriers were chained together and fitted on the abdomen-frame (F3) of Part 2 through two rings.

Figure 3.3 (4). Microscope-trolley.

I: microscope pole I.
II: support pole II.
III: main support pole III.
IV: light source.

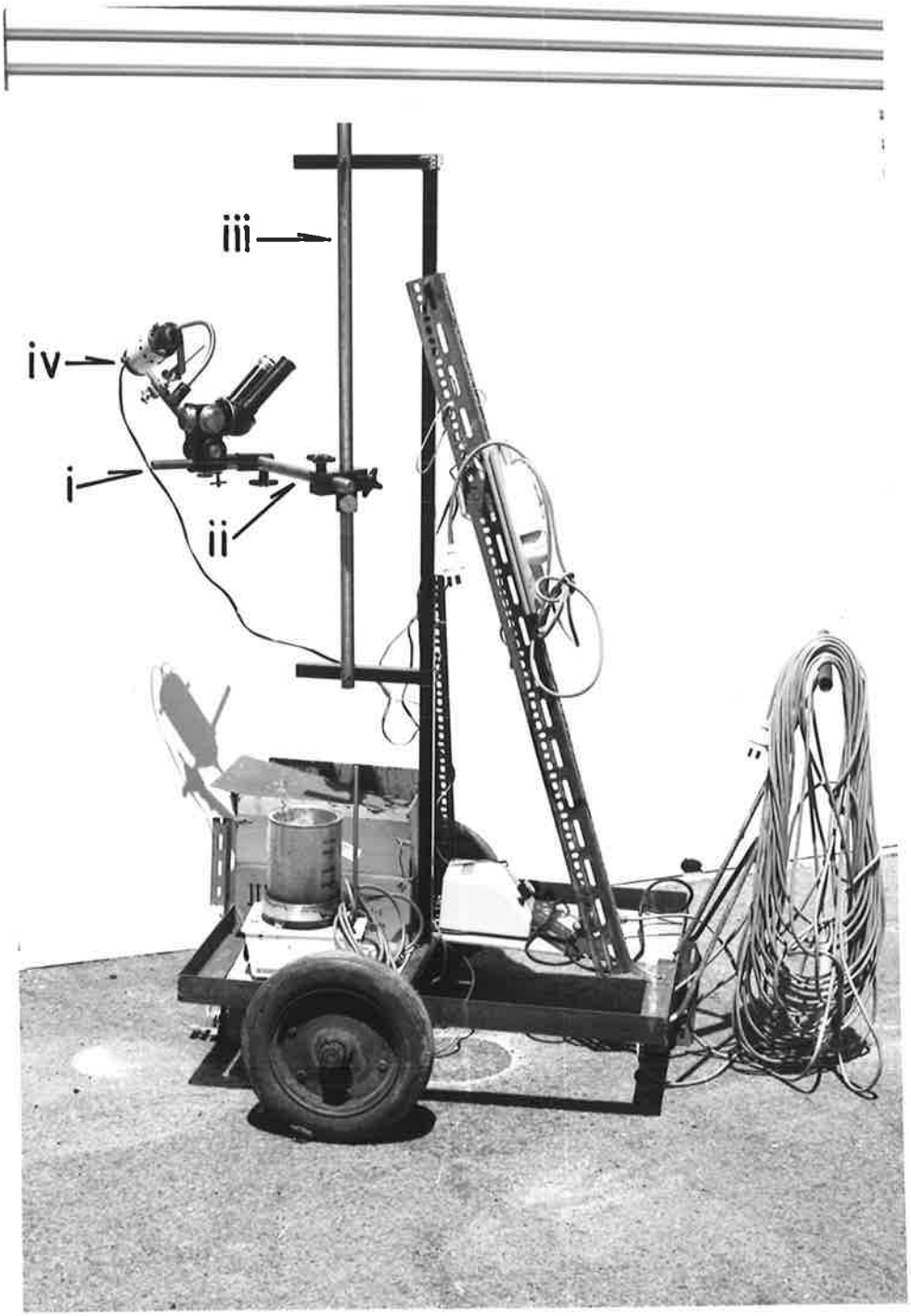
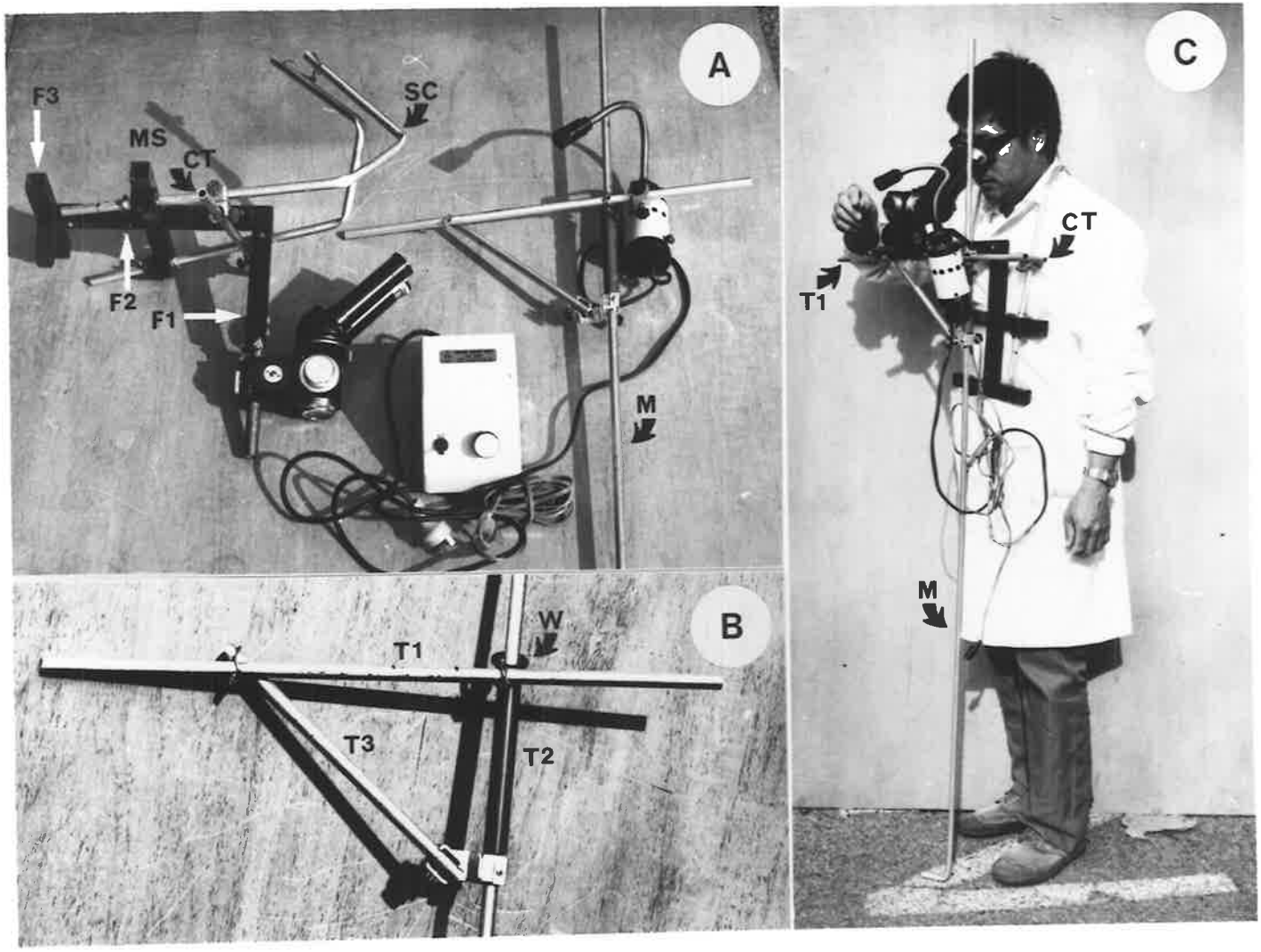

iii
iv
i
ii

Figure 3.3 (5). Shoulder-bracket for microscope.

A: Shoulder-bracket and microscope.

B. Triangular frame.

C. The shoulderable-microscope in operation.


A
F3
SC
MS
CT
F2
F1
M
B
W
T1
T3
T2
C
CT
T1
M

However, before setting a microscope on Part 2, it was always necessary to fix these two shoulder-carriers by use of a so-called "chest-tube" (CT) [in Fig.3.3 (5), A]. So F2 of Part 2 was then fixed between the observer's chest and this chest-tube; this allowed the whole structure to maintain a good working condition at any time.

(3) Fig.3.3 (5)-C shows the shoulderable-microscope in operation.

3.3.6. Photographic equipment

The photographic equipment comprised three parts: a camera, a light source and a camera bracket [Fig. 3.3 (6)].

(i) Camera: A Nikon camera, model F, was used for recording the growth of experimental scale insects on host fruits [Fig.3.3 (6)-A]. This camera had a so-called Type D interchangeable screen which was recommended for use with a long telephoto lens or for closeup work. The fine matte field of this screen ensured unobstructed viewing.

A Nikon telephoto lens, 135mm/f3.5, and 2 pieces of Nikon close-up tubes, each about 27mm in length, was used for macro-photography at a distance about 0.5m from the subjects. This combination of the lens and the tubes offered a image about 1/3 life size on the film.

(ii) Light source: In my experiments, low speed films, ASA 25 or ASA 100, were used. This sort of film gave very clear cut images of targets. As low speed films had been used, a flash (G.N.20/ASA 100) was used as an additional light source, offering uniform light intensity. Rechargeable batteries were recommended for the flash for the purpose of frequently taking of pictures. In my experiments, the photographic event was undertaken upon condition that a fixed aperture of f16 assisted with this flash.

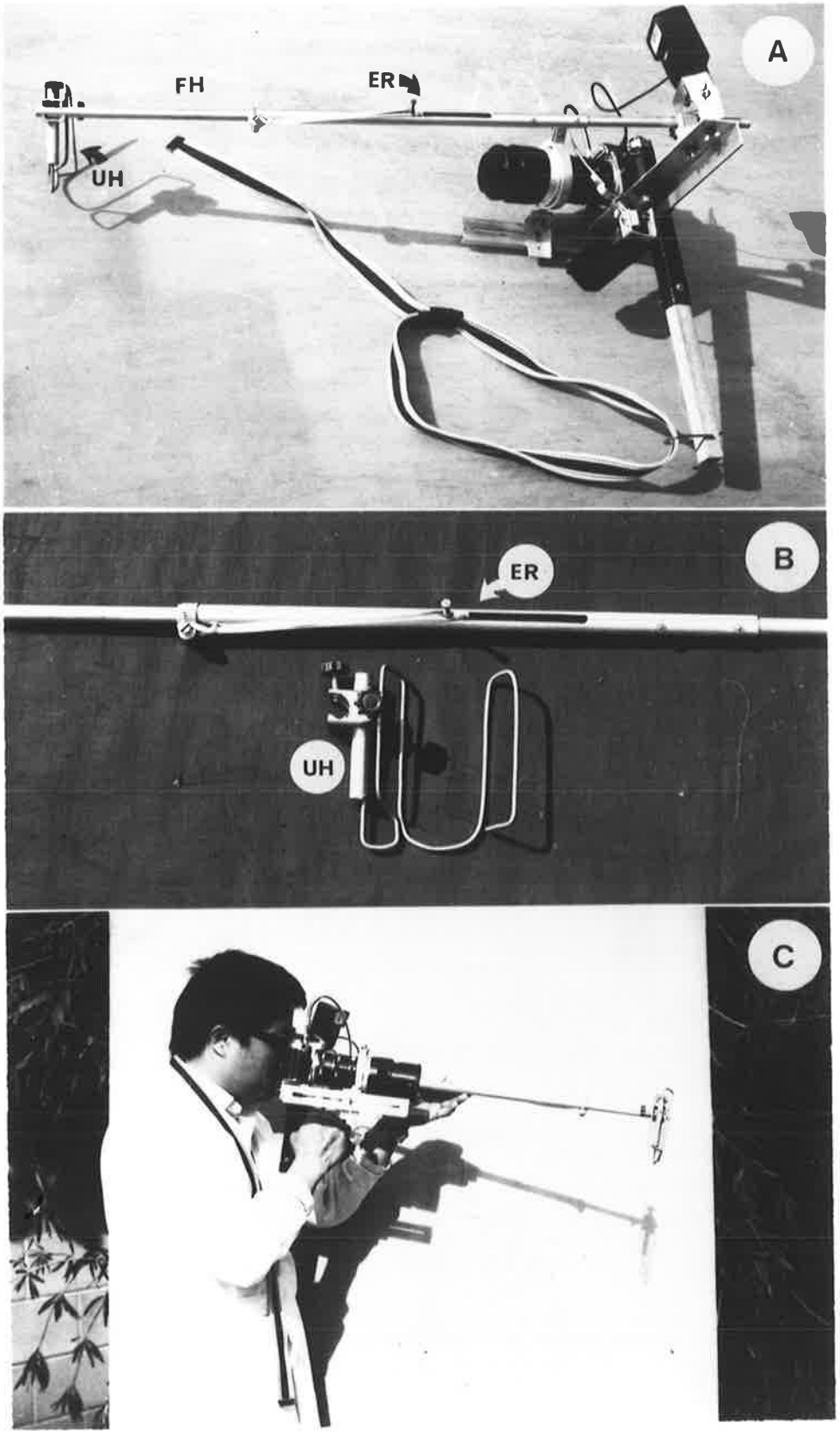
(iii) Camera bracket: This bracket [Fig.3.3 (6)-A] was made of angle aluminium with accessories of a flash support, a so-called fruit-holder and a handle. The fruit-holder, shown as FH in A and B of Fig.3.3 (6), comprised (a) an extending aluminium tube (about 1.5cm in diameter) and (b) a "U" form holder (UH). An expansion range of 10cm was allowed by the structure shown as (ER) in Fig.3.3 (6); this range was suitable for the use of the lens mentioned above. In using this fruit-holder, one should use a shutter sync-cord fixed to the handle to avoid camera-shake. However the use of the fruit-holder was for the sake of convenience only [Fig.3.3 (6), C].

Figure 3.3 (6). Camera bracket.

A: Camera bracket and camera.

B: Fruit-holder.

C: Camera in operation.


A
FH
ER
UH
B
ER
UH
C

REFERENCES

Abdelrahman, I. (1974a). The effect of extreme temperatures on California red scale, Aonidiella aurantii (Mask.) (Hemiptera:Diaspididae), and its natural enemies. Aust. J. Zool., 22:203-212.

Abdelrahman, I. (1974b). Growth, development and innate capacity for increase in Aphytis chrysomphali Mercet and A. melinus DeBach, parasites of California red scale, Aonidiella aurantii (Mask.), in relation to tempeature. Aust. J. Zool., 22:213-230.

Baker, J. L. (1976). Determinant of host selection for species of Aphytis (Hymenoptera:Aphelinidae), parasites of diaspine scales. Hilgardia, 44:1-25.

Bartlett, B. R. and Fisher, T. W. (1950). Laboratory propagation of Aphytis chrysomphali for release to control California red scale. J. Econ. Entom., 43:802-806.

Bliss, C. I., Broadbent, B. M. and Watson, S. A. (1931). The life history of the California red scale Chrysomphalus aurantii (Mask.) II: progress report. J. Econ. Entom., 24:1222-1228.

Bodenheimer, F. S. (1951). Citrus entomology in the Middle East. Junk, The Hague, 663 pp.

DeBach, P. and Erickson, L. (1952). Roots lemons fruits for citrus pest studies. J. Econ. Entom., 45:1097-1098.

DeBach, P. and Fisher, T. W. (1956). Experimental evidence for sibling species in the oleander scale, Aspidiotus hederae (Vallot). Ann. Ent. Soc. Amer., 49:235-239.

DeBach, P. and White, E. B. (1960). Commercial mass culture of the California red scale parasite, Aphytis lingnanensis. Bull. Calif. Agric. Exp. Stn., No. 770:1-58.

Flanders, S. E. (1943). Mass productin of the California red scale and its parasite, Comperiella bifasciata. J. Econ. Entom., 36:233-235.

Flanders, S. E. (1947). Use of potato tubers in mass culture of Diaspine scale insects. J. Econ. Entom., 40:746-747.

Flanders, S. E. (1951). Mass culture of California red scale and its golden chalcid parasites. Hilgardia, 21:1-42.

Henderson, C. R., Stucker, C. L. and McBurnie, H. V. (1943). A laboratory method for rearing and parasitizing the California red scale for toxicological studies. U.S.D.A.B.E. and P. ET-213:1-4.

Mathis, W. (1947). Biology of Florida red scale in Florida. Fla. Entom., 29:13-35.

Quayle, H. J. (1938). Insects of citrus and other subtropical fruits. Comstock Publishing Co., Ithaca, N. Y., 583 pp.

Tashiro, H. (1966). Improved laboratory techniques for rearing California red scale on lemons. J. Econ. Entom., 59:604-608.

Willard, J. R. (1976). Leaf disk method for rearing California red scale, Aonidiella aurantii (Mask.) (Homoptera: Diaspididae). J. Aust. Entom. Soc., 15:7-11.

Winston, P. W. and Bates, D. H. (1960). Saturated solutions for the control of humidity in biological research. Ecology, 41:232-237.

Yust, H. R. and Munger, F. (1943). California red scale. Amer. Assoc. Adv. Sci. Pub., 20:24-35.

CHAPTER 4.

INFLUENCE OF TEMPERATURE ON THE BIOLOGY OF CALIFORNIA RED SCALE

CHAPTER 4. INFLUENCE OF TEMPERATURE ON THE BIOLOGY OF CALIFORNIA RED SCALE

Intensive studies on mortality and/or growth of red scale in relation to extremes of temperatures have been conducted world wide, as well as in Australia. In both laboratory and field, they have been undertaken especially since the 1960's (Munger and Cressman 1948; DeBach 1958, 1965 ; DeBach *et al* ., 1971; Martin and Black 1960; Tashiro 1966; Tashiro and Beavers 1968; Catling 1971 a,b; McLaren 1971, 1978; Habib, Salama and Amin 1972; Willard 1972, 1973, 1976; Abdelrahman 1974; Atkinson 1977, 1983a,b; DeBach, Hendrickson and Rose 1978).

The most intensive work on the mortality of red scale responding to temperature was, perhaps, done by Abdelrahman (1974) and Atkinson (1983a,b). Abdelrahman conducted laboratory experiments to establish the duration of exposure of extreme temperatures which were necessary to cause 50% mortality of different stages of red scale. By contrast, Atkinson's work was done in the field with a natural population of red scale. Nevertheless, further details about the influence of extremes of temperatures on the mortality of red scale are still needed to understand the population dynamics of red scales in South Australia.

In an attempt to obtain the necessary information, a number of experimental cohorts were started at different times through the year at the Waite Institute. This experiment was originally conducted to test the null hypothesis that there were no differences in the mortalities of red scales in relation to extremes of temperatures in summer among different aspects on the tree. The experimental cohorts of red scale were started between late January and early March (later part of the hottest season of each year) in 1983 and 1985. The late start was due to the lack of lemons of a size suitable for experiments until late January of each year. After January, the ambient temperatures were expected to decrease gradually so that significant differences between cohorts with respect to mortality could be expected.

4.2.1. Methods and materials

4.2.1.1. Starting exerimental cohorts of red scales

Each cohort was started on lemons on a tree by the "brush method" (see Chapter 3) and treated under unshaded condition. For each cohort, 4 big but unripe lemons were chosen at random, one on each of the 4 aspects, north, south, east and west, on a tree. A total of 10 cohorts (5 each year) was started.

To start a cohort of red scales, each host lemon was held and an experimental area, about 3.5 cm in diameter, was marked on the lemon, facing upwards. This made the transference of crawlers easier [Fig.4.2 (1)]. Also the side facing outward from the tree canopy was the only place from which an experimental area could be photographed without having to turn the fruit and risk damaging it. A photographic method of recording the progress of a cohort (Maelzer 1976) was considered to be the only method possible without turning each of the scale covers over and killing the scales

Crawlers from the mass culture (see Chapter 3) were transferred to the experimental areas between 9 a.m and noon. On each experimental area, at least 60 "white cap" scales were needed for the experiment. To get sufficient crawlers for the 4 lemons of each cohort, at least 16 butternut pumpkins, fully covered with producing adult females, were needed.

The experimental area on each lemon was shaded after the transferring of crawlers. One day later, after the white cap covers of the scales had been formed, the shades were removed so that the host lemons were again in the natural condition of being in the sun for part of the day.

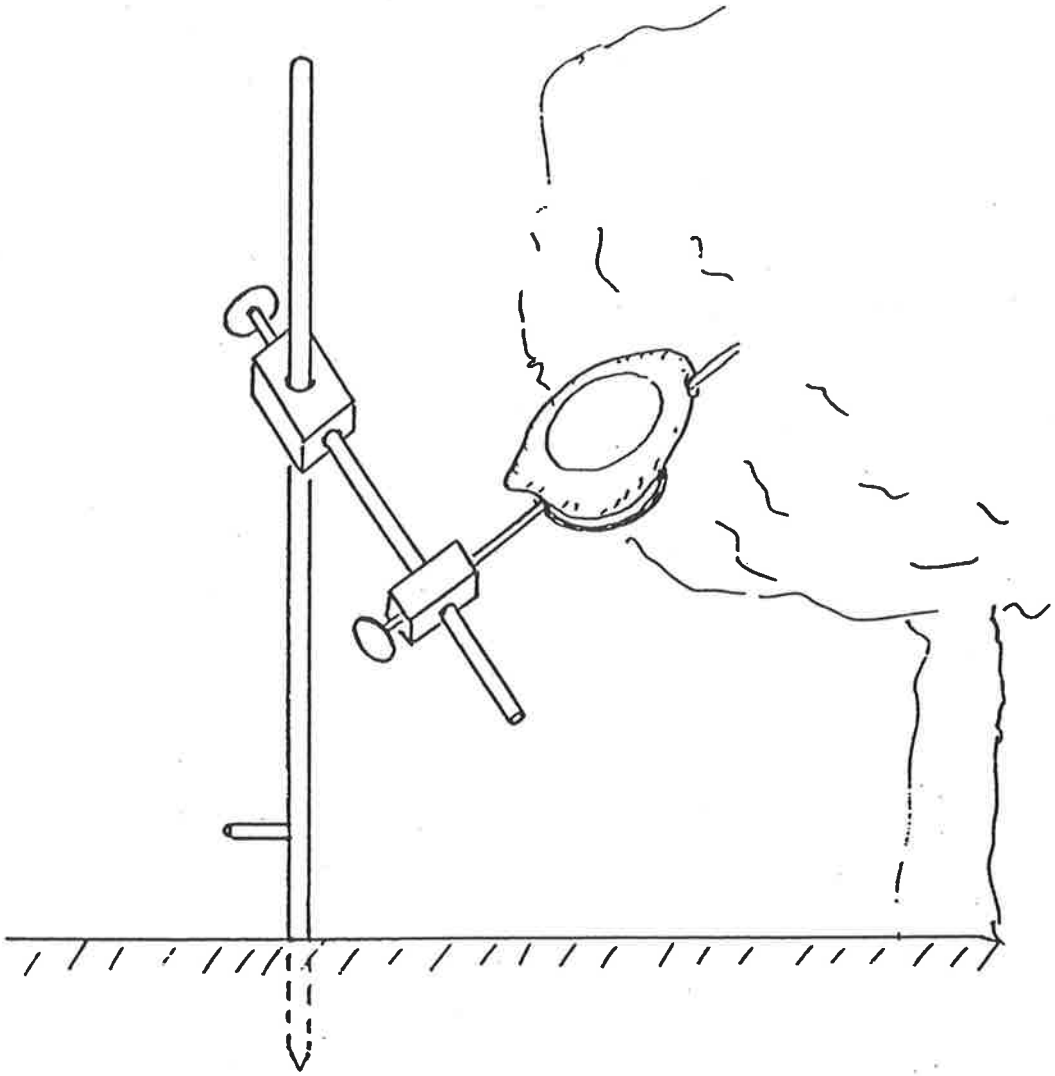


Figure 4.2 (1). Fruit-holder for starting a cohort of red scale on citrus fruits on trees.

4.2.1.2 Use of a photographic method to observe the survival and growth of red scale

Details of the photographic equipment are presented in Section 3.3. Before taking the first batch of pictures of each cohort, the scale covers (from the infested pumpkins) and the dead bodies of crawlers etc, were gently blown away from the experimental areas. The first batch of pictures was taken just before the shades were removed from a cohort.

In the summer of 1983, pictures of each cohort were taken once a fortnight; in the summer of 1985, once a week. The development of red scale on the films could be analysed by either a microscope or a slide-projector. The latter was chosen for convenience and accuracy, as follows.

For each experimental area, the initial picture was projected onto a 30 x 30 cm piece of paper and the positions of the scales marked [Fig.4.2 (2)]. The positions were divided into several observation areas and the scales numbered in sequence [Fig. 4.2 (3) A & B]. Subsequent pictures were projected onto the first, moving the projector back and forth to achieve an accurate fit. Each scale was then recorded as present or absent.

4.2.1.3. Ambient temperature during the year

Temperatures (daily maximum, minimum and average) at the Waite Institute (position 34°58'S, 138°38'E and height above sea level 122.5m) are given in Table 4.2 (1). They are means of the years 1925-83 (Biennial Report, Waite Agri. Res. Inst., 1982-83). The annual mean temperature was 16.5°C; the daily extremes were 44.3°C in January and 0.9°C in June. Maximum temperatures higher than 40°C occurred between November and March which is the hottest period of each year but experimental cohorts could not be started earlier in the summer because host lemons were not sufficiently large for experiments until late January of each year.

Measurement of above-skin temperature in the sun

As mentioned earlier (see Chapter 2) I was not able to put a micro-thermocouple into a red scale without killing it but found that the above-skin temperature of a lemon serves as an indirect measurement of the body temperature of red scale. In this experiment, above-skin temperatures in the sun were measured on four compass aspects of the tree, namely, north, south, east and west.

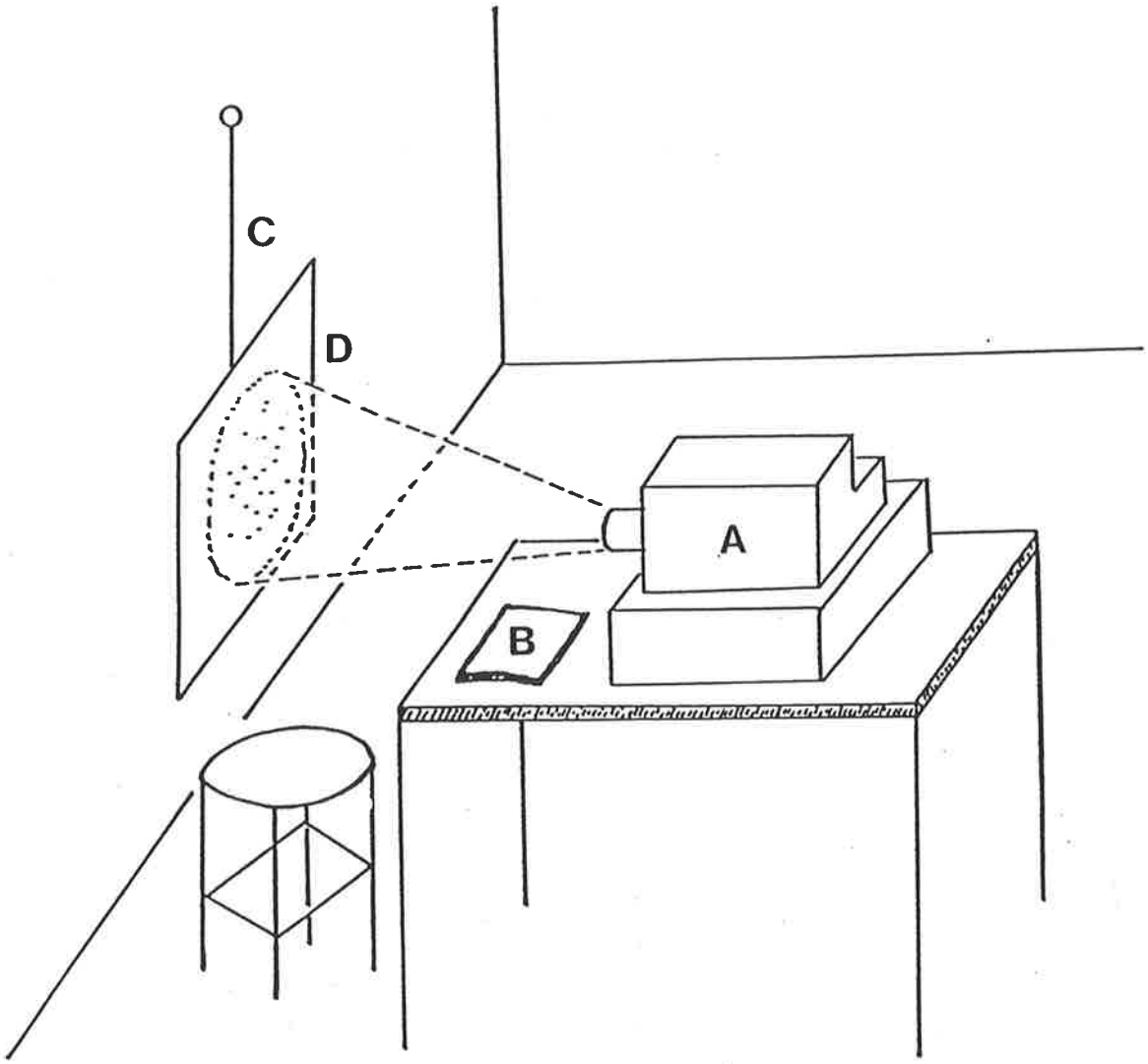


Figure 4.2 (2). Observation of the growth of red scale from color slides. (A: projector; B: record-tables; C: elastic string; D: "screen", a plastic plate).

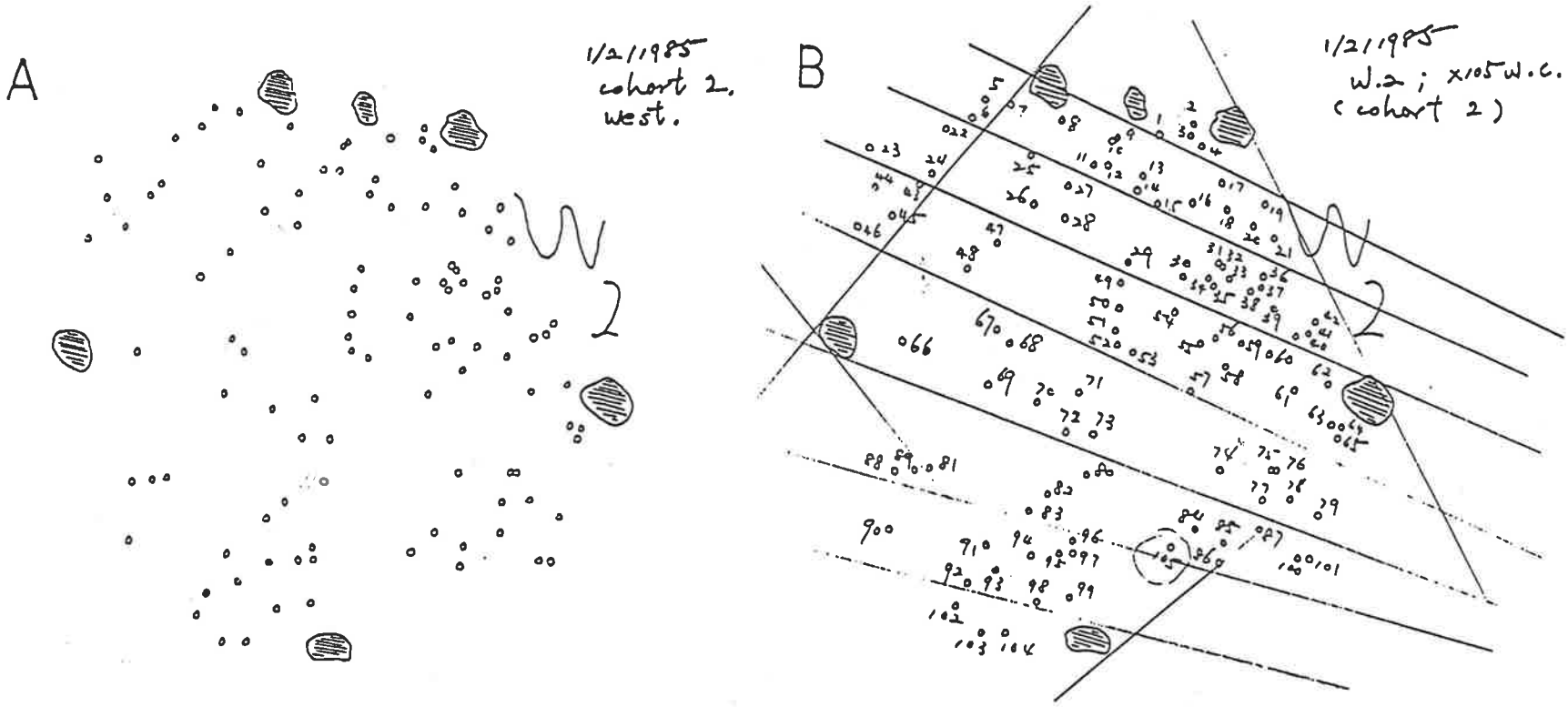


Figure 4.2 (3). The initial position of red scale of white-cap stage.

Table 4.2 (1). Air temperatures, 1925–83, at the Waite Institute, South Australia (Biennial Report 1982–83, Waite Agr. Res. Inst.).

Month	Average daily			Daily extreme	
	Maximum	Minimum	Mean	Highest	Lowest
J	27.9	16.4	22.1	44.3	8.0
F	27.7	16.5	22.1	43.1	8.4
M	25.5	15.4	20.5	40.7	6.0
A	21.4	12.9	17.2	34.6	4.6
M	17.8	10.7	14.2	28.8	3.2
J	15.1	8.6	11.8	25.1	0.9
J	14.2	7.8	11.0	25.5	1.8
A	15.2	8.1	11.7	26.7	2.1
S	17.6	9.4	13.5	33.3	2.1
O	20.3	10.9	15.6	34.6	3.8
N	23.4	12.8	18.1	41.8	4.4
D	25.8	14.7	20.3	42.1	5.8
Year	21.0	12.0	16.5	44.3	0.9

4.2.2. Results

The survival of red scales was distinguished by recording the change (for each individual) from one stage to the next. Those scales which changed in size were obvious survivors. The death of the scales (that did not change) was confirmed after a sufficient time (day-degrees) had elapsed for the completion of growth of the insect to the next stage (see table below). For instance, a 2nd instar scale was considered to be dead if had spent more than 269.0 D.D. >12°C on the tree and was still a 2nd instar. The number of day-degrees (D.D.) >12°C required to complete each stage of red scale on citrus fruit (after Atkinson 1977) were as follows

Stage	D.D. >12°C for each stage	Total
female:		
1st	127.3	127.3
2nd	141.7	269.0
3rd	109.6	378.6
adult (pre-reproduction)	183.8	562.4
male:		
1st to moult	127.3	127.3
1st moult to emergence	190.4	317.7

Table 4.2 (2). The accumulated day-degrees >12°C for each cohort up to the time of the presence of the maximum numbers of female adult red scales.

Cohort	Period	day-degree >12°C
1983		
Co.1	29/1-14/3	523.2
Co.2	6/2-25/3	469.9
Co.3	15/2-10/4	441.3
Co.4	22/2-12/5	454.6
Co.5	2/3-9/6	393.5
1985		
Co.1	no female adults	—
Co.2	31/1-20/3	466.0
Co.3	8/2-1/4	483.1
CO.4	15/2-8/4	431.1
CO.5	8/3-6/5	446.6

The observed numbers of red scale of each cohort during the course of the experiment in 1983 are given in Appendix Tables 4.2 (1) to 4.2 (5) and for 1985 are given in Appendix Tables 4.2 (6) to 4.2 (10). In each of these tables a code is used to classify the data. Thus, for example, "4.2.(1-N)" decodes as "table of data for the north aspect of cohort 1 in 1983". The total number of scales in each cohort are obtained by summing over the N, S, E and W aspects. Thus, in cohort 1, there were initially 995 scales = 272 on the North aspect (Appendix Table 4.2 (1-N), 188 on the south, 343 on the east and 192 on the west.

At each sampling time, estimates were made - from the photograph - of the numbers of scales in each stage of growth. But in many of the cohorts started in summer, all the scales died as white caps or 1st instars. Thus, in cohort 1, all 272 white caps on the northern side of the canopy died before they had progressed to "proper" 1st instars or beyond (Appendix Table 4.2 (1-N)); and similarly all 192 starters died on the western side as whitecaps (Appendix Table 4.2 (1-W)) Only on the southern side did some scales grow progressively through 1st and 2nd instars to become adults (Appendix Table 4.2 (1-S)).

4.2.2.1. The survival-rate of adult scales

For each cohort, the most important estimate was that of the number of scales which survived to become adults. This estimate was made when the maximum number of adults were seen in the cohort, to allow any "slow developers" to complete their development. The number of DD > 12º C from the start of the experiment after which this estimate was made is given in Table 4.2 (2) for each cohort. The numbers ranged from 393.5 to 523.2, and most were considerably greater than the value of about 380 D.D. estimated by Atkinson (1977) to be required by the female to complete development from crawler to adult; and they were greater again that the 320 DD required for the completion of development of the male (Atkinson, 1977). When this estimate of survival to the adult stage was made, any scales which had not become adults were considered to have died before doing so. This estimate, for each aspect of

TABLE 4.2 (3). Percentage survival rates of red scale of each cohort on lemons on trees (1983, 1985), and hour-degree (H.D.) greater than 40°C

Cohort and started date	Initial no. in each cohort	% survival of:			H.D. >40°C
		Male	Female	Total	
		1983			
1: 29/1	995	2.71	2.11	4.82	72.6
2: 6/2	250	6.40	1.20	7.60	43.8
3: 15/2	408	10.29	1.23	11.25	29.5
4: 22/2	358	13.69	6.70	20.39	26.1
5: 2/3	291	30.93	15.46	46.39	7.5
		1985			
1: 24/1	234	0.43	0	0.43	---
2: 31/1	336	19.35	1.49	20.84	8.9
3: 8/2	376	17.82	1.86	19.68	10.4
4: 15/2	400	18.00	0.75	18.75	10.3
5: 8/3	438	22.5	3.88	26.03	10.6

Table 4.2 (4). Percentage survival rates of red scale of each cohort on different aspects of the canopy of a lemon tree, 1983.

Cohort and started time	% survival rate on aspect:			
	male scale insects			
	North	South	East	West
1: 29/1	0	14.36	0	0
2: 6/2	0	15.31	7.69*	0
3: 15/2	6.33	18.52	12.32	0
4: 22/2	0	35.06	23.16	0
5: 2/3	33.33	7.02	40.85	37.31
	female scale insects (up to adult stage)			
	North	South	East	West
1: 29/1	0	11.17	0	0
2: 6/2	0	3.06	0	0
3: 15/2	1.27	1.85	1.45	0
4: 22/2	0	19.48	9.47	0
5: 2/3	5.21	14.04	22.54	23.88

(1). *: This value was obtained from a very small started number of 13.

(2). On each aspect, numbers of red scales ranged 70-270.

Table 4.2 (5). Percentage survival rates of red scale of each cohort on different aspects of the canopy of a lemon tree, 1985.

Cohort and started time	% survival rates on aspect:			
	male scale insects			
	North	South	East	West
1: 24/1	0	1.18	-	0
2: 31/1	27.17	16.92	29.73	6.67
3: 8/2	11.11	20.56	13.92	22.94
4: 15/2	15.91	47.73	16.67	2.63
5: 8/3	6.38	30.48	34.58	22.35
	female scale insects (up to adult stage)			
	North	South	East	West
1: 24/1	0	0	-	0
2: 31/1	0	1.54	5.41	0
3: 8/2	1.23	4.67	0	0.92
4: 15/2	1.14	0	0	1.32
5: 8/3	0	13.33	0	3.53

* Numbers of red scales on each aspect ranged 60-150.

each cohort, is given at the bottom of the table as "% survival-rate" in each of Appendix Tables 4(1) to 4(10).

A summary of the data showing the initial numbers and the percentage survival rates of the male, female and the total in each cohort is given in Table 4.2 (3). The total percentage survival-rates (male + female, summed over all 4 aspects of one cohort) showed minimums of 4.82 in 1983 and 0.43 in 1985 in cohort 1 each year (started late January). On the other hand, maximum survival-rates of 46.39 in 1983 and 26.03 in 1985 occurred in cohort 5 each year (started early March). The monthly mean (and therefore extremes of) temperatures at the growing periods of the different cohorts of scales [see Tab.4.2 (1)] are negatively correlated with the increasing percentage survival-rates of the different cohorts in 1983. So it is likely that the percentage survival-rates in 1983 were a function of extreme temperatures. The data of Table 4.2 (3) suggest, however, that in 1985 the correlation of total percentage survival-rates of scales of each cohort with time of starting was not so apparent. This topic is pursued further in section 4.2.2.1.

It was of further interest to examine the percentage survival rates or male and female red scales separately on each of the 4 aspects (north, south, east and west). The details for each cohort in 1983 are given in Table 4.2 (4); and those for 1985 are given in Table 4.2 (5). These data clearly indicate that the percentage survival rates varied greatly on different aspects. The highest percentage survival rates of scales within each cohort usually occurred on the south side of the tree, follwed by east, north and west in that order. Again, all the observations seem to suggest that the percentage survival of scales within a cohort was a function of the extreme temperatures due to exposure to the sun.

Detailed analyses of the survival and the growth of red scale in relation to extremes of temperatures in the sun are presented in the next section.

4.2.2.2. Relationship between hour-degrees > 40°C and survival of adult red scale

This analysis was based on the assumptions that (a) the parasitization rates were the same among aspects, and (b) the differences in the mortality of red scales among aspects were due only to the differences in extreme temperatures among aspects.

At Adelaide, S. Australia, the extremes of high daily temperatures have occurred between November and March and have ranged between 40.7 and 44.3°C (Table.4.2 (1)). Consequently, the threshold of extreme temperature was established as 40°C to test the influence of extremes on the mortality of red scales in this experiment.

For each cohort the number of hour-degrees (H.D.) >40°C was accumulated for the period from the start of the experiment to the time at which the 3rd instar should have completed its development [see also Section 4.2.3 and Table 4.2 (2).] The number of H D. >40°C for each aspect, namely, north, south, east and west, were calculated from the above-skin temperatures (see Chapter 2) and are given in Appendix Table 4.2 (11).

From the data of Appendix Tables 4.2 (1-11) and Tables 4.2 (4) and 4.2 (5), the values of H.D.>40°C are re-arranged in Table 4.2 (6a) and 4.2 (6b) for 1983 and 1985 respectively so they can be related to the percentage survival of adult scales of each aspect within each cohort.

Linear regression was used to test the hypothesis - for each of the three groups of: females only, males only, and females plus males - that the % survival-rate was a function of H.D. > 40°C. The analyses were done initially for 1983 and 1985 separately. The results are given in Table 4.2 (6). They indicate that:

* there was a significant (negative) regression for each group (i.e. females only, males only, and females plus males) in 1983.
* there was no significant regression for any group in 1985.

The raw data (Tables 4.2(6a, 6b))suggest that the difference between the two years was that the summer of 1985 was relatively cooler and that the X-variable in 1985 (i.e. H.D. > 40°C) consequently had very few values greater than zero.

A test was then made, for each group, that the slope of the regression was not different in the 1983 and in the 1985 data sets. It provided no evidence, for any group, of a difference in slope ($F < 1.0$; with 1,33 d.f; $p > 0.05$). So the data sets for 1983 and 1985 were combined and tested again for regression. The results (for 1983 + 1985, in Table 4.2 (6c)) indicated that:

* there was no regression for female scales
* there was a highly significant regression ($p < 0.01$) for both male scales and for female plus male scales. The latter is clearly dominated by the male data.

The lack of regression for the female scales is probably due to the low survival rates; especially in 1985. The range of survival-rates is better seen in Table 4.2 (3) in which the % survival rates are pooled over all aspects for each cohort starting time. In 1985, the highest survival rate in any cohort was only 3.68%; in 1983 it was somewhat higher (15.46%). By contrast, the % survival rate for males ranged up to 30.93% in 1983 and up to 22.15% in 1985.

It is not reasonable, biologically, to regress the overall % survival-rates of scales (as given in Table 4.2(3)) on the "mean" number of hour-degrees experienced by the scales over all aspects.

In conclusion, the differences between the two years' data and the low values of H.D. > 40°C in relation to relatively low survival-rates, especially of female scales and especially in 1985, suggest that the criterion of H.D. > 40°C was perhaps not a useful one for estimating survival (or mortality) of adult scales and that a lower threshold (say 35°C) may have been preferable.

TABLE 4.2 (6a) The percentage survival of adult females (f), males (m) and females plus males (f + m) of each cohort (Y) on total hour-degrees (H.D.) above 40°C within each aspect (1983).

Aspect	Cohort No.	H.D.	% survival of adults within aspect (Y):		
			f	m	f+m
North	1	46.5	0	0	0
	2	25.5	0	0	0
	3	15.5	1.27	6.33	7.50
	4	13.5	0	0	0
	5	3.0	5.21	33.33	38.54
South	1	0	11.17	14.36	25.53
	2	0	3.06	15.31	18.37
	3	0	1.85	18.52	20.37
	4	0	19.48	35.06	54.54
	5	0	14.04	7.02	21.06
East	1	118.5	0	0	0
	2	79.5	7.7	0	7.7
	3	50.0	1.45	2.32	13.77
	4	43.5	9.47	23.16	32.63
	5	13.5	22.54	40.85	63.39
West	1	125.5	0	0	0
	2	70.0	0	0	0
	3	52.5	0	0	0
	4	47.5	0	0	0
	5	13.5	23.88	37.31	61.19

TABLE 4.2 (6b) The percentage survival of adult females of each cohort (Y) on total hour-degrees above 40°C (X) within each aspect (1985).

Aspect	Cohort	Hour-degrees (X)	% survival of adults within aspect (Y):		
			f	m	f+m
NORTH	1	--	--	--	---
	2	29.0	0	27.20	27.20
	3	41.5	1.23	11.11	12.34
	4	41.0	1.14	15.91	17.05
	5	42.50	0	6.38	6.38
SOUTH	1	--	--	--	--
	2	0	1.54	16.992	18.48
	3	0	4.67	20.56	25.23
	4	0	0	47.73	47.73
	5	0	13.33	30.48	43.81
EAST	1	--	--	--	--
	2	2.5	5.41	29.73	35.14
	3	0	0	13.92	13.92
	4	0	0	16.67	16.67
	5	0	0	34.58	34.58
WEST	1	--	--	--	--
	2	4	0	6.66	6.66
	3	0	0.92	22.94	23.86
	4	0	1.32	2.64	3.96
	5	0	3.53	22.35	25.88

TABLE 4.2 (6c) The test of the hypothesis of null regression of % survival-rate of red scale on hour-degrees >40°C during the growth of the immature stages; in 1983, 1985 and 1983 plus 1985 (i.e. combined); and for females only, males only, and females plus males.

Sex of Scales	Data for Year:	Statistics for regression				
		Intercept	Slope	d.f.	r	p
Females	1983	9.39	- 0.1036	19	- 0.488	<0.05
only	1985	2.56	- 0.0494	15	- 0.246	N.S
	1983 + 1985	5.53	- 0.0599	35	- 0.298	N.S
Males	1983	19.63	- 0.2077	19	- 0.552	< 0.02
only	1985	22.59	- 0.2227	15	- 0.327	N.S
	1983 + 1985	21.33	- 0.2261	35	- 0.545	< 0.01
Females	1983	28.97	- 0.2993	19	- 0.536	< 0.02
plus	1985	25.08	- 0.2708	15	- 0.356	N.S
males	1983 + 1985	26.77	- 0.2746	35	- 0.503	< 0.01

4.2.2.3. Relationship between hour-degrees above 40°C and the survival of instar red scale

An attempt was made to further relate the mortality-rate rate of 1st instars in each cohort to the accumulated hour-degrees >40`C.

For red scales on citrus fruits, about 127 day-degrees above 12`C is required for 1st instar instars to complete their developmental period (Atkinson 1977). So on each sampling day after the start of each cohort, an estimate was made of whether or not all the surviving 1st instar scales had moulted to the next instar. If on any such sampling day, more than about 140 DD > 12°C had elapsed since the start of a cohort, a scale insect which was still a 1st instar was considered to be dead. In Appendix Table 4.2 (12) is given the starting date of each cohort, the sampling date by which all 1st instar development was considered to have been completed, and the number of DD >12°C between the 2 dates. It will be seen from the table that the number of DD>12°C was usually 25-50 DD greater than the 127 DD required for "mean" development of the 1st instar. Thus any slow developers had a chance to complete their development by the date by which all such development was deemed to have been completed. And so, on that date an estimate was made, for each cohort, of the numbers of scales which had died as 1st instars (from the number of 2nd instars), and further estimates were made of the numbers of dead 1st instars which were still on the fruit - and by subtraction, the number of dead 1st instars which had dropped off the fruits. These latter numbers of dead 1st instars are discussed in the next section.

All the relevant numbers are expressed as percentages of the initial number in each cohort for each aspect in Appendix Table 4.2 (13a) for 1983 and Appendix Table 4.2 (13b) for 1985. And in Appendix Table 4.2 (14a) and 14(b) are given the number of hour-degrees >40°C which occurred during the developmental period of the 1st instar scales in each aspect in each cohort.

The main hypothesis to be tested was whether the total % mortality rate of the 1st instars on each aspect of the tree, and in each cohort, was a function of the H.D. > 40°C recorded there. The hypothesis was tested by linear regression for 1983 and 1985 separately. The results, given in Table 4.2(7a) indicate that there was a significant regression for each year, and plots of the data (not given) and further analyses indicated that curvilinear regression was of no greater advantage to the analysis.

It was then of interest to test the difference in slopes of the regressions of the data for the 2 years. This test is given in Table 4.2(7b) and indicates that there was no evidence of the slopes being different. So the data for the 2 years were combined, and the significance of the regression tested again. The regression was now non-significant ($p = 0.1146$). So, finally, the data were analysed to test for a difference in elevations (intercepts) (Table 4.2 (7b)). The results indicated a highly significant difference, with $p<0.001$. This difference in intercepts of the regression lines for 1983 and 1985 suggests strongly that either there were different causes of mortality in the 2 years, or else that the criterion of "heat -dose" (i.e. hour-degrees > 40°C) was not a useful criterion for estimating mortality of scales - as was suggested earlier for adult scales (4.2.2.2).

A similar conclusion can be drawn from the trends of the % dead summed over all aspects per cohort in each year (Appendix Tables 4.2 (13a) and (13b) - and Table 4.2(8)). Thus in 1983, the % total dead decreased from 87.3 in cohort 1 to 17.4 in cohort 5; and there was a significant linear regression of % total dead on cohort number so that the % total dead decreased, on average, by 15.7 per cohort (Fig. 4.2(4)). Similarly there was a linear regression - also with a negative coefficient - for the data of 1985 (Fig. 4.2(5)), but the rate of decrease of % dead with cohort number was about half of that of 1983. This decrease in % mortality of 1st instar scales with increasing cohort number is related, of course, to the later starting dates of the later cohorts - so that % mortality may also be regressed on the number of days from 25 Jan (the earliest starting date of a cohort) - see Fig. 4.2 (5). The decrease in % mortality in both regressions is probably due to the lower mean temperatures and lower extremes of

TABLE 4.2 (7a). Regression of percentage death rate of 1st instar red scale (Y) on hour-degrees above 40° C (X)

Tested item	Intercept	Slope	r	d.f.	p
1983: total % dead vs. H.D.	39.831	0.780	0.483	16	<0.05
1985: total % dead vs H.D.	68.834	1.267	0.489	17	<0.05

TABLE 4.2 (7b). Analysis of variance to test the hypotheses of no difference in slope or intercept of the regression lines describing the % death-rate of 1st instars of red scale in relation to hour-degrees > 40°C; for 1983 and 1985 separately

Analysis after Snedecor and Cochran (1967); Table 14.6.2 therein.

Source of data	d.f.	x^2	xy	y^2	Deviations from regression slope d.f.	S.S.	M.S.
1983	17	12,348.1	9,643.9	24,292.3	16	18,611.8	1,163.2
1985	18	856.8	1,085.6	5,729.7	17	4,362.0	256.9
					13	22,973.8	1,393.1
Pooled	35	13,204.9	10,729.5	30,022.0	34	21,303.9	626.6
		Difference between slopes			1	1,669.9	1,669.9
1983 + 1985	36	13,240.1	5,507.9	32,648.6	35	30,357.3	867.4
			Between adjusted means		1	9,053.1	9,053.1

Testing hypotheses

1. Difference in slope: F = 1,669.9/1,393.1 = 1.20 (d.f. = 1,33); N.S.

2. Difference in elevations: F = 9,053.1/626.6 = 14.4 (d.f. = 1,34); p<0.01

Fig. 4.2 (4) The total % mortality of 1st instar red scales summed over aspects in each cohort and plotted against cohort number. For 1983 and 1985 separately.

Fig. 4.2 (5) The total % mortality of 1st instar red scales summed over aspects in each cohort and plotted against the number of days from 25 Jan (the date on which the earliest cohort was started) to the date of the start of each cohort.

Fig. 4.2 (4)

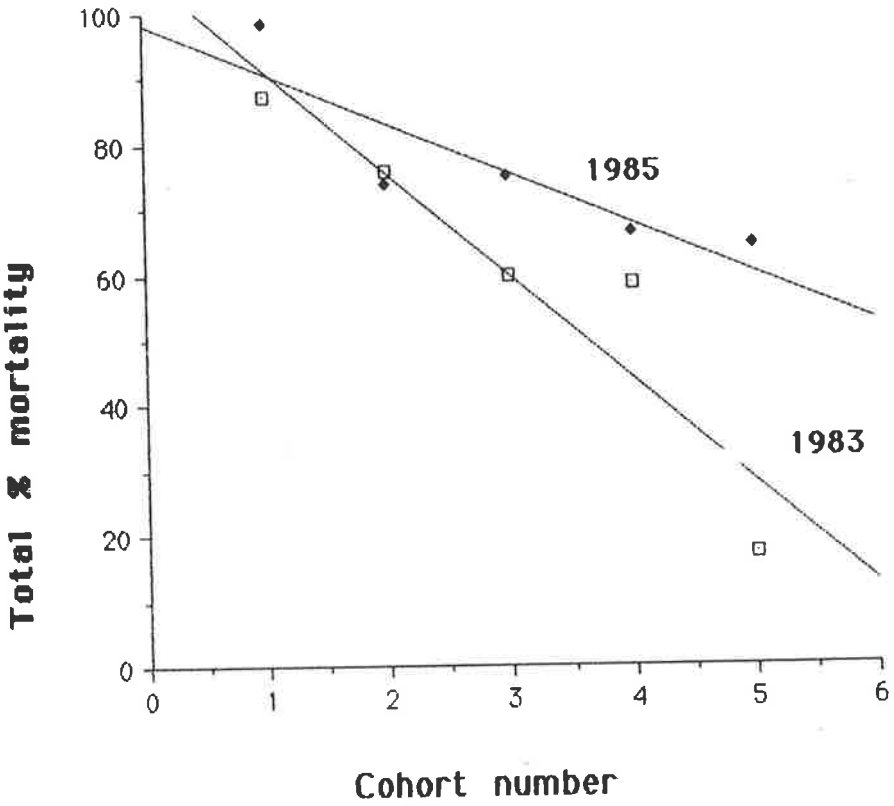
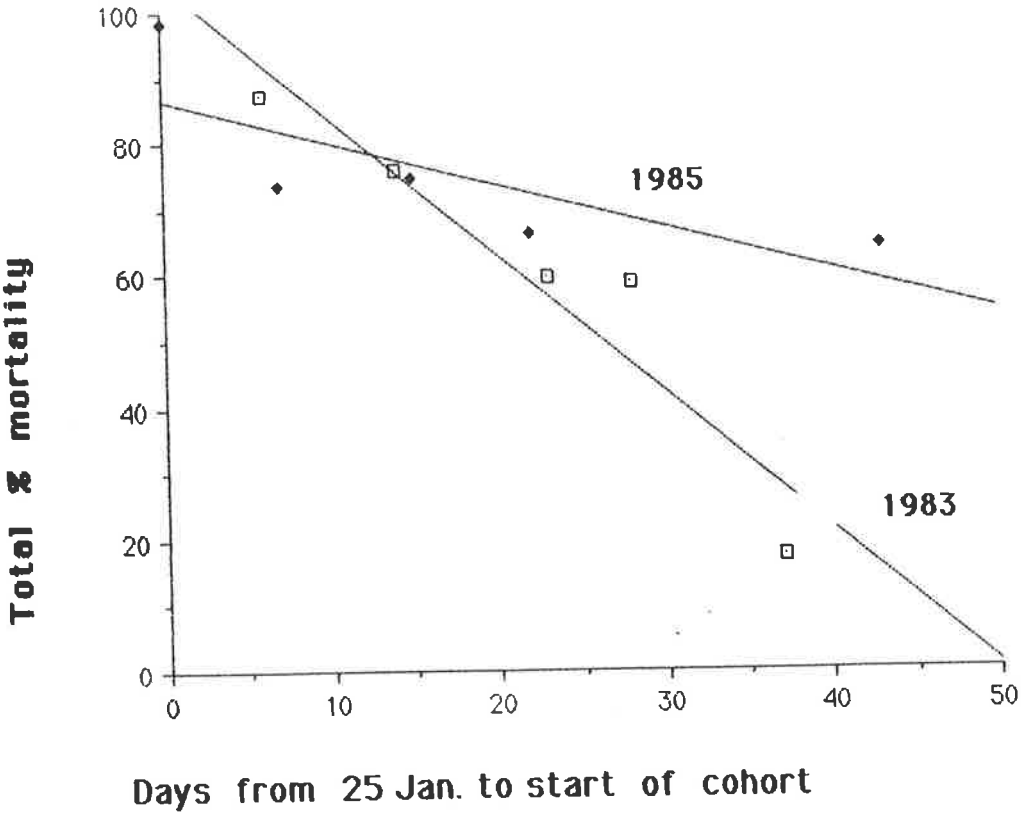


Fig. 4.2 (5)



temperature to which the 1st instar scales were exposed to as the starting dates of the cohorts moved from mid late summer (25 Jan) to early autumn (9 March). But the much greater % mortalities in most of the cohorts in the apparently cooler summer of 1985 suggest that the criterion of H.D. > 40°C was not a useful one.

Finally the data in Table 4.2(8) which are re-arranged from Appendix Tables 13a, 13b, can be used to test the hypothesis that there was no difference in the total % mortality of 1st instar scales between aspects. The means for aspects are given in Table 4.2(8 a,b) separately for 1983 and 1985. For 1983, an ANOVA indicated a significant ($p < 0.02$) difference between aspects, with the means of north (79.7) and west (78.7) being significantly higher than the means of east (43.8) and south (35.9). For 1985 (Table 4.2(8b)), the mean mortalities of east and south were nearer those of north and west but that of south (64.4) was still significantly lower than that of north or west.

4.2.2.4. The drop-off rate of dead 1st instar scales

(i) Introduction

As shown in Appendix Tables 4.2 (1) to (10) and in Appendix Tables 4.2(13a) and (13b), with the lapse of time, some of the dead scales dropped off the host lemons. The rate of dropping off, which will be denoted as the drop-off rate, is of some considerable interest because, if it is known, the % mortality rate of each stage of scale can be estimated from the number of accumulated dead scales on the fruit plus the number of dead scales which have dropped off. In at least one year at Loxton, Maelzer (pers. commun.) estimated that the drop-off rate of dead scales was relatively low and that the % mortality rate (and hence the % survival rate) could be estimated from the rate of accumulation of dead scales on fruits.

For a start, the percentages of dead 1st instars in each cohort which dropped off during the first 150-200 DD > 12°C are given in Appendix Tables 4.2 (13a) and 4.2 (13b) for 1983 and 1985 respectively. And in Appendix Table 4.2 (14a, 14b) are given the numbers of H.D. >40°C to which each aspect of each cohort was exposed to during the course of the 1st stadium. So one can test the hypothesis, which may be of

Table 4.2 (8) The total % mortality of 1st instar red scales; data from Appendix Tables 4.2(13a) and (13b) re-arranged for aspect - and summed over all aspects.

(a) 1983

Cohort number	North	South	East	West	Mean for cohort *
1	100.0	61.7	---	100.0	87.3
2	100.0	34.7	---	93.5	76.0
3	82.2	23.1	41.3	92.8	59.9
4	97.7	19.5	17.9	100.0	58.8
5	18.7	40.4	2.8	7.5	17.4
Mean for aspect	79.7	35.9	43.8	78.7	

* Regression of "mean for cohort" on "cohort number:"
$y = 106.98 - 15.7x$; $r = 0.94$, $p < 0.02$

(b) (1985)

1	100.0	95.3	---	100.0	98.4
2	73.9	72.3	58.1	90.5	73.7
3	80.2	64.5	84.8	69.7	74.9
4	70.4	38.6	63.8	92.1	66.2
5	90.	51.4	49.5	65.9	64.3
Mean for aspect	82.9	64.4	70.9	83.6	

* Regression of "mean for cohort" on "cohort number";
$y = 98.21 - 7.6x$; $r = 0.88$; $p < 0.05$

The real and apparent proportions of 1st instars which dropped off were then multiplied by 100 to give percentages of real and apparent "drop-off" of dead 1st instar scales.

Daily rainfall and wind data were obtained from the Waite Institute meteorological station. The relevant falls of rain (mms) in 1983 and 1985 are given in Table 4.2(9) . Also given in Table 4.2(9) are the days on which the daily wind run (Kms) at 2m exceeded 200 - in contrast to a mean wind run for Feb-April 1983 of 126.6 and for Feb-April 1985 of 110.7. The numbers of scales which drop off are more likely to be correlated with the highest wind gust per day rather than with the total daily wind run. But the two estimates of wind intensity are themselves likely to be correlated and high daily wind runs are easier to use initially.

(iii) Results.

The numbers of dead 1st instars on the fruits and the estimated numbers which dropped off between 2 sampling days are given in Table 4.2 (10) for each of cohorts 1-4 for 1983 and each of cohorts 1-5 in 1985. These numbers are used to calculate the percentage real and apparent "drop-off" (or numbers which dropped-off) for each cohort (ibid). Cohort 5 in 1983 did not have a sufficient number of dead 1st instars to be included in the analysis.

As an example of the calculations (Table 4.2(10)) detailed figures are initially given for cohort 1- s which are derived from Appendix Table 4.2 (1-s), p 242. In this part of cohort 1 there were initially 188 scales on day 0 (31 Jan.) . On day 14 (14 Feb) there were 57 W.C.s., 43 1sts. and 72 second instars. So there were 100 1st instars (i.e. 57 + 43) and 172 scales altogether (i.e. 100 + 72); and 16 had dropped off. This value 16 is therefore the first value of m in Table 4.2 (10) for cohort 1-S, and 100 is the 2nd value of n in the same table. Both real and apparent mortalities are calculated as: (16 x 100)/188) = 9. On day 28 (14 Feb.) there were then only 70 W.Cs + 1st., so the second value of m in Table 4.2(10) is 30. The real % drop-off is then 30 x 100/188 = 16; and the apparent % drop-off is 30 x 100/100 = 30.

Table 4.2(9) The days on which (a) rain fell or (b) daily wind run (Kms) at 2m was high - during January - April 1983 and 1985.

(A) Rain (mms)

1983		1985	
Date	Rain	Date	Rain
17 Feb	1.0*	7 Feb.	3.2
1-4 March	43.8*	16 March	47.6
15 March	9.6	14-15 April	14.4
22-23 March	32.4		
10-12 April	30.4		

* This rain was thunderstorm rain; that on other days was cold front rain.

(B) Daily wind run (Kms) at 2m.

1983		1985	
Date	Wind run	Date	Wind run
17 Feb	223.5	7 Feb.	255.5
3 March	227.2	8 Feb.	216.5
10 March	205.4	2 March	208.3
17 March	205.5	14 April	209.3
19 March	206.6	15 April	237.7
22 March	216.6		
3 April	225.1		
5 April	203.1		
11 April	204.9		
24 April	253.3		
25 April	234.3		

N.B. The mean daily wind run for Feb-April, 1983 was 126.6 and for Feb.-April 1985 was 110.7

Table 4.2(10) The numbers of dead 1st instar scales which were still on the fruits (n) and which had dropped off the fruit (m) with days from the start of the cohort; for each cohort separately in 1983 and 1985. Also given are the % apparent and real "drop-offs".

Cohort 1-s (example)					Total of cohort 1				
			% "drop-off"					% "drop-off"	
Days	n	m	real	app	Days	n	m	real	app
0	188					652			
14	100	16	9	9		550	30	5	5
28	70	30	16	30		331	219	33	40
42	68	2	1	3		261	70	11	21
56	68	0	0	0		229	32	5	12
70	68	0	0	0		200	29	4	13
85	64	4	2	6		161	39	6	15

Cohort 2

0	237			
17	148	17	7	7
31	110	38	16	2 6
45	93	17	7	15
66	88	5	2	5
86	82	6	2	7
107	54	0	0	0
120	43	11	5	20
134	41	2	1	5
148	41	0	0	0

Cohort 3

0	408			
10	235	71	18	18
24	145	7	2	3
38	143	2	1	1
52	136	7	2	5
66	114	22	5	16
82	84	6	2	5
100	80	4	1	5
115	66	14	4	18
129	56	10	3	15
143	48	8	2	14

Cohort 4

0	358			
12	75	138	39	39
22	66	7	2	9
36	59	7	2	11
53	49	10	3	17
64	32	17	5	34
82	24	8	2	25
96	24	0	0	0

Cohort 5

Too few to estimate

Table 4.2(16) cont.

Days	n	m	% "drop-off" real	% "drop-off" app
Cohort 6				
0	234			
7	144	86	37	37
14	102	42	18	29
21	93	9	4	9
29	88	5	2	5
35	71	17	7	19
42	61	10	4	14
54	54	7	3	11
59	54	0	0	0
66	21	33	14	61
Cohort 7				
0	336			
7	147	111	33	33
14	139	8	2	5
22	123	16	4	12
28	108	15	4	12
35	101	7	2	7
47	86	15	4	15
52	81	5	1	6
59	71	10	3	12
66	54	17	5	24
Cohort 8				
0	376			
7	146	119	32	32
14	126	20	5	14
21	114	12	3	10
28	108	6	1	5
39	78	30	8	28
44	69	9	2	12
51	62	7	2	10
65	53	9	2	14
72	34	19	5	36
Cohort 9				
0	400			
7	201	88	22	22
14	162	39	10	19
21	140	22	6	14
32	92	48	12	34
37	63	29	7	32
44	55	8	2	13
51	39	16	4	29
58	22	17	4	44
65	16	6	1	6
Cohort 10				
0	438			
11	331	107	24	24
16	168	12	3	4
23	149	19	4	11
30	86	63	14	42
37	74	12	3	14
42	43	31	7	42
49	29	14	3	33
56	25	4	1	14
63	20	5	1	20

The pattern of drop-off of dead 1st instar scales is best examined graphically, by plotting the percentage real and apparent drop-offs against (a) the number of days from the start of each cohort, and (b) calendar time. The graphs may then distinguish between high drop-off rates which consistently occur either (a) a certain number of days after the start of each cohort, or (b) on (or after) certain calendar days - irrespective of the date on which a cohort was started - as may be expected, for example, after rain or wind or after maximal physiological expansion of the fruits.

In Figs 4.2 (6, a-d) and 4.2(7, a-d) the percentage real drop-offs are plotted against days from the start of the cohort, for cohorts 1-4 in 1983 and cohorts 1-4 1985 respectively. The arrows in these figures mark the days on which rain fell. The figures indicate that there was usually a relatively high percentage drop-off of dead 1st instars in the first 10-30 days of each cohort. In 1983 some of these relatively high (30-40%) percentage drop-offs occurred just after the thunder storm rain of 1-4 March - but some occurred before the rain.

The influence of rain in 1983 is better explored by overplotting the data for cohorts 1-4 (for 1983) against (a) days from the start of each cohort, and (b) calendar date - in figs 4.2(8a) and (8b) respectively. The dates or days on which rain fell are also marked in these figures, and a comparison of the figures strongly suggests that (i) there was a common cause of the relatively high drop-offs of scales in the first 30 days or so in the life of each cohort, and that the initial high drop-offs occurred within about a 12 day interval after about 25 February; - see Fig. 4.2(8b); (ii) by chance, some thunderstorm rain did fall within this critical 12 day period, but it was obviously not wholly, at least, responsible for the high drop-offs because in 2 of the 4 cohorts it fell after the initial high drop-offs had occurred; and (iii) there was obviously no influence of other rains on the drop-off of scales.

The similar data for 1985 are similarly over plotted for cohorts 1-4 against days from the start of each cohort (Fig. 4.2 (9a)) and against calendar date (Fig. 4.2 (9b)). They show no influence of rain on the drop-off of scales.

The wind values given in Table 4.2 (9b) have not been similarly denoted in Figs 4.2 (8a, 8b, 9a and 9b) but it is obvious from a scan of the wind values in the table and of the Figures that wind played no obvious part in the drop-off of dead scales.

Fig. 4.2 (6). The numbers of dead 1st instar scales which dropped off the lemons in 7-14 day intervals in relation to the number of days from the start of the cohort. For each of cohorts 1-4 in 1983.

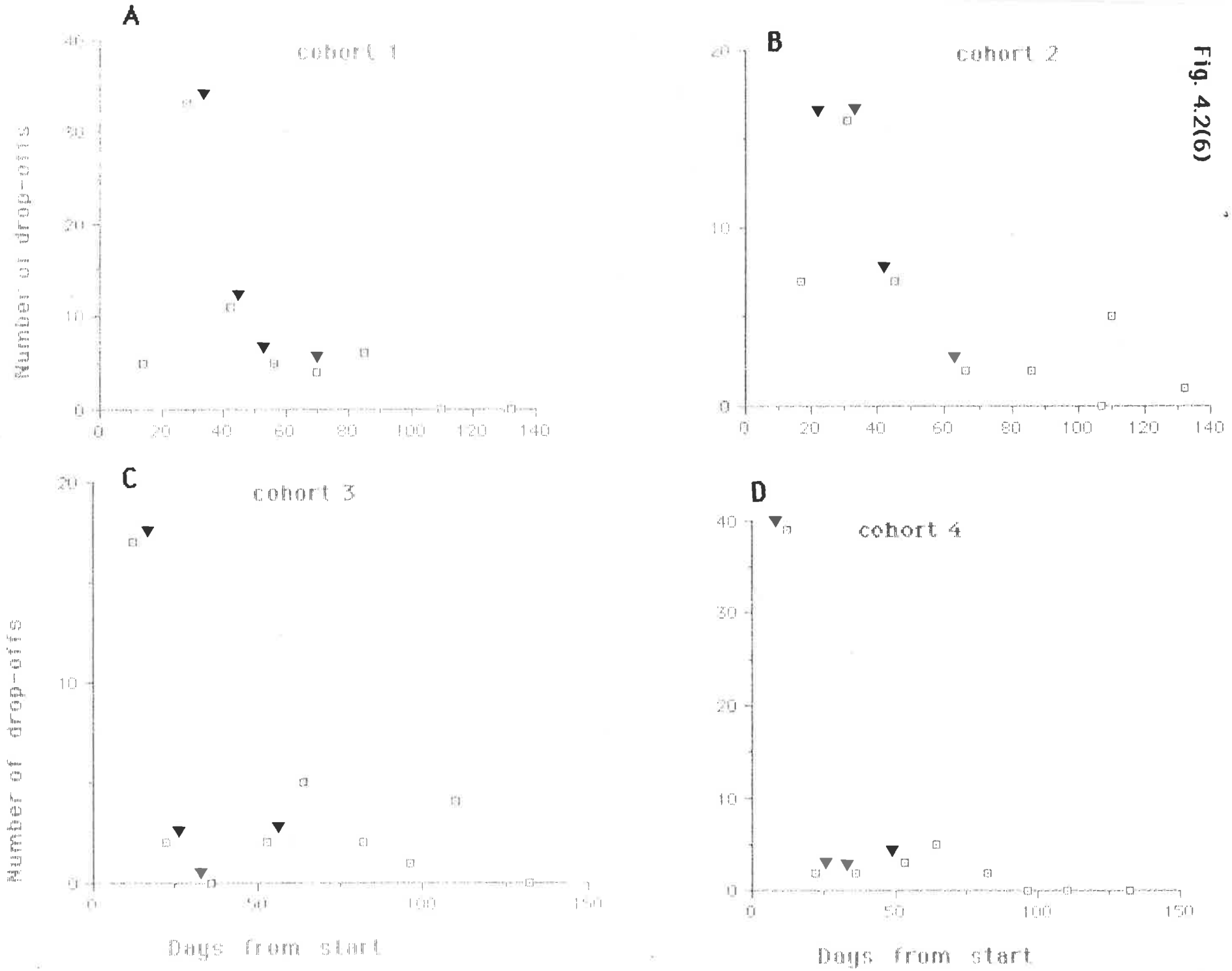

A
cohort 1
B
cohort 2
C
cohort 3
D
cohort 4
Days from start
Days from start

Fig. 4.2(6)

Fig. 4.2 (7) The numbers of dead 1st instar scales which dropped off the lemons in 7-14 day intervals in relation to the number of days from the start of the cohort. For each of cohorts 1-4 in 1985.

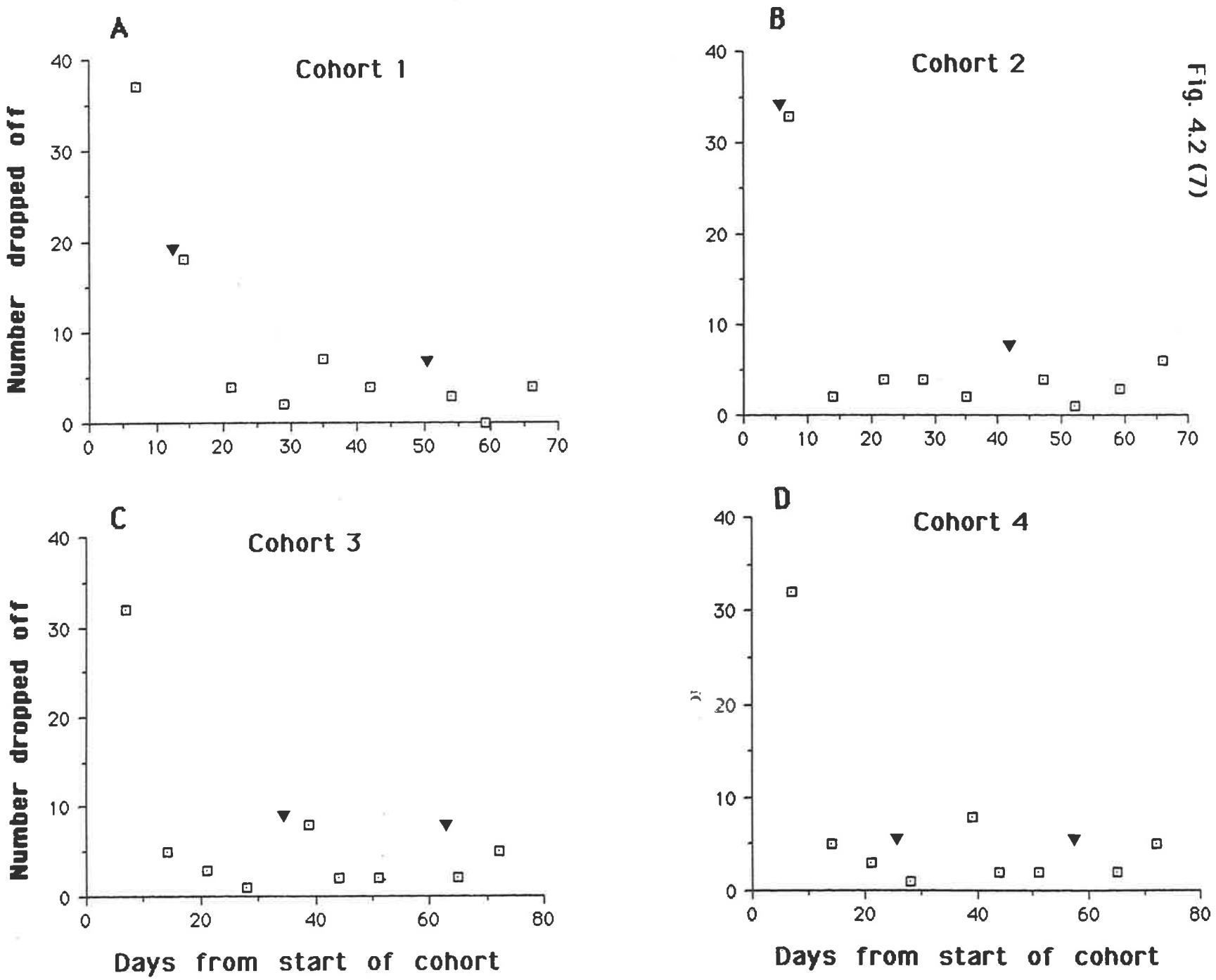

A
Cohort 1
B
Cohort 2
C
Cohort 3
D
Cohort 4
Number dropped off
Number dropped off
Days from start of cohort
Days from start of cohort
0
10
20
30
40
50
60
70
80

Fig. 4.2 (7)

Fig. 4.2 (8a) The numbers of dead 1st instar scales which dropped off the lemons in 7-14 day intervals, overplotted for each of cohorts 1-4 in 1983 against the number of days from the start of the cohort.

Fig. 4.2 (8b) The number of dead 1st instar scales which dropped off the lemons in 7-14 day intervals overplotted for each of cohorts 1-4 in 1983 against calendar date.

Fig. 4.2(8)

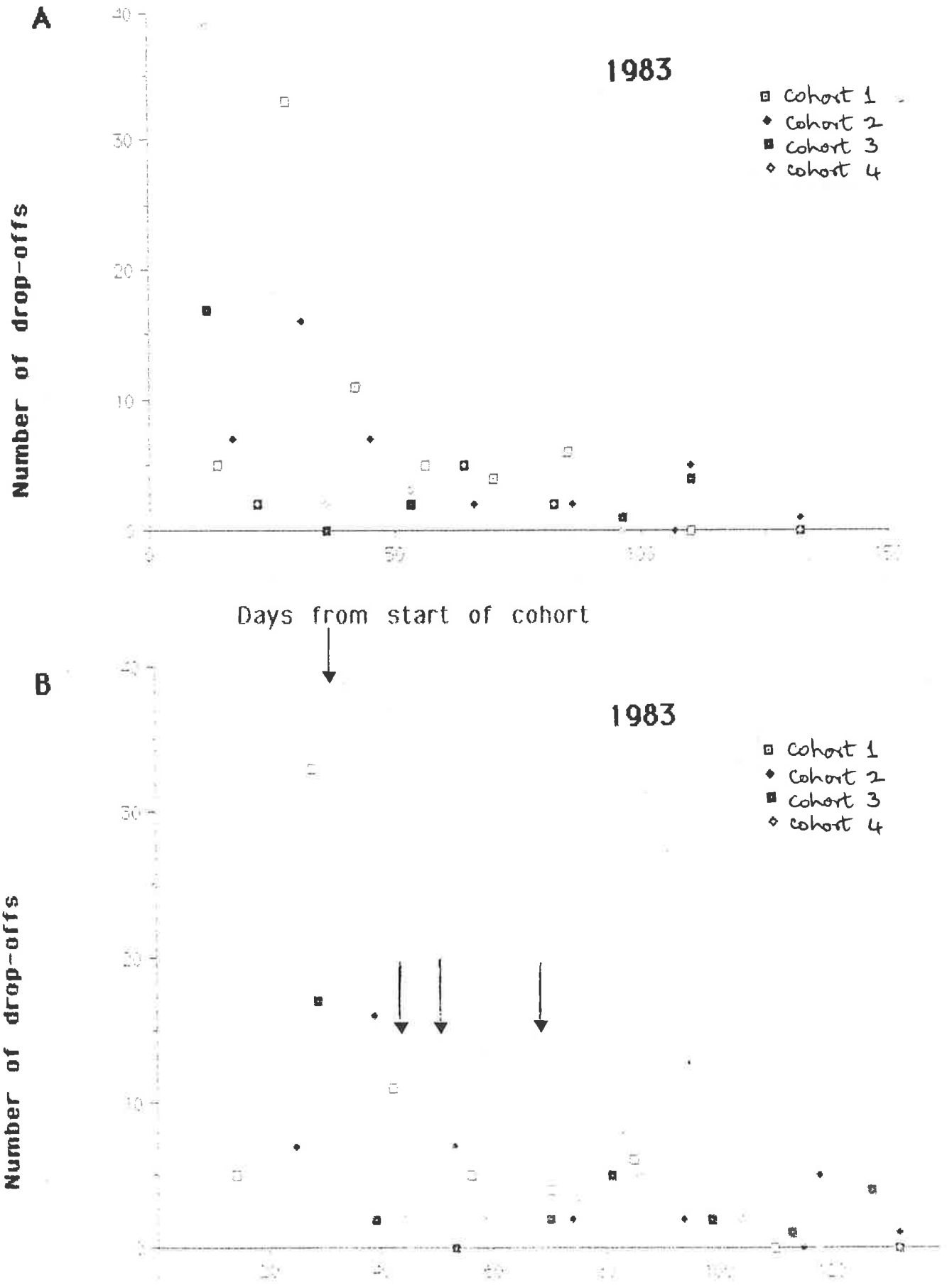
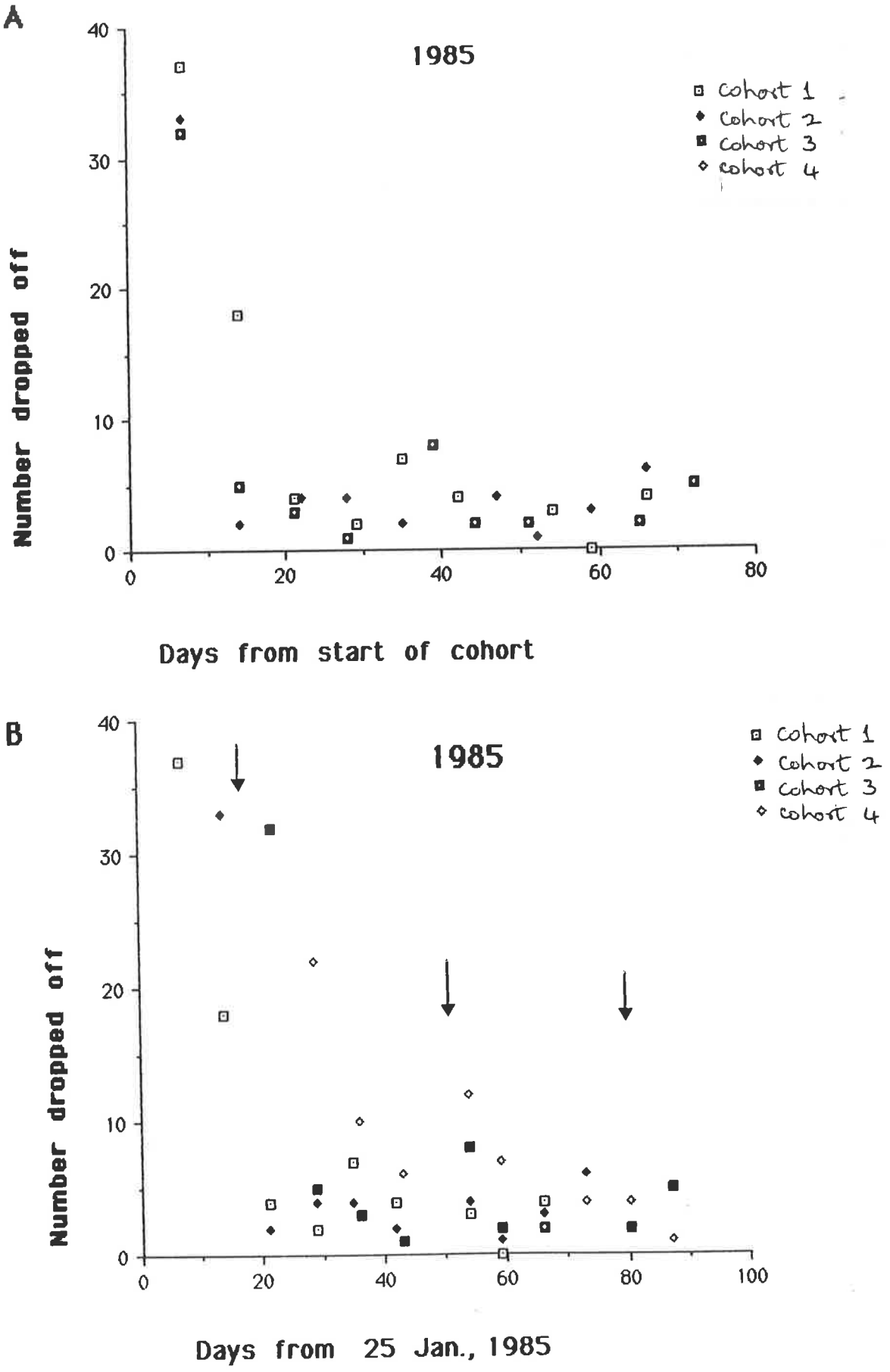

A
1983
Cohort 1
Cohort 2
Cohort 3
Cohort 4
Number of drop-offs
Days from start of cohort
B
1983
Cohort 1
Cohort 2
Cohort 3
Cohort 4
Number of drop-offs
Days from 31 Jan., 1983

Fig. 4.2 (9a) The numbers of dead 1st instar scales which dropped off the lemons in 7-14 day intervals, overplotted for each of cohorts 1-4 in 1985 against the number of days from the start of the cohort.

Fig. 4.2 (9b) The number of dead 1st instar scales which dropped off the lemons in 7-14 day intervals overplotted for each of cohorts 1-4 in 1985 against calendar date.

Fig. 4.2 (9)


A
1985
Cohort 1
Cohort 2
Cohort 3
Cohort 4
Number dropped off
Days from start of cohort
B
1985
Cohort 1
Cohort 2
Cohort 3
Cohort 4
Number dropped off
Days from 25 Jan., 1985

On the other hand, a comparison of Figures 4.2 (9a) and (9b) suggests that in 1985 - unlike 1983 - there was a consistent high drop-off of scales in the first 10-15 days from the start of each cohort (Fig. 4.2(9a)) which had nothing to do with rain or wind occurring on some particular day nor with some plant physiological process occurring in some particular interval of calendar time.

Can anything else be learned from the apparent rather than the real percentage drop-offs? The former were also overplotted, for cohorts 1-4 of 1983 and for cohorts 1-4 of 1985 respectively, against days from the start of each cohort and against calendar time. Whilst apparent drop-off rates are the only rates which can realistically be used, with repeated sampling, in population dynamics, the apparent drop-off rates in this experiment were based on ever-decreasing denominators. So it is not surprising that they were much more variable than the "real" drop-off rates (see Table 4.2(10)) and that they did not show the trends shown by the latter.

Finally, the data for each year were grouped by combining the data for cohorts which were sampled at about the same number of days after the start of each cohort. The percentage real and apparent drop-offs of dead 1st instar scales which were calculated from these grouped data are shown in Table 4.2(11) and in Figs. 4.2(10a,b). The percentage real drop-offs for each year are better fitted by curvilinear rather than by linear regression (Fig. 4.2 (10a)); and the percentage apparent drop-offs are still so variable that no regression is significant (Figs 4.2 (10b)). However, when the data for 1988 and 1985 are combined, the percentage real drop-offs can be described by a curvilinear regression which is significant at $p < 0.01$ (Fig. 4.2(10c)); and the apparent drop-offs can be described by a significant linear regression (Fig. 4.2(10d)).

(iv) Discussion

In conclusion, it is worth discussing briefly the possible common cause of the relatively high drop-off of dead 1st instar scales in the 12 day interval after 25 February, 1983 (Fig. 4.2(8b)). No obvious meteorological phenomenon can be found as the cause. However, on 16 February, 1983, Adelaide experienced one of its

Table 4.2 (11) The number of dead 1st instar scales which were still on the fruit (n) and which dropped off the fruits (m) with time, and the estimated % real and apparent (app) "drop-offs"; data for 1983 and 1985 separately.

Year	Days from start of cohort	n	m	% "drop-off" real	app
1983	0	1655			
	13	1008	256	15.5	15.5
	26	652	273	16.5	27.1
	40	556	96	5.8	14.7
	54	414	49	3.0	8.8
	66.5	434	73	4.4	17.6
	84	351	59	3.6	13.6
	98	158	4	0.2	1.1
	110	133	15	1.0	9.5
1985	0	1784			
	7	972	511	28.6	28.6
	14	697	121	6.8	12.4
	21	619	78	4.4	12.6
	29	482	137	7.7	22.1
	35	387	95	5.3	19.7
	42	314	73	4.1	18.9
	54	265	49	2.7	15.6
	59	234	31	1.7	13.2
	66	165	69	3.9	29.5

Fig. 10. The % numbers of dead 1st instar scales which had dropped off the fruit in relation to the numbers of days from the start of each cohort. Data combined for all aspects and all cohorts.

(a) % real drop-off; for 1983 and 1985 separately.

(b) % apparent drop-offs; for 1983 and 1985 separately.

(c) % real drop-offs; for 1983 + 1985

(d) % apparent drop-offs; for 1983 + 1985.

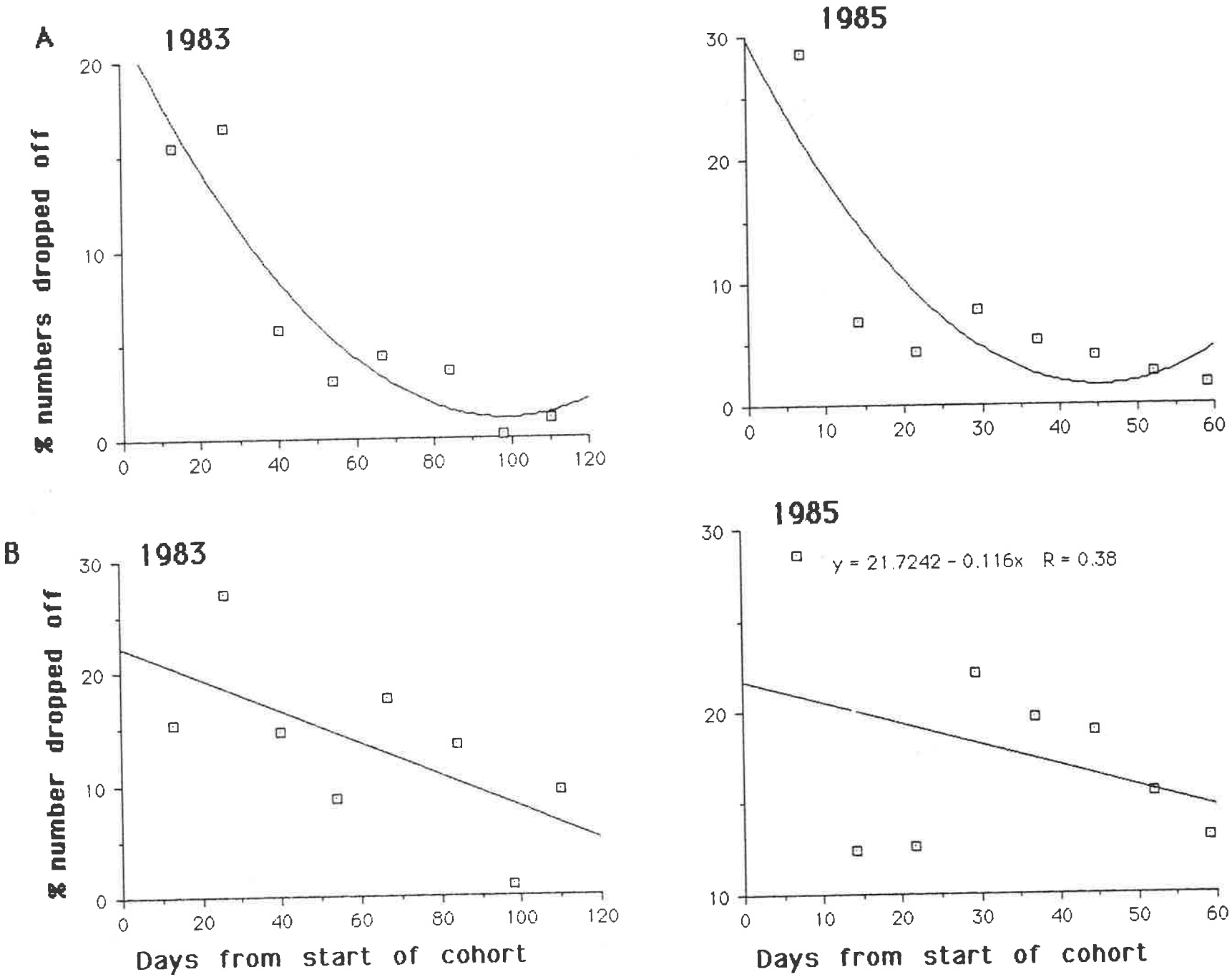
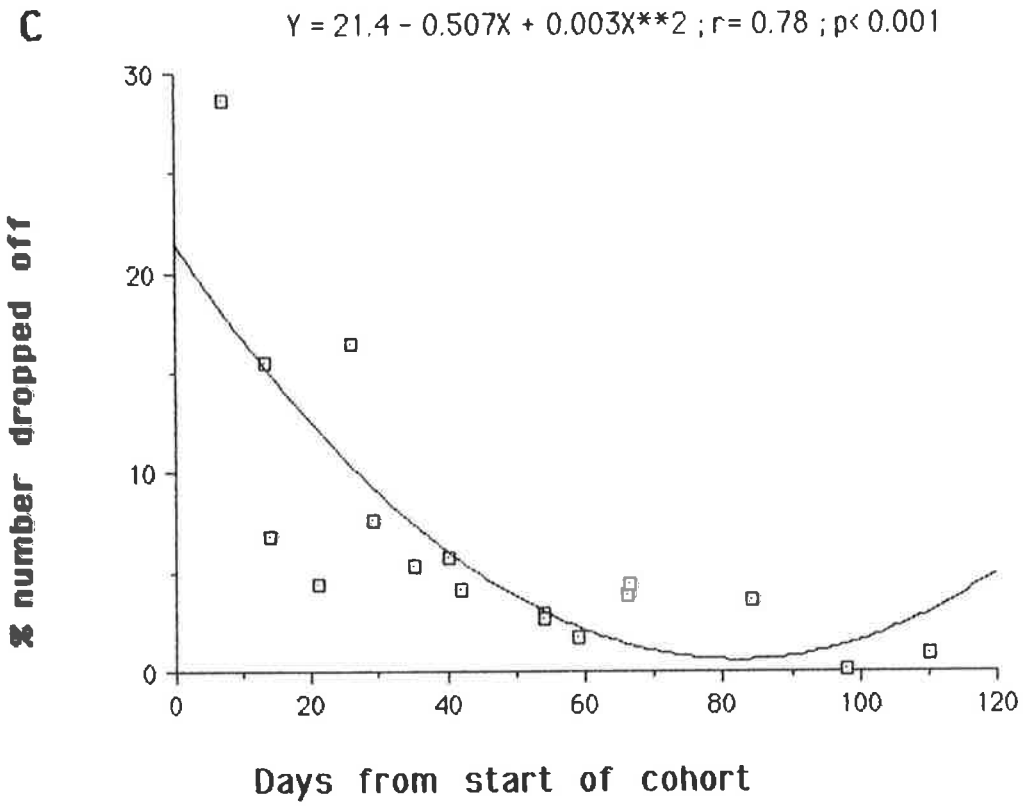

A
1983
% numbers dropped off
20
10
0
0
20
40
60
80
100
120
1985
30
20
10
0
0
10
20
30
40
50
60
B
1983
% number dropped off
30
20
10
0
0
20
40
60
80
100
120
Days from start of cohort
1985
y = 21.7242 - 0.116x R = 0.38
30
20
10
0
10
20
30
40
50
60
Days from start of cohort

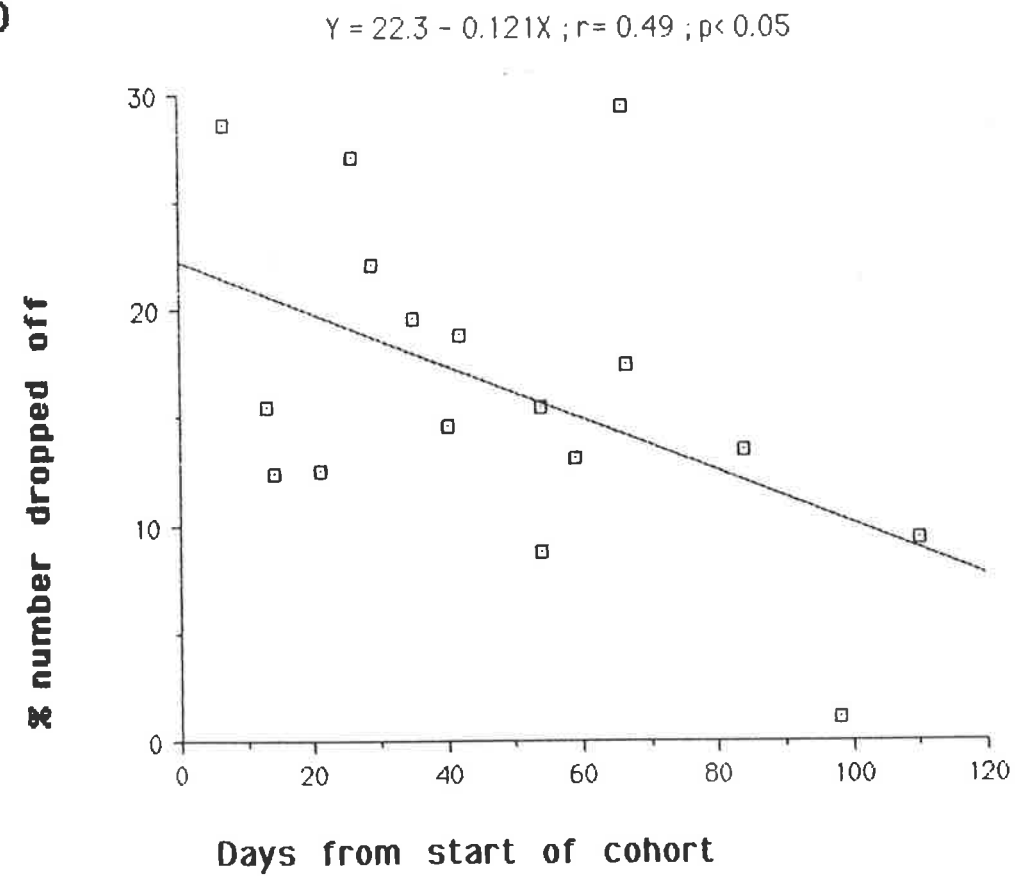
Fig. 4.2 (10)

Fig. 4.2 (10) cont.

C



D



hottest days for many years, with a maximal temperature of 41.8°C and a strong (80 km per hour) northerly wind which ferociously fanned the many bush fires which have labelled this day as "Black Ash Wednesday". During the night a "cool change" swept through Adelaide and was preceded by a 1mm of thunderstorm rain. The high loss of dead scales 10 days later may have been related, somehow, to these events. Perhaps the hot fruit was suddenly cooled by the rain, thereby causing some of the dead scales to be loosened sufficiently so that they were lost later? Or perhaps the trees and hence the fruits were unusually stressed by the huge evaporation rate on that day?

On the other hand, no reason can be thought of for the initial high drop-off in each cohort in 1985 (Fig. 4.2(9a)) other than "natural causes". But the difference between the data for the 2 years really pinpoints our ignorance of the processes and stresses the need for further work to elucidate them.

4.2.2.5 The drop-off rate of dead scales of other instars

The drop-off rates of dead scales of other instars can similarly be expressed as real and apparent rates, and they can similarly be estimated from the data in Appendix Tables 4.2 (1-10). However, some explanation of their derivation is necessary. In any of the relevant tables of data, the initial number of dead scales of any one stage (other than 1st instars) can be estimated as that number on the sampling date on which the numbers of later stages is maximal. For example, in Appendix Table 4.2(5-N), on 16/5,there were 16 2nd instars on the fruit plus 38 males + 3rd instars. On 26/5, there were 15 2nd instars and 37 later stages. So the initial number of dead 2nd instars is taken as 16 on 16/5. To illustrate the point, this value of 16 is marked with an asterisk - and other relevant numbers are similarly marked in the other Appendix Tables 4.2 (1-10). For cohorts 1 to 5, 1985, the numbers that dropped off at each sampling time are also given in Appendix Tables 4.2 (6-10).

The numbers of 3rd instars are too small to analyse and the numbers of 2nd instars and males have to be grouped over aspects and cohorts to make any sense. The totals for 2nd instars and males are given in Table 4.2 (12), and the apparent (rather than real) percentage drop-offs are plotted in Figs 4.2(11a, 11b) respectively. The data

Table 4.2 (12). The numbers of dead 2nd instar and male insects which were still on the fruit (n) and which had dropped off (m) with days from the start of each cohort; and the estimated % apparent drop-off. Data for 1983 and 1985 combined.

Stage of scales	Days from start of cohort	n	m	% apparent drop-off
2nd instars	36	237		
	46	270	20	8.4
	65	153	102	37.8*
	83	144	9	5.9
	103	98	7	4.9
	114	95	3	2.9
	128	86	9	9.5
	142	81	5	5.8
Males	38	349		
	44	345	4	1.1
	52	325	20	5.8
	66	167	33	10.2
	82	152	15	9.0
	102	140	2	1.3
	120	138	2	1.4
	135	135	3	2.2

N.B. More than 50% of this drop was in one cohort (no. 3 in 1983)

Fig. 11. The % numbers of dead 2nd instar or male scales which had dropped off the fruit in relation to the numbers of days from the start of each cohort. Data combined for all aspects, all cohorts and both years (i.e. 1983 and 1985).

(a) % apparent drop-offs of 2nd instar scales.

(b) % apparent drop-offs of male scales

Fig. 4.2 (11a)

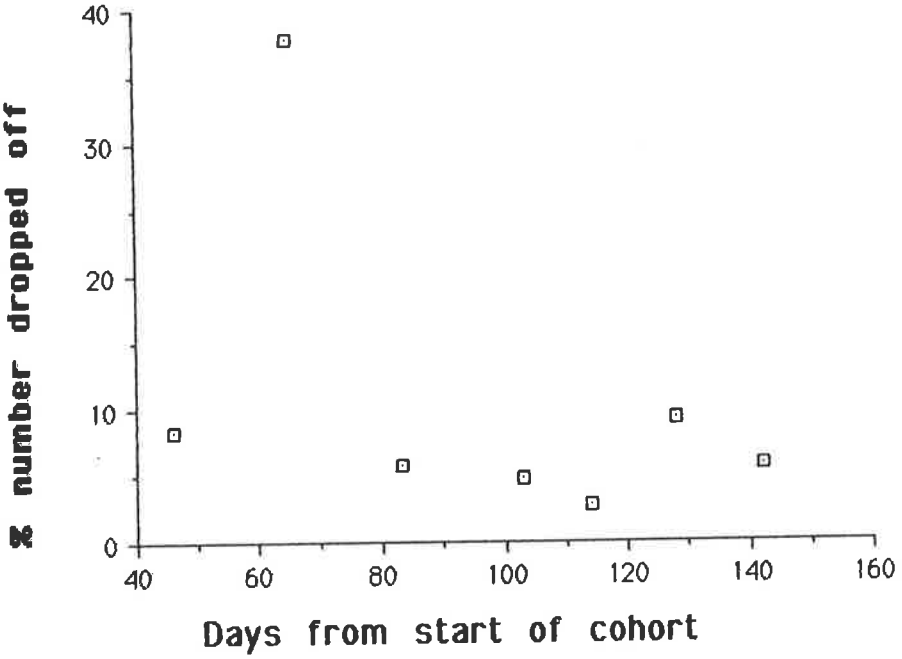
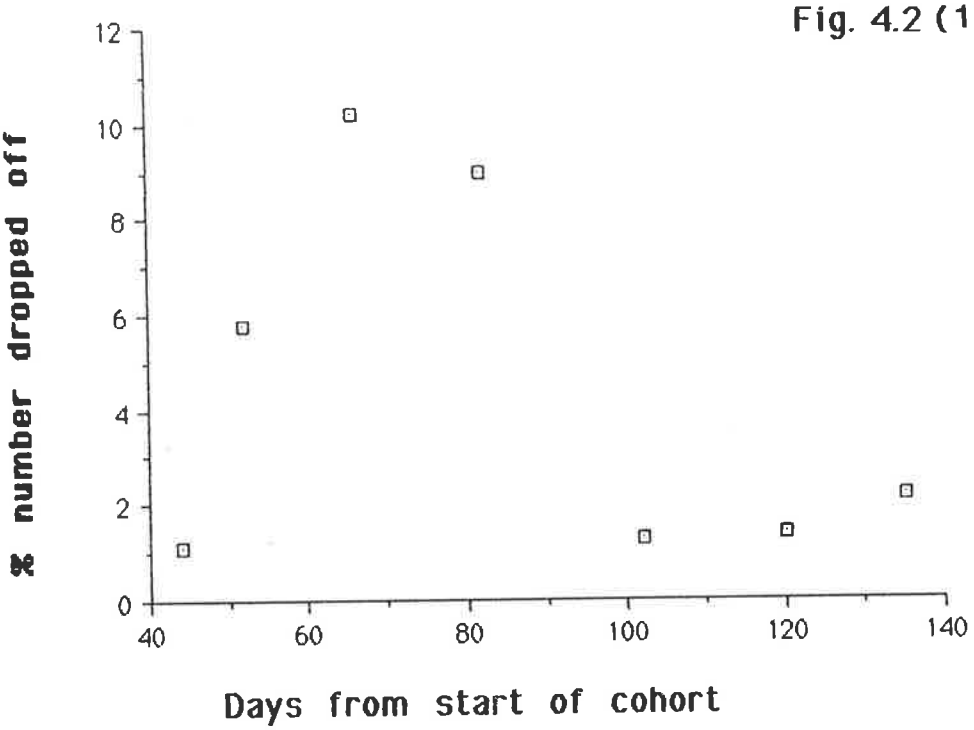


Fig. 4.2 (11b)



indicate that the numbers of 2nd instars and males which dropped off were usually much lower than those of 1st instars (compare Figs 11 to 8 & 9). Even the one "high" drop-off of 38% of 2nds at day 65 (Fig. 11a) was due largely to one cohort (no. 3; in 1983). On the whole the data suggest that the drop-off rate for males especially, was small enough and consistent enough for 3-4 months after the scales died, to allow the numbers of dead scales on the fruit to be used to estimate the mortality-rate.

4.2.3 General discussion

Finally, it is of interest to discuss further the usefulness of estimates of mortality from dead 2nd and male scales still on the fruits and to discuss estimates of mortality of 1st instar scales as well.

The numbers of dead scales which dropped off the fruits in my experiments may have been higher than may occur naturally because:

(i) the crawlers were brushed on to the fruit rather than being allowed to emerge naturally from under the female scale, and whilst the handling may not have affected their short-term mortality, it may have influenced their longer-term mortality and also the probability of them dropping off the fruit after they died.

(ii) the crawlers were restricted, by experimental design, to outward facing portions of oranges which were exposed to hither temperatures than are inward facing portions of fruit (or fruit in shade within the canopy); these outer portions of the fruit may also be subjected to higher degrees of transpiration and skin stretching which may influence the loss of scales from the fruit after they die.

(iii) the data are restricted to the experimental areas of the selected fruits and to approximately equal numbers of scale insects on the 4 main compass aspects; but in summer a large proportion of the scales occur on inward-facing portions of fruit, or on fruit in the shade elsewhere (Maelzer, pers. commun.); and it is also possible that a larger proportion of the population occurs then on the southern side of trees.

So, in conclusion, both the mortality-rate and the drop-off rate of dead scales may be lower than occurred in my experiment - and they may be lower again on oranges than on lemons which tend to mature more quickly than oranges. In particular,

more work is needed on the assessment of the loss of dead scales from fruits and of how such loss may be influenced by rain, wind or plant physiological processes - before the accumulative number of dead scales on fruits can be used with confidence to estimate mortality-rates.

4.3. Mortality of Red Scale and the Duration of Extremes of Temperatures

Extreme temperature (both high and low) is one of the most important factors affecting the mortality of red scale. Abdelrahman (1974) classified the stages of growth of red scale into four categories according to their tolerance to extreme cold and heat. The growing and the egg-maturation stages were most tolerant, followed in order by the moulting stages, the prepupal stage of males and the pupal stage of males. Critical low temperatures were estimated as LD50's of each stage of red scale as follows: about -3°C for the most tolerant stages; +3°C for the crawler-producing stage; about +6°C for the moulting stages and about +10°C for the prepupal and pupal stages of males. And critical high temperatures, again estimated as LD50's, ranged between 46 and 48°C for all stages.

Stage	LD50 low temperature (°C)
Growing stages	-3
Egg-maturation stage	-3
Crawler-producing stage	+3
Moulting stages	+6
Male prepupa and pupa	+10
	LD50 high temperature (°C)
All stages	46 - 48

Abdelrahman did not investigate the influence of durations of extreme temperatures on mortality and his scale insects experienced an extreme of temperature for less than 0.5h in each experiment. In the field, however, red scale may be exposed to an extreme temperature, especially to low temperature, for up to 8 hours. So, my experiment was designed to measure the influence of duration (hours) of extreme temperature on mortality of red scale.

4.3.1. Mortality of red scale

4.3.1.1. Methods and materials

Treatments: The treatments were all the combinations of 3 extremes of temperatures, namely, -2, +5 and +45°C; by 7 durations, namely, 0, 0.5, 1, 2, 4, 6 and 8 hours. In the 0-hour treatment, the temperature deviated to the same temperature as the other durations but then returned at once to the base temperature.

A 'control' treatment was also included in which the red scale were kept at the base temperature all through the experiment.

In nature, temperature fluctuates with a 24-hours periodicity. In summer, high maximum temperatures are attained during days which follow nights with a minimum of about 25°C. In winter, low minimum temperatures are recorded after days with maximum of about 10°C. Consequently, experimental incubators were programmed with a 24-hour cycle of fluctuating temperatures with either (a) a base constant temperature of 25°C from which deviations up to 45°C were made to occur, or (b) a base constant temperature of 10°C from which deviations down to -2°C or +5°C were made. The extreme temperature of 45°C was 2-3°C lower but -2°C and +5°C were close to the LD50's suggested by Abdelrahman (1974) for the growing and moulting stages of scales.

The temperature cycles: The experimental incubators were 8 insulated boxes with a Peltier-effect heater/cooler (the Minifridge, manufactured by Sheen Pty Ltd). The temperature in the boxes was controlled by a microprocessor [Fig.4.3 (1)].

The incubators were programmed to take four hours to change gradually to the experimental extremely low (-2 or +5°C) or extremely high (+45°C) temperatures from the base temperatures; and 4 hours for the temperatures to return to the base temperatures from these extreme temperatures.

Culture of red scale: Experimental red scales were cultured on butternut pumpkins. Cohorts of red scale were started by the brush-method to a marked area on each pumpkin from prior infested hosts (see Section 3.1). These pumpkins were then maintained in an insectary room at 27±1°C and 60% R.H. until red scales had reached the required stages.

Since the culture temperature was 27°C and since some of the treatments were designed to simulate winter days with maxima of 10°C, the scales were slowly acclimatized by lowering the temperature, over 3 days, before exposure to the "winter treatment": on the first day, they were moved to +20°C from 27°C; to +15°C on the second day and to +10°C on the third day. The insects were then placed in the relevant incubators for treatment. After treatment, they were again acclimatized over 3 days, this time to increasing temperature until the return to +27°C, at which temperature were then held for 10 days until mortality was assessed.

Figure 4.3 (1). Experimental incubators (x8).

Scale insects considered killed by the periods of extreme temperature were those which failed to develop beyond the stage at which they had been treated. Under a x25 magnification microscope, each scale cover was turned over and the insect was determined to be alive or dead. Those that were dead were obviously so, with dry and shrivelled bodies.

4.3.1.2. Results

The numbers of red scale used in each treatment are given in Appendix Tables 4.3 (1) to 4.3 (14). They ranged from 50 to 312. The total numbers of scales, the numbers and the percentage rates of dead red scales in each treatment are also given in these appendix tables. Unfortunately, in some of the experiments, some of the incubators lost control and only 6 incubators were used.

Testing variation between the "controls":

It was of interest initially to test the null hypothesis that the mortality of red scale at each of the base constant temperatures (C.T.) was not different from the mortality at the comparable treatment (E.T.) in which temperature was made to change to the extremely low or high temperature and then to immediately change back to the base temperature so that the duration at the extreme temperature was 0 hours. The relevant data are re-arranged from the Appendix Tables 4.3 (1) to (14) and are given in Table 4.3 (1) and a chi-square test was conducted to assess the null hypothesis.

These tests indicated that most of the mortalities at the low constant temperatures were smaller than those at the extremes of low temperatures with 0-hours duration; but no difference was found for the 3rd stage or the 2nd moult female. However, there were few significant differences in mortality between the constant temperature of 25°C and the extreme temperature of 45°C with a duration of 0-hours. The only big difference was for the 1st moult of red scale and the 2nd moult instar of male red scale.

It is next of interest to compare the observed % mortalities at the extreme temperatures and those expected from Abdelrahman's (1974) regression equations. The data in Table 4.3 (1) show that the observed mortalities at the extremes of low temperatures (-2°C and +5°C) were much smaller than those expected from Abdelrahman's equations; but the observed mortalities at 45°C were greater than those expected from the younger

Table 4.3 (1). Percentage dead rate of red scale at (a) the base constant temperatures (C.T.) and (b) each of the extreme temperatures (E.T.), with a duration of zero hours. Also given is the significance of a Chi-square test of the differences between the two rates, i.e. at C.T. and E.T. The expected percentage dead rate of each stage is given from Abdelrahman's (1974) regression equations.

Stage of red scale	observed % dead at temperature (°C): C.T.	E.T.	D.F.	For chi-square test, P:	Expected % mortality dut to E.T.
	+10°C	-2°C			
1st	7.52	24.58	17.06	<0.005	42.1
2nd	1.48	6.58	5.10	<0.05	45.1
3rd	1.09	1.25	0.16	>0.05	41.8
	+10°C	+5°C			
1st moult	6.76	22.40	15.64	<0.005	67.1
2nd moult	2.92	9.24	6.32	<0.025	-
within the 2nd moult:					
male	0	13.46	13.46	<0.005	100.0
female	7.14	5.97	-1.17	>0.05	66.9
	+25°C	+45°C			
1st	16.19	19.77	3.58	>0.05	5.4
1st moult	14.63	27.05	12.42	<0.005	5.2
2nd	14.53	17.53	3.00	>0.05	0
2nd moult	7.83	12.79	4.96	>0.05	-
within the 2nd moult:					
male	6.80	16.67	9.87	<0.05	16.1
female	8.66	9.57	0.91	>0.05	8.2
3rd	1.12	5.06	3.94	>0.05	4.7

C.T.:base constant temperature; E.T.:extreme temperature; D.F.:difference in % mortality between C.T. and E.T.

stages of scales, i.e. 1st moult instar, and were similar to those expected, for the 2nd instar, 2nd moult instar and 3rd instar. The differences at the low temperatures might be due to either the differences fo host used for the culture of experimental scale insects or the acclimatization regimen: I used pumpkins as host but Abderalhman used lemons; and the scale insects in my experiments had experienced an acclimatization regimen, by contrast they were not acclimatized before Abderalhman's experiments.

Testing the influence of different durations of extreme temperature:

Linear regression analysis was conducted to assess the percentage mortalities (Y) of red scale in relation to durations (X) of hours of extreme temperatures for each of the sets of data given in Appendix Tables 4.3 (1) to 4.3 (14). The relevant statistics are summarized in Table 4.3 (2). All but three of the linear regression equations were significant. The only non-significant ones were for the 1st instar and the 2nd instar at -2°C and the 1st moult instar at +45°C; with the last one being just not significant at p=0.05. So it can be concluded that the percentage mortality of the scale insects was nearly always a function of the durations (hours) of the extreme temperatures.

4.3.2. Reproduction of treated adult female scales

This experiment was conducted to test the influence of periods of exposure of the 3rd instar scales to high temperature of +45°C on the reproduction of the subsequent adults.

4.3.2.1. Methods

After the measurement, in the previous experiment, of the mortality of the 3rd instar scale insects exposed to 0-8 hours to temperature of 45°C, the host pumpkins were replaced in a constant temperature room at 25°C and 40-60% R.H. On each of the experimental pumpkins, 20 surviving scales were enclosed within an arena by use of "modeling clay", and the total numbers of red scale progeny which were produced were counted every two days and then removed from the arena. Counts were carried out until the 30th day after the birth of the first progeny. The experiment then had to be terminated because some of the pumpkins began to rot.

Table 4.3 (2). Statistics of the linear regression of the percentage dead rates (Y) of red scale in relation to the durations of hours (X) (ranged 0-8 hours) of extreme temperatures (E.T.). The row data for each regression are given in Appendix Tables 4.3 (1) to 4.3 (14) which are denoted here as Tab.1-14.

E.T.	Tab.	Stage of red scale	Intercept	Slop	r	d.f.	P
-2	1	1st	21.66	+0.26	+0.272	4	>0.05
	3	2nd	22.75	+2.15	+0.559	4	>0.05
	7	3rd	5.21	+2.23	+0.887	5	<0.01
+5	2	1st moult	17.13	+2.39	+0.807	5	<0.05
+5	4	2nd moult	8.50	+3.94	+0.923	5	<0.01
		within the 2nd moult:					
	5	male	15.57	+6.31	+0.898	5	<0.01
	6	female	3.76	+0.95	+0.849	5	<0.05
+45	8	1st	20.33	+2.79	+0.952	3	<0.05
	9	1st moult	24.23	+2.68	+0.797	4	>0.05
	10	2nd	16.77	+1.43	+0.924	4	<0.01
+45	11	2nd moult	9.00	+3.49	+0.934	5	<0.01
		within the 2nd moult:					
	12	male	10.34	+4.28	+0.904	5	<0.01
	13	female	8.12	+2.60	+0.966	5	<0.01
+45	14	3rd	4.11	+1.12	+0.903	4	<0.05

4.3.2.2. Results

The mean accumulated progeny per adult female scale for each treatment is shown in Table 4.3 (3). The mean daily reproductive rate for each treatment was calculated as:

$$= \frac{\text{Total accumulated mean of progeny per adult scale}}{\text{Total reproducing days in each treatment}}$$

and is given in the last line of the Table 4.3 (3). It ranged from 2.01 to 2.91 young per adult scale per day for the treated scales. The "untreated scales" at constant temperature of 25°C gave a mean of 2.37. None of these results were significantly different from each other or from the mean rate of 2.31 reported by Willard (1972) from red scales reared on leaf disks at 25°C. So there is no evidence that the exposure of scales to 45°C as 3rd instar scale insects affected the reproduction ability of the subsequent adults. The regression of total mean progeny on length of period at high temperature was calculated but was not significant.

It was concluded that subjecting 3rd instar scale to periods of high temperature (45°C) does not affect the reproduction of the surviving adult female scales.

4.4. Mortality of Red Scale in the Sun

4.4.1. Experiment 1: Measurement of mortality on the tree

Abdelrahman (1974) established an extremely high temperature of 48.5°C for the LD50 of 1st instar red scale. His temperature was obtained from a laboratory experiment under regularly fluctuating temperatures with a 24-hour cycle. Such a high shade temperature has never been recorded in Adelaide; the highest maximum was 44.3°C between 1925 and 1983 at the Waite Institute (Waite Agri. Res. Inst., 1982-83 Biennial Report). However, in an orchard in nature, insects may experience summer temperatures in the sun which are about 15°C higher than the ambient shade temperature (see Chapter 2). For example, the temperature in the sun could be 50°C when the ambient temperature was about 35°C. The latter temperature is well within the range of ambient temperatures recorded in Adelaide.

The following experiment was conducted to test the influence of extreme temperatures and days of exposure on mortalities of 1st instar and subsequent stages of red scales on oranges on the tree. The experiment ran from 25 February (late summer) to 4 August (mid-winter). It was believed

Table 4.3 (3). Mean accumulated progeny per "treated adult" red scale; of scales which were exposed to durations of 0 to 8 hours of 45°C as 3rd instar scales. Also given are the data for scales kept at a constant temperature (C.T.) of 25°C.

Days	C.T. 25°C	Duration in hours at 45°C				
		0	1	4	6	8
1	2.42					
2	5.32	1.00	1.74	2.34		
3	8.00	4.58	5.32	6.97	2.20	3.60
5	13.26	10.95	10.11	14.86	4.50	8.36
7	20.11	17.32	15.00	23.34	9.85	13.16
9	25.80	23.05	21.32	30.50	15.50	20.60
11	31.68	30.26	27.53	37.76	23.45	27.14
13	34.89	33.11	29.58	41.93	27.95	30.80
14	35.84	34.32	30.84	44.45	29.50	35.52
16	40.31	38.68	34.74	48.45	32.95	40.12
18	44.89	43.21	38.79	52.86	35.35	42.96
20	48.84	47.63	41.58	56.93	37.50	45.52
22	52.95	52.74	44.89	61.14	41.50	49.56
24	57.95	57.42	48.26	68.52	47.10	52.72
26	62.37	62.74	52.00	73.97	54.35	55.36
28	66.63	66.89	54.68	78.52	61.60	57.44
30	71.26	71.84	58.42	84.34	67.50	60.00
Mean	2.37	2.48	2.01	2.91	2.41	2.14

that during this period the extreme ambient temperatures would not be high enough to cause too much mortality in both control and experimental red scales shaded from the sun. However, the experiment was started when a very hot period of weather was forecast and it was based on the expectation that after late summer, the ambient temperatures would not be higher than the temperatures in the sun at the start of the experiment in late summer.

4.4.1.1. Methods and materials

Treatments: The treatments were 4 exposure times in days for 1st instar scales. After seeding the 1st instar scales on to the experimental fruit (see below), the scales in all four treatments were shaded from the sun for the 1st day to allow them to "establish" (i.e. settle down), and then they were given one of the 4 following treatments:

Treatment 1: "Control"; to measure natural mortality; shaded from the sun continuously until the end of the experiment.

Treatment 2: Exposed to the sun for one day only and then shaded from the sun to the end of the experiment.

Treatment 3: Exposed to the sun for 2 days and then shaded from the sun to the end of the experiment.

Treatment 4: Continuously exposed to the sun until the end of the experiment.

Details of treatments: In late summer (25/2/1983), 4 large, still green oranges were chosen from the eastern part of a tree canopy. An experimental area on each orange was marked, about 4 cm in diameter, on the side facing the outer edge of the canopy. About 100 1st instar red scales was started on each of these oranges by the brush method (see Chapter 3), at 9-11 a.m., 25/2/1983. Then the oranges were immediately shaded from the sun to let the crawlers settle down. This day of transfer of the crawlers was denoted as the "1st day" of the experiment. The experimental treatments of the scales were carried out from the second day.

None of the experimental scales were protected from their natural enemies, e.g., Aphytis spp., during the experimental period.

A photographic method was used to record the development of the scales on each of the experimental oranges (Chapter 3; Section 4.2). The first batch of pictures was taken on the second day; the second batch after

another 4 days. Then a batch was taken once every 10 days until the end (on 4/8/1983) of the experiment.

Temperatures in the sun were measured 1mm above the surface of an orange by a recording thermocouple (see Chapter 2); the ambient temperatures of the orchard were recorded by a thermohygrograph in a Stevenson Screen.

4.4.1.2. Results and discussion

The temperature expectations of the experiment were realized in the sense that the highest temperatures in the sun during the course of the experiment were experienced on the 2nd and 3rd day of the experiment (47.0 and 48.3°C respectively). Thereafter the highest temperatures in the sun were 44.0°C or lower, which are too low to cause mortality of red scale according to Abdelrahman's (1974) regression equations. The temperatures >40°C experienced during the course of the experiment are given in Table 4.4 (1).

The day-degrees (denoted as D.D.) >12°C (Atkinson 1977) expected for the development of red scale were calculated and accumulated from the mean ambient temperatures of each day. Using these values of D.D., the expected D.D. to complete development for the different stages of red scales are again given in Table 4.4 (1). Also given are the extremes of temperatures expected during each stadium. Thus the 1st instar scale insects were expected to remain in that stadium from 25/2/1983 to 5/3/1983, i.e. for 122.3 D.D. [Table 4.4 (1)]. During this period, the scales in the sun could possibly have experienced a total of 5 days in which the extremes of temperatures were higher than 40°C. They were then expected to have become 2nd instars, and in this stadium they should have experienced two hot days, with maxima of 44.0 and 41.5°C in the sun [Table 4.4 (1)]. The expected mortalities in probits [calculated by use of Abdelrahman's equations (1974)] and also in percentages for the various extremes of daily temperature recorded are also given in Table 4.4 (1). From the films, the observed numbers of red scales which developed up to different stages are given in Appendix Table 4.4 (1) to 4.4 (4) [see Section 4.2 for method].

As shown in Table 4.4 (1), no mortality due to high temperature was expected after 27/2/1983 in any of the treatments. The extremes in the sun of 47.0°C on 26/2/1983 and 48.25°C on 27/2/1983 were expected to cause independent mortalities of 24.7% and 45.1% respectively. Hence, the expected percentage mortality of 1st instar red scales was 24.7

Table 4.4 (1). Experiment 1. Day-degrees >12°C (Atkinson 1977) for the development of each expected stage of red scales and the expected percentage and probit mortality (Expec. mort.) due to extreme temperatures >40°C in the sun in each expected stage of red scale; 25/2-4/8, 1983.

Period: Stage: Day-degree	Extreme temperature			Expec. mort.	
	Date	In sun	Air*	%	(probit**)
25/2-5/3 1st: 122.3 D.D.					
	26/2	47.0	38.0	24.7	(4.3167)
	27/2	48.25	38.0	45.1	(4.8766)
	2/3	42.5	29.5	0	(2.1702)
	3/3	41.75	31.5	0	(1.7904)
	5/3	40.5	29.0	0	(1.1421)
6/3-26/3 2nd: 152.8 D.D.					
	6/3	44.0	37.5	0	(0.7160)
	11/3	41.5	33.0	0	(-)
27/3-9/5 3rd: 112.0 D.D.		-			
10/5-4/8 adult: 36.8 D.D.		-			

*: Obtained from a Stevenson Screen.

**: Probit values, calculated from Abdelrahman's equations (1974a).

in Treatment 2, in which scale insects were exposed to the sun for one day; and the accumulative percentage mortality of scales in Treatment 3, in which scales were exposed to the sun for two days, was expected to be 24.7+45.1x(100.0-24.7)/100=58.7. In Treatment 1 (control; shaded), ambient temperatures were not expected to cause any mortality of the 1st instar scales. And in Treatment 4, as in Treatment 3, the expected accumulated percentage mortality of the 1st instar scales was 58.7, because after the "3rd day" (27/2/1983), the extreme temperatures in the sun were not high enough to cause any expected mortality of red scales.

These expected mortalities are given for the respective treatments in Table 4.4 (2). The initial total number of red scales and the observed percentage mortality of the 1st instars in each treatment are also given in Table 4.4 (2). The percentage mortalities were calculated from the following formula:

$$= \frac{\text{Total initial no.of scales - No.of 2nd instar scales}}{\text{Total initial no.of scales}} \times 100\%$$

with the numbers of 2nd instars and subsequent stages of scales being given in Appendix Table 4.4 (1) to 4.4 (4).

Of initial interest is the relatively high natural mortality of 50% in the "control" (Treatment 1) of scales which had been shaded from the sun and had never experienced a temperature higher than 40°C. This relatively high natural mortality may have been due partly to the relatively high temperature on the day of transfer of the crawlers. It may also have been due to attack by Aphytis spp. Obviously higher percentage mortalities, 72.1-80.4%, were caused in the other treatments due to the higher temperatures in the sun; but they were not much different from each other.

The percentage mortalities in the treatments other than the control were then corrected by Abbott's (1925) formula to compensate for the natural mortality of the control (Treatment 1). These corrected mortalities, which purport to indicate the influence of only extremes of temperature on mortality, are also given in Table 4.4 (2). They ranged from 44.2 in Treatment 4 up to 60.8 in Treatment 3; and those in treatments 3 and 4 were not significantly different from the expected percentage dead from Abdelrahman (1974). However, the mortality in Treatment 2 was significantly higher than that expected.

Table 4.4 (2). Experiment 1. The observed and expected percentage dead of 1st instar red scales. [Observ.: observed total dead; Cor.: corrected dead by Abbott's (1925) formula for mortality in the control, Treatment 1; Expe.: expected dead from Abdelrahman (1974) regression equations].

Treatment	Initial no. of scales	% dead of red scale			Exposure time in days (X)
		Observ.	Cor.(Y)	Expe.	
1: shaded	70	50.0	0	0	0
2: exposed for one day	57	73.7	47.4	24.7	1
3: exposed for two days	97	80.4	60.8	58.7	2
4: unshaded	104	72.1	44.2	58.7	2

* Abbott's formula: $P = C + P' \times (100-C)/100$

where P : total % dead in the treatment.

C : % dead in the control.

P': % dead due to the treatmental factor.

The generation mortality of insects in the various treatments was also of interest because sometimes the harm that has been done by extremes of temperatures cannot be detected until much later in the life cycle (Andrewartha and Birch 1954). The numbers of insects in the different stages at each sampling date are given in Appendix Tables 4.4 (1) to 4.4 (4). It was assumed that by the last sampling date (4 August) all the stages of scales other than adult scales were dead, so that the number of adults (male and female) then present was the total number that had survived in the generation. It was also clear from the photographs, however, that 2 adult female scales had been lost from Treatment 1 [see Appendix Table 4.4 (1)]. The numbers of adult female scales that survived in each treatment are given in Table 4.4 (3). Similarly it was possible, from the photographs, to determine when a particular scale had survived to become an adult male; and similarly again, on 4 August, a few numbers of such scales were still on the fruits but a large number of scales had been lost earlier [Appendix Tables 4.4 (1)-4.4 (4)]. The numbers of adult male scales that survived in each treatment are also given in Table 4.4 (3).

Also given in Table 4.4 (3) are (1) the initial numbers of scales (white-caps) in each treatment, (2) the numbers of scales that were dead or were lost from the fruits before becoming adults and (3) the percentage mortality, which is the generation mortality.

Between Treatments 1 and 2, a chi-square test was conducted on the assumption of no difference on the dead of red scale [Tab.4.3 (3)] between the treatments; a chi-square value of 8.439 (d.f.=1, $P<0.01$) indicated that the mortality of scales in Treatment 2, which had been exposed to the sun for one day as 1st instars, was significantly higher than that of the control (Treatment 1). In other words, the percentage mortality in Treatment 2 was significantly higher than that of the control. Similarly, the percentage mortality of Treatments 3 and 4 were significantly greater than that of the control; but the percentage mortalities in Treatments 2, 3 and 4 were not different from each other.

Finally, the percentage of scale insects which survived to became adult females in each treatment is again given in Table 4.4 (3). The analysis of such generation survival percentages is always difficult because the percentages are always small and the differences between treatments will not be significant unless very large initial numbers of insects are used. The differences between treatments are then more usefully interpreted in terms of the population trend index

Table 4.4 (3). Experiment 1. Numbers, survival and dead, and percentage generation mortalities of red scales. Also given is the value of chi-square test on the null hypothesis of no difference in dead numbers of red scales between Treatments 1 and 2.

Treatment	Init.* number	Alive number:			Dead number	% rate:	
		Female	Male	Total		Dead	Female
1:shaded	70	10	22	32	38	54.3	14.3
2: exposed for one day	57	4	8	12	45	78.9	7.0
3: exposed for two days	97	3	9	12	85	87.6	3.1
4: unshaded	104	4	14	18	86	82.7	3.8

(1). *: initial total numbers.

(2). For comparison of dead numbers of red scales between treatments 1 and 2:

chi-square = 8.439 (d.f.=1, $P<0.01$)

(Harcourt 1969, Southwood 1978). The mean fecundity of red scale is approximately 100, and the overall sex ratio of the survivors was 21 females : 53 males, or 28% of females. So, a survival rate of 1 female out of 28, or 3.57% is required to maintain equal numbers in the next generation. The population trend index for the various treatments can therefore be roughly estimated as:

Treatment 1: 14.3/3.57=4.01
Treatment 2: 7.0/3.57=1.96
Treatment 3: 3.1/3.57=0.87
Treatment 4: 3.8/3.57=1.06

These figures suggest that the first hot day, on 26/2/1983, reduced the population trend index from 4.01 to 1.96 in Treatment 2, and the second hot day on 27/2/1983 further reduced the population trend index in Treatments 3 and 4 from 4.01 to 0.87 and 1.06 (mean of 0.965) respectively. The data suggest therefore that (a) each of the hot days reduced the population trend index by a factor of 0.5, and (b) the two hot days in a row caused the scale population to remain at about the same numbers rather than increasing by a factor of 4.0. An exploration to the mortality caused by 3 or more hot days in a row should not be made from the data in this experiment but obviously 3 or more hot days either in a row, or during the life of an immature scale, could have an even greater depressive influence on the population trend index.

4.4.2. Experiment 2: Mortality on lemons in the sun but off the tree

In experiment 1, the measurements of the influence of extreme temperatures in the sun on mortalities of scale insects were carried out on oranges on the tree. However, such an experiment is difficult to conduct and mortality due to other causes is difficult to separate from that caused by high temperature in the sun. The experiment would be much easier to conduct and to interpret if it could be done on fruit away from the tree. So the following experiment was conducted, with fruits off the tree, to determine if similar results could be obtained as in the previous experiment.

4.4.2.1. Methods and materials

There were only two treatments, namely insects on lemons in the shade (treatment 1) and insects on lemons in the sunlight (treatment 2). About 50 1st instar red scale were started on each of 8 waxed lemons by the brush-method (see Chapter 3). The lemons were then kept at 25°C and 60% R.H. for three days before treatment. They were then aged about 39 day-degrees >12°C.

At 10:00 a.m. on 15/2/1985 all 8 lemons were placed on the ground in the shade in the orchard of the Waite Institute. 4 of them (treatment 2) were exposed to the sun for 1.5 hours, from 2:00 p.m. to 3:30 p.m. and then were shaded again until 5:00 p.m. Both groups of lemons were then taken back into the insectary and kept at 25°C and 60% R.H. till the surviving scale insects of the control (treatment 1) had reached the 2nd moult instar. The death of each insect was then assessed by turning it over under the microscope (x25 magnification).

The under-skin temperature (see Chapter 2), about 5mm under the skin of a lemon, was recorded with a thermocouple once every 15 minutes for lemons in the sun.

4.4.2.2. Results and discussion

The air (ambient) and under-skin temperatures are shown in Appendix Table 4.4 (5). The former ranged from 31.4 to 34.6°C, and the latter from 39.1 to 47.3°C. The extreme high of 47.3°C was similar to that recorded in experiment 1.

The initial numbers and observed percentage mortalities of red scales in both treatments are given in Table 4.4 (4). Also given in this table is the expected percentage mortality of 1st instar red scales from Abdelrahman's (1974) regression. The observed mortality of scales in Treatment 2 was corrected by Abbott's (1925) formula for natural mortality in the control (Treatment 1); and is also given in Table 4.4 (4). The expected mortality of the scales due to the extreme of 47.3°C was 29.2% and was obviously much lower than that corrected (100%). So, I suggest two main possibilities causing the difference in mortalities of scale insects between expected and corrected:

(1) Duration of the extreme temperature. The duration of extreme temperatures has been shown to be an important factor causing high mortalities in scale insects (see Section 4.3). In my experiment the

Table 4.4 (4). Experiment 2. Observed, corrected and expected percentage mortatliy of 1st instar red scales.

Treatment	Total no. of scale	% mortalities of red scale:		
		Observed	Corrected*	Expected**
1:shaded from the sun	220	17.27		0
2:exposed to the sun	231	100.00	100.00	29.2

*: by Abbott's (1925) formula.

**: by Abdelrahman's (1974) regression equation.

duration of temperatures between 45 and 48°C accumulated a total of about 1.3 hours. By contrast, it seems that the duration of the extreme temperatures in Abdelrahman's experiments would not be longer than several minutes. As a result, a much higher death rate was observed in my experiment.

(2) Comparing the results of Experiment 1 in Section 4.4.1 which was run at a similar high temperature (47.0°C on 26/2/1983 and 47.3°C on 15/2/1985), the corrected percentage mortality, by Abbott's (1925) formula, in Treatment 2, in which scales were exposed to the sun for one day, was 47.4% [Tab.4.4 (2)] and was much lower than the 100.0% recorded in this later experiment. I believe that the physical variation of host fruits, "on" or "off" the tree, might be the main cause which strongly increased the mortality of scale insects in the sun.

4.5. Mortality of Cohorts of Red Scale Responding to Low Temperature

4.5.1. Introduction

This experiment was conducted to assess whether or not the mortality of red scales in relation to extremes of low temperature in the field could be predicted by the regression equation from Abdelrahman (1974).

4.5.2. Methods and Materials

The experiment was run at Loxton (South Australia) during the period 11-19/8/1983. It had only two treatments, namely, (1) insects exposed to low temperatures, and (2) insects not exposed to low temperature (control).

For treatment 2, the scale insects on host lemons were maintained in an insectary room under a natural fluctuation of temperature to measure the natural mortality of scales.

For treatment 1, red scales on host lemons were placed on the ground under the canopy of a tree, about 50 meters away from this insectary. The lemons were covered by a plastic sheet, about 25cm height, to keep the rain off.

Culture of the experimental red scales: Experimental red scales were cultured on waxed-lemons (see Chapter 3). Big but unripe lemons were used in this experiment. Crawlers of red scale for experimental cohorts were transferred to the experimental area of each host lemon by the brush method from prior infested butternut pumpkins of a mass culture at 25°C and 60%

R.H. (see Chapter 3). After the transferred crawlers had settled down, the host lemons were then maintained in an insectary room at 25±1°C and 60% R.H. to let the scales grow to the so-called "young stage" of each required instar. For instance, a total of about 130 day-degrees >12°C (Atkinson 1977) was required for the completion of development of 1st instar red scale; this instar comprises the growing and the moult stage. So, for the growing stage of 1st instar, it was considered as about 65 day-degrees >12°C; the so-called "young stage" was then considered as about 20 day-degrees old, about one third of the total required day-degrees for full development of the growing stage. Similarly, later instars were taken to about 1/3 development.

Measuring temperatures: In the orchard the ambient temperature was recorded from a shaded thermocouple 15 cm above the ground. Skin-temperature (see Chapter 2) was also recorded. Temperatures in the insectary room were recorded by a thermohydrograph.

Acclimatization of scale insects: The influence of acclimatization on the mortality of red scale in the field is unknown. So, all the experimental scale insects were made to experience a short period of "acclimatization" before and after their experimental treatment. Each stage of red scale was maintained at temperatures fluctuating between 13 and 16°C for several days. The temperatures within this range were higher than the threshold temperature of development of 12°C for red scales (Atkinson 1977); but would neither accumulate too many day-degrees of development, above 12°C, to age the experimental scales beyond the instar required, nor affect the mortalities of the scale insects.

Recording the development of red scales: This experiment was run in an orchard in Loxton, 200 km north-east of Adelaide where the insects were prepared. So the scale insects were transported several times during the experimental period. Some dead scale covers may have been lost due to this kind of motion. To avoid this, the development of the cohorts was recorded by the photographic method (see Chapter 3). The first batch of pictures was taken before moving the scales to the Loxton laboratory. The second batch was taken 10 days after all lemons with scales had been taken back to the insectary room in Adelaide and kept at constant temperature. The period of 10 days was believed to be sufficiently long enough for each

stage of red scale to complete its own development cycle and to get beyond the stage which had been treated. Hence, by a comparison of these two batches of pictures (see Section 4.2 for method), the influence of extreme temperatures on the mortalities of scale insects could be estimated. Scale insects which were still in the treated stage 10 days after they had been returned to the insectary at 27±1°C were considered as dead.

4.5.3. Results and discussion

Observed total number of scales and the numbers and percentage rates of dead scales in each stage are given in Table 4.5 (1). The temperatures in the field and in the insectary are given in Appendix Table 4.5 (1) and (2) respectively. In the insectary only the ambient temperatures were recorded. In the field the ambient temperatures were nearly the same as the above-skin temperatures, so only ambient temperatures in the field are given in Appendix Table 4.5 (1).

In the field, during the experimental period of 11-19/8/1983, the lowest temperature was +1.5°C (on the 8th day, 18/8/1983) [App.Tab.4.5 (1)] and it was +10.5°C (also on 18/8/1983) in the insectary room [App.Tab.4.5 (2)]. These two values were established as the extremely low temperature for scale insects in this experiment. The expected percentage mortalities of each stage of scales insects due to a low of 1.5°C were calculated by use of Abdelrahman's equations (1974) and are also given in Table 4.5 (1).

The actual percentage dead was corrected by use of Abbott's (1925) formula. Both the observed and the expected dead in each stage are given in Table 4.5 (1). As shown in this table, differences between observed and expected mortalities could be put into two categories: young stages and mature stages. The former involved 1st instar, 1st moult instar and 2nd instar; the latter involved 3rd and pre-reproducing adult stage. Obviously, the differences were not significant in the young stages. By contrast, the mature stages showed a significant difference between the observed and the expected mortality.

The differences in mature stages may have been caused by (1) the different ranges of experimental temperatures which were used, and (2) the influence of acclimatization for the experimental scale insects. In my experiment, in the field, the temperatures ranged from +1.5 to +24.0°C; by contrast, a bigger range was used in Abdelrahman's experiments (-5 to +25°C). Due to the smaller temperature range and the acclimatization method used, mature stages of scales could possibly present a higher

Table 4.5 (1). Percentage dead, observed and expected, of each stage of red scale responding to extremes of low temperatures.

Stage	Treatment	Total no. of scales	% dead rate of scales: observed	expected.
1st	1:control	150	56.0	4.7
	2:field	116	64.7	22.1
	**Corrected % dead		19.8	18.3
1st moult	1:control	238	40.3	1.9
	2:field	229	95.2	99.5
	**Corrected % dead		92.0	99.5
2nd	1:control	284	16.2	2.1
	2:field	156	25.0	19.4
	**Corrected % dead		10.5	17.7
3rd	1:control	51	0	10.1
	2:field	44	0	26.8
	**Corrected % dead		0	18.6
P.R.*	1:control	56	0	10.3
	2:field	36	0	31.0
	Corrected % dead		0	23.1

*: pre-reproduction female adult scales.

**: by use of Abbott's (1925) formula.

tolerance to the tested low temperature of +1.5°C. Besides, the influence of the duration of an extreme temperature (see Section 4.3) was not taken into account in Abdelrahman's concept. So I believe Abdelrahman's (1974) regression equations could give some information for a prediction in percentage dead of red scale responding to extreme low temperatures but not much, especially on mature stages of scale insects. Since the influence of acclimatization were seemly revealed in my experiments in Section 4.3, to expect a better result on the prediction of a mortality of red scale due to extreme of low temperatures, one should consider the positive influence of acclimatization on the reduction of mortality of red scale.

REFERENCES

Abbott, W. S. (1925). A method of computing the effectiveness of an insecticide. J. Econ. Entom., 18:265-267.

Abedelrahman, I. (1974). The effect of extreme temperatures on California red scale, Aonidiella aurantii (Mask.) (Hemiptera:Diaspididae), and its natural enemies. Aust. J. Zool., 22:203-212.

Andrewartha, H. G. and Birch, L. C. (1954). The distribution and abundance of animals. Univ. Chicago Press, Chicago, 782 pp.

Atkinson, P. R. (1977). Preliminary analysis of a field population of citrus red scale, Aonidiella aurantii (Mask.), and the measurement and expression of stage duration and reproduction for life tables. Bull. Entom. Res., 67:65-87.

Atkinson, P. R. (1983a). Estimates of natural mortality related to environmental factors in a population of citrus red scale, Aonidiella aurantii (Hemiptera:Homoptera:Diaspididae). Bull. Entom. Res., 73:239-258.

Atkinson, P. R. (1983b). Environmental factors associated with fluctuation in the numbers of natural enemies of a population of citrus scale, Aonidiella aurantii (Hemiptera:Homoptera:Diaspididae). Bull. Entom. Res., 73:417-426.

Catling, H. D. (1971a). Biological control of red scale are we exploiting this approach sufficiently ? in "The S. A. Citrus Journal, June, 1971:5-9".

Catling, H. D. (1971b). Studies on the citrus red scale, Aonidiella aurantii (Mask.) and its biological control in Swaziland. J. Entom. Soc. So. Afr., 34:393-411.

DeBach, P. (1958). The role of weather and entomophagous species in the natural control of insect populations. J. Econ. Entom., 51:474-484.

DeBach, P. (1965). Weather and the success of parasites in population regulation. Canad. Entom., 97:848-863.

DeBach, P., Hendrickson, R. M. and Rose, M. (1978). Competitive displacement: Extinction of the yellow scale, Aonidiella citrina (Coq.) (Homoptera:Diaspididae), by its ecological homologue, the California red scale, A. aurantii (Mask.) in Southern California. Hilgardia, 46:1-35.

DeBach, P., Rosen, D. and Kennett, C. E. (1971). Biological control of coccids by introduced natural enemies. in C. B. Huffaker (ed.), "Biological Control", Plenum Press, N. Y., pp. 165-194.

Deevey, E. S., Jr. (1947). Life tables for natural populations of animals. Quart. Rev. Biol., 22:283-314.

Habib, A., Salama, H. S. and Amin, A. H. (1972). Population of Aonidiella aurantii on citrus varieties in relation to their physical and chemical characteristics. Ent. exp. & appl., 15 (1972):324-438. N. Holl. Uitg. Mij. Amsterdam.

Harcourt, D. G. (1969). The development and use of life table in the study of natural insect populations. Ann. Rev. Entom., 14:175-196.

Maelzer, D. A. (1976). A photographic method and a ranking procedure of estimating numbers of the rose aphid Macrosiphum rosae (L,) on rose buds. Aust. J. Ecol., 1:89-96.

Martin, B. H. and Black, R. F. (1960). Heat treatment of citrus for control of red scale. Aust. J. Agric. Res., 11:197-207.

McLaren, I. W. (1971). A comparison of the population growth potential in California red scale, Aonidiella aurantii (Mask.), and yellow scale, A. Citrina (Coq.), on citrus. Aust. J. Zool., 19:189-204.

McLaren, I. W. (1978). Biological control of citrus scale pest. Proc. Int. Soc. Citriculture., 1978:147-149.

McLaren, I. W. and Buchana, G. A. (1973). Parasitism by Aphytis chrysomphali Mercet and A. melinus DeBach of California red scale, Aonidiella aurantii (Mask.), in relation to seasonal availability of suitable stages of the scale. Aust. J. Zool., 21:111-117.

Munger, F. (1948). Body-temperature measurements of the California red scale. J. Econ. Entom., 41:422-423.

Munger, F. and Cressman, A. W. (1948). Effect of constant and fluctuation temperatures on the rate of development of California red scale. J. Econ. Entom., 41:424-427.

Pearl, R. and Parker, S. L. (1921). Experimental studies on the duration of life. I. Introductory discussion of the duration of life in Drosophila. Amer. Natur., 55:481-509.

Price, P. W. (1975). Reproductive strategies of parasitoids. in P. W. Price (ed.), "Evolutionary Strategies Of Parasitic Insects And Mites", Plenum, N. Y., pp.87-111.

Slobodkin, L. B. (1962). Energy in animal ecology. Adv. Ecol. Res., 1:69-101.

Southwood, T. R. S. (1978). Ecological methods with particular reference to the study of insect populations, (2nd ed.). The English Language Book Society & Chapman and Hall, 524 pp.

Tashiro, H. (1966). Improved laboratory techniques for rearing California red scale on lemons. J. Econ. Entom., 59:604-608.

Tachiro, H. and Beavers, J. B. (1968). Growth and development of the California red scale, Aonidiella aurantii. Ann. Entom. Soc. Amer., 61:1009-1014.

Ward, K. M. and Jonston, C. J. R. (1937). Citrus red scale, progress report on investigations, 1935-36, J. Dep. Agric. Vict., 35:397-416.

Willard, J. R. (1972). Studies on rates of development and reproduction of California red scale, Aonidiella aurantii (Mask.) (Homoptera: Diaspididae). Aust. J. Zool., 20:37-47.

Willard, J. R. (1973). Survival of crawlers of California red scale, Aonidiella aurantii (Mask.) (Homoptera:Diaspididae). Aust. J. Zool., 21:567-573.

Willard. J. R. (1976). Leaf disk method for rearing California red scale, Aonidiella aurantii (Mask.) (Homoptera:Diaspididae). J. Aust. Entom. Soc., 15:7-11.

CHAPTER 5.

BIOLOGY AND ECOLOGY OF *Aphytis melinus* DeBach

CHAPTER 5. BIOLOGY AND ECOLOGY OF *Aphytis melinus* DeBach

5.1. Host-Feeding of Female Adult of *A. Melinus*

Marchal (1909) was the first to notice the host-feeding habit of *Aphytis* adults. Soon, some reports of similar observations were given by Quayle (1910) and Imms (1916). Later, Flanders (1951) pointed out that a culture of Hymenopterous parasites may cause the "mutilation" of scales by feeding to obtain the material needed for the development of their eggs. He suggested that the influence of host-feeding by *Aphytis* adults was so effective as to destroy an entire culture of host and parasite, if the parental parasite population had been excessive in relation to the available host population. He said that each adult during its life was capable of thus destroying 40 or more scales assuming the wasps had access to honey.

DeBach, Fleschner and Dietrick (1953) described the host-feeding of *A. chrysomphali* as follows. The parasite forms a feeding tube by mean of a waxy secretion which hardens around the site pierced by the ovipositor. The body liquid of the scale is sucked out through this tube by the adult parasite. DeBach *et al*. (ibid) and Debach and White (1960) also thought that host-feeding by *Aphytis* spp. adults was necessary for oviposition, and that "host-feeding" caused more mortality in scales than that caused by actual parasitization. Host-feeding of *Aphytis* spp. has subsequently been considered an important cause of mortality of red scale (DeBach, Fleschner and Dietrich, 1953; DeBach and White, 1960; DeBach and Sundby, 1963).

The mutilation of red scale by *Aphytis* wasps was first quantified by Abdelrahman (1974b). In his experiments the wasps were provided with honey as food and each wasp killed an average of four 3rd instar red scales daily, two by oviposition and two by host-feeding. Abdelrahman (ibid) ranked the scale stages on the mutilation due to wasps' host-feeding as: 1st moult (most mutilated), 2nd instar, 1st instar, 3rd instar, male pupa in order; 2nd moult, pre-adult, producing-adult stage were unmutilated. By comparison, later, Rosen and DeBach (1979), in "Species Of *Aphytis* Of The World", presented a similar concept. They believed the first instar and the first moult stage of red scale are not acceptable for oviposition but readily utilized for "host-feeding" by female wasps of *Aphytis* spp. Insects of 2nd and 3rd instar are acceptable for both oviposition and host-feeding.

However, nobody has studied the mortality caused by oviposition and host-feeding of adult A. melinus in the absence of a honey source, which is more likely to be relevant to the ecology of red scale in the main citrus producing areas of S. Australia where nectar or honey dew are unlikely to be available for most of the year (D.A.Maelzer, pers. commun.).

Accordingly, my experiments were designed to determine: (a) whether the "host-feeding" habit of Aphytis was sufficient by itself to increase the fecundity of females of A. melinus, and (b) to measure the mortality of red scale that then occurred. The experiments comprised two parts, namely,

Part 1: Laboratory experiments, in which artificially started cohorts of red scale were offered to A. melinus adult females.

Part 2: Field experiments, in which adult females of A. melinus had access to selected red scales from the natural population.

5.1.1. Experiments and results

Part 1. Laboratory experiments

General methods

Three experiments were run in a constant temperature room at 25±1°C, 60% R.H. and a photoperiod of L:D=14:10 hours. Each experiment comprised 2 replications of each of the same 3 treatments, which were:

1: control, with scale insects only.
2: in each of the 2 replications, 15 female wasps were caged with scale insects on the lemon; wasps were not provided with honey.
3: in each of the 2 replications, 15 female wasps were caged with scale insects on the lemon; honey was placed on the skin of each lemon for the wasps as food.

The first experiment was conducted with 1st instar scales only; the second with 3rd instar scales only; the third with a mixture of 1st, 2nd and 3rd instars scales.

For each experiment, cohorts of red scales were started on waxed lemons by the "brush" method (see Chapter 3). They were then placed in an insectary room at 27±1°C and 60% R.H. till the required experimental stages. Both experimental scale insects and parasitoid wasps were caged on each of host lemons by a "fruit-cage" (see Chapter 3) with a bottom diameter of 5.5cm.

One-day-old female wasps of A. melinus were sucked up in "collection tubes" from the mass culture (see Chapter 3). Before being introduced to the treatments, they were first allowed to mate in the tubes for 1-2 hours, but were not provided with food (honey).

Each experiment was allowed to run until all the wasps in treatment 2 (no honey) had died. All the wasps in treatment 3 were then removed.

The mortality of red scales was assessed five days after all the fruits had been freed of wasps, by turning over each scale insect and examining it under a x25 magnification microscope.

Experiment 1: With 1st instar red scales

Results

The numbers of dead and live red scales in each treatment are given in Table 5.1 (1). This Table also shows the numbers of dead and live scales expected in Treatments 1 and 2 on the null hypothesis of no differences between treatments.

The mortality of red scale ranged from 11.9% in the control to nearly 100% in treatment 3 in which the wasps had access to honey. Treatment 3 was obviously different to the other 2 treatments and a chi-square test on the first two treatments gave a value of 44.53 (d.f.=1, $P<0.0025$) indicating that the wasps caused a significantly higher mortality of scales than occurred in the control; and clearly the wasps caused an even higher mortality when they had access to honey in treatment 3.

The mortality of wasps which were not provided with honey, in treatment 2, is shown in Table 5.1 (2). The survival time of wasps ranged from 1 to 3 days, with a mean of 1.7 ± 0.1 days. By contrast, none of the wasps was dead at the end of day 3 in treatment 3 in which honey was provided.

Mortality (%) due to wasps' host-feeding in the treatments was corrected by Abbott's (1925) formula:

$$P = Pc + Pt \times (100-Pc)/100$$

So: $$Pt = (P-Pc)/[(100-Pc)/100]$$

where,

P : total observed mortality in the treatment.

Pc : mortality in the control.

Pt : mortality due to the treatmental factor in the treatment.

Table 5.1 (1). Experiment 1. Observed numbers, alive and dead, and percentage dead of 1st instar red scales. Also given are the expected numbers in Treatments 1 and 2 on the assumption that there was no difference between them.

Treatment	Obsserved no.:			%	Expected no.:	
	Alive	Dead	Total	Dead	Alive	Dead
1: Control:						
rep.1	166	23	189			
rep.2	204	27	231			
total	370	50	420	11.90	327	93
2: Wasps + no honey:						
rep.1	224	102	326			
rep.2	173	66	239			
total	397	168	565	29.73	440	125
3: Wasps + honey:						
rep.1	4	179	183			
rep.2	2	278	280			
total	6	457	463	98.70		

To test the difference between Treatments 1 and 2:
chi-square = 44.53 (d.f.=1, $P<0.0025$)

Table 5.1 (2). Experiment 1. Numbers of wasps of *A. melinus* which died each day in Treatment 2 in which the wasps were not provided with honey as food.

Day	Numbers of dead wasps
0	0
1	14
2	12
3	4
Total	30

LD50 = 1.7 $\pm$ 0.1 days

And the daily consumption of red scale by wasps' host-feeding was calculated in each of treatments 2 and 3 as:

$$= \frac{\text{Corrected number of dead scales}}{\text{Numbers of wasps x Mean life time of wasps}}$$

However, the corrected mortalities caused by host-feeding are given in Table 5.1 (3). The "mean life time" of wasps in treatment 2 was 1.7 days; in treatment 3 it was considered as 3 days [Tab.5.1 (2)]. So, the mean consumptions of scales due to host-feeding per wasp per day was 2.24 in treatment 2 and 5.07 in treatment 3 [Tab.5.1 (3)]. These mean rates were not significantly different ($t=2.52$, d.f.=2, $P>0.05$).

So the data suggest that the wasps killed scales at the same rate per day, whether they did or did not have access to honey. However, those with access to honey lived longer and consequently killed a larger number of scales

Experiment 2: With 3rd instar red scales

This experiment was conducted to determine the influence of host-feeding on both mortality and parasitism of red scales, and also on the survival of the wasps themselves.

Results

Mortality of red scale in each treatment is shown in Table 5.1 (4). The observed percentage of dead scales ranged from 4.18 in the control (with scale only) up to 33.61 in treatment 3, in which wasps were provided with honey as food. Using Abbott's (1925) formula, the corrected death rates were 5.53% for wasps with no honey in treatment 2 and 30.71% for wasps with honey in treatment 3 [also Tab.5.1 (4)]. These rates are obviously significantly different.

The difference between treatments 1 and 2 was also tested. The number of dead scales expected on the null hypothesis are given in Table 5.1 (5). The chi-square value of 6.66 (d.f.=1, $P<0.01$) indicated that host-feeding of the wasps that were not supplied with honey caused a death rate of scales greater than the natural mortality.

Also given in Table 5.1 (4) are the percentage rates of parasitization of red scales. A much higher parasitization rate of 23.24% was caused by

Table 5.1 (3). Experiment 1. Consumption of scales due to host-feeding of A. melinus per wasp per day in Treatments 2 and 3, with two replications (rep.) for each treatment. The "corrected dead" were corrected by Abbott's (1925) formula for mortality in the control (Treatment 1).

Treatment	% rate of dead		Dead scales due to host-feeding	Consumption: scale no./per wasp per day
	Observed	Corrected		
1:control	11.90			
2:wasps + no honey:	29.73	20.24		
rep.1			66	2.59
rep.2			48	1.88
mean				2.24
3:wasps + honey:	98.70	98.52		
rep.1			180	4.00
rep.2			276	6.13
mean				5.07

Cmparison of means of Treatments 2 and 3:

$t = 2.52$ (d.f.=2, $P>0.05$)

Table 5.1 (4). Experiment 2. Numbers, total (live + D. + Para.), dead (D.) and parasitized (Para.), and percentage rates of the dead and parasitized 3rd instar red scale in each treatment, with two replications (rep.). The "corrected" dead were corrected by Abbott's (1925) formula for mortality in the control (Treatment 1).

Treatment	Number of scale			% rate of:			Corrected:	
	Total	D.	Para.	D.	Para.	Total	% D.	No.D.
1:control:								
rep.1	127	3	0					
rep.2	112	7	0					
total	239	10	0	4.18	0	4.18	4.18	
corrected				4.18	0	4.18		
2:wasps + no honey:								
rep.1	163	12	7					9
rep.2	185	21	10					10
total	348	33	17	9.48	4.89	14.37	5.53	19
corrected				5.53	4.89	10.42		
3: wasps + honey:								
rep.1	140	32	25					43
rep.2	101	49	31					31
total	241	81	56	33.61	23.24	56.85	30.71	74
corrected				30.71	23.24	53.95		

Table 5.1 (5). Experiments. The chi-square test on the null hypothesis that there was no difference in dead numbers of 3rd instar red scales betwee treatments 1 and 2.

Treatment	Numbers of red scales		
	Alive	Dead	Total
1: scales only	229	10	239
2: scales + wasps	298	33	331
total	527	43	570

chi-square value = 6.66 (d.f.=1, $P<0.01$)

wasps feeding on honey than that of 4.89% caused by wasps which had no access to honey. They were obviously different.

Again, the wasps did not live long in treatment 2 in the absence of honey and the numbers of wasps that died each day are given in Table 5.1 (6). The pattern of mortality was very similar to that of the wasps in experiment 1 [Table 5.1 (2)]; and a mean longevity of 1.8±0.1 days was calculated. By contrast, none of the wasps was dead at the end of day 4 in treatment 3 in which they had been provided with honey as food; again, as in experiment 1.

The daily consumptions of scales per wasp in each of treatments 2 and 3, for both death (due to host-feeding) and parasitization, were calculated as for Experiment 1 and are given as in Table 5.1 (7). When the wasps were not supplied with honey (treatment 2) the total mean consumption of scales per wasp per day was 0.67; within this, 0.35 scales dead due to host-feeding and 0.32 scales parasitized. And in treatment 3, the total mean was 1.09 scales; within this, 0.62 scales dead and 0.47 scales parasitized. A t-test was conducted to test each of the null hypotheses that these rates of death (due to host-feeding) and the parasitization of scales showed no difference between treatments. The value of $t=2.65$ ($d.f.=2$, $P>0.05$) indicated that there was no difference between the two means of dead scales due to host-feeding; another value of $t=2.01$ ($d.f.=2$, $P>0.05$) indicated there was no difference, again, between the two means of parasitized scales. So the significantly different total numbers of dead and of parasitized scales in Treatment 2 (no honey) and in treatment 3 (with honey) [Tab.5.1 (4)] were clearly due to the greater longevity of the wasps that had access to honey.

Experiment 3: With a mixture of 1st, 2nd and 3rd instar red scales

This experiment was conducted to determine whether female wasps of A. melinus would feed on and kill equal proportions of 1st, 2nd and 3rd instars red scales when they had access to a mixture of all three stages (see also: General methods).

Results

Numbers of live and the numbers and percentages of dead and parasitized of scales of each stage in each of the 3 treatments are given in Appendix Tables 5.1 (1)-5.1 (3); also given are the corrected numbers and percentage rates of dead scales responding to wasps' host-feeding (see methods shown in Experiment 1).

Table 5.1 (6). Experiment 2. Numbers of females wasps of A. melinus which died each day when they were not provided with honey as food in Treatment 2.

Day	Numbers dead
0	0
1	12
2	14
3	2
4	2
Total	30

LD50 = 1.8 ± 0.1 days

Table 5.1 (7). Experiment 2. Mean consumptions of red scales per female wasp of A. melinus per day in Treatments 2 and 3, two replications (rep.) for each treatment. Also given are values of t-test on the null hypothesis there was no difference between treatments.

Treatment	Mean consumption due to factor of:		
	Host-feeding	Parasitization	Total
2:wasps + no honey:			
rep.1	0.33	0.26	
rep.2	0.37	0.37	
mean	0.35	0.32	0.67
3:wasps + honey:			
rep.1	0.72	0.42	
rep.2	0.52	0.52	
mean	0.62	0.47	1.09
For comparison of means:			
t-value	2.65	2.02	
P (d.f.=2)	>0.05	>0.05	

Table 5.1 (8) to 5.1 (11) show:

In Table 5.1 (8) the "total dead" for each treatment, with "total dead" being the sum of those killed and parasitized over all instars. Percentage rates of in the three treatments ranged from 8.87% in the control to nearly 100% in treatment 3 in which wasps were provided with honey. The natural mortality, 8.87%, in the control was obviously lower than that due to host-feeding and oviposition of wasps in Treatments 2 and 3. And the wasps caused an obviously higher percentage rate of total dead (sum of dead and parasitization) over all stages of scales when they had access to honey (96.35), than when they were not provided with honey (37.59).

Similarly, the obviously higher percentage rate of dead over all stages of red scale due to host-feeding only was caused when the wasps were provided with honey (89.49) [App.Tab.5.1 (3a)], than when they had no access to honey (31.55) [App.Tab.5.1 (2a)]. Further analyses were carried out as follows.

The numbers of wasps which died each day in treatment 2 in which the wasps were not given access to any food except scales, are shown in Table 5.1 (9). The range of longevity was 1-4 days, with a mean of 1.6 ± 0.2 days, which was similar to those as 1.7 ± 0.1 days in Experiment 1 [Table 5.1 (2)] and 1.8 ± 0.1 days in Experiment 2 [Table 5.1 (6)]. Again, also similar to those in the above mentioned experiments, at the end of day 4, none of the wasps was dead when they were provided with honey as food (Treatment 3).

Using the same arithmetic as in Experiment 1, the daily consumptions of scales for both the dead due to the wasps' host-feeding and due to the parasitization in each stage of scales in treatments 2 and 3 were calculated from the data in Appendix Table 5.1 (2) and (3). The daily consumption of each stage of scales due to host-feeding of wasps in Treatments 2 and 3 are given in Table 5.1 (10). Two sorts of comparisons can be made between the means in Table 5.1 (10), namely (a) between treatments, for each stage of red scale separately, and (b) between stages of red scale within treatments. A t-test was conducted for each comparison of type (a); the values of t , given in Table 5.1 (10a), showed none of the t-tests was significant. A t-test was similarly used to test the difference between the mean of 3rd instar female scales and that of each of the other stages within each treatment. These values of t are given in Table 5.1 (10b); and clearly again indicate no differences between the means (of consumption of scales per wasp per day) for the different stages

Table 5.1 (8). Experiment 3. Numbers, live and total dead (dead + parasitized), and percentage total dead of red scale in each treatment, with two replications (rep.).

Treatment	Numbers of scales			% rate of total dead
	Alive	Total dead	Total	
1: Control:				
rep.1	331	35	366	
rep.2	316	28	344	
total	647	63	710	8.87
2: Wasps + no honey:				
rep.1	211	152	363	
rep.2	214	104	318	
total	425	256	681	37.59
3: Wasps + honey;				
rep.1	16	386	402	
rep.2	11	326	337	
total	27	712	739	96.35

Table 5.1 (9). Experiment 3. Numbers of wasps of *A. melinus* died each day in Treatment 2 in which wasps were not provided with honey as food.

Day	Numbers dead
0	0
1	17
2	10
3	1
4	2
Total	30

LD50 = 1.6 $\pm$ 0.2 days

Table 5.1 (10). Experimemt 3. Consumption numbers on each stage of red scales due to host-feeding per female wasp of A. melinus per day in Treatments 2 and 3, with two replications (rep.) for each treatment (obtained from App.Tabs.5.1 (2) and 5.1 (3)). Also given are the value of t-test for each null hypothesis of no difference between either the means of Treatments 2 and 3 or the means within each treatmetn.

Stage of red scale	Numbers of daily consumption of scales	
	In Treatment 2	In Treatment 3
1st:		
rep.1	0.46	1.78
rep.2	1.00	1.42
mean	0.73	1.60
2nd female:		
rep.1	0.54	1.55
rep.2	0.92	1.20
mean	0.73	1.38
3rd female:		
rep.1	3.04	1.25
rep.2	1.25	1.17
mean	2.15	1.21
2nd male:		
rep.1	0.62	1.43
rep.2	0.58	1.23
mean	0.60	1.33
Total:		
rep.1	4.66	6.01
rep.2	3.75	5.02
mean	4.21	5.52

Table 5.1 (10a). The t-value to test the difference between means of Treatments 2 and 3, for each stage of scale separately.

Stage of red scale	t-value	P (d.f.=2)
1st instar	2.68	>0.05
2nd female instar	2.52	>0.05
3rd female instar	1.05	>0.05
2nd male	1.64	>0.05
for Total	1.94	>0.05

Table 5.1 (10b). The t-value to test the difference between the mean of the 3rd instar scales and that of each of the other stages within each of Treatments 2 and 3 separately.

With stage	Within Treatment 2		Within Treatment 3	
	t-value	P(d.f=2)	t-value	P(d.f.=2)
1sr instat	1.52	>0.05	2.12	>0.05
2nd female	1.55	>0.05	0	>0.05
2nd male	1.73	>0.05	1.11	>0.05

of scale within each of Treatments 2 and 3. So although the consumption rate of 3rd instar females in treatment 2 was seemingly triple that of other stages of scales [Tab.5.1 (10)], the variability between the replicates was very high and made the difference between means non-significant.

As well as the measurement of wasps' host-feeding, it was of interest to assess the mean daily consumption of scales due to parasitization of wasps. This assessment was made by the formula below:

$$= \frac{\text{Numbers of parasitized scales}}{\text{numbers of wasps x mean life time of wasps}}$$

The "mean life time of wasps" was again taken to be 1.6 days in treatment 2 and to be 4 days in treatment 3.

The mean daily consumption of scales due to parasitization are given in Table 5.1 (11); they ranged from 0.21 scale per wasp per day up to 0.38 scale. The overall mean was 0.30 scales per wasp per day in treatment 2 and 0.38 in treatment 3. The t-test value of 0.94 (d.f.=2, $P>0.05$) indicated that these means were not different.

The total consumption of scales per wasp per day was the sum of those dead due to wasps' host-feeding plus those parasitized. They were 0.30(parasitized) +4.21(host-feeding) =4.51 scales in treatment 2 in which wasps with no honey; and 0.38+5.52=5.90 in treatment 3 in which wasps with honey as food. These totals were not considered significantly different from each other, because there was no difference between treatments either in those dead due to host-feeding or those parasitized.

Part 2. Field experiments

Between April and May 1985, field experiments were carried out on oranges on trees in the orchard of the Waite Institute. Experimental scales were selected from the natural population by removing the unwanted scales with the aid of a x25 magnification shouldered-microscope (see Chapter 3).

Table 5.1 (11). Experiment 3. Mean daily consumption of parasitization of red scale per wasp in Treatments 2 and 3, with two replications for each treatment. Also given is the value of t-test for the null hypothesis no difference between the means of the treatments.

	in Treatment 2	in Treatment 3
Replication 1	0.38	0.38
Replication 2	0.21	0.38
Mean	0.30	0.38

$t = 0.94$ (d.f.=2, $P>0.05$)

General methods

Three treatments were established as that in the laboratory experiments of Part 1; but different numbers of replicates and numbers of wasps per replicate were used. The treatments were as follows.

1: "Control", with red scales only; scales were caged on each of 2 oranges (replicates).
2: 5 female wasps of A. melinus with scale insects were caged on each of 4 oranges (replicates); wasps were not provided with honey.
3: 5 female wasps with scales were caged on each of 4 oranges (replicates); honey was provided to wasps as food and was placed on the surface of each fruit.

The wasps were caged (see Chapter 3 for cages) on oranges for 5 days. The oranges were then picked off the tree, and after being freed of wasps, they were placed in an insectary room at 25±1°C and 60% R.H. for another 5 days. After that, each of the scale insects was turned over and determined to be alive or dead under a x25 magnification microscope.

Experiment 4: With 1st instar scales

Results

Numbers of live scales and numbers and percentage rate of dead 1st instar red scales in each of the three treatments are given in Table 5.1 (12). Also given are the expected numbers, live and dead, of scales in treatments 2 and 3 on the null hypothesis of no difference between means of Treatments 2 and 3. As shown in this table, the observed percentage dead rates ranged from 8.80 of the control with scales only up to 65.56 of treatment 3 in which wasps were provided with honey as food. Obviously, significantly higher percentage dead rates were caused by wasps in treatments 2 and 3 than was in the control. A chi-square test was conducted to assess the above mentioned null hypothesis between treatments 2 and 3. The chi-square value of 22.86 (d.f.=1, $P<0.01$) indicated that wasps caused a significantly higher mortality of scales when they had access to honey as food.

Unfortunately, I did not record the numbers of wasps that died each day, so it was not possible to assess the daily consumption of scales by wasps.

Table 5.1 (12). Experiment 4. Observed numbers, alive and dead, and percent rate (dead only) of 1st instar red scales in each treatment. Also given are the expected numbers of alive and dead scales in Treatments 2 and 3 on the assumption that there was no difference betwee treatments.

Treatment	Observed numbers			%	Expected numbers	
	Alive	Dead	Total	Dead	Alive	Dead
1:Control:						
*rep.1	57	3	60			
rep.2	57	8	6			
total	114	11	125	8.80		
2:Wasps + no honey:						
rep.1	37	21	58			
rep.2	47	15	62			
rep.3	16	33	49			
rep.4	34	27	61			
total	134	96	230	41.74	110	120
3:Wasps + honey:						
rep.1	22	26	48			
rep.2	12	37	49			
rep.3	10	23	33			
rep.4	18	32	50			
total	62	118	180	65.56	86	94

(1). *rep. = replication.

(2). to test the difference between Treatments 2 and 3:

chi-square = 22.86 (d.f.=1, $P<0.01$)

Experiment 5: With 3rd instar red scales

Results

In this experiment the total dead numbers of scales was initially again taken to be the sum of dead plus parasitized. The numbers of live scales and the numbers and percentage rates of total dead scale insects are given in Table 5.1 (13); also given are the expected live and total dead numbers in treatments 2 and 3 on the null hypothesis of no differences between treatments. The percentage total dead (dead + parasitized) of red scales ranged from 44.97 in the control with scale only up to 91.27% in treatment 3 in which wasps were provided with honey as food. The percentage total dead in the control was significantly lower than those in Treatments 2 and 3. Subsequently, a chi-square test was used to assess the difference between treatments 2 and 3. The chi-square value of 16.65 (d.f.=1, $P<0.01$) indicated that wasps caused a significantly higher percentage total dead on scales when they had been provided with honey as food.

Further analyses were conducted to separately assess the differences due to parasitization and due to host-feeding in treatments 2 and 3.

(i) Testing influence of adult food on parasitization of red scales:

The numbers of live scales and numbers and percentage rate of parasitized scales are re-arranged and given in Table 5.1 (14). Also given are the expected numbers, alive and parasitized, of scales in treatments 2 and 3 on the null hypothesis of no difference between treatments. Some of the scales in this experiment had, of course, been parasitized before the experiment started, and this natural rate of parasitization was assessed by the rate of parasitism in the control treatment 1. None of the adult parasites from the naturally parasitized scales emerged during the course of the experiment. The parasitization of scales ranged from 16.96% in the control with scale only up to 74.03% in treatment 3 in which wasps were provided with honey as food. The parasitization rates in Treatments 2 and 3 were obviously higher than that of the "natural parasitization rate" in the control.

A chi-square test was conducted to assess the difference between Treatments 2 and 3. The chi-square value of 9.22 (d.f.=1, $P<0.01$) indicated that wasps caused a significantly higher parasitization of scales when they had access to honey.

Table 5.1 (13). Experiment 5. Observed numbers, alive and total dead (T.D.) (dead + parasitized) of 3rd instar red scales in each treatment. Also given are the expected numbers in Treatments 2 and 3 on the assumption of no difference between treatments.

Treatment	Observed numbers			%	Expected numbers	
	Alive	T.D.	Total	T.D.	Alive	T.D.
1: Control:						
*rep.1	44	37	81			
rep.2	49	39	88			
total	93	76	169	44.97		
2: Wasps + no honey:						
rep.1	15	37	52			
rep.2	9	67	76			
rep.3	16	39	55			
rep.4	13	39	52			
total	53	182	235	77.45	37	198
3: Wasps + honey:						
rep.1	5	67	72			
rep.2	5	52	54			
rep.3	4	46	50			
rep.4	6	44	50			
total	20	209	229	91.27	36	193

(1). *rep.=replication.
(2). To test the difference between Treatments 2 and 3:

chi-square = 16.65 (d.f.=1, $P<0.01$)

Table 5.1 (14). Experiment 5. Observed numbers, alive and parasitized (Para.), and percent parasitization of 3rd instar red scales in each treatment. Also given are the expected numbers in Treatments 2 and 3 on the assumption of no difference between treatments.

Treatment	Observed numbers			% Para.	Expected numbers	
	Alive	Para.	Total		Alive	Para.
1:control, no wasps:						
*rep.1	44	10	54			
rep.2	49	9	58			
total	93	19	112	16.96		
2:wasps + no honey						
rep.1	15	13	28			
rep.2	9	26	35			
rep.3	16	7	23			
rep.4	13	14	27			
total	53	60	113	53.10	43	70
3:wasps + honey						
rep.1	5	21	26			
rep.2	5	10	15			
rep.3	4	15	19			
rep.4	6	11	17			
total	20	57	77	74.03	30	47

(1). *rep. = replication.

(2). To test the difference between Treatments 2 and 3:

chi-square = 9.22 (d.f.=1, $P<0.01$)

(ii) Testing influence of food for adult wasps on the death rate of red scales due to host-feeding:

Again, numbers of live scales and numbers and percentage rates of dead scales in each treatment are re-arranged and given in Table 5.1 (15). Also given are the expected numbers, alive and dead, of scales in treatments 2 and 3 on the null hypothesis of no difference between treatments.

The percentage death rates of red scale in treatments 2 and 3 were obviously greater than that of the control (Treatment 1); and a chi-square value of 36.57 ($P<0.01$) indicated that the percentage death rate of scales in Treatment 3 was significantly higher than that in Treatment 2.

The corrected percent dead of red scales due to wasps' host-feeding only was then calculated (see Part 1) as:

(1) in Treatment 2, (wasps had no access to honey):
(69.71-38.00)x100/(100-38.00)=51.15(%)
(2) in Treatment 3, (wasps had access to honey):
(88.37-38.00)x100/(100-38.00)=81.24(%)

Obviously, the percentage death rates of scales due to wasps' host-feeding in treatments 2 and 3 were significantly different from each other.

Again, since I did not record the number of wasps which died each day, it was not possible to further assess the mean consumption of scales by wasps' host-feeding.

5.1.2. Discussion

The main conclusions from these experiments are that host-feeding of female wasps of *A. melinus* on red scales did not allow the wasps to live as long as those wasps which had access to honey as food; as a result, host-feeding had no (or very little) function in increasing the total eggs laid by wasps. So I suggest that intensive study is still needed on the biology of female wasps of *A. melinus* under conditions without a honey supply. From this kind of study, results could possibly be closer to the natural influence of wasps on a population regulation of red scale in orchards.

Table 5.1 (15). Experiment 5. Observed numbers, alive and dead, and percent dead of 3rd instar red scale in each treatment. Also given are the expected numbers in Treatments 2 and 3 on the assumption of no difference between treatments.

Treatment	Observed numbers			% Dead	Expercted numbers	
	Alive	Dead	Total		Alive	Dead
1:contol, no wasps:						
*rep.1	44	27	71			
rep.2	49	30	79			
total	93	57	150	38.00		
2:wasps + no honey						
rep.1	15	24	39			
rep.2	9	41	50			
rep.3	16	32	38			
rep.4	13	25	38			
total	53	122	175	69.71	58	117
3:wasps + honey						
rep.1	5	46	51			
rep.2	5	42	47			
rep.3	4	31	35			
rep.4	6	33	39			
total	20	152	172	88.37	57	115

(1). *rep. = replication.
(2). To test the difference between Treatments 2 and 3:

chi-square = 36.57 (d.f.=1, P<0,01)

5.2. Longevity of Female Adults of A. melinus

Extensive tests have been carried out in California and in S. Australia to determine the longevity of Aphytis adults at various constant temperatures. Most of the tests were run under 50% R.H. and in the absence of hosts, with honey provided as food for the parasitoids (Abdelrahman 1974a, Rosen and DeBach 1979). The observed longevity of A. melinus adults in relation to temperature is given in Table 5.2 (1). Based on these values Abdelrahman explained the biological control of red scale by Aphytis. On the other hand, people have also noted that the longevity of Aphytis is not always as long as expected (Flanders 1951; Rosen and DeBach 1979) and it seems that in most of the studies of the biology of Aphytis, honey is always provided to keep the Aphytis adults alive. However, in the field, without a supply of honey, wasps of Aphytis may not survive sufficiently long to do what has been expected of them in experiments.

Although the longevity of wasps supplied with honey may be regarded as some sort of potential longevity for this species, I do not believe that these figures can be used in a prediction of the searching efficiency of Aphytis under natural conditions.

In consequence, I believed that an intensive study on the longevity of A. melinus wasps under unfavourable conditions of food supply was still needed and my experiments were designed accordingly.

The experiments comprised both laboratory and field experiments. They were carried out with only female wasps of A. melinus and they were aimed to simulate conditions in winter and summer, at both of which times there may be a negligible supply of carbohydrate in the field for the adult wasps.

5.2.1. Part 1. Laboratory experiments: Longevity of A. melinus wasps on different foods at constant temperatures

Experiment 1: At 10°C

10°C occurs quite frequently in the winter in Adelaide, South Australia. In winter no flowers are present in orchards to produce nectar for wasps to eat and the honeydew on citrus trees is likely to be washed away by the winter rain. Under these conditions can wasps stay alive long enough to cause a high parasitization on the population of red scale? To answer this question in an indirect way, the following experiments were designed.

Table 5.2 (1). Mean longevity (days) of *Aphytis melinus* wasps at constant temperatures and 50–60% R.H. (after Rao and DeBach 1969; Abdelrahman 1974a).

Temperature (°C)	Mean longevity (days)	
	Rao and DeBach	Abdelrahman
4.4	3	–
10.0	84	–
15.6	104	–
20.0	–	54.1 (31–85)
21.1	53	–
25.0	–	29.8 (13–61)
26.7	20	–
30.0	–	18.0 (9–27)

Methods 48 one-day-old female wasps were sucked into collection tubes (see Chapter 3), 1 wasp per tube, and were placed in an incubator at 10±0.5°C and an artificial photoperiod of L:D=14:10 hours. The tubes were placed in a container with saturated solution of Nacl to maintain a constant humidity of about 75% R.H. (Winston and Bates 1960).

Results Survival time in days, the accumulated numbers of dead and percentage death rates are given in Appendix Table 5.2 (1). The percentage death rates of wasps are plotted against survival time (days) in Fig.5.2 (1). The mean longevity of wasps was established as 7.7±0.3 days which was significantly shorter than that of 84 days [Table 5.2 (1)] for wasps fed on honey. However, the accumulated percentage death rates (Y) plotted against survival time in days (X) gave a sigmoid curve which is well described by the function below:

$$Y = 103.882 / [\ 1 + \exp(5.500 - 0.739\ X)]$$

Experiment 2: At 30°C

30°C can be the maximum temperature in late summer in an orchard in South Australia. At that time, flowers are rarely present in any orchard to offer the nectar to wasps of *A. melinus* as food and if the citrus trees in this orchard are very "clean", with no other "honey-dew" insects producing food for the wasps, what will happen to the survival of *A. melinus*? Aiming at this question, the following experiment was conducted.

Methods The "Treatments" were the different foods provided to the wasps, as follows:

Treatment 1: Control, in which wasps were not provided with any food.

Treatment 2: In each collection tube, only water was provided to the wasp through the wick from a "water-tube" [Fig. 5.2 (2)].

Treatment 3: Honey, streaked on the wall of each collection tube, was provided to the wasps as food.

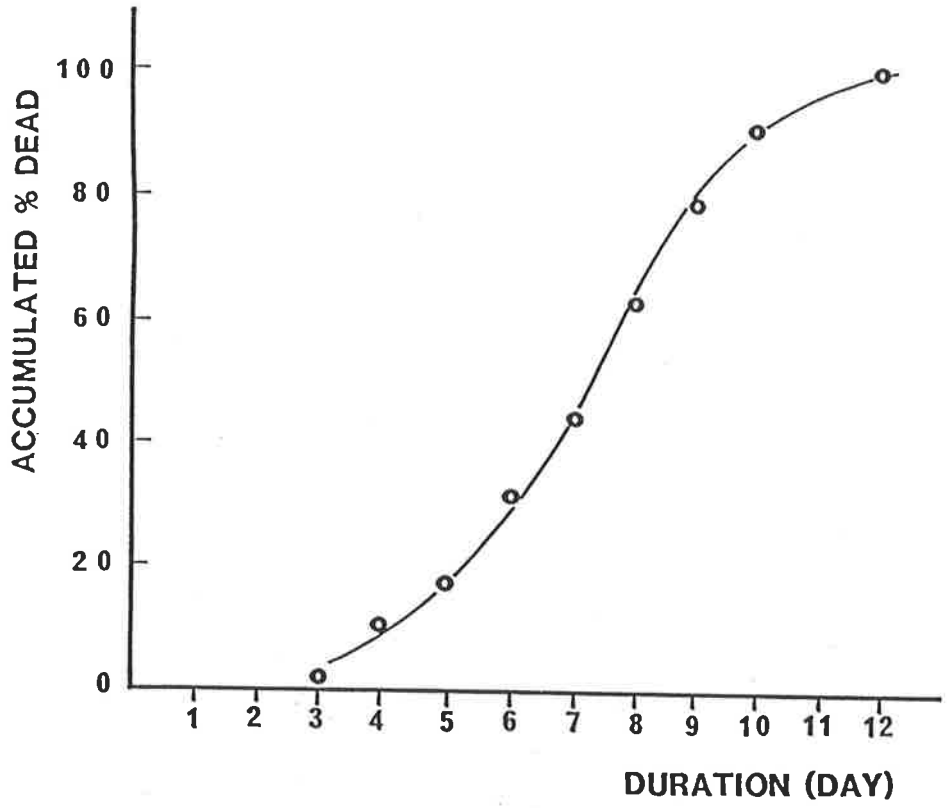


Figure 5.2 (1). Experiment 1. The relationship between the accumulated % dead rate (Y) of wasps of A. melinus and the survival duration of days (X) at 10±0.5°C, 75% R.H. and the artificial photoperiod of L:D = 14:10 hours. The regression equation is:

$$Y = 103.882 / [1 + \exp(5.500-0.739X)]$$

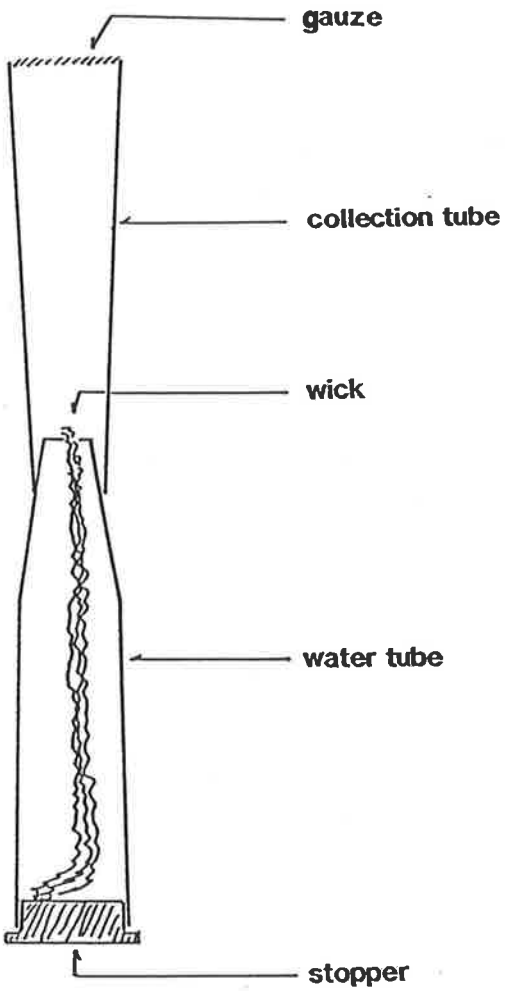


Figure 5.2 (2). Collection tube for wasps of A. melinus with a water supply tube.

37, one-day-old female wasps of A. melinus were used for each of the three treatments; they were sucked up into the collection tubes, one wasp each tube. The tubes with wasps were maintained in an insectary room at a constant temperature of 30±1°C and an artificial photoperiod of L:D=14:10 hours to simulate a natural condition in an orchard; no humidity control. During the experimental period, the humidity was about 40% R.H.

Results The survival time (days) and accumulated number of dead wasps in each treatment are given in Appendix Table 5.2 (2).

The accumulated percentage death rates of wasps in treatment 3 are also given in this table and are plotted against survival time (days) in Fig.5.2 (3). The relation between percentage death rate (Y) and survival time (X) is a sigmoidal curve but, for convenience, the data between 5% and 95% (from day 7 up to 19) were easily described by the linear regression equation as:

$$Y = -48.14 + 7.69\ X \quad (r=0.994,\ d.f.=7,\ P<0.01)$$

Again the mean longevity of wasps in Treatments 1 and 2 was about 1 day while in Treatment 3 (honey-fed) the mean longevity was about 13 days. However, the mean longevity in Treatment 3 was 13.7±0.6 days (range: 3-22 days) which was shorter than the mean of 18.0±0.5 (range: 9-27) days obtained by Abdelrahman (1974a) where wasps were fed on both honey and 3rd instar host red scales [Table 5.2 (1)]. This difference might be due to (i) differences of humidity (about 40% R.H. for the former and about 70% for the latter), and (ii) differences of food (absence of scales in the former but scales provided in the latter).

Experiment 3: Longevity of wasps at different constant temperature and constant 75% R.H.

Based on the results of the above two experiments, this experiment was designed to test the longevity of wasps of A. melinus at constant temperatures, which were considered as the optimum ones, with 75% R.H. respectively.

Methods There were 2 treatments at each of 6 temperatures (15.0, 17.5, 20.0, 22.5, 25.0 & 27.5°C): Treatment 1, honey provided; Treatment 2, no honey or water. For each treatment, 30 one-day-old female wasps were

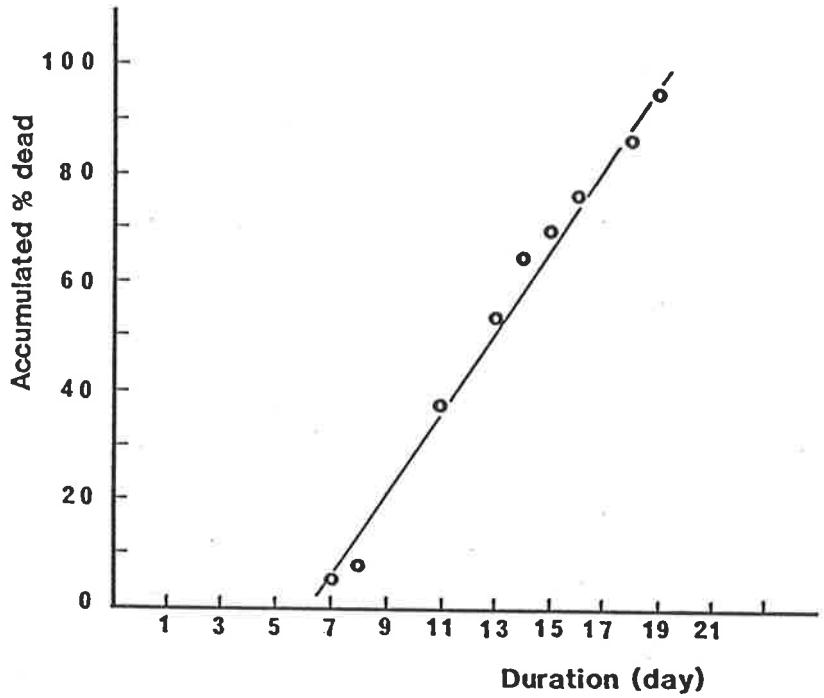


Figure 5.2 (3). Experiment 2. From Day 7 up to Day 19, the relationship between the accumulated % dead rates (Y) of wasps of A. melinus and the survival duration days (X) in Treatment 3 in which wasps were provided with honey as food at 30°C, an artificial photoperiod of L:D=14:10 hrs and a humidity of about 40% R.H.

$Y = (-48.14) + 7.69X$ ($r=0.994$, $d.f.=7$, $P<0.01$)

individually sucked up in collection tubes (see Chapter 3), one wasp each tube; tubes were kept in the "humidity boxes" (see section 3.3) using a saturated solution of NaCl to maintain a constant 75% R.H. 1 humidity-box was placed in each incubator with the photoperiod set to L:D=14:10 hours.

Results In Treatment 2, the accumulated numbers of dead wasps are given in Table 5.2 (2). The LD50 was as short as 1-2 days at temperatures between 17.5 and 27.5°C; but it was 5.9±0.4 (S.E.) days at 15°C. By contrast, at the time that the death of wasps in treatment 2 was assessed, the percentage death in treatment 1 was less than 5% at all temperatures.

The accumulated percentage death rates at 15°C [calculated from Table 5.2 (2)] are given in Appendix Table 5.2 (3) and are plotted in Fig.5.2 (4). In this figure, the relationship between the percentage rates and the survival duration days at 15°C was described by the linear regression equation as:

$$Y = -26.54 + 14.17\ X \quad (r=0.991,\ d.f.=5,\ P<0.01)$$

where, Y: % death rates; X: duration of days

and this equation was significant.

5.2.2. Part 2. Field experiments: Test of longevity of female adults of A. melinus on oranges on the tree

This experiment was conducted on female wasps in the Waite Institute orchard in the late autumn, 11/5/85 - 9/6/85. It involved the use of a microscope in the field to select the experimental red scales from the natural population on oranges on the tree and to observe daily the death of the wasps (see Section 3.3 for details of use of the "shoulderable-microscope").

Methods The Treatments were differences of food for female wasps of A. melinus caged (see Section 3.3) on oranges on the tree in the orchard. For each treatment, a total of 4 oranges was used. They were established as follows.

Table 5.2 (2). Experiment 3. Accumulated dead numbers of female wasps of Aphytis melinus at different constant temperatures, with 75% R.H. and an artificial photoperiod of L:D=14:10 hours, in treatment 2 in which wasps not provided with food.

Duration (day)	Dead number of wasps at temperature (°C):					
	15.0	17.5	20.0	22.5	25.0	27.5
0	0	0	0	0	0	0
1	1	11	9	23*	13	21*
2	2	18*	21*	29	30*	30
3	5	28	30	30		
4	7	30				
5	12					
6	18*					
7	23					
8	26					
9	30					

1: "*", observed LD50's time of wasps.

2: At the time of the LD50's of wasps, none of the percetage death rate of wasps in the control treatment was higher than 5%.

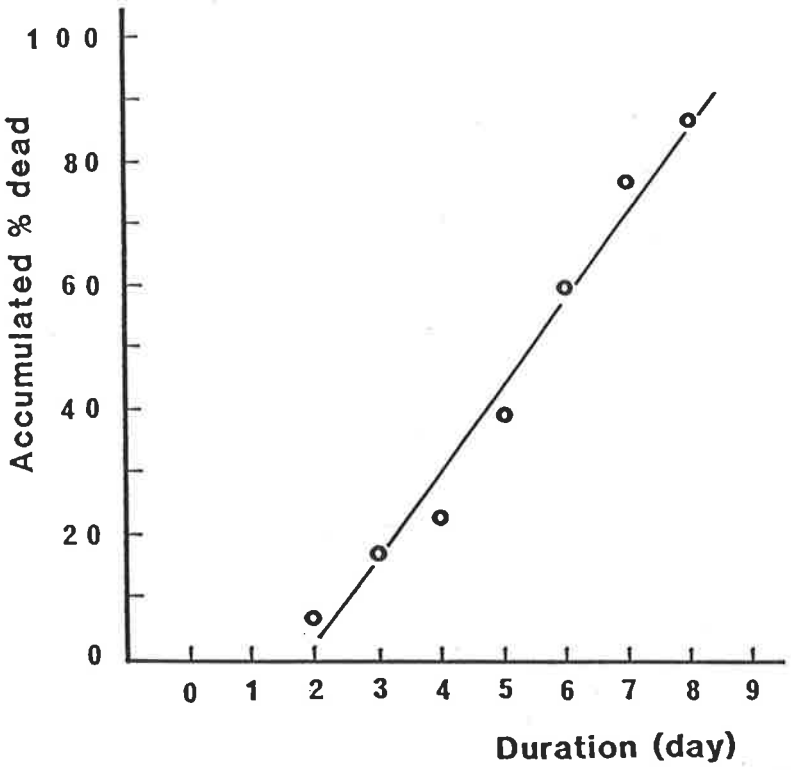


Figure 5.2 (4). The relationship between the accumulated percentage dead rates (Y) of wasps of A. melinus and the survival duration in days (X). The linear regression equation below is of the relationship between the percentage dead rates between 6.7-86.7% and the survival duration between day 2 and 8:

$Y = -26.54 + 14.17X$ ($r=0.9905$, $d.f.=5$, $P<0.01$)

Treatment 1: Control; 8 wasps of A. melinus were caged on each of the 4 oranges whose skin was clean with neither red scales nor other food source, i.e., honeydew or extract of oranges, for wasps; to test the effect of different foods on elongating the survival time of wasps in other treatments.

Treatment 2: 8 wasps were caged on each of the 4 oranges on which, under a x25 magnification microscope, all the red scales on the experimental area were removed. Fluid from the orange would be oozing out from each of the broken mouthparts of the 3rd instar red scales. This extract of oranges was assumed to be used by wasps as food.

Treatment 3: 8 wasps were caged on each of the 4 oranges with 3rd instar red scales. 3rd instar scales which were thought to be parasitized were removed. The parasitized scales were a little bit pale-yellow and the edges of the covers were sometimes lifted away from the orange skin. The broken mouthparts, very few, of the live 3rd instar scales were covered by use of melting paraffine wax to stop the oozing of fruit fluid. So Wasps in this treatment were assumed to feed only on the scales remaining.

Each of the experimental oranges was shaded from the sun by a white plastic sheet (about 20 x 20 cm) so that the temperatures inside the cages would not be affected by the sun but would fluctuate with the ambient temperatures of the orchard (see Section 3.2).

The total of dead wasps in each cage was counted daily under a x25 magnification microscope. This procedure also showed whether the experimental wasps had been joined by any newly emerged wasps from parasitized red scales from the natural population.

Results The accumulated numbers and percentages of dead wasps in each of the treatments are given in Appendix Table 5.2 (4) and the percentages are plotted against time in Fig.5.2 (5) a, b and c for treatments 1, 2 and 3 respectively.

Observation on treatment 3 was ended at Day 15 because the experimental wasps had been joined by newly emerged wasps from the perior parasitized red scales of the natural popualation.

The mean survival time of wasps in the control was 7.2 ± 0.8 days (range: 3-15 days) and the relationship between the accumulated percentage

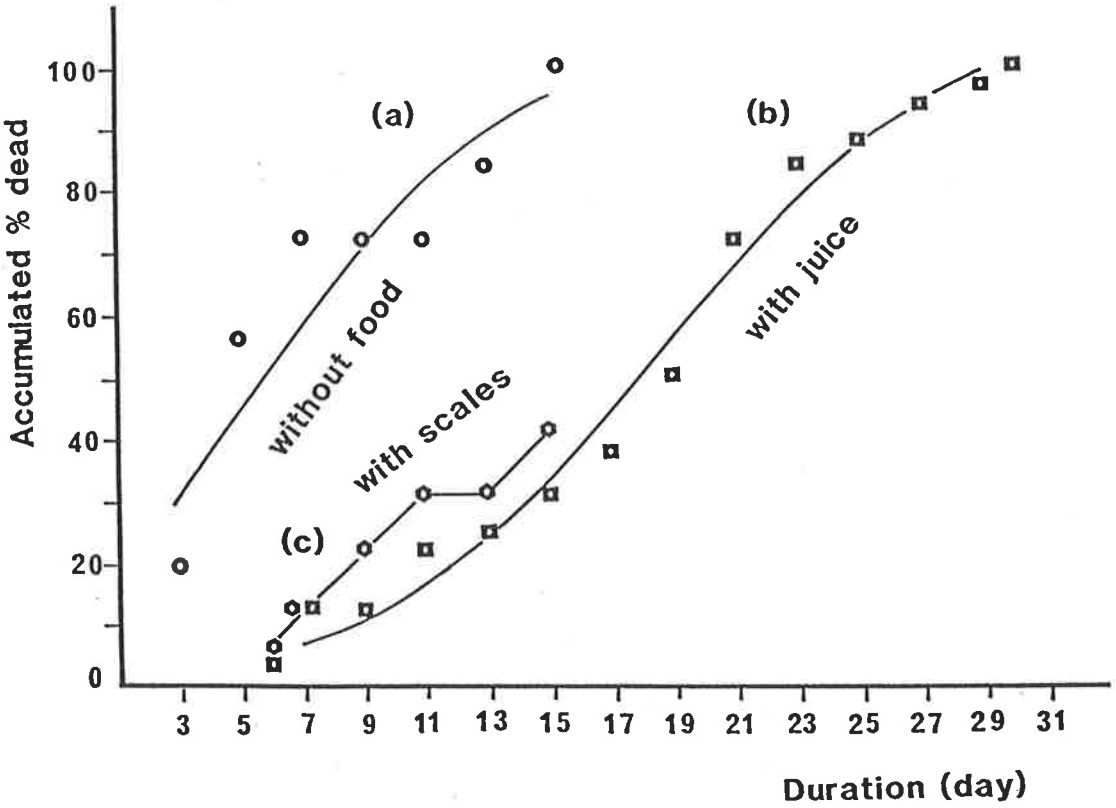


Figure 5.2 (5). The relationship between the accumulated percentage dead rates (Y) of wasps of A. melinus and the survival duration days (X) on oranges on the tree.

(a). In treatment 1, in which wasps were not provided with food.
$Y = 104.504 / [1 + \exp(1.626 - 0.262\ X)]$

(b). In treatment 2, in which wasps fed on the juice oozing from the broken mouthparts of scales (3rd instar) as food.
$Y = 108.247 / [1 + \exp(4.144 - 0.224\ X)]$

(c). In treatment 3, in which wasps survived due to the hostfeeding on 3rd instar scales. The observation was ended at Day 15 because after that time the experimental wasps were joined with the newly emerged wasps from the previously parasitized scales of the natural population.

death rates (Y) and survival time in days (X) is described by the "S" curve regression equation:

$$Y = 104.504 / [1 + \exp(1.626 - 0.262 X)]$$

By comparison, the wasps in treatment 2, feeding on the juice oozing from the broken mouthparts of scales, survived much longer than those in control treatment 1. In treatment 2 the mean survival time of wasps was 18.1±1.2 days (range: 6-30 days), double that in treatment 1. This indicated that orange juice did have an effect on the survival of wasps. Again, the relationship between the accumulated percentage dead rates (Y) and time (X) is described by the "S" curve regression equation:

$$Y = 108.247 / [1 + \exp(4.144 - 0.224 X)]$$

Further, during the experimental period between 11/5/85 and 9/6/85, the mean ambient temperature was 11.3°C. At this temperature, the LD50 of wasps is at least 84 days (at 10°C) if the wasps have been provided with honey as food [Table 5.2 (1)]. This LD50 is 5 times the 18.1 days of treatment 2 in which wasps feeding on the juice of oranges and 12 times the 7.2 days of treatment 1 in which wasps were provided with no food. Obviously, the survival ability of wasps under the so-called "quite natural condition" is significantly shorter than that of so-called "the survival potential" where the wasps are supplied with honey.

Before day 15 the accumulated percentage death rates for treatments 2 and 3 were quite close to each other but were significantly smaller than Treatment 1. At day 14, percentages were 90.63, 31.25 and 40.63 in treatments 1 (no food), 2 (orange exudate) and 3 (host feeding) respectively.

All the observations indicated that orange juice was at least as good as body-juice of scales for the prolongation of the survival of Aphytis wasps in late autumn. This suggested that the habits, host feeding and feeding on orange exudate from some sort of damage could be helpful to prolong survival time during the late autumn and/or early winter.

5.3. Influence of Duration of High Temperature on Mortality of A. melinus Pupa

Extremes of temperatures have been noted as one of the most important natural causes of mortality of Aphytis. DeBach, Fisher and Landi (1955) reported that high temperatures (32.2°C) greatly lowered the life expectancy of adults and the survival of immature stages of A. lingnanensis. Later, some intensive work was conducted by Abdelrahman (1974a) on the influence of extremes of temperatures on mortalities of different stages of A. melinus in the Waite Institute, S. Australia. He established the LD50's temperatures and linear regression equations of the relationships between mortalities of A. melinus and extreme temperatures under laboratory conditions. But still, however, little was known on the influence of duration of extreme temperature on the mortality of A. melinus. This kind of information is important to an understanding of population regulation of this parasitoid which may be exposed to a period of several hours high temperature on a hot day in summer.

This experiment was conducted on pupae of A. melinus only. There were problems to prevent the study of other stages, namely, (1) it was difficult to distinguish the remains of eggs after death, since a dead egg could have had dried to become a very thin membrane somewhere under a scale cover and (2) it was of little significance to measure the survival of adults since their survival was mainly a function of supply of a carbohydrate food (see Sections 5.2 and 5.4). However, my experiment was conducted to (a) assess the influence of the duration of an extreme temperature in a simulated summer day on the null hypothesis that the death rate of A. melinus pupae would not vary and (b) to test the Abdelrahman's (1974a) linear regression equation for the prediction of the mortality of pupae responding to extreme temperatures.

5.3.1. Methods and materials

The 6 treatments were different durations at 45°C within one day (24 hours), namely, 0, 1, 2, 4, 6 and 8 hour(s). And for the above mentioned "purpose (b)", the zero hour duration of extreme temperature was set up. The temperature of 45°C, about 4°C lower than the temperature of 48.5°C of the LD50 for A. melinus pupae (Abdelrahman, 1974a), was very close to 44.3°C, the highest value ever recorded at the Waite Institute (Biennial Report, 1982-83, Waite Agri. Res. Inst.).

(1) Host red scales

Host red scales were started on waxed lemons (see Section 3.1). Crawlers were transferred by the "brush method" (see Section 3.1). The host lemons were then maintained at 27°C and 60% R.H. till scale insects had reached the 3rd instar (see Chapter 3).

(2) Adult wasps of A. melinus

Adults were obtained from the mass culture at 25°C and 60% R.H. Three days before the start of the experiment, all adult wasps were brushed off the pumpkins. The pumpkins were then enclosed in the plastic emergence-containers. Each container was 20 cm tall and 20 cm in diameter; honey was streaked onto the wall as food for the newly emerged wasps. One day before the oviposition treatment, wasps were carefully sucked up into collection-tubes (Section 3.2) for mating; honey was again provided on the wall of each tube.

(3) Oviposition of A. melinus adult wasps

Lemons with 3rd instar red scales were put with the wasps in gauze-cages, 40 x 40 x 18cm. The wasps were allowed to lay eggs on the scale for 2 hours at 25°C and 60% R.H. The wasps were then blown off the lemons in a stream of air. Finally, the lemons were kept at 25°C and 60% R.H. for 10 days till the pupae of A. melinus had reached the stage of CEP (see Section 5.5), pupa with claret color eyes. By turning over some covers of "spare scales", this stage of pupae was confirmed. Then the lemons bearing pupae of A. melinus on scales were placed into incubators for the different treatments.

(4) Methods

Six incubators were programmed exactly the same as in Section 4.3 with a 24-hours fluctuating cycle of temperatures. The base temperature of this fluctuation was 25°C. From this value, the temperature was raised slowly (in 4 hours) to 45°C. Six different durations at 45°C were set, one for each of the 6 incubators. After the treatments, again in 4 hours, the temperature was lowered to 25°C again. Removed from the incubators, the treated pupae were then kept at 25°C and 60% R.H. in an insectary room for another 6 days so that pupae killed by the treatment were obvious. On the 7th day, the dead were counted by turning each of the scale covers over.

5.3.2. Results and discussion

The initial numbers and percentage death rates for each stage of A. melinus pupae are given in Table 5.3 (1). Also given in this table is the expected total percentage death rate, calculated from Abdelrahman's (1974a) linear regression equation. This equation was: Y=(-108.34)+67.25X, where X is the log of the temperature and Y is the probit value. The total percentage dead varied from 7.32% at zero hour duration up to 48.84% at 8 hours, about a 7-fold difference. The expected dead value of 1.5% was not much different from the observed lowest value of 7.32% responding to the zero duration of 45°C but was significantly smaller than those responding to durations longer than 1 hour. This comparison led to the conclusion that Abdelrahman's equation could be used for a estimation of % dead rate on A. melinus pupae responding to a extreme temperature with a zero duration only. Secondly, again from Table 5.3 (1), I believe that during a hot summer period, the number of dead A. melinus pupae could mainly depend on the duration of extreme temperatures and not on the extreme only. A linear regression was calculated to test the null hypothesis that the total percentage death rate (Y) of A. melinus pupae was not the function of the duration of hours of extreme temperature of 45°C. This calculation gave Y=12.16+4.37X ($r=0.9622$, $d.f.=4$, $P<0.01$) and was significant. This indicated that the total percentage death rate of A. melinus pupae is a function of the duration of extremely high temperature. The positive slope of this equation states that the longer the duration, the higher the total death rate.

Furthermore, it was noted that the influence of the durations of the extreme temperature on the dead of A. melinus pupae was detected in different stages of the pupal life cycle. As shown in Section 5.5, the development of pupae follows a series of stages, namely, NEP, AEP, CEP, REP, BEP and GEP. Examination of Table 5.3 (1) showed that the death of pupae could be put into three categories, namely, responding to durations of (1) 0 to 1 hour, (2) 2 to 4 hours and (3) 6 to 8 hours. In Type (1), most of the pupae died in stages REP and GEP but safely developed through the CEP and BEP stages. In Type (2) most death occurred in stages REP, BEP and GEP, but still none in the young CEP stage. Finally, responding to the duration of 6-8 hours in Type (3), the highest death rate occurred in the treated young CEP stage; among the other stages, the death rates were not significantly different from each other.

Table 5.3 (1). Percentage dead within each stage of A. melinus pupae due to the treatment duration (hours) of extreme temperature of +45°C

Duration (hours) (X)	Initial total no. of pupae	% dead rates in stage: CEP	RED	BEP	GEP	Total % dead (Y)
0	41	-	2.44	0	4.88	7.32
1	34	2.94	5.88	0	11.76	20.58
2	32	-	6.25	3.13	15.63	25.01
4	40	-	2.50	10.00	15.00	27.50
6	31	12.90	9.68	6.45	6.45	35.48
8	43	27.91	9.30	6.98	4.65	48.84
expected*						1.5

(1). *: obtained from Abdelrahman's (1974a) linear regression equation:

$$y = -108.34 + 67.25\ x$$

where, x: log value of temperature (°C);

y: probit value (of dead of papae).

(2). linear regression equation of total % dead (Y) of pupae on treatmental duration of hours (X):

$$Y = 12.16 + 4.37\ X\ (r=0.9622;\ d.f.=4,\ P<0.01)$$

Combining my results and Abdelrahman's (1974a), I believe that intensive laboratory studies of the influence of duration of high summer temperatures, i.e., 35-40°C, was still needed on the null hypothesis of no dead of A. melinus insects would be caused due to the variation of duration of extreme temperatures.

5.4. Searching Efficiency of Female Wasps of A. melinus in Cages at 25±1°C and 60% R.H.

5.4.1. Review and design of the present experiment

5.4.1.1. Introduction

Several biological concepts have been used to describe the relationship between an insect and its natural enemies. Solomon (1949) was the first to propose the concepts of the "functional response" and "numerical influence". The latter is now commonly used as the "numerical response". These two concepts, which described the density-dependent influence of natural enemies proposed that to be density-dependent, a natural enemy (predator) must take a greater proportion of the population as the host density increases. In other words, to be density-dependent, a predator must respond to changes in the numbers of the host (Nicholoson 1933; Varley 1947). The nature of this response was proposed to be twofold. First, a functional response to (say) an increase in the host density, because of the increased availability of prey, so that as host density rises, a predator will attack a given number of prey more rapidly. Secondly, a frequent, but not invariable result of the first response is an increase in the numbers of the predator (a numerical influence), due to an increased rate of survival or of reproduction, or both; this may or may not be sufficient to produce an increase in the ratio of predator to prey. The numerical relationship is most important when the predator develops rapidly and passes through several generations to each generation of the host, as do many parasitic insects (Flanders 1947).

Since Solomon (1949), the concepts of "functional response" and "numerical influence (response)" have been discussed at length by many workers as they have tried to measure the two processes described by the concepts. Originally the functional response was not thought of as the response of ONE predator, but such a restriction became fashionable after Holling's (1959) famous sand-paper disk experiment. Thus Murdoch (1973) explains: The functional response (Solomon 1949) is defined by a function, N=f(D), that relates the number of prey eaten per predator per unit time

(N) to the density of the prey (D). It describes how the attack rate of an individual predator varies with prey density. So, too, Hassell (1978) says: Solomon defined a functional response as a change in the numbers of prey attacked in a fixed period of time by a single predator when the initial prey density is changed. And Hughes et al (1984) further explain: Solomon (1949) and others since have divided the predator-prey relationship into two components, (1) the functional response, which is defined as the change in attack rate per predator with variation in prey density, and (2) the numerical response, which is the change in predator numbers with variations in prey density. Several workers have noted that this division fails to comfortably accommodate certain phenomena since shown to be important--especially the relative distributions of predator and prey and the influence of environmental factors. Finally, Huffaker et al (1968) point out that the modelling of the interaction of parasite-host or predator-prey is most simply achieved by using data which describe the response of only one predator or parasitoid in each experimental unit to attack hosts (or prey) at a number of fixed densities.

5.4.1.2. What is "searching efficiency" ?

The concept of "functional response" arose from attempts to quantify the searching efficiency. Nicholoson and Bailey (1935) represented the "area of discovery" of natural enemies to the study of "searching efficiency". They believe that a parasitoid has an "areal range" and an "area of discovery", both of which are supposed to be constant. An "area of discovery" is calculated by the following formula:

$$= \frac{\text{No.of prey attacked during the survival time of predator}}{\text{No. of prey in the "areal range" of this predator}}$$

However, in experiments with parasitoids, an areal-range can hardly be established so "numbers of prey (or host) exposed to the predator (or parasitoid)" is always be used instead for the bottom line of the formula.

On the other hand, Hassell and Varley (1969) suggested that the area of discovery is:

$$a = Q / P^m$$

or, $\ln a = \ln Q - m \times \ln p$

where a = area of discovery
P = density of predator
Q = quest constant
m = mutual interference constant

Luck, Allen and Baasch (1980) give values of "ln Q" and "m" of A. melinus for use in Hassell & Varley's equation and are copied in Table 5.4.(1). The table also shows values of "a" calculated for 1 value of "p" at different temperatures. However, Luck et al believe the values of "m" depend on the experimental temperatures. The values of "m" ranged between 0.297 at 32°C and 0.835 at 27°C; "ln Q" ranged between -1.35 at 27°C and -2.46 at 21°C; and the calculated "a" values were between 0.085 at 21°C and 0.259 at 27°C. In Luck's (ibid) data, the biggest value of "ln Q", -1.35, occurred at 27°C; by comparison, similar values, -2.46 and -2.42, occurred at 21 and 32°C. It seems to indicate that 27°C was the optimum temperature for wasps to search for hosts.

However, later, Hassell (1982) established a concept as: The term "searching efficiency" has been used by both applied and theoretical ecologists in roughly the same sense ---- a more efficient predator attacks a larger proportion of the prey over a given period of time than does a less efficient one. A universal, rigorous definition, however, of use both in population models and in assessing the performance of natural population in the field, is still lacking. He (ibid) believes that a step towards a rigorous definition of "searching efficiency" had been given by the simplest of equations for the functional response to prey density by Holling (1959). Holling's so-called "disc equation" is as follows:

$$N(e) / P = a' \times T(s) \times N$$

where,

N = the number of prey.
P = number of predators.
N(e) = the number of prey encountered by P (predators).
T(s) = the time spent for searching by the predators.
a' = the instantaneous measure of searching efficiency.

Table 5.4 (1). Obtained at three constant temperatures, namely, 21, 27 and 32°C, data of Ln value for the quest constant (ln Q), mutual interference constant (m) and area of discovery (a) (after Luck et at. 1980); also the calculated data of "a" when "P" is of 1 per experimental unit for adult wasps of A. melinus.

	At temperature (°C) of:		
	21	27	32
ln Q	-2.46	-1.35	-2.42
m	0.37	0.835	0.297
a*	0.085	0.259	0.089

*: Calculated value by use of Luck's equation.

The instantaneous searching efficiency, a', is then calculated by the formula:

$$a' = N(e) / [N \times P \times T(s)]$$

5.4.1.3. Design of the present experiment

The following experiments were conducted with the purpose of quantifying the performances of searching wasps of A. melinus in an arena which was as close as possible to nature. The experiments were similar to classical "functional response" ones; but differed from the classical ones in the range of densities of hosts and the total numbers of hosts. The rationale was that in a population the host, under natural conditions, the frequency of each density was unlikely to be the same.

5.4.2. Methods and materials

5.4.2.1. Treatments

In the following experiments, treatments consisted of various combinations of: differences in food supply to the searching wasps; different sizes and shapes of cage; different densities of scale but a constant total number of scale. Densities of red scale per lemon were established as 2, 4, 8 and 16 in order and numbers of lemons for densities were established as 8, 4, 2 and 1 respectively [Tab.5.4 (2)].

A total of three replications for each experiment was kept at 25±1°C, 60% R.H. and an artificial photoperiod of L:D=14:10 hours for 5 days. This photoperiod was used to simulate the "long day" in summer. After each treatment the scale insects were kept for another 5 days under the same conditions before the measurement of death and parasitism. Since I had had only one big- (or medium-) cage, so for some experiments, in which this cage was used, "3 replications" meaned each of these experiments was repeated at 3 different times. Consequently, the variance among the so-called "3 replications" in each experiment was test by use of 2-way ANOVA method [see Tab.5.4 (8)].

5.4.2.2. Materials

The experimental cages were of three different sizes and shapes, namely:

(1) Small cages: Size 0.4m x 0.4m x 0.18m high. The frame was wood, the sides were very fine gauze glued to the wooden frames and the bottom was plywood. The top was a piece of transparent perspex sheet which was

Table 5.4 (2). Densities of red scales and required numbers of host lemons for each density in each replications (cages) of each experiment.

Densities: no. of red scale per host lemon	Lemons for each densities:	Total numbers of red scale within each density
2	8	16
4	4	16
8	2	16
16	1	16
Total in each replication	15	64

screwed to the top frame after the lemons with red scales and the wasp (or wasps) had been placed in the cage.

(2) Big cages: Size 1.5m x 1.5m x 2.0m high [Fig.5.4 (1)]. It was made of very fine gauze enclosing a wooden top-frame. The bottom part was held down with a plastic frame, 1.5m x 1.5m x 0.2m high.

(3) Medium cages: These cages was modified from the above mentioned "big-cages" by reducing the height from 2.0m to 0.2m. The other dimensions were unchanged.

Experimental cohorts of red scales were started on lemons by the brush method (see Section 3.1). When the scales had reached the 3rd instar, the lemons were cleaned gently with a very fine brush and the required number of red scale on each lemon was obtained by removing the surplus scales under a x10 microscope.

In small and medium cages, 15 of the lemons were placed in three rows on the bottom. Lemons were not allowed to touch each other. In the medium cages, the interval between rows was 33cm, 25cm between lemons within each row.

In each of the big cages, 15 lemons were placed in a universe of three dimensions. The lemons were randomly positioned on 15 holders fixed to 5 sticks, 3 to a stick at 3 heights, namely, 0.60m, 0.95m, and 1.30m. Each stick was planted in a pot and the pots were placed in a circle, 0.65m in diameter, in the center of the cage [Fig.5.4 (1)].

One-day-old wasps (see Chapter 3) were released from a collection tube placed at the centre of the floor the cage.

5.4.3. Experiments

Eight experiments were conducted to measure (i) searching efficiency and (ii) the influence of differences of food supply on searching efficiency. The experiments were as follows:

(a) Using the "small cage"

Experiment 1: One female wasp per cage, given no food except the host red scales.

Experiment 2: One female wasp per cage, given honey on the top surface of the cage.

Experiment 3: Five males and five females per cage, given honey as above.

Figure 5.4 (1). Big cage, 1.5 x 1.5 x 2.0m high.

(b) Using the "big cages"

Experiment 4: One female wasp per cage, given no food.

Experiment 5: One female wasp per cage, given honey on a metal sheet (6 x 2.5cm) hung in the middle of the cage.

Experiment 6: Five males and five females per cage, given honey on a metal sheet as above.

(c) Using the "medium cages"

Experiment 7: One female wasp per cage, given no food.

(d) Using the "big cages"

Experiment 8: One female wasp per cage, given one small, flowering orange tree at the centre of the cage to supply flower nectar.

5.4.4. Results and discussion

5.4.4.1. General results

The details of death and parasitism in each of the 8 experiments are given in Appendix Tables 5.4 (1) to 5.4 (8). Obtained from these tables the percentage dead due to host-feeding of A. melinus, the parasitism and the total dead (sum of the dead and the parasitized) of scale insects in each experiment are given in Table 5.4 (3).

As shown in this table, in experiments with one female wasp of A. melinus, the total dead of scale insects varied between 5.21% in Experiment 7 and 22.39% in Experiment 2; in experiments 3 and 6, each with 5 pairs of wasps (5 males + 5 females), they were 48.44% and 27.08% respectively. The results of the different experiments can be compared in many ways. The detailed analyses were conducted as follows.

5.4.4.2. One female wasp

(i) No food. The results of Experiments 1, 4 and 7 are used to test the null hypotheses that there was no difference, due to cage size, on dead (and/or parasitized) scales given one female wasp without food.

Data were obtained from Appendix Tables 5.4 (1), 5.4 (4) and 5.4 (7) and are given in Table 5.4 (4). The chi-square value of 8.1534 (d.f.= 2, $P<0.05$) rejects the null hypothesis. The highest total dead numbers were in the small cages (Experiment 1). However, as shown in Table 5.4 (4), it

Table 5.4 (3). Percentage rates, namely, dead due to host-feeding of parasitoid wasp and parasitized (para.), of 3rd instar red scale.

Size of cage	food for wasps in experiment:	No.of wasps per cage	Total no. of scales in 3 cages	% rate of scales		
				para. (P.)	dead (D.)	total dead (=P.+ D.)
Small	1: none	1	192	1.04	11.98	13.02
	2: honey	1	192	13.54	8.85	22.39
	3: honey	5 (pairs)	192	34.38	14.06	48.44
Big (h=2m)	4: none	1	192	2.08	5.12	7.20
	5: honey	1	192	10.94	13.02	23.96
	6: honey	5 (pairs)	192	19.79	7.29	27.08
Medium (h=0.2m)	7: none	1	192	0	5.21	5.21
Big (h=2m)	8: F.O.T.*	1	192	13.02	17.19	30.21

*: F.O.T.: one small flowering orange tree in each of the three cages.

Table 5.4 (4). Numbers, live, dead (due to host-feeding) and parasitized, of red scales in Experiments 1, 4 and 7; also given are the chi-square values on tests of differences on the dead and the parasitism of red scales.

Experiment	Numbers of red scales			
	Alive	Dead	Parasitized	Total
1	168	23	2	192
4	178	10	4	192
7	182	10	0	192

chi-square values:

(1). for test the total dead (dead due to host feeding + parasitized): =8.1534 (d.f.=2,$P<0.05$)

(2). for test the dead due to host-feeding: =8.7109 (d.f.=2, $P<0.05$)

(3). for test the parasitism: =4.0444 (d.f.=2, $P>0.05$)

was obvious that within the total dead, there was no significant difference among the numbers of parasitized scales (Chi-square =4.0444, d.f.=2, $P>0.05$). In other words, in the absence of food (i.e. honey) for wasps, the number of parasitized scales was not a function of cage size. Consequently, a chi-square was calculated to test the null hypothesis that there was no difference between numbers of scale killed by host feeding. The chi-square value of 8.7109 suggests that the number of dead scales is a function of cage-size. Significantly more scales were killed by host feeding in the small cages (Experiment 1).

(ii) With food. The results of Experiments 2, 5 and 8 were used to test the null hypothesis that there was no difference, due to cage size, on dead (and/or parasitized) scales given one female wasp with food (honey or nectar). The relevant data were obtained from Appendix Tables 5.4 (2), 5.4 (5) and 5.4 (8) and are given in Table 5.4 (5). Obviously there was no significant difference between the numbers of parasitized scale, suggesting that parasitism was not a function of cage size. So chi-square was only calculated to test the numbers killed by host-feeding. The chi-square value of 6.0246 (d.f.=2, $P<0.05$) indicates that significantly more scale were killed in big cages (Experiments 5 & 8) than in small (Experiment 1).

(iii) Searching efficiency. Obtained from Appendix Tables 5.4 (4), 5.4 (5) and 5.4 (8) the numbers of dead and parasitized scales due to the total of 3 female parasites in each experiment are re-arranged and given in Table 5.4 (6). In the following analysis the searching time of parasites with no food in Experiment 4 was assumed to be as long as their survival time of 2 days at 25°C (see Section 5.2). By contrast, searching time was 5 days for parasites in Experiments 5 and 8 since they were provided with food (see Section 5.2). The daily consumptions of scales per female parasite for host-feeding and parasitism are calculated and given, again, in Table 5.4 (6). The daily consumption of scales by host-feeding ranged between 1.7 (in Experiments 4 and 5) and 2.2 (in Experiment 8) scales per parasite. The daily rate of parasitism ranged between 0.7 (in Experiment 4) and 1.7 (in Experiment 8) scales per parasite. These observations seem to lead to agreement with DeBach's (1969) concept: *Aphytis* female wasps kill more scale insects by feeding on them than by oviposition. The total consumption of scales per parasite per day ranged between 2.4 (in Experiment 4) and 3.9 (in Experiment 8). These numbers are not

Table 5.4 (5). Numbers, alive, dead (due to host-feeding) and parasitized, of red scales in Experiments 2, 5 and 8; also given are the chi-square values on tests of the difference on the dead red scales.

Experiment	Numbers of red scales			
	Alive	Dead	Parasitized	Total
2	149	17	26	192
5	146	25	21	192
8	134	33	25	192
chi-square			=6.0246 (d.f.=2, $P<0.05$)	

Table 5.4 (6). Numbers, dead (D.) and parasitized (P.), of red scales in Experiments (Exp.) 4, 5 and 8. Also given are the assumed searching days of parasites: 2 days for Experiment 4 and 5 days for Experiments 5 and 8; the mean consumptions (cons.) of scales per parasite per day due to host-feeding (HF.) and parasitism; the searching efficiency (a') and area of discovery (a) of parasites. Abdelrahman's (1974b) data at 25°C are followed in the last row.

Exp.	No.of scales			Searcing days	Cons.due to:			a'	a
	D.	P.	Total		HF.	P.	Total		
4	10	4	14	2	1.7	0.7	2.4	0.0122	0.0244
5	25	21	46	5	1.7	1.4	3.1	0.0160	0.0800
8	33	25	58	5	2.2	1.7	3.9	0.0201	0.1005
*	50.6	61.6	112.2	29.8	1.7	2.1	3.8		

*: after Abdelrahman (1974b), at 25°C, the numbers of red scales killed by parasites' host-feeding and ovipodition.

significantly different from each other. By comparison with Abdelrahman's data (1974b) [also Table 5.4 (6)] it is obvious that the numbers killed by host feeding or by parasitism were similar in Experiment 5 and 8 but that the parasitism figure of 0.7 scale per wasp per day in Experiment 4 in which wasps had no access to honey was obviously smaller than Abdelrahman's 2.1.

As mentioned above parasites killed many more scale insects in the presence of food than they did in its absence. However, it was still of interest to assess the difference in searching efficiency of female parasites with different food supplies. Consequently, from the data of Experiments 4, 5 and 8, the null hypothesis, that the searching efficiency of female of A. melinus was not a function of foods, was tested. Searching efficiency was calculated from the formula (see Section 5.4.2):

$$a' = N(e)/[N \times P \times T(s)]$$

Since parasites lay eggs and feed on a certain number of scales daily (Abdelrahman 1974b), the T(s) for this formula was calculated using a time of 2 days for Experiment 4 and 5 days for Experiments 5 and 8 (see Section 5.2). For each of the three experiments, "N(e)" was the total number (dead due to host-feeding + parasitized) of dead scales in Table 5.4 (6); "N" was 192 (original scales); "P" was 3 (female parasites). The values of the searching efficiency are then given also in Table 5.4 (6). They ranged between 0.0122 (in Experiment 4) and 0.0201 (in Experiment 8). Again, they did not seem significantly different from each other. Subsequently, "a" (area of discovery) was calculated as $a = a' \times T(s)$; for Experiments 4, 5 and 8, $a = 0.0244$, 0.0800 and 0.1005 respectively [Tab.5.4 (6)]. The values of "a" are obviously smaller than the calculated value of 0.259 at 27°C from Luck's equation [Table 5.4 (1)]. This is because the survival time of parasites in Experiment 4 was assumed as 2 days, which might be obviously shorter than in Luck's experiment; even in Experiments 5 and 8, the assumed survival time of 5 days is probably shorter than in Luck's experiments. In conclusion, the searching efficiency of wasps of A. melinus was not a function of different foods; in other words, searching efficiency is similar throughout the wasp's lifetime no matter whether they had access to food. By contrast, the "area of discovery" of searching wasps was definitely a function of different foods.

5.4.4.3. Interaction among parasites

Data obtained from Appendix Tables 5.4 (2), 5.4 (3), 5.4 (5) and 5.4 (6) are re-arranged in Table 5.4 (7) to test the null hypothesis that there was no difference among sizes of cages on the "mutual interference constant" of searching female wasps of A. melinus. To test this null hypothesis, the "area of discovery" method was used. The a-values for the experimental period of 5 days for each of the 4 experiments were calculated from the modified Nicholoson's (1935) formula:

$$a = N(e) / (N \times P)$$

where,

N(e): total number of dead scale (dead + parasitized)

N: initial scale numbers (192 for each experiment)

P: total numbers of parasites in each experiment

The a-values are given in Table 5.4 (7) and ranged between 0.0181 (in Experiment 6) and 0.0799 (in Experiment 5). However, in small cages in Experiments 2 and 3, the retarding rate of a-values was related to an increase in the density of parasites: the a-value went down by 50% (from 0.0764 to 0.0358) while the density went up by 4 times (from 1 to 5 in each cage). By contrast, in big cages in Experiments 5 and 6, they were very close: a-value decreased by 5 times while density of parasites increased by 4 times. Obviously, a-values were severely varied by differences of either the densities of parasites or sizes of cages, the searching universe. Consequently, I believed that the mutual interference of wasps of A. melinus could not be constant; or could restrictively be constant.

5.4.4.4. Variation among densities of host scales and replications in each experiment

This section deals with the use of a 2-way ANOVA method to test the null hypothesis that there was no difference among either experimental replications or scale densities with respect to numbers of dead and/or parasitism of red scales in each experiment. From Appendix Tables 5.4 (1) to 5.4 (8), the F values for dead numbers due to host-feeding and due to parasitism are calculated and are given in each (cont.) in Appendix Tables 5.4 (1) to 5.4 (8) respectively. Further, from these appendix tables, the F-values are re-arranged and are given in (i) and (ii) of Table 5.4 (8).

Table 5.4 (7). Numbers, live, dead, parasitied (para.) and total dead (T.D.) (dead + parasitized), of red scales due to different numbers of female wasps of A. melinus in Experiments (Exp.) 2, 3, 5 and 6. Also given are values of "area of discovery", a, of parasites.

Exp.	Total no. of parasites	Scale numbers of				Total no.of red scales in each Exp.	a
		Live	Dead	Para.	T.D.		
2	3	149	17	26	43	192	0.0747
3	15	89	37	66	103	192	0.0358
5	3	146	25	21	46	192	0.0799
6	15	140	14	38	52	192	0.0181

Table 5.4 (8). Obtained from Appendix Tables 5.4 (1) to 5.4 (8), F-values of the 2-way analyses of variance among 4 densities of red scales and among 3 replications in each of the 8 experiments (Exp.).

(i). for the dead scale numbers due to host-feeding of parasites.

Exp.	For replications		For densities of scales	
	F-value	P (d.f.=2,6)	F-value	P (d.f.=3,6)
1	1.0000	N.D.	7.4615	<0.05
2	0.4667	N.D.	4.3333	N.D.
3	1.3125	N.D.	0.2969	N.D.
4	1.2352	N.D.	1.1765	N.D.
5	0.4286	N.D.	3.2500	N.D.
6	1.0000	N.D.	4.0000	N.D.
7	0.2000	N.D.	0.8000	N.D.
8	3.9296	N.D.	0.1549	N.D.

* N.D.: P>0.05, not significant.

(ii). for the parasitism of red scales.

Exp.	For replications		For densities of scales	
	F-value	P (d.f.=2,6)	F-value	P (d.f.=3,6)
1	-		-	
2	1.2581	N.D.	0.1290	N.D.
3	0.0407	N.D.	1.0679	N.D.
4	-		-	
5	1.0000	N.D.	13.667	<0.01
6	2.9496	N.D.	4.9076	<0.05
7	-		-	
8	3.5882	N.D.	0.5294	N.D.

* N.D.: P>0.05, not significant.

As shown in this table, most of the F-values were not significant except for dead numbers on densities of scales in Experiment 1 and for parasitism on densities of scales in Experiments 5 and 6.

The above analysis indicates that female wasps of A. melinus are normal search for scale insects at random. On consideration, this analysis leads to the disagreement of the classical concept of "functional response" (Holling 1959; Huffaker et al 1968; Hassell 1978; Podoler 1981; and others). I believe this was due to my experimental design: (1) quite big searching universe of offered to the searching wasps, and (2) different densities of host scales presented to the parasites in the same treatment. As a result, parasites in my experiments were acting under more natural conditions than those given by previous workers. Under my conditions, parasites had more freedom for their searching activity than they would in a very small universe, such as in petri dishes only 10cm in diameter, for example (Podoler 1981).

5.5. Development of A. Melinus at Constant Temperature of 25°C and Constant 75% R.H.

Rosen and Eliraz (1978) conducted an intensive study on the biology and systematic of development of stages in Aphytis chilensis (Howard). To identify the developmental stages of larvae they suggested the shape of the mandibles as usually the best character. The number of spiracles may also be of value. They believed that all aphelinid genera have three larval instars (Nikol'skaya and Yasnosh, 1966) and A. chilensis is no exception. The three instars differ markedly in the shape and size of their mandibles. Data from their studies, at 28±1°C and 70±5% R.H. are given below.

Differences among stages of A. chilensis

Stage of larva	Length of mandibles (micron)	Pairs of spiracles	Length of larva-body (micron)	Time for development (days)
1st	8	4	168 (128-250)	3
2nd	13	8	262 (190-308)	3
3rd	16	8	804 (760-840)	6*
total				12

* including the prepupal stage.

In their study (ibid) one-day-old wasps were allowed to lay eggs for 1 hour on Oleander scales cultured on potatoes. Subsequently, samples were taken daily and the various developmental stage of A. chilensis were measured by turning over the covers of parasitized host scales.

From the above table, I believed that body-length of larvae could be used to identify the age of larvae more precisely. So I tried to develop a new method for distinguishing the larval age of A. melinus, as follows.

5.5.1. Methods and materials

The experiment was run at a constant temperature of 25°C, 75% R.H. and an artificial photoperiod of L:D=14:10 hours. Red scales were prepared on waxed lemons (see Chapter 3) and were maintained at 25°C and 60% R.H. to grow to the 3rd instar. Wasps were introduced from a mass culture on host red scales on butternut pumpkins at 25°C and 60% R.H. A total of 23 eggs of A. melinus was used in this experiment.

Before the host red scales were subjected to wasps for parasitization, all the lemons were carefully cleaned with a very fine brush. The lemons with 3rd instar scales were then placed in "small cages" (see Section 5.4), 0.4 x 0.4 x 0.18m high.

Some different from the method of selecting one-day-old wasps (see Chapter 3), 4 days before the experimental wasps were selected, host pumpkins with parasitized red scales were cleaned through running tap water for several seconds to wash pumpkins' extract away; 2 days before the oviposition treatment, all the cleaned pumpkins were carefully brushed by very fine brushes to remove the "old wasps" away; pumpkins were then enclosed in containers (20cm height, 20cm diameter). Honey was placed on the side wall of each of the containers for wasps as food. One day before experimental treatment, wasps of A. melinus were selected from these containers. They were carefully sucked up into collection tubes (also Chapter 3); honey was also struck on the side-wall of each tube for wasps as food. Wasps were allowed to mate in these tubes for one day and were then released into the "small cages" and allowed to lay eggs in scales for 2 hours. Finally lemons were individually passed through the blowing air and were then free of parasitoid wasps. Subsequently, each of the scale covers was carefully torn away under a x25 magnification microscope and the presence of eggs on the dorsal aspect of each scale body was confirmed. A total of 23 eggs were used in this experiment. Lemons with parasitized

scale insects were finally enclosed in containers [Fig.5.5. (1)], 25 x 22 x 15cm high. Saturated solution of NaCl kept the humidity at 75% R.H (Winston and Bates 1960).

The development of A. melinus was observed daily. Hatching of eggs was observed under a x100 magnification microscope. Subsequently, also under a x100 magnification microscope, the larval body-length was measured. The development of pupae was monitored using variation in eye-color.

5.5.2. Results and discussion

23 eggs were studied. All of them were initially on the dorsal aspect of the scale body. These eggs were considered as female (Abdelrahman 1974c).

(1) Hatching. All the eggs hatched on the 4th day after oviposition.

(2) Variation in body-length of larvae. The variation of body-length of larvae is given in Table 5.5 (1). The length was measured each day after hatching. The mean body-length of larvae on the 1st day was 0.148 micron, which was similar to the length of eggs. On the 2nd and 3rd day, the length of the larvae increased rapidly. By the 2nd day the mean body length had doubled. By the 3rd day it had tripled. There was no significant difference between day 4 and day 5, now about 5 times the initial length on day 1.

(3) Durations of the development of stages of pupae were estimated as days after hatching of eggs. Stages of the pupa were distinguished by variation in eye-color, from eye-less to colorless to green. The pupal period was divided into 6 stages, from eye-less to green-eye stage as below (D.A. Mealzer, pers. comm.):

1: NEP: newly formed pupa with no eyes.
2: AEP: pupa with apricot and light gray eyes.
3: CEP: pupa with claret color eyes.
4: REP: pupa with dark red eyes.
5: BEP: pupa with black eyes.
6: GEP: pupa with green eyes.
- GONE: emerged.

Development times for pupae are given in Table 5.5 (2). Larvae took 5.39±0.10 days after hatching to complete development and expelled meconia on the 5th day. Unfortunately, I did not observe the first stage of the pupa (NEP). An interval of one day at 25°C must be long relative to this stage. So observation of the pupae was started from the AEP stage. After

Figure 5.5 (1). Container with the saturated solution of NaCl to maintain a constant 75% R.H.

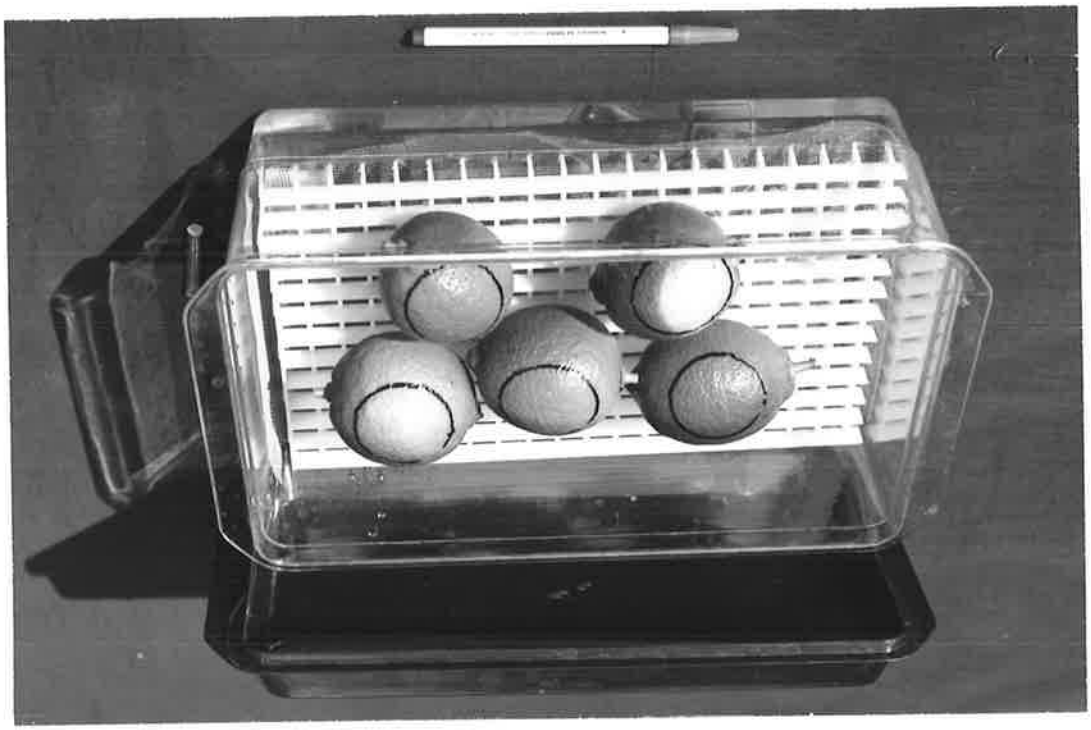


Table 5.5 (1). Mean body-length (m.m.) of A. melinus larva in relation to developmental duration (days) after the hatching of egges at 25°C and 75% R.H.

	Body-length on Day:				
	1	2	3	4	5
Mean	0.148	0.291	0.444	0.708	0.712
S.E.	0.004	0.008	0.017	0.009	0.090
Range	0.120–0.173	0.227–0.400	0.360–0.613	0.640–0.747	0.667–0.800

Table 5.5 (2). Mean developmental duration in days (at 25°C and 75% R.H.) of pupae of A. melinus after the hatching of eggs.

Stage of pupa	Duration (days) after the hatching of eggs:		
	Mean	± S.E.	Range
L.E.M.*	5.39	0.10	5-6
1: NEP**	-	-	-
2: AEP	6.17	0.08	6-7
3: CEP	7.17	0.08	7-8
4: REP	8.17	0.08	8-9
5: BEP	9.22	0.09	9-10
6: GEP	10.30	0.10	10-11

*: fully developed larvae expelling meconia.

**: no observation was done on the NEP stage.

hatching, insects took 6.17±0.08 days to get to the AEP stage. Subsequently, each of the following stages required almost one day to complete their development at 25°C and 75% R.H. Pupae of A. melinus required about 5 days altogether to complete their developmental cycle. Adults emerged between day 10 and day 11 after the hatching of eggs.

A. melinus took a total of 14 days, namely, 4 days for egg, 5 days for larva, and 5 days for pupa, to complete one generation at 25°C and 75% R.H. In other words, it needs a total of (25-11) x 14 = 196 day-degrees >11°C (Abdelrahman 1974b) for the completion of development. This day-degree sum was about that for red scale to complete 2 stages, or about 2/5 of that for red scale to complete one generation at 25°C (Atkinson, 1977). The observed duration of development in female A. melinus was 1 day or two longer than that of 16.2 days obtained from scales whose cover had not been torn away at 25°C and 75% R.H. (Abdelrahman, 1974b). This suggested that the treatment of insects in this experiment reduced the duration of development.

(4) The size and shape of the mandibles of larvae varied with time after hatching. 4 sizes were distinguished between day 1 and day 5 [Fig.5.5 (2): A-D]. The mandibles were observed under x500 magnification from slides of only 2-3 larvae each day after the hatching of eggs. The larvae were directly mounted in Berlese's gum-chloral mounting medium. After mounting, larvae became semi-transparent in 20-25 minutes and in a suitable condition for the observation of the mandibles.

However, result of my observation was given for reference only as follows. On day 1 after the hatching of eggs, the mandibles [Fig.5.5 (2), A] were minute, about 7.6 microns in length and 6.9 microns in width; on day 2, mandibles [Fig.5.5 (2), B] were bigger, triangular, about 11.0 microns long and 8.3 microns wide; on day 3, the mandibles [Fig.5.5 (2), C] were larger and more acutely pointed than that on day 2, about 14.4 microns long and 9.6 microns wide; and the size and shape of mandibles of larvae on day 4 and 5 were nearly the same as 19.3 and 19.9 microns long respectively and 11.0 (day 4 and 5) microns wide [Fig.5.5 (2), D]. In this experiment, I mentioned 4 differences of the sizes and shapes of the mandibles of larvae. But this does not mean I have established a total of 4 stages instead of the establishment of a total of 3 differences for the 3 instars of Aphytis larvae respectively (Azim 1963a & b; Rosen and Eliraz 1978). It is the only purpose of this experiment to develop a technique of estimating the ages of larvae of Aphytis.

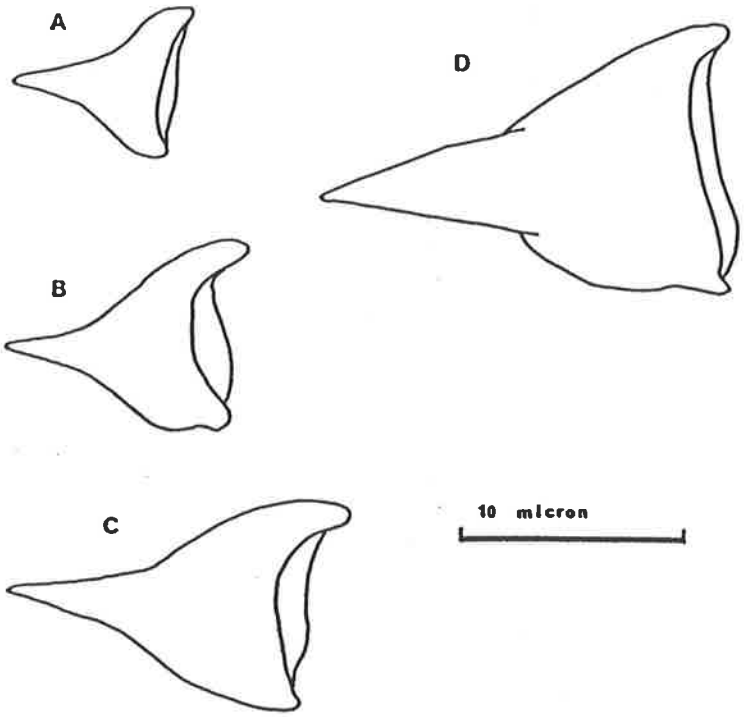


Figure 5.5 (2). Shapes of mandibles of larvae of A. melinus DeBach at time after the hatching of egges.

A: on Day 1.
B: on Day 2.
C: on Day 3.
D: on Day 4 & 5.

(5) This technique was developed for the measurement of developmental durations of larvae and pupae of A. melinus at 25°C and 75% R.H. Since the ranges of body-length in relation to the developmental durations (days) of larvae were grouped very well, I believed the time of 5 days used before (see Section 5.4) was long enough for assessing the age of larvae of A. melinus in parasitized scales. Consequently, I hope this technique could be used in experiments, such as these in Section 5.4, to measure the actual time (day) of laying eggs of wasps that could be used instead of the assumed time that had been employed in the prior experiments (see Section 5.4) on the searching efficiency of wasps.

REFERENCES

Abbott, W. S. (1925). A method of computing the effectiveness of an insecticide. J. Ecom Entom., 18:265-267.

Abdelraman, I. (1974a). The effect of extreme temperatures on California red scale, Aonidiella aurantii (Mask.) (Hemiptera:Diaspididae), and its natural enemies. Aust. J. Zool., 22:203-212.

Abdelrahman, I. (1974b). Growth, development and innate capacity for increase in Aphytis chrysomphali Mercet and A. melinus DeBach, parasites of California red scale, Aonidiella aurantii (Mask.), in relation to temperature. Aust. J. Zool., 22:213-230.

Abdelrahman, I. (1974c). Studies in ovipositional behaviour and control of sex in Aphytis melinus DeBach, a parasite of California red scale, Aonidiella aurantii (Mask.). Aust. J. Zool., 22:231-247.

Atkinson, P. R. (1977). Preliminary analysis of a field population of citrus red scale, Aonidiella aurantii (Mask.), and the measurement and expression of stage duration and reproduction for life tables. Bull. Entom. Res., 67:65-87.

Azim, A. (1963a). Aphytis chlindratus Compere (Hymenoptera, Aphelinidae), an effective parasit of Pseudaonidia duplex Cockerell. Mushi 37:53-63.

Azim, A. (1963b). Systematic and biological studies on the genus Aphytis Howard (Hymenoptera, Aphelinidae) of Japan. Par 2. Biology and mass production. Jour. Fac. Agric. Kyushu Univ., 12:291-321.

DeBach, P. (1969). Biological control of diaspine scale insects on citrus in California. Proc. 1st Interna. Citrus Symp. (Riverside, 1968), 2:801-822.

DeBach, P., Fisher, T. W. and Landi, J. (1955). Some effects of meteorological factors on all stages of Aphytis lingnanensis, a parasite of the California red scale. Ecology, 36:743-753.

DeBach, P., Fleschner, C. A. and Dietrick, E. J. (1953). Natural control of the California red scale in untreated citrus orchards in southern California. Proc. 7th Pacif. Sci. Congr., 4:255-259.

DeBach, P. and Sundby, R. A. (1963). Competitive displacement between ecological homologues. Hilgardia, 34:105-166.

DeBach, P. and White, E. B. (1960). Commercial mass culture of the California red scale parasite, Aphytis lingnanensis. Bull. Calif. Agric. Exp. Stn., No.770:1-58.

Flanders, S. E. (1947). Use of potato tubers in mass culture of diaspine scale insects. J. Econ. Entom., 40:746-747.

Flanders, S. E. (1951). Mass culture of California red scale and its golden chalcid parasites. Hilgardia. 21:1-42.

Hassell, M. P. (1978). The dynamics of Arthropod predator-prey systems. Princeton University Press, Princeton.

Hassell, M. P. (1982). What is searching efficiency? Ann. Appl. Biol., 101:170-175.

Hassell, M. P. and Varley, G. C. (1969). New inductive population model for insect parasites and its bearing on biolognical control. Natural, London, 223:1133-1137

Huffaker, C. B., Kennett, C. E. and White, E. G. (1968). Some parameters in the role of enemies in the natural control of insect abundance. in "Insect Abundance" (T. R. E. Southwood, ed.), pp. 59-75. Blackwell, Oxford.

Hughes, R. D., Jones, R. E. and Gutierrez, A. P. (1984). Short-term patterns of population change: The life system approach to their study. in C. B. Huffaker & R. L. Rabb (ed.), " Ecological Entomology", Chapter 11, pp. 310-357, Jon Wiley & Sons, Inc.

Hollig, C. S. (1959). Some characteristics of simple types of predation and parasitism. Can. Entom., 91:385-398.

Imms, A. D. (1916). Observations on the insect parasites of some Coccidae. I: On Aphelinus mytilaspidis Le Baron, a chalcid parasite of the mussel scale (Lepidzosaphes ulmi L.). Quart. J. Microsc. Sci., N. S., 61:217-274.

Luch, R. F., Allen, J. C. and Baasch, D. (1980). California red scale/Aphytis models. in C. B. Huffaker (ed.), "New Technology of Pest Control", pp.379-393, A wiley-Interscience Publication.

Marchal, P. (1909). C. R. Acad. Sci. Paris., 148:1223-1225.

Murdoch, W. W. (1973). The functional response of predators. J. Appl. Ecol., 10:335-342.

Nicholson, A. J. (1933). The balance of animal populations. J. Anim. Ecol. Suppl., 2:132-178.

Nicholson, A. J. and Bailey, V. A. (1935). The balance of animal populations, Part 1. Proc. Zool Soc. London, 551-598.

Nikol'skaya, M. N. and Yasnosh, V. A. (1966). Aphelinids of the European part of the U.S.S.R. and the Caucasus. Operd. Faun. SSSR 91. Nauka, Moscow and Leningrad, 296 pp. (In Russian).

Podoler, H. (1981). Effect of variable temperatures on responses of Aphytis melinus and A. lingnanensis to host density. Phytoparasitica, 9:179-190

Quayle, H. J. (1910). Aphelinus diaspidis Howard. J. Econ. Entom. 3:398-401.

Rosen, D. and DeBach, P. (1979). Species Of Aphytis Of The World. Kerter Publishing House Jerusalem Ltd., 801 pp.

Rosen, D. and Eliraz, A. (1978). Biological and systematic studies of developmental stage in Aphytis (Hymenoptera:Aphelinidae), I. Developmental history of Aphytis chilensis Howard. Hilgardia, 46:77-95.

Solomon, M. E. (1949). The natural control of animal populations. J. Anim. Ecol., 18:1-35.

Varley, G. C. (1947). The natural control of population balance in the knapweed gall-fly (Urophora jaceana). J. Anima. Ecol., 16:139-187.

Winston, P.W. and Bates, D. H. (1960). Saturated solutions for the control of humidity in biological research. Ecology, 41:232-237.

CHAPTER 6.

GROWTH OF *Phacelia* sp. AND ITS INFLUENCE ON *Aphytis melinus* DeBach

CHAPTER 6. GROWTH OF *Phacelia* sp. AND ITS INFLUENCE ON *Aphytis melinus* DeBach

Introduction

As described in Chapter 5, the longevity, reproduction ability, area of discovery, searching efficiency and so on, of female wasps of *A. melinus* could be distinctly reduced by the shortage of carbohydrate food supply, such as honey or nectar of citrus flowers. Huffaker (1959) noted that attempts have been made in the U.S.S.R. to improve the efficiency of *A. proclia* (Walk.) in the biological control of San Jose scale, *Quadraspidiotus perniciosus* (Comst.), by planting a *Phacelia* cover crop to provide nectar. Three crops of *Phacelia* increased the parasitism from 5% to 76%. Based on these results, the following experiment was conducted to measure the effect of *Phacelia* sp. on the potential for biological control of red scale in South Australia. This experiment was conducted under laboratory conditions of constant temperatures with artificial photoperiod.

6.1. Growth of *Phacelia* sp.

Methods

Phacelia sp. plants were grown at different constant temperatures and a fixed daylength.

This species was expected to colonize in orchards in S. Australia. In October 1984 (middle of spring), after seed-soaking for one day, they were kept at 27°C for about 2 days and were then sown on 15/10/1984. When the young plants had 2 genuine leaves on each (10th day after seeding) they were replanted individually in flowerpots, 20 cm diameter, 20 cm height. The plants grew under natural fluctuation of temperatures with a mean of 17.7°C for 2 weeks and were then removed to a plant growth room at 15°C and an artificial photoperiod of L:D=16:8 hours for 28 days. Next, the plants were removed to plant growth rooms under constant temperatures, namely, 15, 20, 24 and 28°C, with a photoperiod of L:D=16:8 h. 5 pots were put in each growth room in trays with about 2 cm depth of water. The whole process was conducted to roughly simulate a possible growth period for plants from early spring to summer.

Results and discussion

(i) Height of *Phacelia* sp.

The variation in mean height among groups of 5 plants responding to temperatures is recorded in Appendix Table 6.1 (1) and plotted against days in Figure 6.1 (1), A to D for 15, 20, 24 and 28°C, respectively. The height of the plants originally ranged from 14.4 up to 20.6 cm, which were established as thresholds under treatment-temperatures. In 21-33 days time, namely, 21 days at 24 and 28°C, 24 days at 20°C and 33 days at 15°C, plants reached their maximum height before flowering. Obviously, the number of growth days required to reach maximum height was reduced at the higher temperatures. At 28°C, plants took 21 days to reach the maximum height of 57.6 cm; by contrast, it was 33 days for plants to get the maximum height of 90.2 cm at 15°C. However, given below are the regression equations for the relationship between heights (Y: cm), started from above mentioned so-called thresholds of plants, and growing duration of days (X) at differences of constant temperatures.

15°C: $Y = 106.384 / [1 + \exp(1.679-0.109\ X)]$
20°C: $Y = 83.305 / [1 + \exp(1.556-0.193\ X)]$
24°C: $Y = 80.656 / [1 + \exp(1.453-0.200\ X)]$
28°C: $Y = 59.740 / [1 + \exp(0.595-0.203\ X)]$

Maximum plant height (Y) is plotted against temperature (X) in Figure 6.1 (2) [data from Appendix Table 6.1 (1)] giving a linear regression equation, $Y=127.01-2.38X$ ($r= -0.9747$; d.f.=2; $P<0.05$). The regression indicates that maximum height is a linear function of temperature: the higher the temperature, the shorter the plant.

The above measurements suggest that *Phacelia* sp. could be planted in mid-spring and grow well into summer since during this period the mean temperatures ranged from 15.6°C up to 22.1°C (Biennial report, 1982-1983. Waite Agri. Res. Inst.). They could grow in summer under irrigation though they would grow better in the cooler seasons such as spring and autumn. As an assumption, that to grow *Phacelia* sp. in orchard in S. Australia throughout the period from early spring till late autumn might be a great help to *Aphytis* female wasps on the host-feeding and parasitism on red scales.

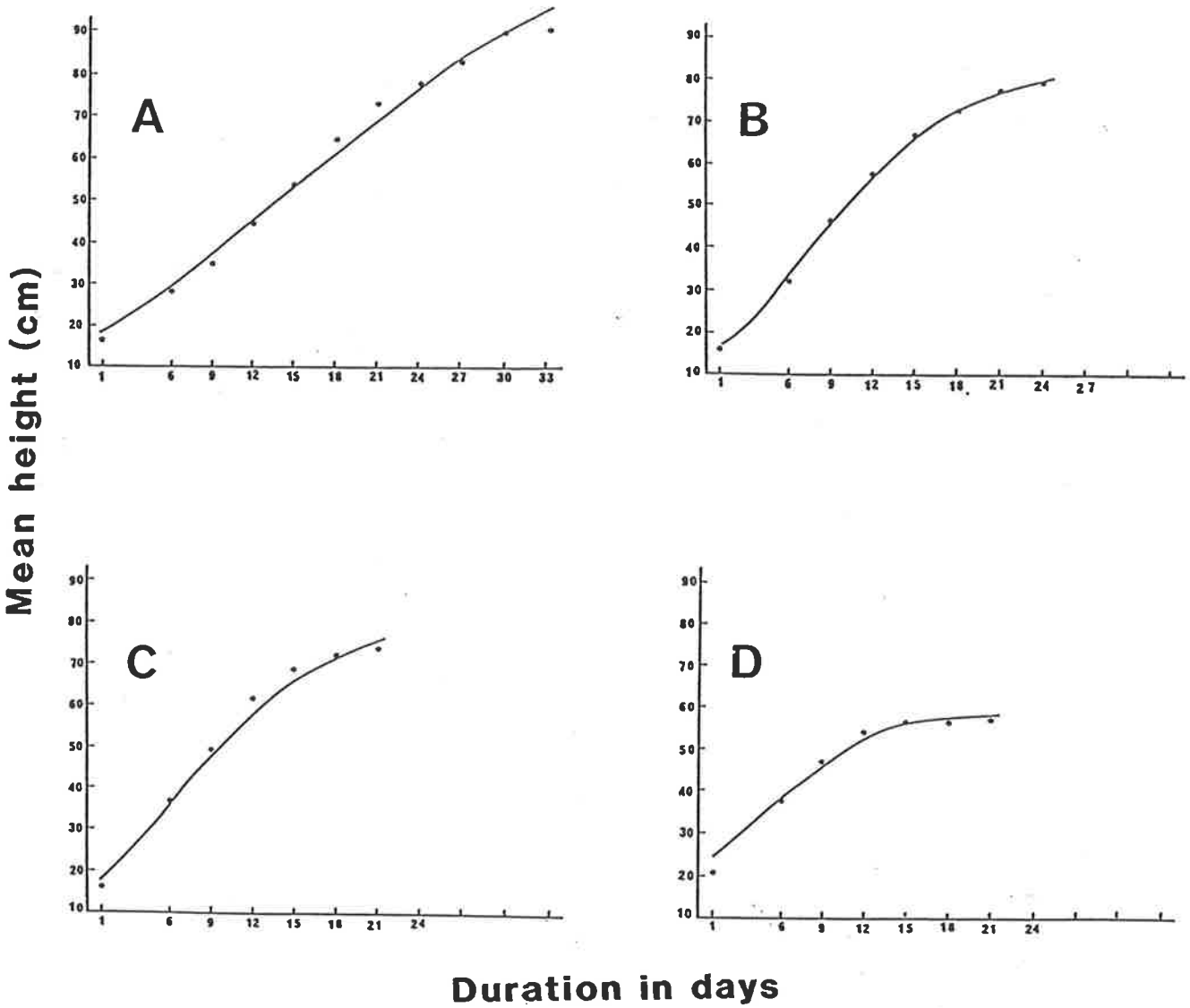


Figure 6.1 (1). The variations of mean height (cm) of Phacelia sp. in relation to growing durations (days) at different constant temperatures.
A: at 15°C; B: at 20°C; C: at 24°C; D: at 28°C.

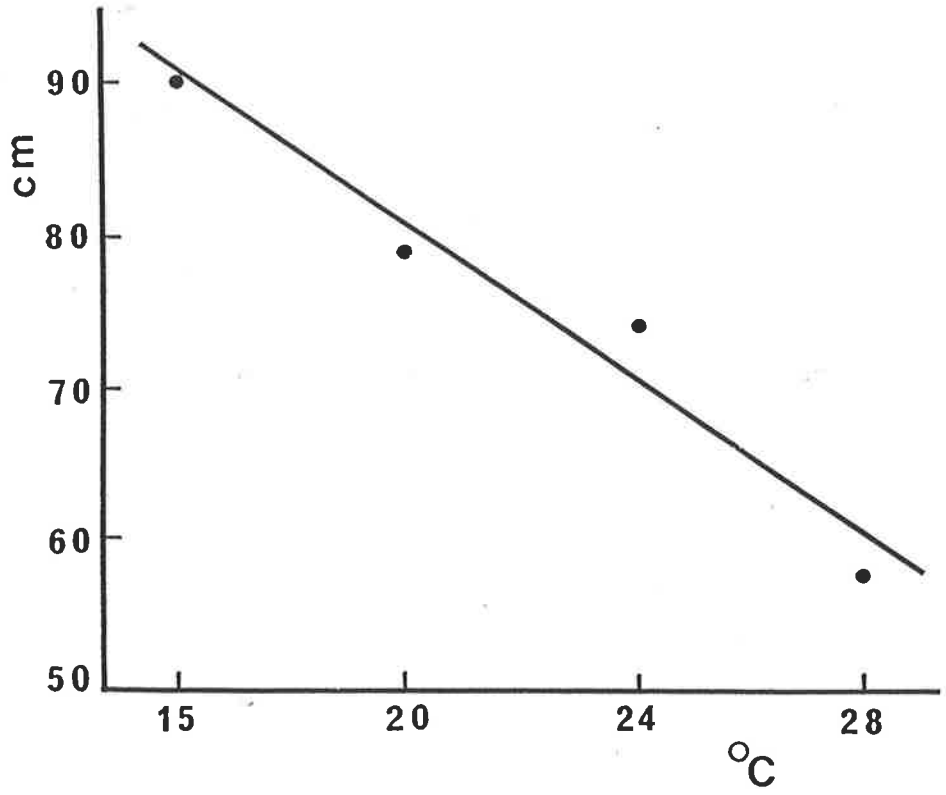


Figure 6.1 (2). The relationship between the maximum height (Y) in cm of Phacelia sp. plants and constant temperatures (X) in °C, with the artificial photoperiod of L:D=16:8 hours.

$Y = 127.01 - 2.38\ X$ ($r = -0.9747$, $P<0.05$)

(ii) Mean number of inflorescences

Plants of Phacelia sp. had one indefinite inflorescence on each of the effective tillers. The mean numbers (mean of 5 plants) of inflorescences per plant at each temperature are shown in Table 6.1 (1). As in the case of plant height, the number of inflorescences per plant is also a function of temperature. After plants had been removed from 15°C into each of the 4 treatment constant temperatures, most of the inflorescences (6–7 inflorescences per plant) appeared in one week. By contrast, appearance times of all the inflorescences were quite different, namely, 8.8 inflorescences by the 18th day at 28°C, 11.4 by the 21st at 24°C, 8.6 by the 21st at 20°C, and 10.4 by the 27th at 15°C.

Obviously, Phacelia sp. plants had definite effective tillers with similar appearance time. This suggested it was necessary to seed several batches of Phacelia sp. throughout the main infestation period of red scale in order to provide a sufficient nectar source for wasps of Aphytis in nature. The interval of seeding could be determined by the time at which about 50% of the total flowers of the indefinite-inflorescences had processed. For further details, see later sections.

(iii) Numbers of the accumulated total and the fresh flowers

Since the total flower numbers of each of the inflorescences on each plant were similar, the total numbers of flowers were only measured on the inflorescences of each main stem (one for each plant) of the plants; the mean (mean of 5 plants at each temperature) data are given in Appendix Table 6.1 (2).

Unfortunately, I have data obtained at temperatures of 20, 24 and 28°C only; I lost data at 15°C because the air conditioner broke down 10 days after the appearance of the first flower. The mean total flower numbers are plotted against durations (days) after the first flower had presented in Figure 6.1 (3), namely, A at 20°C, B at 24°C and C at 28°C. And obtained from Appendix Table 6.1 (2), again, the duration of the flowering period at different temperatures are given in Table 6.1 (2); also given in Table 6.2 (2) are the regression equations of relationship between accumulated numbers of flowers and durations (days) of flowering periods. However, as shown in Table 6.1 (2) and Figure 6.1 (3), A at 20°C, B at 24°C, and C at 28°C, durations of flowering were similar (range 25–27 days) at the different temperatures and plants had the same requirement of 13 days for the accumulation of 50% of the total flowers at all 3 testing temperatures.

Table 6.1 (1). Mean numbers (mean of 5 plants) of inflorescences per Phacelia sp. plant at different constant temperatures, with the artificial photoperiod of L:D=16:8 hours. (From 30/11/84).

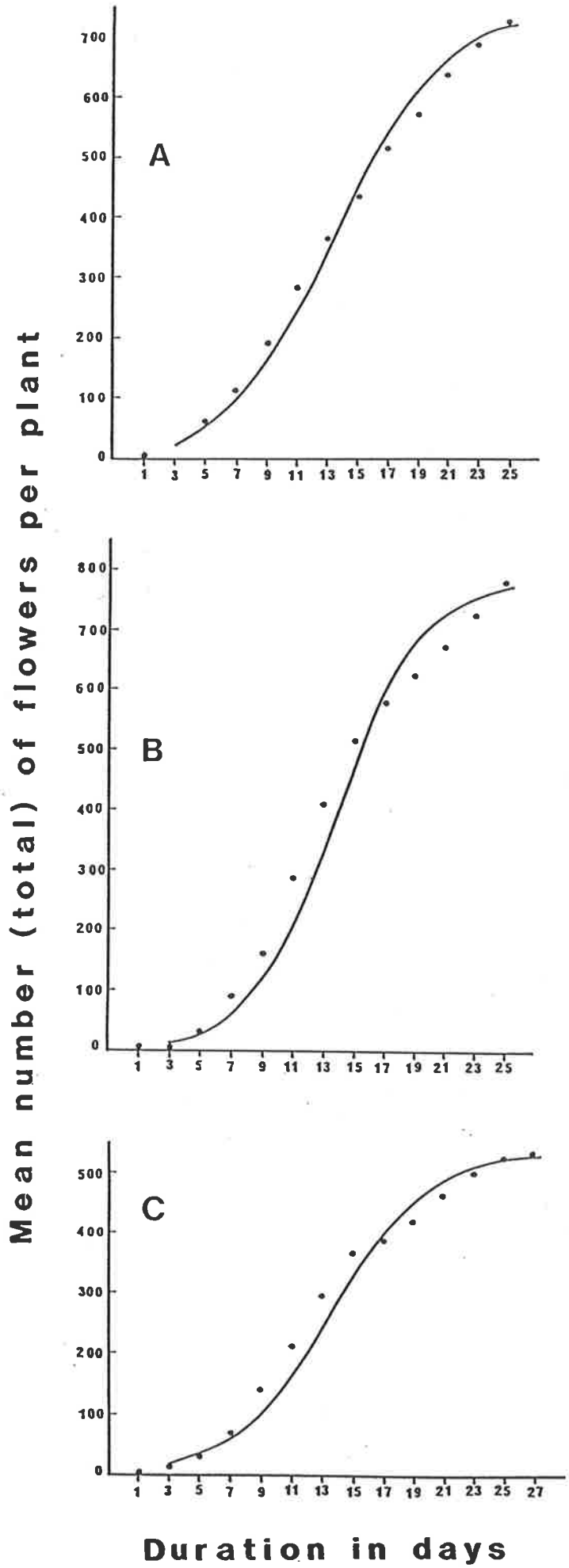
Day	At temperature (°C):			
	15	20	24	28
1	1.0	0.4	0	1.6
7	7.6	6.2	7.4	7.6
12	8.4	7.6	9.0	8.6
15	8.4	7.8	10.8	8.8
18	9.6	8.6	11.4	8.8
21	10.0	8.6	11.4	
24	10.4			
27	10.4			

Table 6.1 (2). Duration in days (Durat.) of flowering period of Phacelia sp. at different constant temperatures (in °C), with the artificial photoperiod of L:D=16:8 hours; also given are the observed required days to accumulate 50% of total flowers (D:50%) and regression equations of the relationship between flower numbers (Y) and duration days (X) of flowering process

°C	Durat.	D:50%	Equations
20	25	13	Y=749.926 / [1 + exp(3.856-0.279X)]
24	25	13	Y=786.963 / [1 + exp(4.968-0.358X)]
28	27	13	Y=545.092 / [1 + exp(4.084-0.297X)]

Figure 6.1 (3). The mean total flower numbers of Phacelia sp., mean of 5 plants, against duration of the flowering period in days at different constant temperatures in °C, with the artificial photoperiod of L:D=16:8 hrs.

A: at 20°C;
B: at 24°C;
C: at 28°C


A
B
C
Mean number (total) of flowers per plant
Duration in days

Subsequently, since flowers could hardly remain as fresh for more than 2 days under temperatures of 20-28°C, the following measurement was conducted for the relationship between numbers of the so-called fresh flowers and duration of flowering time of plants. The mean numbers of flowers remaining fresh were observed once every 3 days; data are given in Appendix Table 6.1 (3) and are plotted against time after the appearance of the first batch of flowers in Figure 6.1 (4). Mean numbers of fresh flowers per main stem per plant showed ranges as follows: 0.4-107.2 at 20°C, 0.4-126.4 at 24°C and 3.2-73.8 at 28°C. However, after the first flowering, the numbers of fresh flowers increased rapidly in one week to reach values which were about 1/2 of the maxima [Fig.6.1 (4)]. The maxima of fresh flowers were observed about two weeks after the start of flowering, namely, 107.2 by the 11th-day at 20°C, 126.4 by the 13th-day at 24°C and 73.8 by the 11th-day at 28°C. The maximum at 28°C was about 70% of that at 20 and 24°C. This indicated, again, that plants of Phacelia sp. would grow better in relatively cool times of year than in the summer. Subsequently, in another two weeks time, plants finally ended the flowering process. Furthermore, as shown in B and C of Figure 6.1 (4), starting at day 17-19, the numbers of fresh flowers went up again because of being joined with newly formed small inflorescences on the main stems. This increase lasted only a short period of 4-5 days and subsequently led to the end of the whole flowering process.

The above measurements suggested an interval of about 2 weeks for seeding Phacelia sp. for a continuous supply of nectar to Aphytis wasps.

(iv) Production of nectar

Measurement was done only on the variation of the production of nectar during the so-called "day-time".

Methods: The measurement of volumes of nectar was carried out under a x10 microscope. Flowers were individually pinned to a dissecting dish with wax layer. After the top petal had been carefully torn away with fine forceps, the nectar on the base of the ovary was sucked into a 1-microliter "Microcaps" micro-pipette (made in U.S.A. by Drummond Scientific Co.) by capillarity.

Within one day, nectar was measured at intervals of 1.5-2.0 hours from 8:00 a.m. till 6:00 p.m. The plants were given a long-day photoperiod of L:D=16:8, set to start at 8:00 a.m. The measurements were started at 8:00

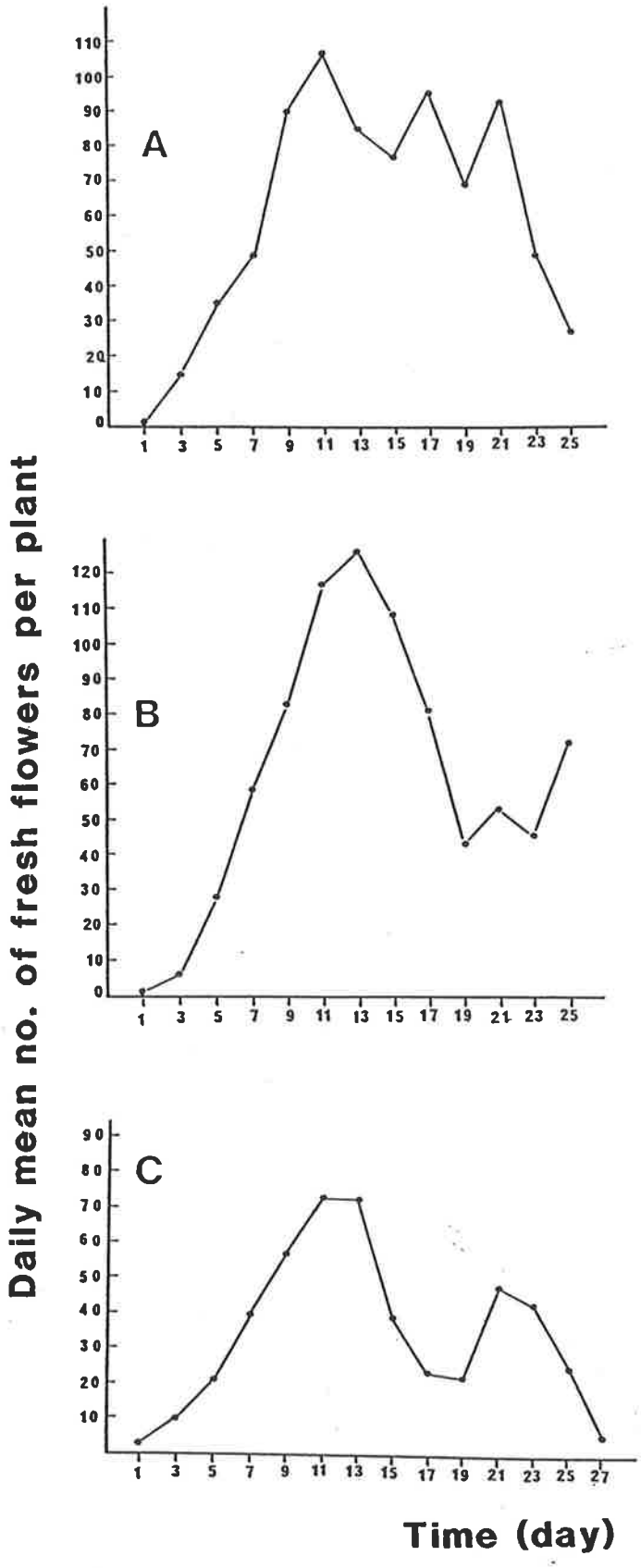


Figure 6.1 (4). Daily mean numbers of fresh flowers of Phacelia sp., mean of 5 plant, at different constant temperatures in °C, with the arificial photoperiod of L:D=16:8 hrs.
A: at 20°C; B: at 24°C; C: at 28°C;

a.m. 5 samples from each of the 4 test temperatures were measured, the last at 6:00 p.m., 2 hours before the end of the photoperiod.

Each sample consisted of 7 flowers. At each sampling time, nectar volume was measured on 7 batches of 4 flowers, 1 flower from each temperature in each batch. In this way the 4 samples were measured over the same period of time, as far as possible. The mean volumes of nectar of the 7 flowers from each temperature were then calculated.

Results: The mean volume of nectar per flower is given in Appendix Table 6.1 (4) and plotted against sampling time in Figure 6.1 (5). At all the experimental temperatures, the production of nectar represented a similar reduction trend after so-called sunrise; but during the period between 8:00 a.m. and 6:00 p.m., they never reached zero value. Clearly, the smallest volume of nectar produced at highest temperature of 28°C at any time. But it was somewhat different at other temperatures. At 20°C and 24°C, production of nectar reduced rapidly in 2 hours after so-called sunrise; then, rose again to reach a new peak at time 5 hours after sunrise at 24°C, but 8 hours at 20°C; respectively, from the peaks, the production of nectar dropped down again. It was of interest that at 15°C and 28°C, the drop in production could be predicted by a linear regression equation; by contrast, the production of nectar was not a linear function of time after sunrise at 20°C and 24°C respectively. However, the linear regressions, at 15°C and 28°C, of the relation between volumes of nectar and time after "sunrise" are given in Table 6.1 (3).

Obtained form the above analyses, it was clear that the nectar of Phacelia sp. could be an efficient food source for Aphytis wasps since it was available for most of the day.

6.2. Influence of Nectar on Female Wasps of A. melinus

6.2.1. On longevity

Methods: In the control Treatment 1, wasps were provided with water only. Flower-nectar of Phacelia sp. was provided to female wasps of A. melinus in Treatment 2 to test the null hypothesis that the nectar had no effect on survival.

One-day-old wasps were sucked into collection tubes (see Chapter 3), 4 wasps per tube. 16 tubes were filled, 8 supplied with nectar, 8 as controls.

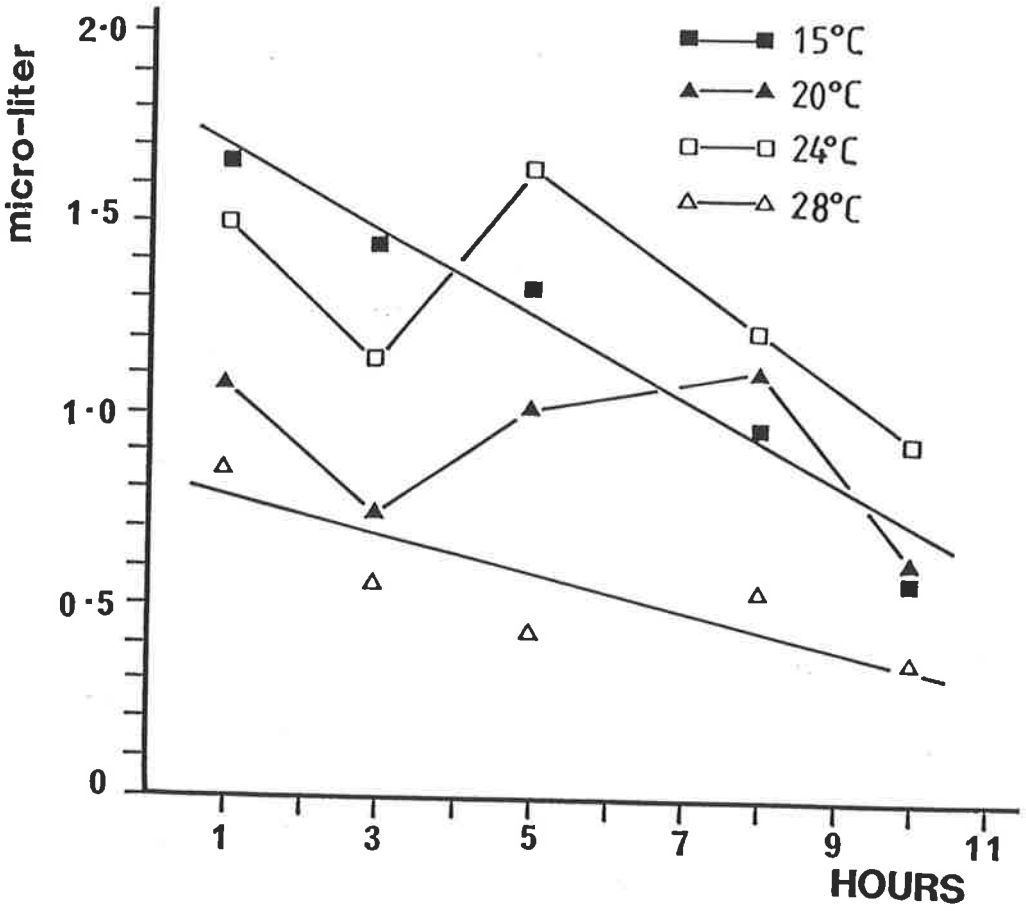


Figure 6.1 (5). The relationship between the mean volumes (micro-liter), mean of 7 flowers, of flower-nectar of Phacelia sp. and time (hours) after sunrise, which was set up at 8:00 of an artificial photoperiod of L:D=16:8 hrs.

Table 6.1 (3). Statistics of linear regression of the mean volume (Y), micro-litre, of nectar per flower (mean of 7 flowers) at 15°C and 28°C on time (X) of hours (range 1-10 hours) after the so-called sunrise, started at 8:00 a.m. for the artificial photoperiod of L:D=16:8 hours.

Tem.(°C)	Intercept	Slope	d.f.	r	P
15	1.82	-0.11	3	-0.9848	<0.01
28	0.84	-0.05	3	-0.9295	<0.05

Nectar was collected with micropipettes and placed on the wall of each of the 8 tubes. All the collection tubes with wasps were kept at constant temperature of 25°C and 60% R.H.

Observations of death of wasps were carried out once each day in the first 5 days; once every 2 days from the 6th day until all wasps were dead in the nectar tubes in Treatment 2.

Results and discussion: Data on the death of wasps are given in Appendix Table 6.2 (1) and plotted against the observation time in Figure 6.2 (1). All the wasps in the control Treatment 1 died within 3 days (mean 1.5±0.1, range 1-3). By contrast, in Treatment 2 some wasps fed on nectar lived as long as 28 days (mean 18.8±0.9, range 6-28); none died in the first 5 days. The regression equation, $Y=115.510/[1 + \exp(5.256-0.266X)]$ describes the relationship between accumulated percentage dead wasps (Y) and time (X). However, even though the longevity of wasps fed on nectar was about 4 times longer than that of wasps surviving on host-feeding only (see Sections 5.1 and 5.2), it was still much shorter than the longevity of 29.8 days obtained from wasps fed on honey (Abdelrahman 1974b). As a conclusion, the nectar of Phacelia sp. was not considered so good as honey for the survival of wasps of A. melinus; but was much more efficient than host-feeding on red scale.

6.2.2. On searching efficiency of wasps

The present experiment was conducted to assess the null hypothesis that the nectar of Phacelia sp. was not so efficient as honey on the searching efficiency of A. melinus on red scale. Actually, this experiment was a part of experiments described in Section 5.4. Hence, all the designs were same as in Section 5.4.

Methods: The treatment to wasps of A. melinus was the combination of densities of host red scales and host fruits for each density of red scales. In each of the 3 replications (big cages), 5 pairs of one-day-old wasps (5 males and 5 females) were kept at 25°C and 60% R.H. for 5 days for the measurement of the searching efficiency of wasps. However, see Section 5.4 for details.

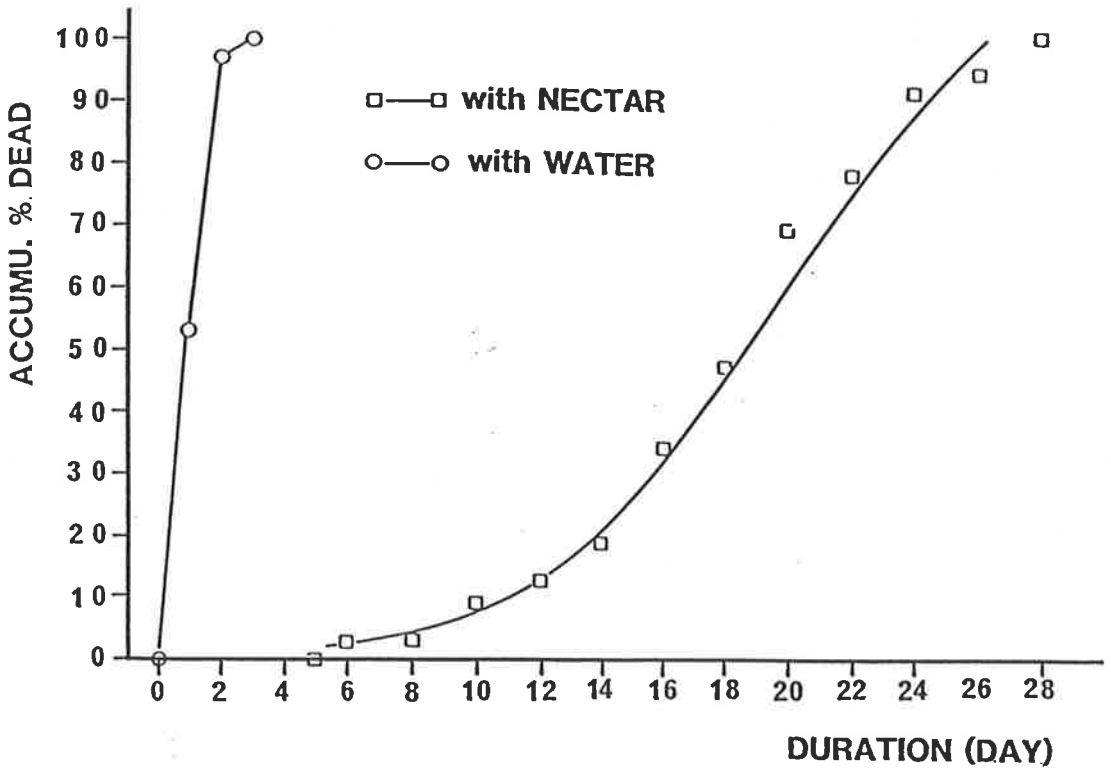


Figure 6.2 (1). The accumulated % dead rates of wasps of Aphytis melinus against the survival time (in days) at 25°C and 60% R.H.

Table 6.2 (1). Data of the death and parasitism of red scales in the present experiment and in Experiment 6 (Exp.6) in Section 5.4, in which wasps fed on honey.

Experiment	Total no. of scales	Total dead no. of scales*	% rate of in scales:		
			parasitized	dead	total
present	192	27	6.25	7.81	14.06
Exp. 6	192	52	19.79	7.29	27.08

*: sum of the dead and the parasitized.

Results and discussion: Data of parasitism and death (due to host-feeding) of red scale in each of the 3 replications are given in Appendix Table 6.2 (2). Obtained from this table, a total of 14.06% scales died (7.81% due to host-feeding and 6.25% due to parasitism). The death rate and parasitism rate were not significantly different from each other. These data are compared with the results of Experiment 6 in Section 5.4. In these two experiments (Exp.), conditions were all the some except for the differences of foods for wasps: in Experiment 6, wasps were provided with honey as food and it was nectar in the present experiment. The comparison is presented in Table 6.2 (1). They were not much different from each other in percentage dead due to host-feeding; but significantly different in percentage parasitism. Wasps fed on honey caused more than twice the parasitism of red scales than did wasps fed on nectar of Phacelia sp. Since citrus nectar had been considered to be an excellent food, as good as honey or even better, for Aphytis (Gerson 1968; Avidov et.al. 1970), the above analysis suggests that the flower-nectar of Phacelia sp. is not as good as citrus nectar.

Furthermore, since the purpose of growing Phacelia is to provide a continuous food supply to Aphytis wasps, I recommended the method of artificially placing honey on trees in orchards instead of growing Phacelia when citrus flowers are absent. If the honey could be well protected from the consumption of other insects, I believe that this method could be more conveniently used for the control of red scale in orchards.

REFERENCES

Abdelrahman, I. (1974). Growth, development and innate capacity for increase in Aphytis chrysomphali Mercet and A. melinus DeBach, parasites of California red scale, Aonidiella aurantii (Mask.), in relation to temperature. Aust. J. Zool., 22:213-230.

Avidov, Z., Balshin, M. and Gerson, U. (1970). Studies on Aphytis coheni, a parasite of the California red scale, Aonidiella aurantii, in Israel. Entomophaga, 15:191-207.

Gerson, U. (1968). The comparative biologies of two hymenopterous parasites of the chaff scale, Parlatoria pergandii. Entomophaga, 13:163-173.

Huffaker, C. B. (1959). Notes on entomology in the USSR (unpublished). Taken as a member of the U.S. Agricultural and Technical Exchange Delegation in Entomology in USSR, 1959.

CHAPTER 7.

SEASONAL ABUNDANCE OF CALIFORNIA RED SCALE

CHAPTER 7. SEASONAL ABUNDANCE OF CALIFORNIA RED SCALE

7.1. Introduction

To understand the population regulation of red scale, studies on the seasonal fluctuations in numbers of both red scale and its natural enemies, especially Aphytis parasitoids, have been made in many parts of the world by many people (DeBach et al 1950, 1960, 1971, 1978; DeBach 1958, 1965, 1969; Ebeling 1959; McLaren 1971; McLaren et al 1973; Atkinson 1977, 1983a, b; Maelzer 1979; Reeve & Murdoch 1985; and others) but such detailed information has never been obtained for the local population of red scale and its natural enemies in the experimental orchard at the Waite Institute in Adelaide, South Australia. Such data were needed to compare with other studies of red scale in Australia, namely in Victoria by McLaren (1971) and McLaren et al (1973); in Queensland by Smith (1978); at Loxton, S. Australia by Maelzer (unpublished). In particular, there are a very large number of citrus trees in the metropolitan area of Adelaide and Adelaide has a different climate to the horticultural area along the River Murray in S. Australia which is called the Riverland and includes the towns of Waikerie, Berri, Renmark and Loxton [Fig.7.1 (1)]. The Riverland is in the arid zone of Australia. It's climate is characterized by very hot summers, cold winters, and an annual rainfall of 250 mms. It is, however, the center of commercial production of citrus in S. Australia, aided by irrigation from the River Murray. By contrast, Adelaide has milder summers and winters and an annual rainfall of 530 mms.

In the experimental orchard at the Waite Institute the annual rainfall is also supplemented by irrigation over summer but, because of it's milder climate, the population regulation of red scale is likely to be quite different from that in the Riverland. The annual average daily temperature was about 16.5°C, mean between 1925-83; the extremes of temperatures had ever been recorded were 44.3°C the highest in January and 0.9°C the lowest in June (Biennial report, 1982-83, of the Waite Institute). Accordingly, the annual day-degree (D.D.) sum >12°C (see Atkinson, 1977) available for the development of red scale is (16.5-12)x365=1642.5 (D.D.). Thus red scales may be able to complete about 3 generations each year in this orchard.

My study therefore involved the fluctuations of numbers of red scale and its natural enemies, especially Aphytis melinus, in the Waite Institute. One of its purposes was to evaluate the role of various

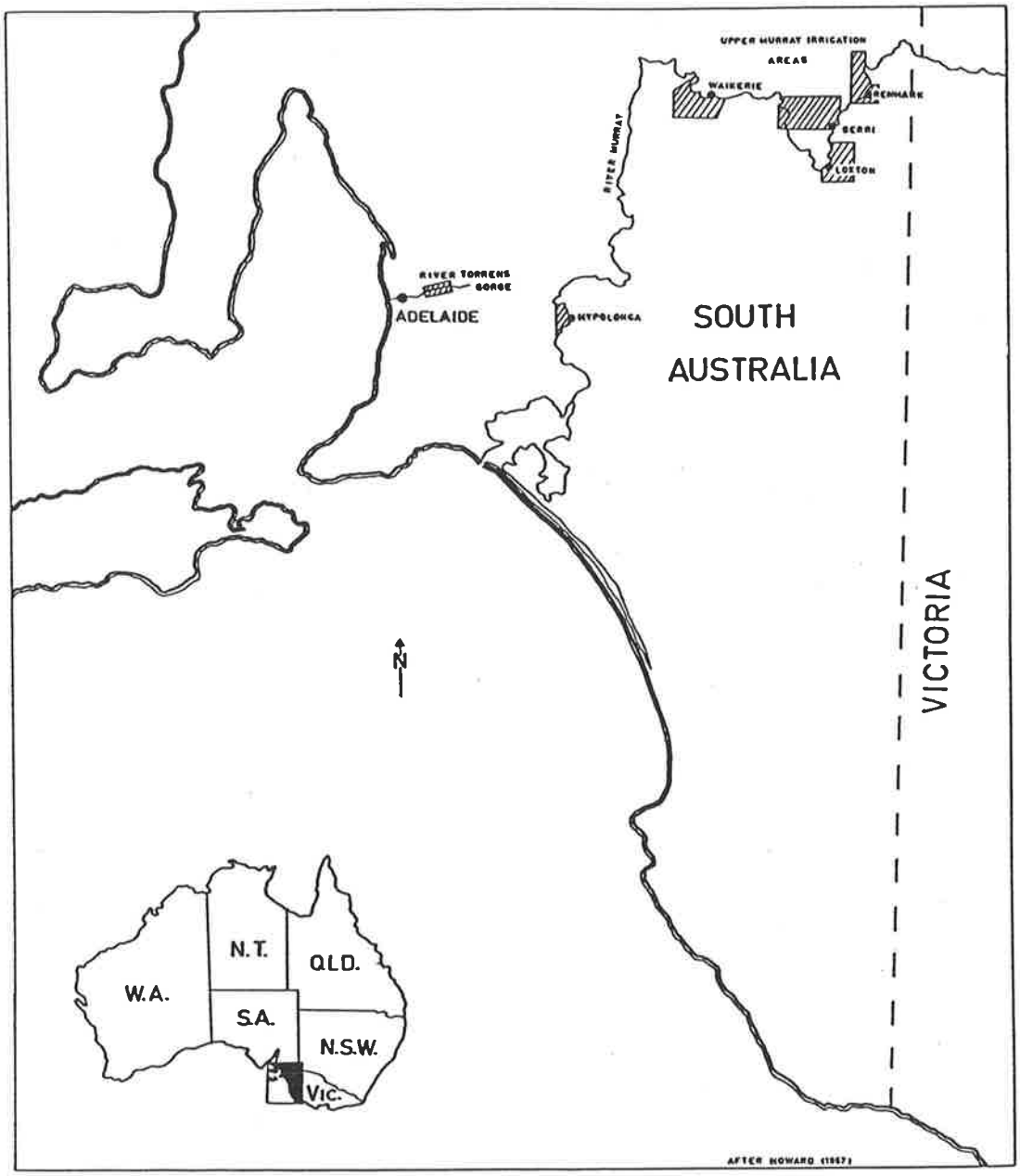


Figure 7.1 (1). Growth regions of citrus in South Australia.

mortality factors in the population dynamics of red scale. Such study was necessary for the proper planning of future experiments to measure the degree of control exerted by natural enemies on the red scale population.

7.2. Study Orchard and Sampling Method

7.2.1. Study Orchard

To evaluate the influence of natural enemies, DeBach, Huffaker and MacPhee (1976) suggest that population levels of both prey and natural enemies must be measured over a number of generations on some common basis. Consequently, my study was conducted through the period May 1984 to March 1986.

A. melinus had been released in the Waite Institute orchard many years earlier and had been maintained without insecticidal sprays for most of that time. The orchard comprised 3 adjacent rows of citrus trees, one of Washington Navel oranges, one of Valencia oranges, and one of Lisbon lemons. The trees were about 12 years old but were maintained at a height of about 3 m. They were fertilized with the usual fertilizers for commercial citrus production, and were irrigated over summer using under-tree micro-sprinklers with mains water which was a mixture of River Murray water and rainwater from the Adelaide catchment area. This study was confined to red scale on the row of lemon trees.

Ambient temperature was measured with a thermohygrograph in a Stevenson screen in the orchard.

7.2.2. Sampling method

7.2.2.1. Distribution of red scale on lemon trees

The choice of a sampling method for red scale and its parasitoids depends on the distribution of red scale within and between potential sampling units. A sampling method of red scale was devised by D.A. Maelzer (unpublished) in the Waite Institute, S. Australia. He accepted the suggestion from Atkinson's (1977) study in S. Africa that the population processes on fruits, leaves and twigs were similar and that therefore it sufficed to sample fruits only to get relative numbers of red scale and its parasitoids at each sampling date. Maelzer also discussed the results of a sampling experiment in terms of the relationship between the sample size and the cost of the sample as time consumed. He suggested that an optimum sample size of 4 fruits from each of 15 trees gave a precision of about 25% and at a cost of 48 man-hours or 3 man-hours per tree. However, I could

not afford the cost of such a large sample and since he had suggested that the variability of red scale numbers was not significantly different between trees, I considered it was suitable for me to spend 9 man-hours on 4 lemons from each of 3 trees for each sample of red scale and its natural enemies.

However, since Maelzer's data came from oranges at Loxton, and my study was to be on lemons in Adelaide, it was initially necessary for me to also do a sampling experiment in which one of the prime objectives was to test the null hypothesis that, in the Waite Institute orchard, red scales had a random distribution on lemons on trees. For this purpose, a total of 24 lemons were chosen from a tree at random. The lemons came from different parts of the canopy: 12 lemons from the interior part and another 12 from the outer canopy. One lemon was picked from each of the 3 different heights, namely, top, middle and bottom of the tree canopy, and from each of the 4 compass directions, namely, N. S. E. and W.

7.2.2.2. Subsampling method

On each lemon, 4 long axes were chosen at random. Along each axis, a number of circles, each 1.5 cm diameter, were marked (one by one) on the skin. The numbers of red scales were then counted within each circle.

7.2.2.3. Results of the sampling experiment

The numbers of observation circles on each lemon and the total number of scales are given in Appendix Table 7.2 (1) for lemons from the inner canopy and in Appendix Table 7.2 (2) for the outer canopy. Also given in these tables were the mean numbers of scale per observation circle. They ranged between 1.17 and 18.16 for the inner canopy and between 1.75 and 10.36 for the outer. An ANOVA was conducted to test the null hypothesis that the mean numbers of red scale were the same among the 4 aspects and at the 3 different heights on the canopy.

To examine the trend in numbers more easily, the mean numbers of scale insects per observation circle were rearranged as in Appendix Table 7.2 (3). The results of the ANOVA are given in Table 7.2 (1) and indicated that there was no difference between heights or between the inner and outer canopy ($P>0.05$). However, the F value was significant for aspects, so the means for aspects are compared in Table 7.2 (1a). The comparisons indicated that West was significantly greater than East. However, since West was not different from North or South, and North and South were not

Table 7.2 (1). Analysis of variance, ANOVA, of mean numbers of red scales per observation circle (15mm diameter) on lemons (for 4 aspects x 3 heights x 2 canopy parts).

Source of variation	Sum of squares	d.f.	mean squares	F
Canopy	24.99	1	24.99	1.76
Height	22.14	2	11.07	0.78
Aspect	146.41	3	48.80	3.44
Error	241.11	17	14.18	
Total	434.65			

Table 7.2 (1a). Totals and means of scales for L.S.D.-test on the comparison of any two aspect-means.

Aspect	No. of samples	No. of scales on each aspect	
		Total	Mean
North	6	36.33	6.06
South	6	32.06	5.34
East	6	18.80	3.13
West	6	59.86	9.98

(I). t(0.05) for 10 d.f.= 2.228

so, LSD (0.05)=2.228 x $(2x14.18/6)^{0.5}$=4.84

(II). So, comparing means of aspects of L.S.D. for difference between any 2 means:

West(9.98) North(6.06) South(5.34) East(3.13)

different from East, I decided that it would be suitable to regard aspects as not significantly different and therefore to take the same number of fruit from each aspect. Also, for convenience, the fruit would be taken from the outer part of the canopy.

7.3. Field Sample of Red Scale

7.3.1. Sampling techniques

My study was expected to assess a natural population of red scale on lemons. So lemons were not harvested and fallen lemons on the ground were not removed from the study orchard because these acts might have had an important effect on the rate of growth of the population of red scale and/or its parasitoids. Similarly, because of the small number of trees in the orchard, care was taken not to interrupt the life cycles of red scale or its parasitoid enemies.

The mean and range of the ambient temperature for each sampling interval are given in Table 7.3 (1); given in Table 7.3 (1a) are the daily mean temperatures (means of 1925-83) in the Waite Institute (Biennial Report 1982-83, Waite Agri. Res. Inst.). Shown in Table 7.3 (1), the mean ranged between 11.7°C (5/5-25/8, 1985) and 24.3°C (27/1-3/2, 1985); the lowest temperature was 3°C in interval 2 (4/5-22/7, 1984) and the highest temperature was 41°C in interval 13 (27/1-3/2, 1985). The highest temperature of 41°C was 5-8°C lower than that required for the LD50's for all stages of scale insects (Abdelrahman 1974); the lowest temperature of 3°C was 3-7°C lower than that similarly estimated for LD50's by Abdelrahman (ibid). The influence of the mean and extremes of temperature in each observation interval on the mortality of red scale will be assessed in the following sections.

Population data of red scale were obtained from a periodic sample from three lemon trees (see Section 7.2). From each tree, one lemon was randomly sampled from each of the 4 directions, namely, north, south, east and west; from these 12 lemons, scale insects were assessed to be alive, dead and/or parasitized by turning over the scale cover of each insect. The samples of red scale were carried out with an interval about 95 day-degrees (D.D.) >12°C between sampling dates [Table 7.3 (2)]; which was an accumulated value of the deviation of the daily mean ambient temperature (from a Stevenson Screen) and the constant 12°C.

Table 7.3 (1). Daily mean and extreme temperatures (°C) in each observation interval, sampling interval, in the orchard of Waite Institute.

NO.	Interval	Highest	Lowest	Mean
2	4/5-22/7/84	24	3	13.2
3	23/7-4/10	25	5	12.4
4	5-23/10	31	8	16.2
5	23/10-8/11	32	9	17.9
6	9-19/11	36	12	20.9
7	20/11-6/12	36	9	17.5
8	7-16/12	35	11	21.8
9	17-28/12	36	11	19.9
10	29/12/84-11/1/85	36	11	19.4
11	12-19/1	40	11	22.9
12	20-26/1	38	11	22.5
13	27/1-3/2	41	12	24.3
14	4-13/2	33	11	23.6
15	14-24/2	34	12	21.3
16	25/2-9/3	34	10	18.8
17	10-17/3	37	14	26.3
18	18-30/3	31	13	19.9
19	31/3-14/4	32	10	19.7
20	15/4-4/5	28	10	16.8
21	5/5-25/8/85	26	4	11.7
22	26/8-6/10	27	4	13.2
23	7-29/10	28	6	15.5
24	30/10-12/11	30	8	19.1
25	13/11-1/12	32	10	17.1
26	2-18/12	31	10	18.1
27	19/12/85-3/1/86	35	9	17.7
28	4-15/1	34	10	19.6
29	16-27/1	29	10	19.6
30	28/1-7/2	37	10	21.3
31	8-16/2	37	11	22.7
32	17/2-2/3	36	13	20.3
33	3-12/3	40	12	21.8

Table 7.3 (1a). Daily mean temperature (means of 1925-83) in the Waite Institute, South Australia. (Biennial Report 1982-83, Waite Agri. Res. Inst.).

Month	Average daily (°C)		
	Maximum	Minimum	Mean
January	27.9	16.4	22.1
February	27.7	16.5	22.1
March	25.5	15.4	20.5
April	21.4	12.9	17.2
May	17.8	10.7	14.2
June	15.1	8.6	11.8
July	14.2	7.8	11.0
August	15.2	8.1	11.7
September	17.6	9.4	13.5
October	20.3	10.9	15.6
November	23.4	12.8	18.1
December	25.8	14.7	20.3
Year	21.0	12.0	16.5

Table 7.3 (2). Day-degrees >12°C of each sampling interval (interv.). 4/5/84-11/3/86.

Sampling interval	Date	Day-degrees of:		
		Each interv.	Accum.*	Accum.**
2	4/5-21/7/84	85.5	-	-
3	22/7-/3/10	65.9	-	-
4	4/10-22/10	80.8	80.8	80.8
5	23/10-7/11	93.9	174.7	174.7
6	8/11-18/11	110.2	284.9	284.9
7	19/11-5/12	93.7	378.6	378.6
8	6/12-15/12	98.4	477.0	477.0
9	16/12-27/12	94.9	571.9	571.9**
10	28/12/84-10/1/85	103.5	675.4	103.5
11	11/1-18/1	87.1	762.5*	190.6
12	19/1-25/1	83.4	83.4	274.0
13	26/1-2/2	98.6	182.0	372.6
14	3/2-12/2	116.3	298.3	488.9
15	13/2-23/2	101.8	400.1	590.7**
16	24/2-8/3	87.9	488.0	87.9
17	9/3-16/3	114.2	602.2	202.1
18	17/3-29/3	102.8	705.0	304.9
19	30/3-13/4	115.0	820.0	419.9
20	14/3-3/5	96.5	916.5	516.4
21	4/5-24/8	71.8	988.3	588.2**
22	25/8-5/10	82.1	1070.4*	82.1
23	6/10-28/10	85.9	85.9	168.0
24	29/10-11/11	99.7	185.6	267.7
25	12/11-30/11	97.2	282.8	364.9
26	1/12-17/12	103.9	386.7	468.8
27	18/12/85-2/1/86	92.8	479.5	561.6**
28	3/1-14/1	90.4	569.9	90.4
29	15/1-26/1	91.1	661.0*	181.5
30	27/1-6/2	102.4	102.4	283.9
31	7/2-15/2	96.4	198.8	380.3
32	16/2-1/3	115.9	314.7	496.2
33	2/3-11/3	98.4	413.1	594.6**
mean		95.6±2.1(SE)		

*: day-degrees (>12°C) for the development of each observed generation of California red scale.
**: day-degrees (>12°C) for the development of each theoretical generation of California red scale (see Atkinson 1977).

7.3.2. Results and discussion

The series of samples started on 3/5/84 (autumn) and ended on 12/3/86 (late summer), with an interval of about 95 day-degree >12°C between the samples. An interval of 95 day-degrees is almost long enough for 3rd instar female scale insects to complete their development and is about 2/3 of the requirement of development for other stages (Atkinson 1977).

A total of 33 samples was assessed and the 32 intervals between them were numbered in sequence for convenience. The first interval was denoted "No.2" and the last "No.33" so that each numbered interval corresponded to the number of the sample that followed it.

Sample data were expressed as log [(numbers of scales in 100 observation circles) + 1] and were denoted the "log total numbers" or "log live scales". The log total numbers (sum of dead and alive) of each stage of red scale are given in Appendix Table 7.3 (1). Log live scales data for each stage are give in Appendix Table 7.3 (2). One sample (No.4) could not be taken and so, in these two tables, the mean values of samples 3 and 4 were used instead of the missing data of sample 4 for the statistical analyses in the sections below.

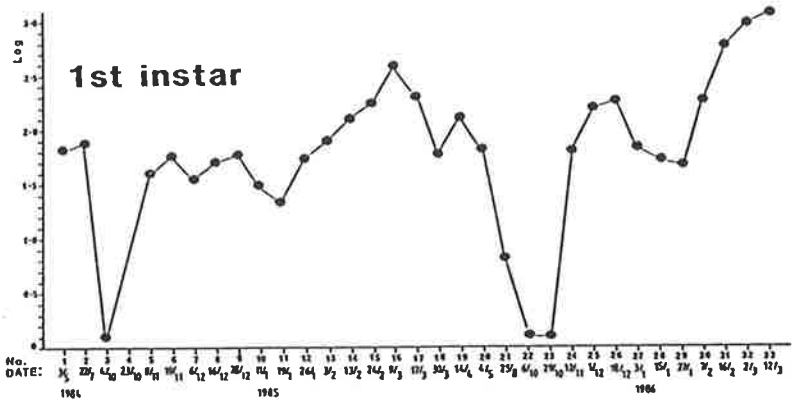
The total numbers of red scale per 100 observation circles and percentage dead and parasitism of each stage of red scale are calculated from the original observations and are given in Appendix Tables 7.3 (3)-7.3 (8).

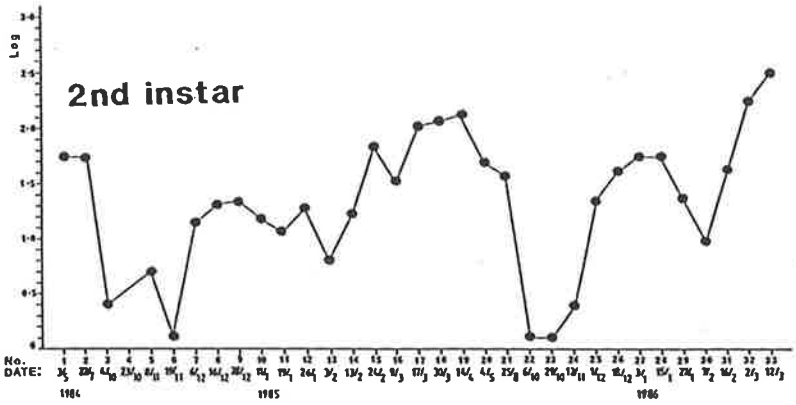
7.3.2.1. Establishment of annual generations of red scale

The data for all stages of live scales are re-arranged in Figure 7.3 (1) for the analysis of the timing, through the year, of the generations of red scale in the Waite Institute orchard. The day-degree sums for each observation interval are given in Table 7.3 (2); the day-degree sums required for the development of each stage of red scale on citrus fruits (after Atkinson 1977) are given in Table 7.3 (2a). In this analysis, the so-called observed generation is established to start from the increase of the population of red scale after overwintering. At this point, each of the trough log values is used to estimate a distinction between two generations.

As shown in Figure 7.3 (1), for the 1st instar, the graph of the numbers of live scales shows 4 distinguishable troughs at 4/10/84 (mid-spring), 19/1/85 (early summer), 6/10/85 (mid-spring) and 27/1/86 (early summer) in order. Obviously, the seasonal appearance dates of the

Figure 7.3 (1). Log (X+1) number of live red scale (for 1st, 2nd, 3rd and adult stage) per 100 observation circles (15mm diameter each circle) on lemons on each observation date.


1st instar
Log
No.
DATE:
1984
1985
1986


2nd instar
Log
No.
DATE:
1984
1985
1986


3rd instar
Log
No.
DATE:
1984
1985
1986

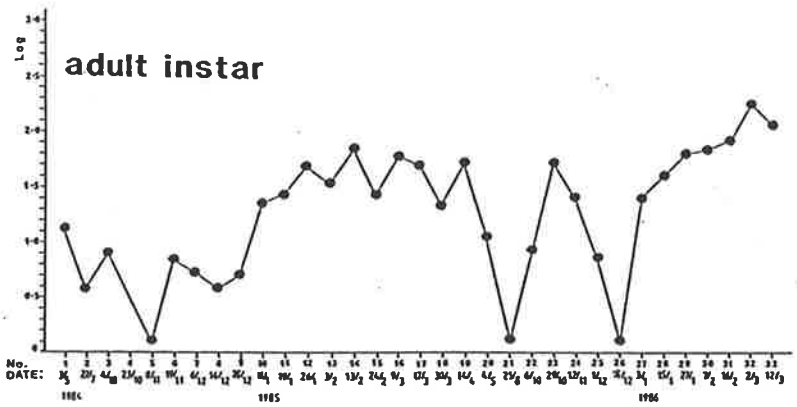

adult instar
Log
No.
DATE:
1984
1985
1986

Table 7.3 (2a). On citrus fruits, requirements of day-degrees >12°C for the completion of the development of each stage of red scale (after Atkinson, 1977).

Stage of scale	Day-degrees for each stage	Accumulated day-degrees
1st	127	127
2nd, female	142	269
3rd, female	110	379
adult, female	184	563

trough values were very similar in each year with the spring troughs in early October and the summer troughs in late January. However, from this figure, the annual infestation period of red scale on lemons in the study orchard runs from late October (mid-spring) to late August (mid-winter). The accumulated day-degrees in this period were calculated as 1750.8 between observation intervals 4 and 21 [Table 7.3 (2)]. This value is long enough for red scale to complete about 3 generations but, according to the appearance time of the fluctuation of the live 1st instars within the infestation period of Oct. 1984 to Oct. 1985, only 2 generations were observed. The 1st generation lasted from late October to mid-January of the following year, the 2nd one from mid-January to late August.

Secondly, the appearance times of the troughs for live scales of the 2nd and 3rd instar were compared with those of the 1st instar scales [Figure 7.3 (1)]. The fluctuations of numbers of the 2nd and the 3rd instar scales were similar to those of the 1st instar but they were different in appearance time.

In the 2nd instar graph, again, 4 troughs were present. Comparing the 1st and 3rd troughs with those of the 1st instar, the 2nd instar troughs appeared in observation intervals 6 and 22/23. From the 1st trough, the population of the 1st instar red scale grew up again in interval 5 and the 2nd instar in interval 7. The latter one was about 200 D.D.>12°C later than the former one. The value of 200 D.D. is about 70 D.D. longer than that of 127 D.D. of the completion of the development of 1st instar red scale. So, a reasonable annual starting time for 2nd instar red scale could be established as between early and mid November (mid-spring). Obviously, these 2nd instar scales developed from the newly bound scales in October (mid-spring); in other words, the 1st instar scales can not be an effective overwintering stage and the new annual generations started from newly born 1st instar scales but not from "overwintering 1st instars".

7.3.2.2. The seasonal fluctuation of numbers of red scale

All the observed data, total scales and live scales within the total, of the field samples are plotted against sampling time in Figures 7.3 (2)-7.3 (10). Figures 7.3 (2)-7.3 (8) show the data for white-cap, 1st, 1st moult, 2nd, 2nd moult, 3rd and female adult stage respectively. Data for male scales are in Figure 7.3 (9) while Figure 7.3 (10) shows the data for scales of all stages. Also plotted in these figures are the

percentage rates of the total dead (sum of dead and parasitized) and the parasitized scales of each stage.

The analyses of the seasonal abundance of red scales were represented as follows.

White-cap:

The field sample data are given in Appendix Table 7.3 (3) and plotted in Figure 7.3 (2). As shown in this figure, the population of white-caps did not show any distinguishable fluctuation. So, I did not do any further analysis for this stage.

1st instar:

As shown in Figure 7.3 (3), the percentage dead of 1st instar red scale increased from the threshold value of about 70-85% in July or August (winter) to reach a peak of 100% in early October (mid-spring). In the next month it dropped to about 15-35% in early November (late spring) [also App.Tab.7.3 (3)]. This value was estimated as the first trough for 1st instars; the reduction in percentage dead indicated that a new infestation generation of 1st instar scale insects started in October. However, after that the percentage dead increased again in January (early summer), the hottest time of the year. It reached a new peak value of about 80% in 1985 [55% in 1986, see App.Tab. 7.3 (3)]. In late January the percentage dead started to fall again; in about one month it fell to the 2nd trough of about 20% on 9/3/85 [and on 16/2/86 to the even lower value of about 5%, see App.Tab. 7.3 (3)]. From March (late summer), the percentage dead rose again till the following October (mid-spring).

Figure 7.3 (3) also shows that, after the winter, the log total number (live + dead) of 1st instar red scale dropped down to the 1st trough in early spring (between early October and early November). At that time, the log number of live scales increased; by contrast, a reduction on percentage dead rates of scales was observed. I believe this was the beginning of a new infestation season after overwintering of scales. Subsequently, from early November (mid-spring), two cycles of log total number of red scale were observed: the first was from late October (mid-spring) to late January (early summer) and the second was from late January (early summer) to the following October (mid-spring). The peak value of the 2nd cycle was much higher than that of the 1st one. Thus in 1984-85, the peak of the 1st cycle was 2.0996 (on 11/1/85) while the peak of the 2nd cycle was 2.5533

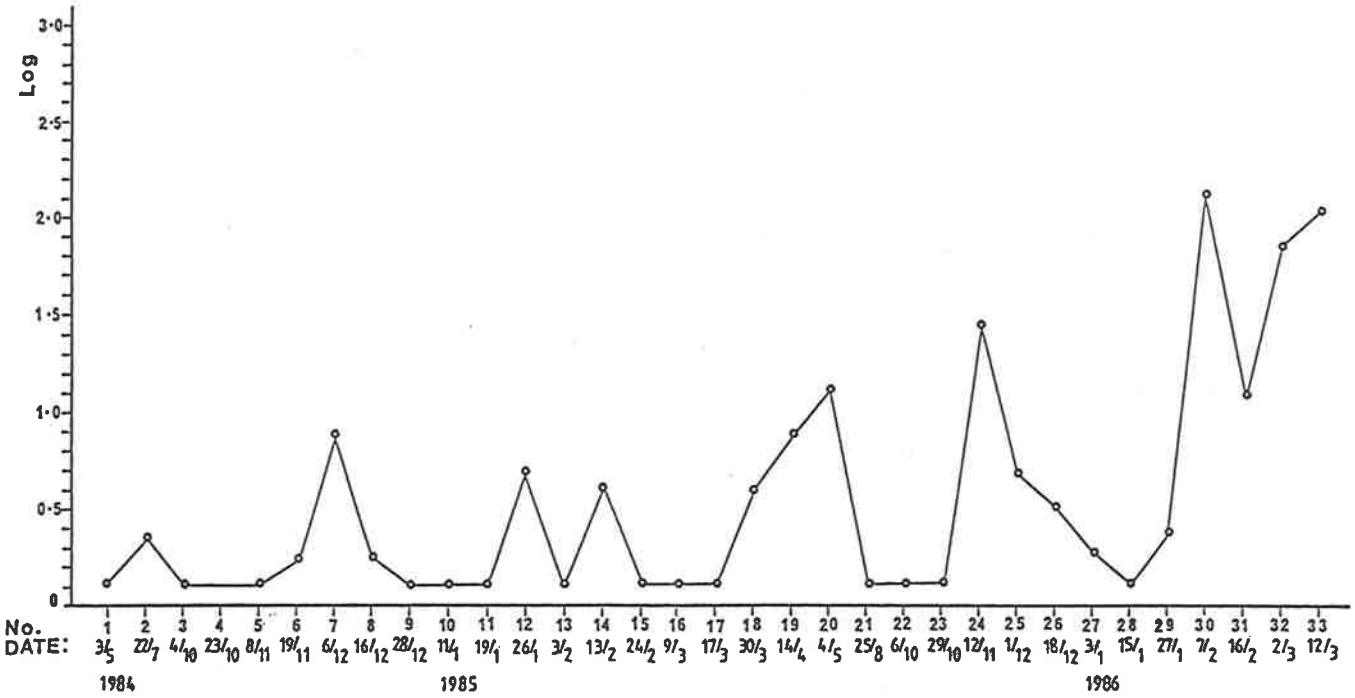


Figure 7.3 (2). Log (X+1) number of live red scale of white-cap instar per 100 observation circles (15mm diameter each circle) on lemons on each observation date.

Figures 7.3 (3)-7.3 (9). Log (X+1) numbers and % rate of red scale per 100 observation circles (15mm diameter each circle) on lemons on each observation date.

Fig. 7.3 (3): 1st instar.
Fig. 7.3 (4): 1st moult instar.
Fig. 7.3 (5): 2nd instar.
Fig. 7.3 (6): 2nd moult instar.
Fig. 7.3 (7): 3rd instar.
Fig. 7.3 (8): adult (female) instar.
Fig. 7.3 (9): male red scale.

Legend:

●——● : log no. of total red scale (live + dead).
○——○ : log no. of live red scale.
■——■ : % total dead (dead + parasitized) of red scale.
⬡——⬡ : % parasitization of red scale.

Figure 7.3 (10). For red scales overall stages. Log (X+1) numbers and % rates per 100 observation circles (15mm diameter each circle) on lemons on each observation date.[●——● : log no. of total scales (live + dead);○——○ : log no. of live scale only;■——■ : % total dead (dead + parasitized) of red scale; ▲——▲ : % dead only]

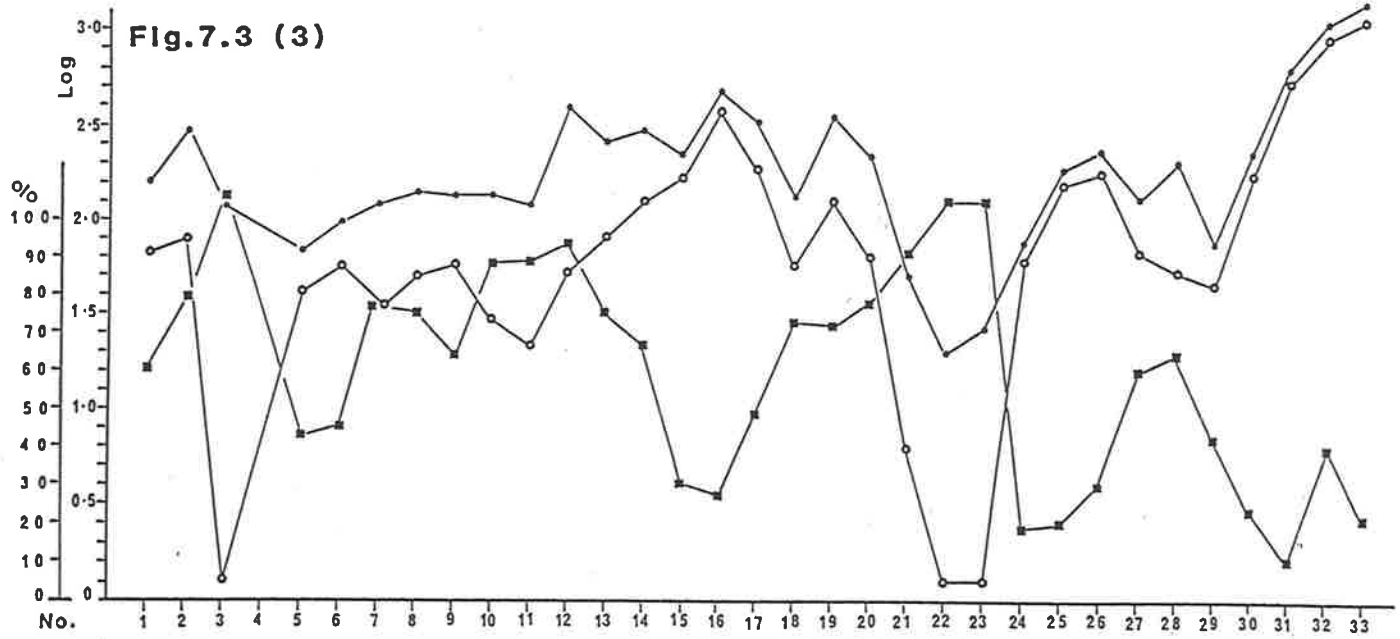


Fig.7.3 (3)
Log
%
No.

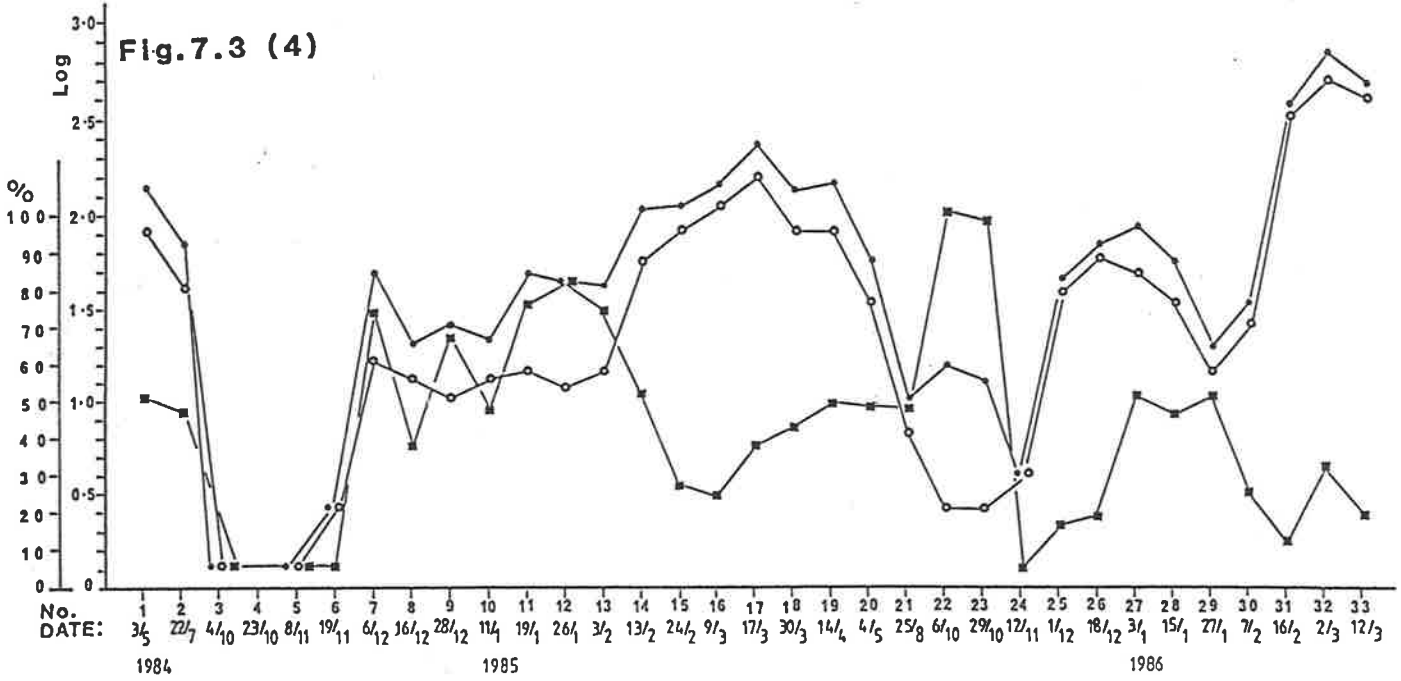


Fig.7.3 (4)
Log
%
No.
DATE:
1984
1985
1986

Fig.7.3 (5)

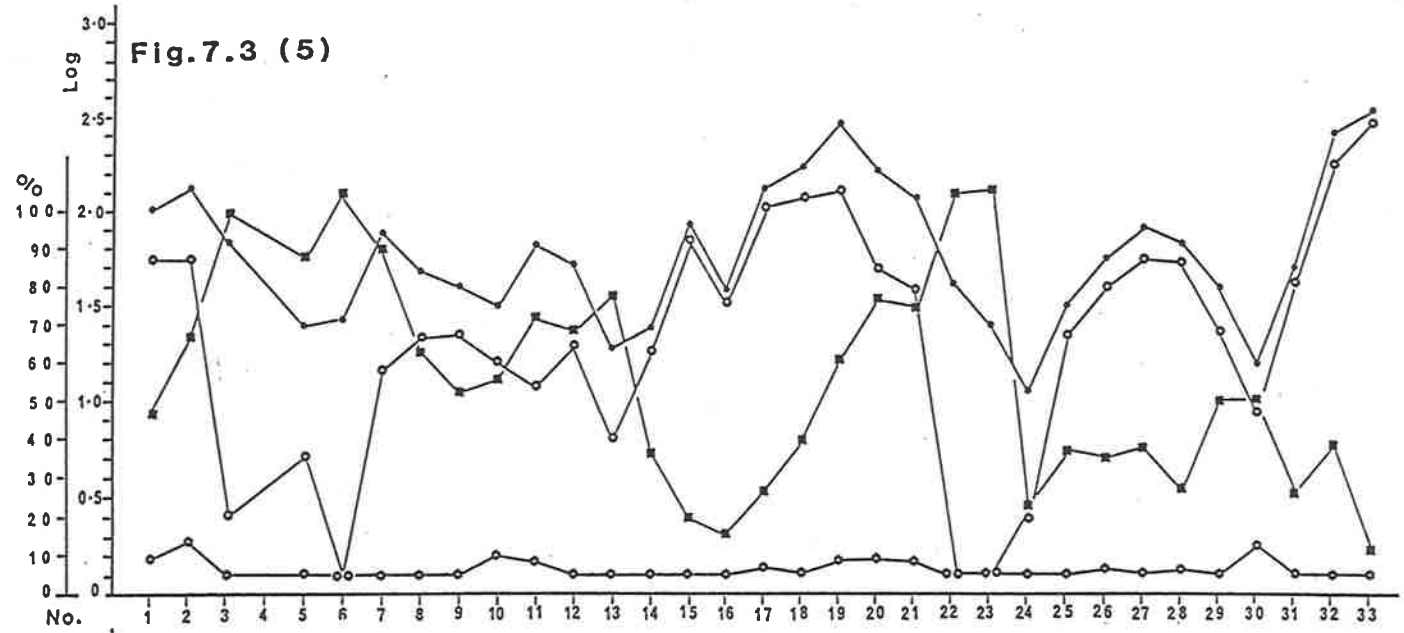


Fig.7.3 (6)

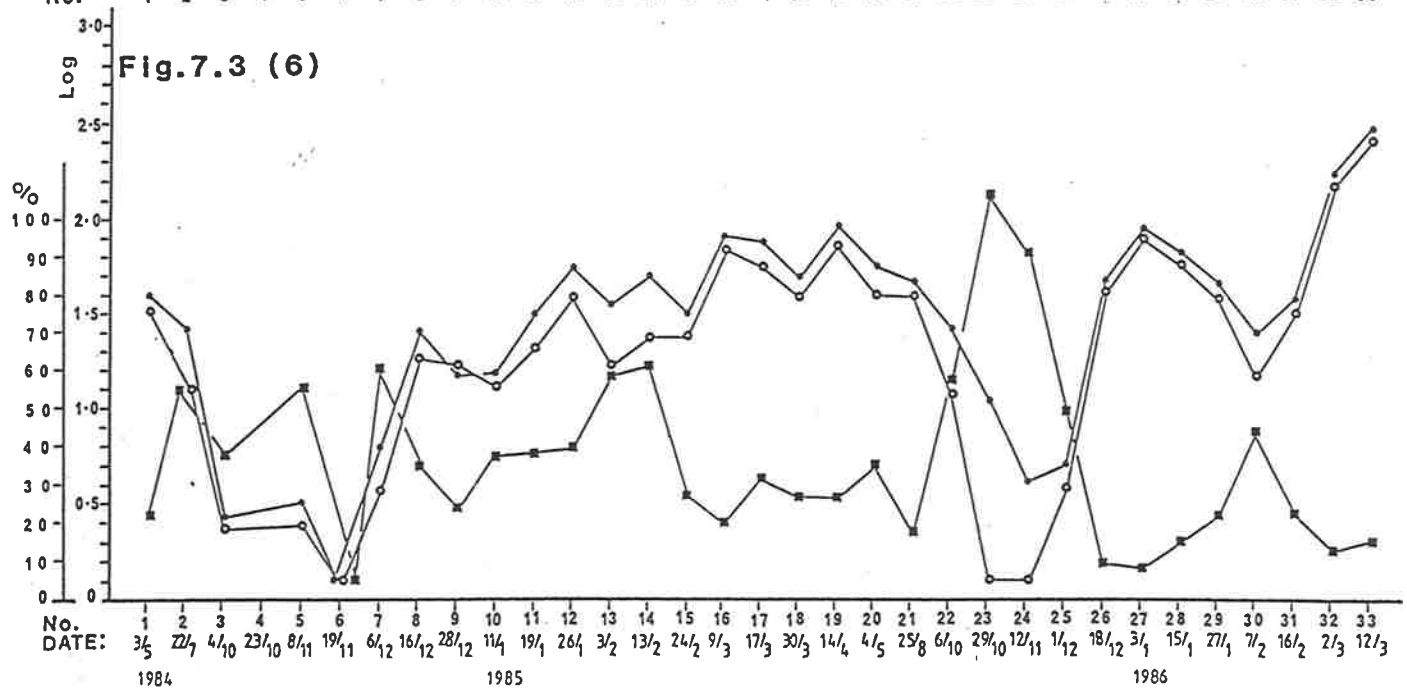


Fig.7.3 (7)

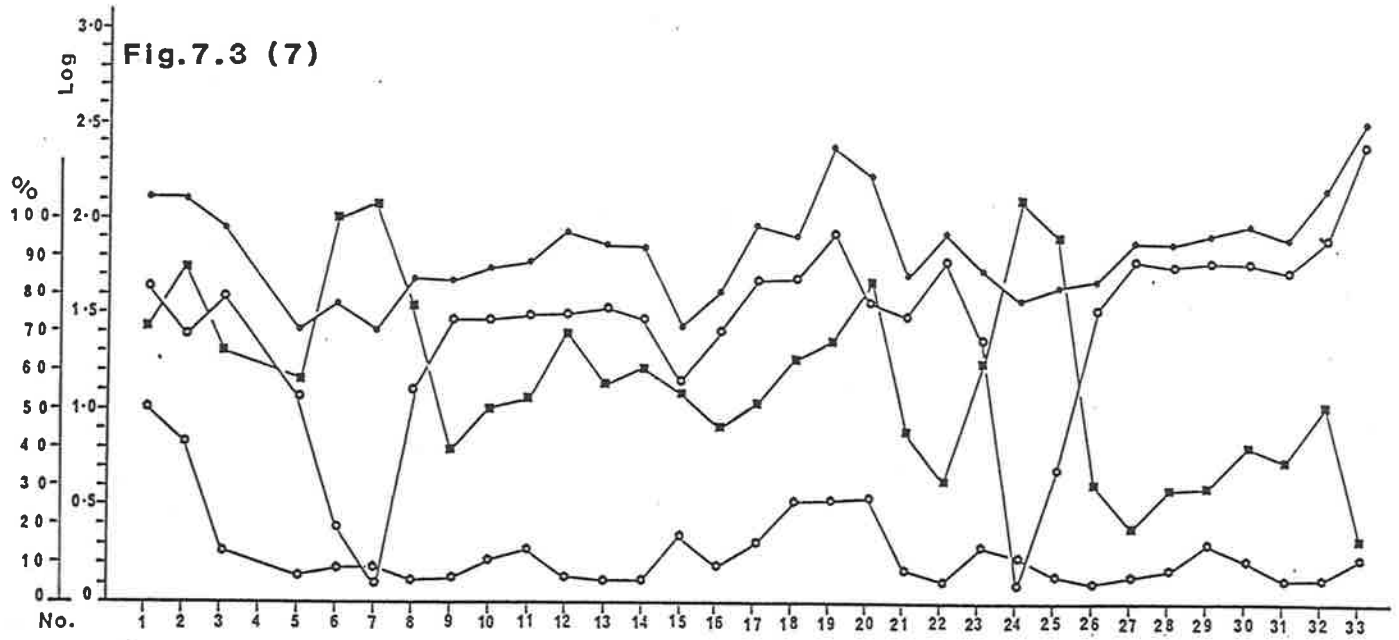


Fig.7.3 (8)

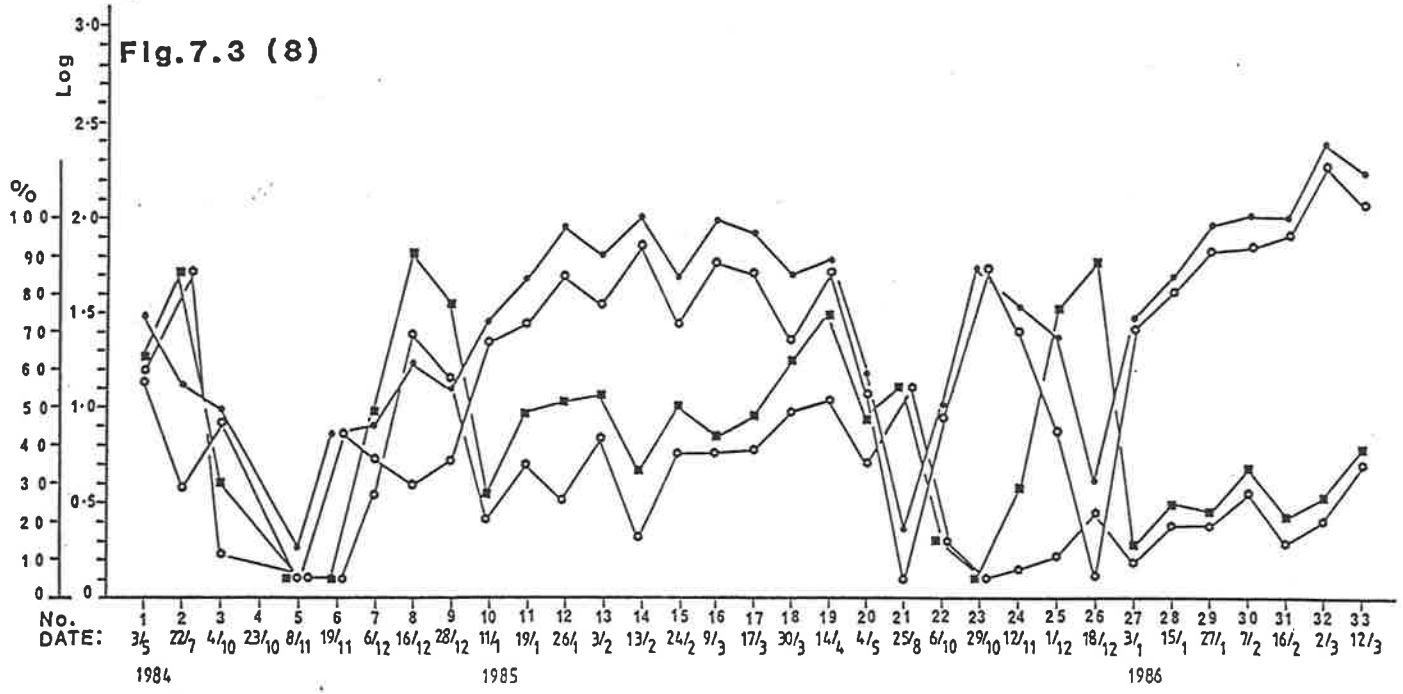


Fig.7.3 (9)

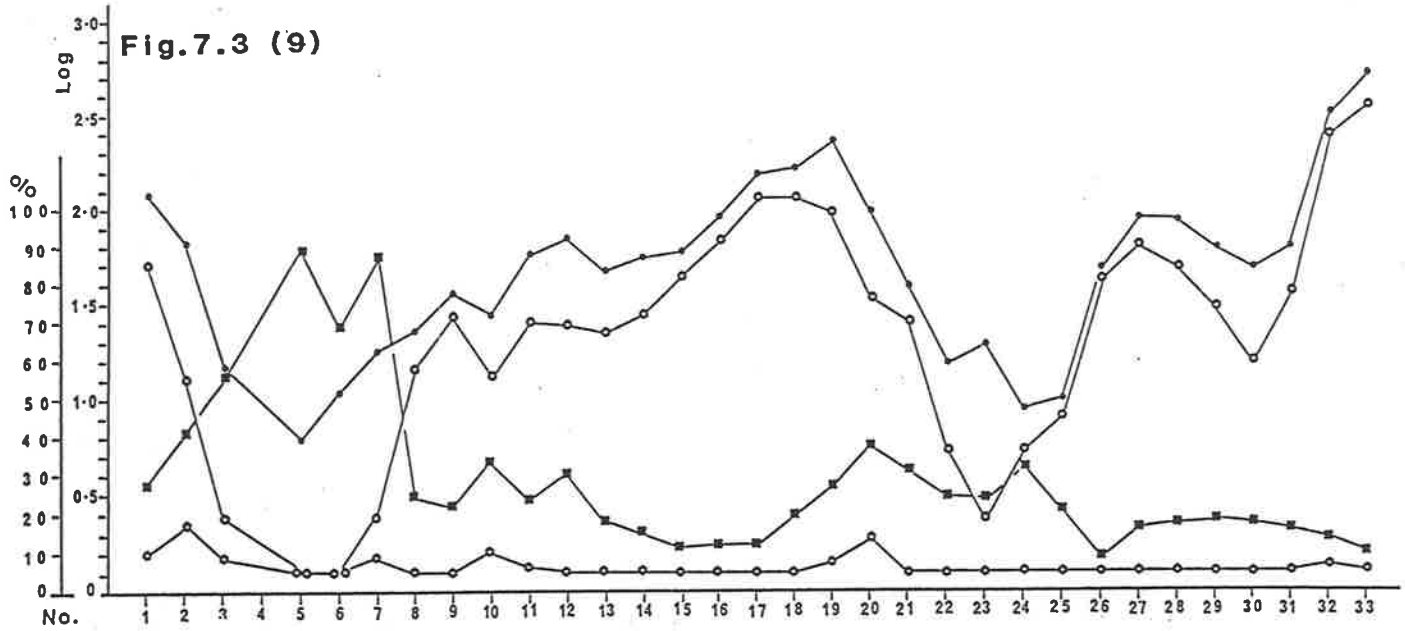
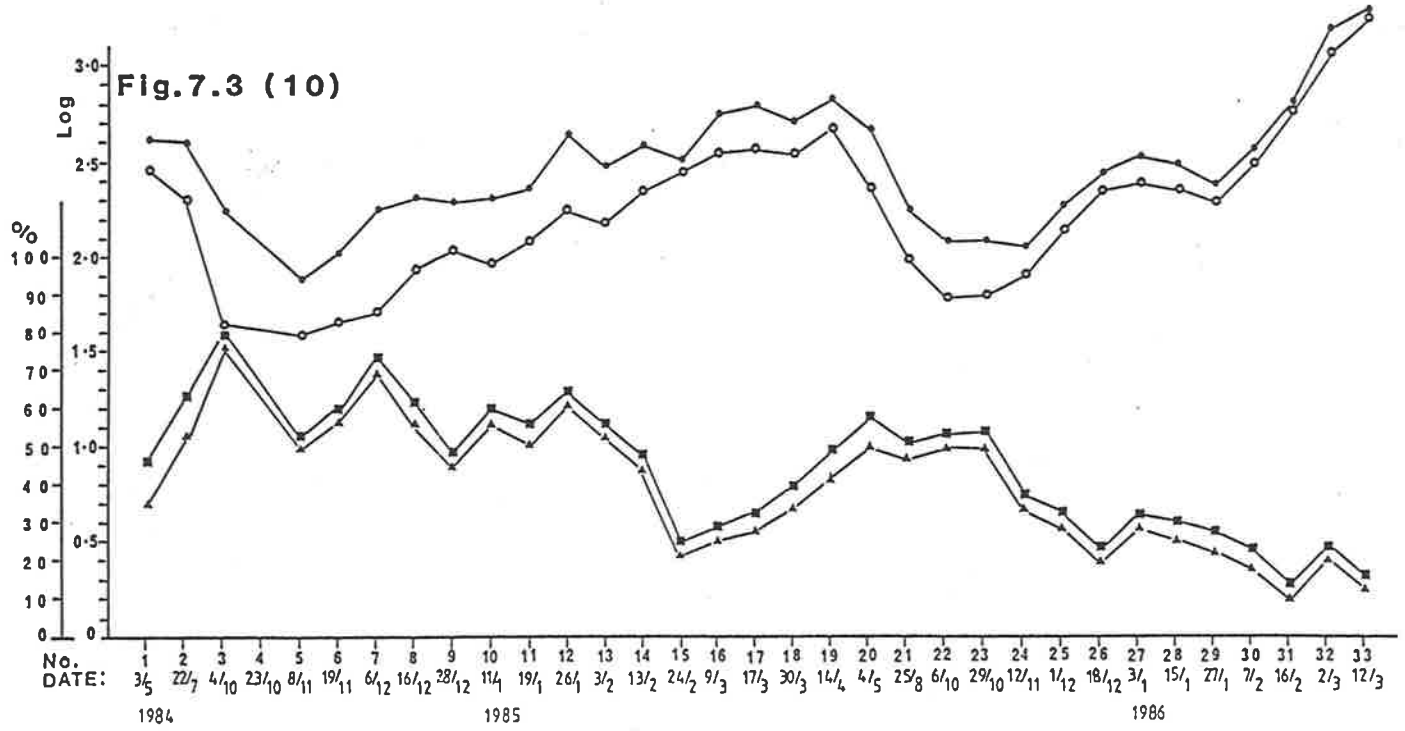


Fig.7.3 (10)



(on 9/3/85) for the 2nd range. In arithmetic numbers, the latter was about 3 times that of the former [App.Tab.7.3 (3)].

However, after the winter, in October (early spring), the log number of live 1st instars was almost zero but increased rapidly in early November (mid-spring) to reach a high value [from zero on 29/10/85 to 1.6908 on 12/11/85, see App.Tab.7.3 (2)]. By contrast, the percentage dead severely dropped from the peak of 100% down to about 15% [App.Tab.7.3 (3)]. From November to late January the number of live 1st instars oscillated around the above-mentioned high value; i.e., in the period 12/11/85-7/2/86, around the log value of 1.6908 with a range of 1.5630 to 2.1471 [App.Tab.7.3 (2)]. Within this period (also in 1984-85) there was a peak in late December: before this point, the log numbers of live 1st instar red scale generally presented a positive increase trend; by contrast, a negative trend presented after this point. The log numbers of live 1st instar red scale reached the trough value in late January then rapidly increased again to reach a new peak in mid March (late summer). The number of 1st instars increased 18-fold between the trough on 19/1/85 and the peak on 9/3/85, a period of less than 2 months. However, from mid March, the log numbers of live 1st instar red scale fell again till the following November.

The rise in log numbers indicated that a new annual infestation season of 1st instar red scales had started in between late October and early November. The end of the annual infestation came some time between late July and late August, since after that time it was almost impossible to find live 1st instar red scale on lemons. Based on this, I suggest that there is an annual infestation season of red scale of about 10 months from late October to the following August in orchards in Adelaide, South Australia. The monthly mean temperatures (mean of 1925-83) were 15.6°C for October and 11.7°C for August (Biennial Report 1982-83, Waite Agri. Res. Inst.). Therefore my observation agrees with McLaren's (1971) concept which was obtained in Victoria, Australia: that the threshold of population growth occurred at about 15°C for red scale; and population of red scale maintained a positive growth coefficient down to about 13°C.

1st moult:

Data for the 1st moult instar are plotted in Figure 7.3 (4). Similar to the 1st instar, the annual infestation season runs from late October to the following August. During the season, the log numbers fluctuate in 2

distinct cycles, namely, (1) the summer cycle which starts in mid November and ends in late January and (2) the autumn cycle, from February to the following October. The latter cycle oscillates at a much higher level than the former. Also the peak log value of the latter range was much higher than that of the former; i.e., in 1986, the log total number of the 1st peak of the 1st moult instar was 1.8229 (on 3/1/86) and the 2nd peak was much higher at 2.7232 (on 2/3/86) [App.Tab.7.3 (1)]; in arithmetic numbers, the latter was about 8 times the former. Furthermore, by comparison with the 1st instar red scale, similar fluctuations of percentage dead occurred in the 1st moults. The highest percentage dead, above 90%, occurred in October, the lowest values, 7-18%, between late February and early March [App.Tab.7.3.(3)].

2nd instar:

Figure 7.3 (5) shows that, during winter (June to September), the percentage total dead (sum of dead and parasitized) of the 2nd instar red scale was confined within a range of 60-70%. After winter, this percentage increased rapidly: in October (early spring), it reach the peak of about 100%. Subsequently, throughout the hottest period between mid December and early February, the percentage decreased to fluctuate around a relatively lower level, i.e., it ranged between 56.04-71.88% in the period of 16/12/84-3/2/85 and around an even lower level of 30.99-44.83% in the period of 1/12/85-7/2/86. Within these periods, the percentage parasitism of the 2nd instar red scale was never over 7% which was very close to the highest value I had ever observed (8.46% on 22/7/84) [App.Tab.7.3 (4)]. However, the percentage total dead of red scale reduced to the trough values of smaller than 10% in early or mid March (10% on 9/3/85 and 7.39% on 12/3/86), with zero parasitization rate. Then the percentage total dead increased again to reach the peak value of about 100% in the following October [App.Tab. 7.3 (4)].

Again, also shown in Figure 7.3 (5), throughout the whole field sample period, the percentage parasitization rates of the 2nd instar red scale stayed within a very low range, 0-4%. The highest value was 8.46% obtained on 22/7/84 when the percentage dead value was 51.47 [App.Tab.7.3 (4)].

Finally, considering the fluctuation of log number of live scale insects [also Fig.7.3 (2)], the log number of live scales showed two trough and two peak values during each annual infestation period. By comparison with the increase in percentage total dead of red scale in Figure 7.3 (5),

in October the log number of live 2nd instars showed a decreasing trend which was maintained at the very low level, about 0.5 or even lower to almost zero. From this very low level, the first leap in increase of log number of live scales started in November and reaching the 1st peak some time between late December and early January. The value of the 1st peak was 1.2275 on 28/12/84 by comparison with the previous threshold of 0.1334 on 19/11/84; in arithmetic numbers, the former was about 12 times the latter. After the 1st peak the log number of live scales fell to another trough value in early February but this value was higher than that of the former trough mentioned above, i.e., it was 0.6655 on 3/2/85, compared with the first trough which was 0.1334 on 19/11/84. From the 2nd trough in early February, in about one month time, the log number of live scales rapidly increased to reach the 2nd peak about a month later, between mid March and mid April (2.0153 on 14/4/85 and in arithmetic numbers, about 22 times of that of the 2nd trough on 3/2/85). But very soon, from the 2nd peak, the log number of live scales decreased again to an extremely low value in the following October. For example, from the above-mentioned peak, it dropped down to 0.1279 on 6/10/85 then, in another 20 days, to zero on 29/10/85 [App.Tab.7.3 (2)].

Due to the above mentioned very low parasitism rates, the log <u>total number</u>, sum of live and dead, of the 2nd instar red scale presented a similar fluctuation trend to the log number of live scales throughout the whole field sample period. This fact, again, might indicate that, in my study orchard, parasitoids had never been an efficient density-dependent control agent in the population regulation of 2nd instar red scale.

<u>2nd moult</u>:

Figure 7.3 (6) shows the fluctuation of percentage dead (in my study orchard, it had never involved any parasitization rate) of 2nd moult which had two peaks, the first in mid-spring (late October to mid November), the second in mid-summer (early or mid February). The first peak could be as high as 100%; by contrast, the second one was much lower (55.68% on 13/2/85) [App.Tab.7.3 (4)]. However, about 2 months from the first peak the percentage dead dropped down to the first trough in late December (late spring); by comparison, in less than one month after the second peak, the second trough appeared in early March (late summer). The values of these two troughs were very low (only 3.07% on 3/1/86) and no higher than 18% [on 28/12/84, see App.Tab. 7.3 (4)]. So, I believe, for the 2nd moult a new

annual infestation season started not later than late November.

However, from Figure 7.3 (6), again, it was noted that the log total and log live number of scale insects fluctuated with a similar trend. After winter, with an increase in percentage dead rates, both the log total and the log live numbers of red scale synchronously dropped down to zero between late October and mid November. Subsequently, they both increased rapidly. From mid December, the log total and the log live number kept growing till the following mid April. In this period, like the 2nd instars, two types of increasing trend in log numbers were observed, namely, (1) a similar increase rate between 1984 and 1985 and (2) a distinct trough in early February to divide the trend into two growth regions, i.e., between 1985 and 1986.

From above analysis it was concluded that the annual infestation cycle of the 2nd moult stage was from late November to late November, sometimes with two obviously different development cycles divided in early February.

3rd instar female:

Data, namely, log number (for "total" and live only) and percentage rates (total dead or parasitized only) are shown in Fig. 7.3 (7). Between mid April and early May log total number (sum of live, dead and parasitized) dropped to the trough values of early November, i.e., from 2.2583 on 14/4/85 down to 1.4822 on 12/11/85 [see also App.Tab.7.3 (1)]. In arithmetic numbers, the trough value was only about 1/6 of the previous high value. From early December, starting from the very low trough value, the log total number of red scales increased again. In about 2 months time it reached a new high level in the hottest season in the year, to 1.8664 on 7/2/86, about a 2.5-fold increase in arithmetic number of red scale. However, throughout the hot season, between mid December and mid February, the log total number of red scale varied within a quite narrow range. The samples between 16/12/84 and 13/2/85 varied between 1.5651 and 1.8365, which was about a 1.9-fold difference in arithmetic numbers. Then, from late February (or early March), the log total numbers of scale insects increased rapidly again to the peak in the following mid or late April, i.e., from 1.3222 on 24/2/85 to 2.2583 on 14/4/85, a 9-fold increase [App.Tab. 7.3 (1)].

The fluctuations of log live numbers were quite different to that of log total numbers [see also Fig. 7.3 (7)]. Between early November and early December the log number of live scales dropped severely to near zero.

This kind of reduction was accompanied by an increase in total percentage dead from 50% up to over 95% (within these total dead rates, parasitization rate was as low as about 5%) [also App.Tab. 7.3 (5)]. After this point in early December, log numbers of live scales fluctuated close to the log total numbers with a similar trend until the following October. Again, as shown in Fig.7.3 (7), a very sharp reduction in log number of live scales presented between early November and mid December. By contrast, there was no such reduction in the log total numbers of scale insects. The log number of live 3rd instars dropped severely from 0.9981 on 8/11/84 down to 0.1310 on 6/12/84 [App.Tab. 7.3 (2)] but at the same time the log total numbers of scale insects did not present any significant variation (only from 1.3097 down to 1.3013 [App.Tab. 7.3 (1)]). This might indicate that a high mortality of the overwintering 3rd instar scale occurred in mid to late spring. As shown in Fig. 7.3 (7), this high mortality could not possibly be caused by the Aphytis parasitoid since the parasitization rate showed no significant increase. The same picture was seen in the spring of 1986.

Obtained from above analyses, finally, the beginning for a so-called new summer generation of 3rd instar red scale was established at time in between mid November and early December, mid and late spring.

It was noted that the highest percentage total dead (parasitized + dead) of red scale occurred in between mid and late spring; but not in the hottest period in the year, i.g., it ranged between 53.84-98.15% in the period of 8/11-6/12/, 1984, the mid-spring and around a even lower level of 35.35-64.85% in the hottest period of 28/12/84-24/2/85, early to mid-summer. Also noted was that within these percentage total dead, the parasitization rates were never higher than 12% but were generally lower than 3% [App.Tab.7.3 (5)]. This might indicate: (1) the population growth of 3rd instar red scales was not regulated by high temperatures in summer; and (2) in my study orchard, parasitoids could not be an efficient agent in the natural control on numbers of 3rd instar insects.

Adult female red scale:

Figure 7.3 (8) shows that, the percentage total dead (parasitized + dead) presented a significant reduction from time in between April (early autumn) till late October or early November; but during this period, that the total numbers of scales synchronally reduced. This might indicate that during this period, most of the dead scales dropped off host fruits.

Subsequently, the total number (live + dead) of scales rose again, this indicated a new infestation season was started; also indicated that the overwintering 3rd instar red scale is the most important source for the infestation degree of red scale in the following year. By comparison with the increase of total numbers of scales, the percentage total dead (dead + parasitized) of scales rose rapidly again to a peak of about 80% in mid December. Within this increase, the percentage parasitization of scales also presented a clear upwards trend. At that time, the death of adult female scales was mostly occurred by parasitism of Comperiella bifasciata Howard, especially during the hottest period between late spring and summer [also App.Tab.7.3 (6) and 7.3 (8)]. For instance, between 6/12/84 and 30/3/85, the percentage parasitization rates were about 2-3 times the percentage dead (dead only) rates; on 9/3/85, it reached the value about 8 times the dead rate [App.Tab.7.3 (6)]. This was quite different to that in the 2nd and the 3rd stage in which the parasitism had never been the main cause of death in scales [App.Tab.7.3 (4) and 7.3 (5)].

It was noted that in the period between autumn (April) of 1985 to summer (January) of 1986, two troughs of log number of adult scales were observed for the total scales (live+dead), as well another two for the live scales. The first trough presented in late August (mid winter); the 2nd in mid December (late spring). These two trough values presented before and after a peak which appeared in between late October and mid November. This observation might indicate that the overwintering insects, the 3rd instar insects started to develop at time not later than early October (mid spring). However, from the second trough, the log total and the log live numbers of adult red scales synchronously rose again throughout the whole period between late December (late spring) and the following April (early autumn) into another variation cycle [Fig.7.3 (8)].

Male red scale:

Figure 7.3 (9) shows that, after winter, trough values of log numbers of live male scales were observed in between late October (early spring) and mid November (mid-spring). Subsequently, both the log total number (dead + parasitized) and the log live number of scales increased rapidly till the following April (early autumn). After April, both of them dropped again to the trough in the following October. This increase was believed to indicate a start of a new annual infestation season of male red scales. It was noted that this kind of increase (1985-86) could be divided into

two parts: the first part was observed in the period between early December (late spring) and early February (mid-summer); the second one was in the period between early February and mid April (mid-summer). That the increase rate of the latter was much higher than was the former. Accompaning the variations of log numbers of male scales, the percentage total dead (dead + parasitized) remained at quite low values of not higher than 30% [App.Tab. 7.3 (7)] throughout the hottest period between late December and late February during the year. And, it was noted that during this period, the parasites did not play any role on the natural control of male scales. By comparison, in between mid-autumn (May) and late autumn (June) the parasitism rates could be higher; but not higher than 13% [App.Tab. 7.3 (7)]. This indicated, again, parasites could not be an efficient control agent on the population growth of male insects in my study orchard.

For the whole population of red scale :

Figure 7.3 (10) shows that the log total number (live + dead) and the log live number of red scales of the whole population overall stages fluctuated with a same trend. They started to rise in early November (late spring); reached the peak in late March (late summer); then dropped down to a trough value in the following October (early spring). The locus of log values was looked like a bell in the period between early November and the following early October. Within this period, the peak value of the total numbers of scales was about 8–13 times that of the trough values. Further, throughout the whole experimental period, the percentage rates of the total dead (sum of dead and parasitized) and the percentage rates of dead of red scale fluctuated reversely to that of log numbers in a same trend: the decrease trend presented from early October (early spring) until late February (mid-summers); then rose again until the next October [also App.Tab.7.3 (8)]. This might indicate the parasitoids of red scales had never been an efficient control agent on the population growth of red scale. However, as shown in Fig.7.3 (10), the parasitism rates of red scale, which were assessed as the variation between the percentage of the total dead (dead + parasitized) and the dead only, were never higher than 12% (on 3/5/84) but generally lower than 5% [also App.Tab.7.3 (8)].

7.3.2.3. Growth of the population of red scale

7.3.2.3.1. In relation to parasitoid, A. melinus

DeBach (1969) believed that the variation of the percentage of total dead (dead + parasitized) of red scale was always correlated with a certain percentage of parasitization. His example of this kind of relation is shown below:

% parasitism	% total dead
1	35
5	63
10	75
25	84

Obviously, such a relation demands that a high "total dead" is always associated with a high parasitism of red scale. By contrast, no such relationship was observed in the "all stages" figures of my field data [App.Tab.7.3 (8)]. Consequently, the analysis concentrated on the 3rd instar scales, the most favorable stage for parasitism. However, obtained from Appendix Table 7.3 (5), the percentage parasitization of 3rd instar red scales was plotted against the percentage of total dead scales, sum of dead and parasitized, in Fig.7.3 (11). The linear regression method is conducted to assess the null hypothesis that a total dead of red scale was not a function of the parasitization. The regression coefficient is not significantly different from zero and the null hypothesis is not rejected. In other words, my field data led to the disagreement of DeBach's concept and indicated that the percentage of total dead (dead + parasitized) of red scale did not relate to the percentage parasitization rates in the 3rd instar red scales. Again [Fig.7.3 (11)], a high percentage total dead of scales did not always involve a high percentage parasitization rate; the very low parasitism rates, i.e., either 5% or 10% parasitism could be involved in any of the total dead rates which ranged from 10% up to 100%. Since I believe that the survival time of Aphytis female wasps is a function of the carbohydrate supply (see Chapter 5), I suggest some possibilities to explain the differences between DeBach's concept and my data: In DeBach's study orchard, Aphytis spp. wasps could always find a satisfactory carbohydrate source either from nectar or from honeydew; by contrast, neither of these sources of supply was available for wasps in my study orchard. However, in my study, after the citrus trees flowered in October, there were no other plants to supply nectar to Aphytis wasps during the infestation period of red scale from late spring until

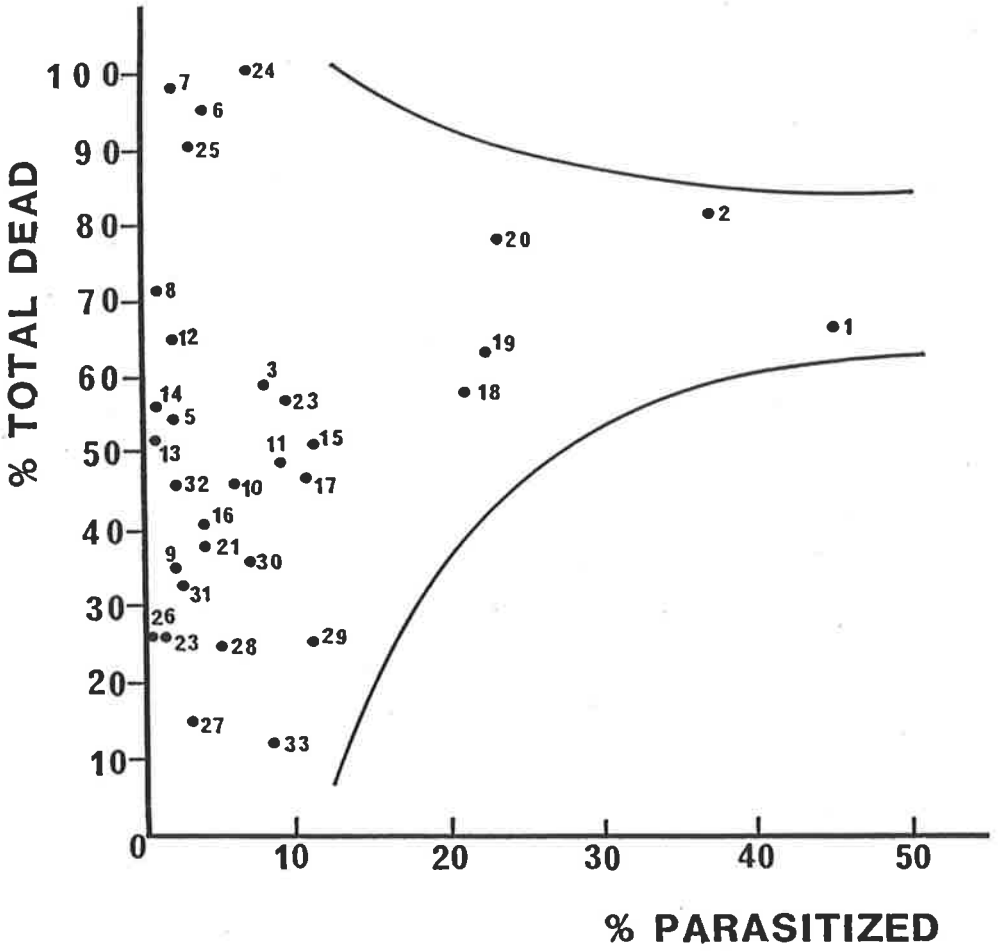


Figure 7.3 (11). Relationship between the % total dead (dead + parasitized) of 3rd instar red scale and the % parasitization within the total dead.

early autumn; on the other hand, there were no honeydew-insects on the citrus trees to supply honeydew to the parasites. All these factors made it impossible for A. melinus to survive long enough to maintain a high parasitization rate on red scales. As a result, A. melinus showed itself to be a poor agent of natural control of the red scale population in my study orchard.

7.3.2.3.2. In relation to daily mean ambient temperature

Methods:

This section attempts to explain the seasonal abundance of LIVE red scales on lemons in relation to ambient temperatures, namely, mean, extremely high and extremely low temperatures. Two plotting methods associated with a linear regression method were used as follows:

Method 1: The rate of increase, r, of the population of red scale was plotted against extremes of ambient temperatures. r was calculated from the log numbers of red scale at 2 successive sampling times, i.e., time t to time t+1; the formula is as follows:

$$r = \log N(t+1) - \log N(t)$$

Method 2: Log values were plotted as log N(t+1) against log N(t).

Use of Method 1 on testing relationship between r-values and ambient temperatures.

(i) To daily mean ambient temperatures:

r values, calculated from the log live numbers of red scales of each stage [Appendix Table 7.3.(2)] are shown in Appendix Table 7.3 (9). The r values and the temperatures for each sampling interval [Table 7.3 (1)] are used to calculate the statistics for the linear regressions of r on temperature [see Table 7.3 (3)]. As shown in this table, equations of these stages, namely, the 2nd moult, the 3rd (female) and the adult female, were not significant; by contrast, equations for other stages and also for the total live scales of the whole population over all stages were significant. These indicated that in stages of 2nd moult, 3rd and adult female scale insects, the live numbers were not significantly varied by mean temperature. In other words, they could survive anytime throughout the sampling period, including the winter time. They are, therefore,

Table 7.3 (3). Statistics of linear regression of the growth rate R, R=log[N(t+1)/N(t)], of each stage of live red scales on mean temperature of each of the observation intervals.

Stage of red scale	Intercept	Slope	r	P	C.T. (°C)
1st	-1.2400	0.0668	0.3966	<0.05	18.6
1st moult	-1.2817	0.0681	0.4890	<0.01	18.8
2nd	-1.0735	0.0573	0.3859	<0.05	18.7
2nd mout	-0.6787	0.0369	0.2982	-	
3rd female	-0.2242	0.0130	0.1085	-	
adult female	-0.1409	0.0009	0.0676	-	
male	-1.1244	0.0600	0.5423	<0.01	18.7
total	-0.7168	0.0389	0.6114	<0.01	18.4

1). d.f.= 32-2 = 30

2). "-": P>0.05

3). "C.T.": Critical temperature for R=0.

possible overwintering stages; by contrast, the other stages were not so.

Finally, the critical temperatures for r=0 were calculated; they are also given in Table 7.3 (3) for each stage. They were all very close together ranging only from 18.4 to 18.7°C. This result reveals the possibility of being able to predict the beginning of the annual population growth of red scale in Adelaide, S. Australia. By comparison with the fluctuation of daily mean temperature [Tab.7.3 (1a)] in the Waite Institute, the annual population growth of each stage of red scale mentioned above was started in November and stopped in the March (not later than April) of the following year, since during this period the daily mean temperature ranged between 18.1-20.5°C (was 17.2 in April).

(ii) To extreme temperatures:

Further analyses were conducted on the relationships between the r-values and extremes of ambient temperatures. Again, the linear regression equation method was used to assess the null hypothesis that the r-value (Y) was not a function of extremes (X) of ambient temperatures.

Data were re-arranged from Table 7.3 (1) for temperatures and from Appendix Table 7.3 (9) for r-values. The extremes of temperature <10°C (down to 3°C) for each sampling interval and their relevant r-values are given in Appendix Table 7.3 (10) while in Appendix Table 7.3 (11) the data of extremes of T.>35°C (up to 41°C) and their relevant r-values are given. The two thresholds of 10 and/or 35°C are about 10°C different to the lowest and highest temperatures recorded in my study area between 1925 and 1983 (Biennial Report 1982-83, Waite Agri. Res. Inst). Further, as an example, the r-values for "total scale" from Appendix Table 7.3 (10), are plotted against temperatures <10°C in Figure 7.3 (12). The linear regression was calculated as $Y = 0.0717X - 0.6367$ ($r=0.6548$; $d.f.=16$, $P<0.01$) and is given in Table 7.3 (4). The statistics for all the other stages are also given in Table 7.3 (4), for temperatures <10°C; similarly, in Table 7.3 (5) are given the statistics for temperatures >35°C. Analyses were carried out firstly for extremes of temperatures <10°C. As shown in Table 7.3 (4), regression equations for the 1st instar, 1st moult and male insects were statistically significant; the regression for "total of the population" was also significant. By contrast, other stages were not significant. By comparison with the analyses in the above sub-section (i), the possible overwintering age structure of red scale was extended to include the 2nd instar insects, namely, 2nd, 2nd moult, 3rd and adult stage. None of the

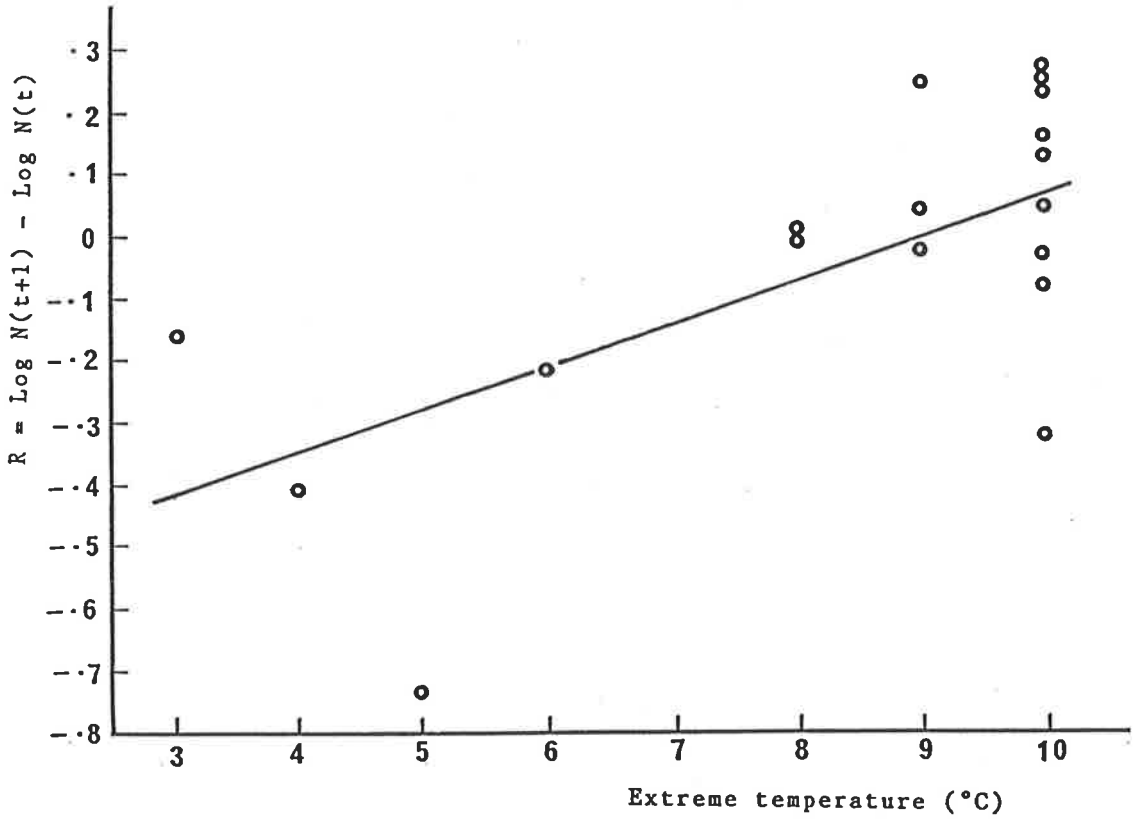


Figure 7.3 (12). Relationship between the R-value, R=log[N(t+1)/N(t)], and the extreme tmeprature (<10°C) of each observation interval. Y=(-0.6367) + 0.0717X (r=0.6548, d.f.=16, P<0.01).

Table 7.3 (4). Statistics of linear regression of the growth rate R, R=Log[N(t+1)/N(t)], of each stage of live red scales on extremes of low temperatures, T<10°C.

Stage of red scale	Intercept	Slope	r	P*	C.T. (°C)
1st	-1.4158	0.1717	0.5265	<0.05	8.2
1st moult	-1.2325	0.1386	0.5705	<0.01	8.9
2nd	-0.8939	0.0963	0.3804	-	
2nd moult	-0.7314	0.0828	0.3779	-	
3rd	-0.0486	0.0003	0.0125	-	
adult female	-0.4124	0.0482	0.2064	-	
male	-0.8129	0.0807	0.5063	<0.05	10.1
total	-0.6367	0.0717	0.6548	<0.01	8.9

1). d.f.=18-2=16

2). *: "-"= P>0.05

3). "C.T.": Critical temperature for R=0.

Table 7.3 (5). Statistics of linear regression of the growth rage R, R=log [N(t+1)/N(t)], of each stage of live red scales on extreme temperatures, T>35°C.

Stage of red scale	Intercept	Slope	r	P
1st	-1.3032	0.0369	0.2266	>0.05
1st moult	1.0441	-0.0233	-0.1194	>0.05
2nd	2.7204	-0.0698	-0.3032	>0.05
2nd moult	2.2908	-0.0580	-0.3216	>0.05
3rd	0.4296	-0.0008	-0.0440	>0.05
adult female	3.9952	-0.1025	-0.4828	>0.05
male	2.0823	-0.0501	-0.2924	>0.05
total	0.6809	-0.0149	-0.2270	>0.05

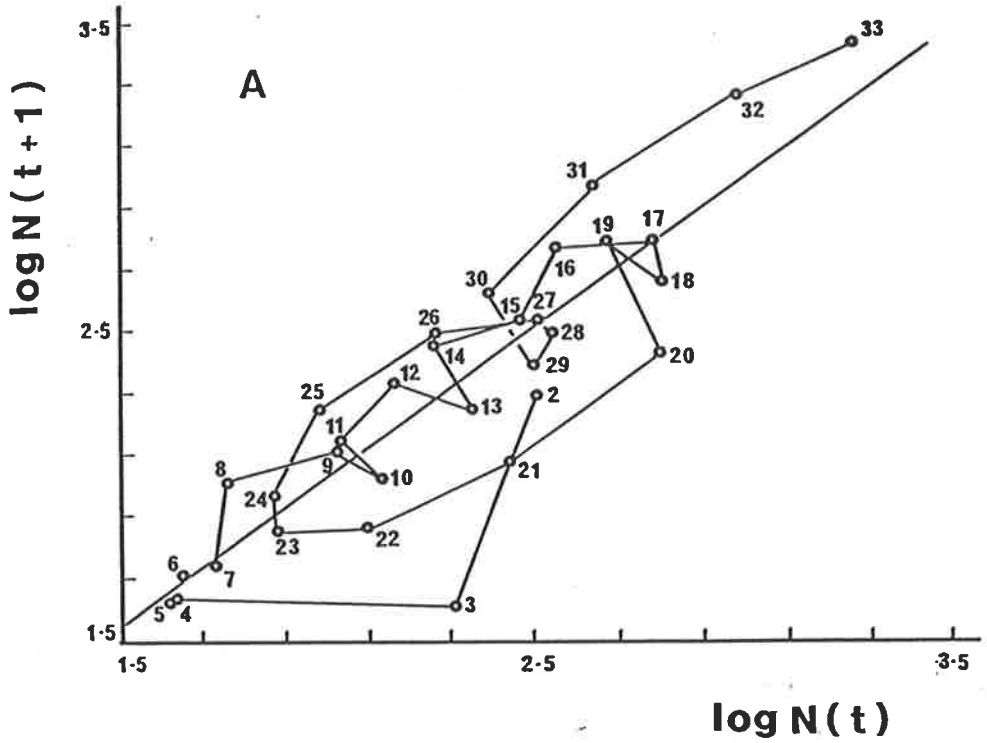
d.f.=14-2=12

"high-temperature" regressions (Table 7.3 (5)) was significant. This indicated that extremes of temperature >35°C had no function in the regulation of the population of red scale in my study orchard.

However, from the above analyses, another possibility for the prediction of the beginning of an annual infestation period of red scale is that the daily minimum should have reached about 8.5°C. This value was the mean of the threshold temperatures for r=0 for 1st instar and 1st moult instar red scale [Table 7.3 (4)]. However, daily minima below 8.5°C cause a significant mortality in red scales. Accordingly, the annual population growth of red scale in the Waite Institute, is estimated to begin in September and to end in June [Tab.7.3 (1a)]. This range is wider than that (Nov. to April) in section (i); it is quite close to the annual infestation period (Oct. to Aug.) in this institute (see section 7.3.2.1).

Use of Method 2 to test the variation of the growth rate (r) of a red scale population.

Method 2 was Moran's (1950) plotting method for the analysis of animal population dynamics, especially for the single-factor analysis in population dynamics (Morris, 1959, 1963; Southwood, 1967; Rogers, 1979). Atkinson (1983a) used this method to estimate the natural mortality related to environmental factors in a population of red scales in the hot low lands of Swaziland and the eastern Transvaal. However, the Moran method was originally used for the variation of a population from generation to generation. Unfortunately, I have not got enough data on the variation of red scale numbers from generation to generation, only the variation from one sampling interval to the next which was about 95 day-degrees (>12°C), only one fifth of the required day-degrees for the completion of one generation for red scale. Nevertheless I have used Moran's method to determining growth in density independent mortality acting on red scale population under natural conditions. However, the log number of "total" live scales of all stages of the population at time t+1 in each observation interval [App.Tab.7.3 (2)] is plotted against that at time t in Fig.7.3 (13)-A. Linear regression was again used to establish a model of the relationship and the equation is estimated as $Y=0.0960+0.9707X$ ($r=0.8763$, $d.f.=30$, $P<0.01$) and is given in Table 7.3 (6). However, statistics for the linear regression equations for each stage of live scales are given in Table 7.3 (6) respectively. All the regression equations were statistically significant. This indicated that in my study orchard the number of each stage of red scale was regulated not by density-dependent but by density-independent factors.



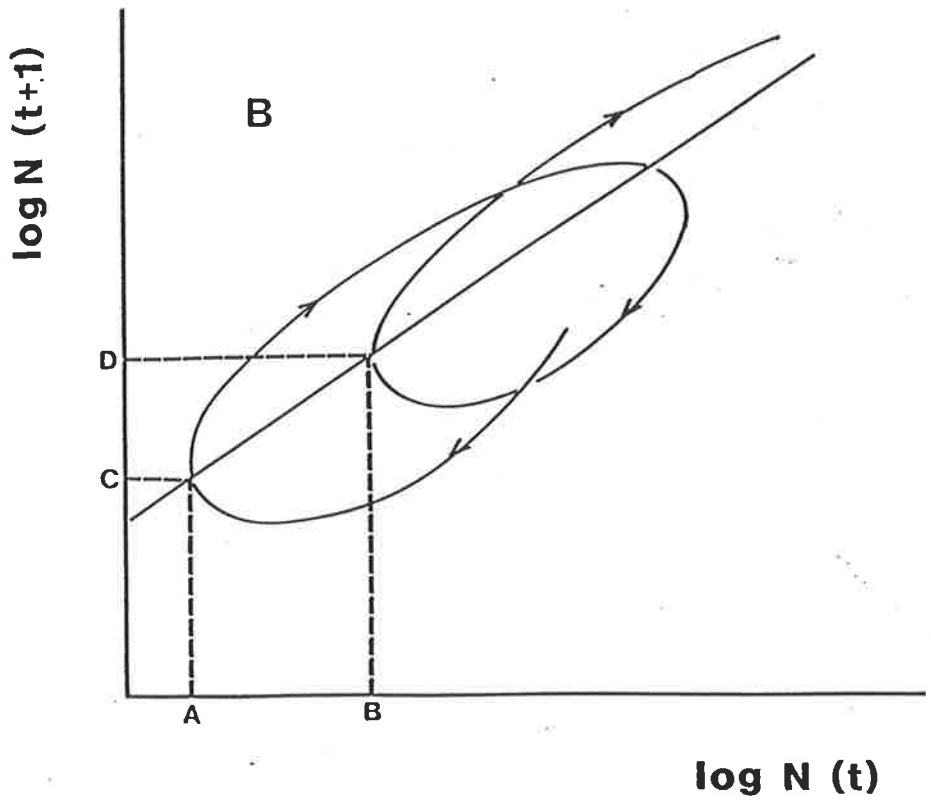


Figure 7.3 (13). For the total live red scales overall stages, relationship between log numbers of red scales at sampling time t+1, Y, and time t, X.

A: $Y=0.096+0.971X$ ($r=-0.8763$, d.f.$=30$, $P<0.01$).
B: idealistic curve of that in A.

Table 7.3 (6). Statistics of linear regression of Log N(t+1), Log numbers of each stage of live red scales at time t+1, on Log N(t).

Stage of red scale	Intercept	Slope	r	P
1st	0.5367	0.6878	0.6487	<0.01
1st moult	0.2533	0.8065	0.7731	<0.01
2nd	0.4124	0.6696	0.6335	<0.01
2nd moult	0.2695	0.7840	0.7373	<0.01
3rd	0.4815	0.6522	0.6066	<0.01
adult female	0.3693	0.6940	0.6705	<0.01
male	0.2390	0.8602	0.8099	<0.01
total	0.0960	0.9707	0.8763	<0.01

d.f.=32-2=30

Furthermore, looking back at the variation of data plotted in Fig.7.3 (13)-A, it was clear that the trend of an ascending spiral development of the population growth was observed to fit the above analysis. The locus of this "spiral development" was separated by the line of the linear regression equation into two parts: positive r-values in summer time on the upper part and negative r-values in autumn and winter on the the lower part. The starting point for the positive r-values in spring time were on or nearly on the regression line [see point 5 and point 23 in Fig.7.3 (13)-A]. These points indicated the differences of threshold numbers of overwintering red scales. However, from Fig.7.3 (13)-A, the above mentioned difference between two springs, 1985 and 1986, is idealized and shown as the distances between A and B on the X axis or between C and D on the Y axis in Fig.7.3 (13)-B.

However, I hope that this modified "Moran plot method" could help to reach an understanding on the population regulation of red scale under natural conditions.

REFERENCES

Atkinson, P. R. (1977). Preliminary analysis of a field population of citrus red scale, Aonidiella aurantii (Mask.), and the measurement and expression of stage duration and reproduction for life tables. Bull. Entom. Res., 67:65-87.

Atkinson, P. R. (1983a). Estimates of natural mortality related to environmental factors in a population of citrus red scale, Aonidiella aurantii (Hemiptera:Homoptera:Diaspididae). Bull. Entom. Res., 73:239-258.

Atkinson, P. R. (1983b). Environmental factors associated with fluctuation in the numbers of natural enemies of a population of citrus scale, Aonidiella aurantii (Hemiptera:Homoptera:Diaspididae). Bull. Entom. Res., 73:417-426.

DeBach. P. (1958). Application of ecological information to control of citrus pests in California. 10th Intern. Cong. Entom. Proc., (1956), 3:187-194.

DeBach, P. (1965). Some biological and ecological phenomena associated with colonizing entomophagous insects. in: Genetics of Colonizing Species, pp. 287-306, Academic Press, N. Y.

DeBach, P. (1969). Biological control of diaspine scale insects on citrus in California. Proc. 1st Intern. Citrus Symp., (Riverside, 1968), 2:801-822.

DeBach, P., Dietrick, E. J., Fleschner, C. A. and Fisher, T. W. (1950). Period colonization of Aphytis for control of the California red scale. Preliminary Tests, 1949. J. Econ. Entom., 43:783-802.

DeBach, P., Hendrickson, R. M. and Rose, M. (1978). Competitive displacement: Extinction of the yellow scale, Aonidiella citrina (Coq.) (Homoptera:Diaspididae), by its ecological homologue, the California red scale, A. aurantii (Mask.) in Southern Califonia. Hilgardia, 46:1-35.

DeBach, P., Huffaker, C. B. and MacPhee, A. W. (1976). Evaluation of the impact of natural enemies. in C. B. Huffaker and P. S. Messenger, "Theory and Practice of Biological Control", Chapter 11, pp.255-298, Academic Press, N. Y., 1976.

DeBach, P., Rosen, D. and Kennett, C. E. (1971). Biological control of coccids by introduced natural enemies. in C. B. Huffaker (ed.), "Biological Control", Plenum Press, N. Y., pp. 165-194.

DeBach, P. and Sisojevic', P. (1960). Some effects of temperature and competition on the distribution and relative abundance of Aphytis lingnanensis and A. chrysomphali (Hymenoptera:Aphelinidae). Ecology, 41:153-160.

Ebeling, W. (1959). Subtropical fruit pests. Univ. of Cal., Division of Agricultural Science, Los Angeles, 436 pp.

McLaren, I. W. (1971). A comparison of the population growth potential in California red scale, Aonidiella aurantii (Mask.), and yellow scale, A. citrina (Coq.), on citrus. Aust. J. Zool., 19:189-204.

McLaren, I. W. and Buchana, G.A. (1973). Parasitism by Aphytis chrysomphali Mercet and A. melinus DeBach of California red scale, Aonidiella aurantii (Mask.), in relation to seasonal availability of suitable stages of the scale. Aust. J. Zool., 21:111-117.

Moran, P. A. P. (1950). Some remarks on animal population dynamics. Biometerics, 6:250-258.

Morris, R. F. (1959). Single-factor analysis in population dynamics. Ecology, 40:580-588.

Morris, R. F. (1963). Predictive population equation based on key factors. Mem. Entom. Soc. Can., 32:16-21.

Reeve, J. D. and Murdoch, W. W. (1958). Aggregation by parasitoids in successful control of the Califonia red scale: a test of theory. J. Anim. Ecology, 54:797-816.

Rogers, D. (1979). Tsetse populaiton dynamics and distribution: a new analytical approach. J. Anim Ecol., 48:825-849.

Smith, D. (1978). Biological control of scale insects on citrus in southeastern Queensland: I. Control of red scale Aonidiella aurantii (Mask.). J. Aust. Entom Soc., 17:367-371.

Southwood, T. R. E. (1967). The interpretation of population change. J. Anim. Ecol., 36:519-529.

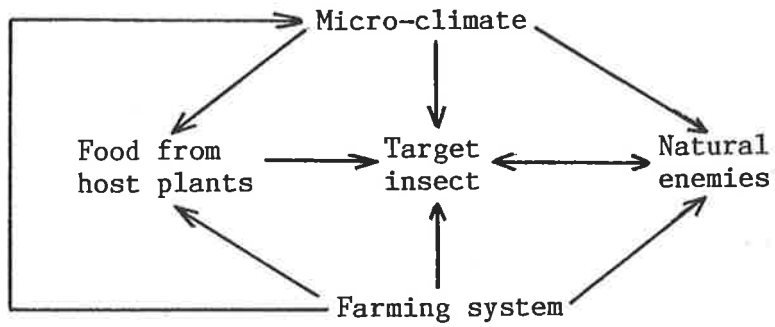
CHAPTER 8.

GENERAL DISCUSSION

CHAPTER 8. GENERAL DISCUSSION

8.1. On Population Regulation of Red Scale

Any rise and decline of the population of a species is dependent on its environment. The relationship between a species and its environment can be summarized by the following flow chart (H.F. Chao, pers. comm.):



Shown in this flow chart, the influence of natural enemies on the population regulation of the "target insect" is more variable than other factors. So, for a practical purpose of biological pest control, one must know (1) the reproductive potential and the reproductive ability and (2) the survival potential and the survival ability for both the "target insect" and/or the "natural enemy". The "potential" is the maximum, in number of offspring or survival duration, which one female can reach under optimum environmental conditions; by contrast, the "ability" is the offspring and/or survival time of a female in less favourable conditions. Consequently, a "good parasite" is expected to have a high reproductive (or survival) ability as close as possible to its reproductive (or survival) potential at any natural condition.

Many researchers have studied California red scale and its Aphytis enemies with respect to the reproductive and/or survival potential of these insects. By contrast, I concentrated on the studies of the reproductive and/or survival ability. My study has attempted to examine (a) the extremes of temperatures on the survival of red scale and its parasite A. melinus, (b) the factors affecting the degree of control exercised by A. melinus on red scale and (c) the estimation of the influence of extreme

temperatures and A. melinus on the infestation of red scale on lemons in the orchard (Chapters 4, 5 and 7).

As well, I have tried to suggest how an improved farming system, e.g. growing plants to provide flower nectar for parasites as food, would improve the biological control of red scale by A. melinus (see Chapter 6). I conclude that (i) in the Waite Institute Orchard, red scales live under optimum temperature conditions for survival and (ii) in this orchard, A. melinus is not an effective control agent on the population growth of red scale (see Chapter 7).

However, in the orchard of the Waite Institute, particular attention was paid to the first and second increase-intervals (denoted as ICIT) for red scale population growth at the beginning of the annual infestation period. Study of these ICITs should give information about the overwintering stages of red scale which would allow one to plan the control of red scale by A. melinus. These ICITs initiated a persistent increase in log number of live scales of each stage; they are re-arranged in Figure 8.1 (1) for each stage: in "A" for 1984-85, and in "B" for 1985-86. In 1984-85 there was only one ICIT in the spring and early summer (October to December 1984) and the population started from a very low level, near zero, after the winter decline in numbers [App.Tab.7.3 (2)]. By contrast, in 1985-86, the 3rd instar and adult (female) stages each had two ICITs: the first between late August and early October (mid-winter to early spring); the second from mid November to early December (mid-spring to late spring) for 3rd instars and from mid December to early January (late spring to early summer) for adult red scale. In 1984-85, the ICIT of 3rd and adult stage red scale presented after the ICIT of the whole population (overall stages). This might indicate that these red scales came mainly from the young scales of the so-called spring generation but not from the overwintering red scales of 1984. By contrast, I believe that the first ICIT in 1985-86 involved the survivors of the overwintering younger stages, namely, 2nd instars and 2nd moult instars; the second ICIT involved the offspring of the first. However, all these led to a further suggestion that between late August and early October is a very important period for the natural control of red scale by A. melinus in this study orchard. During this period the parasitoids, if present in sufficient number, can have a very great effect on the population of red scale, killing not only the spring brood but also large numbers of "mother" scales, the overwintering individuals. Unfortunately, in my study orchard, the

Figure 8.1 (1). Presentation time of the so-called ICIT increase interval (-**-) in log numbers of live scales of each stage. Where, E.=early, M.=mid, L.=late.

Stage of red scale	August	October			November			December			January		
	L.	E.	M.	L.	E.	M.	L.	E.	M.	L.	E.	M.	L.

(A) 1984-85

Population	-	-	-	-	-	*	*	*	*	*	-	-	-
1st instar	-	-	*	*	*	*	*	*	*	*	-	-	-
1st moult	-	-	-	-	-	*	*	*	*	*	-	-	-
2nd instar	-	-	*	*	*	*	*	*	*	*	-	-	-
2nd moult	-	-	-	-	-	-	-	*	*	*	*	-	-
3rd instar	-	-	-	-	-	-	-	-	-	-	*	*	*
Adult	-	-	-	-	-	-	-	*	*	*	-	-	-
Male	-	-	-	-	-	-	-	*	*	*	*	-	-

(B) 1985-86

population	-	-	-	-	-	*	*	*	*	*	-	-	-
1st instar	-	-	-	-	-	*	*	*	*	*	-	-	-
1st moult	-	-	-	-	-	*	*	*	*	*	-	-	-
2nd instar	-	-	-	-	-	*	*	*	*	*	-	-	-
2nd moult	-	-	-	-	-	-	-	*	*	*	*	-	-
3rd instar	-	-	*	*	*	*	*	*	*	*	*	-	-
Adult	-	-	*	*	*	*	*	*	*	*	*	*	*
Male	-	-	-	-	-	*	*	*	*	*	-	-	-

parasitoids could not parasitise enough red scales to effect control [see Fig. 8.1 (2)] during this period. It is possible that, in the previous season, the number of 2nd instars dropped too early (from mid-april) when the parasitization of red scale was at its yearly peak. The parasitoids emerging after this peak could not find suitable hosts to maintain a high population of Aphytis. Then, after overwintering, the parasitoids further lost suitable hosts as the 3rd instars moved into the adult stage. Such arguments tend to agree with the concept that the scarcity of suitable hosts at certain times of the year may limit the efficiency of Aphytis by reducing the chances of the parasite achieving its reproductive potential (McLaren 1971, McLaren and Buchanan 1973).

Similar to D.A. Maelzer's (unpublished data) results, obtained from the field experiments in Loxton, S. Australia, my field data indicate that 3rd instar scale insects were the most important overwintering source for the following spring infestation season, being the largest class of the stage distribution of the overwintering population [Appendix Table 7.3 (2)]. Consequently, I recommended September (in my study orchard) as a critical period for the biological control of red scale. If A. melinus wasps were to be released between September and early November, these wasps could depend on the citrus flower nectar to extend their longevity, searching efficiency and host-feeding on spring scale insects since nectar has been shown to be as good as honey in these respects (see Chapter 5).

8.2. On Estimation of the Influence of Aphytis on the Natural Control of Red Scale

The exclusion method (DeBach and Huffaker 1971) uses paired cells, one open, one closed, to estimate the effect of natural enemies, especially wasp parasitoids. The heavy infestation of red scale in the closed cell was thought to be due to the exclusion of parasites. However, my laboratory studies have revealed that the control ability of parasitoids is a function of food (carbohydrate) supply. Without carbohydrate food supply, it is always far lower than the potential control influence (see Chapter 5). So, what is the principle of the Aphytis spp. on biological control of red scale in nature? Based on my results (Chapter 5), I suggest a modified cage-experiment using a natural population of red scale to answer this question. Three cages (treatments) must be used: one open cage and two closed cages. In one of the closed cages, a carbohydrate food is provided for the newly emerged parasites for their survival. I believe

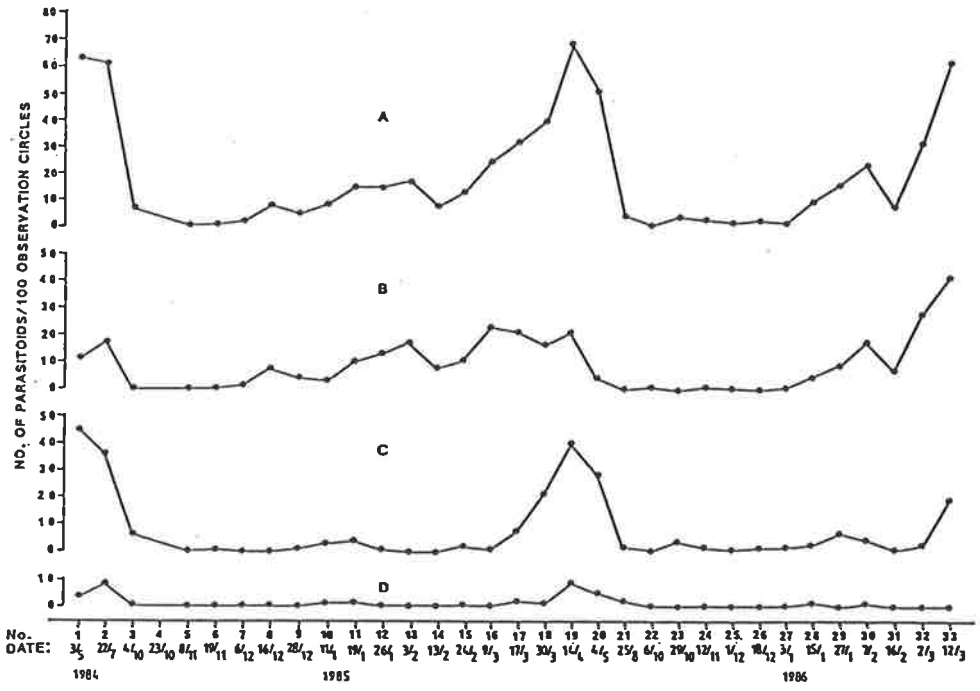


Figure 8.1 (2). Numbers of parasitoids per 100 observation circles (15mm diameter) on lemons on each sampling date.

Where, A: for total red scales overall stages.
B: in adult (female) instar.
C: in 3rd instar.
D: in 2nd instar (female).

that this technique can show either the effect of parasitoids on biological control of the scale insect or the influence of food on the control ability of parasitoids. It is assumed that in the other closed cage (with no carbohydrate food) the newly emerged Aphytis parasitoids cannot live long enough to control the population growth of red scale. The figures below might support these suggestions:

Insect	Food supply (or host)	Temp. (°C)	Lon. (day)	Repr.per adult		Author
				Daily	Total	
1:A.M.	No food	25	1.8	0.3	0.6	Section 5.1
2:A.M.	Honey	20	54.1	1.0	54	Abdelrahman 1974
	Honey	25	29.8	2.1	63	Abdelrahman 1974
3:CRS	L.F.	-	105.2	1.3	137	Yust 1943; orchard
4:CRS	C.L.D.	20	153.3	1.0	153	Willard, 1972
	C.L.D.	25	123.3	1.4	173	Willard, 1972
5:CRS	L.F.	21.7	27.4	1.5	38	Zhao, unpublished field data; summer, 1986*.
6:CRS	Pump.	25	>30	2.4	72	Section 4.3

where, (1) Lon.: reproductive days.
(2) Repr.per adult: reproduction per female adult.
(3) A.M.: A. melinus.
(4) CRS : California red scale.
(5) L.F.: lemon fruit.
(6) C.L.D.: citrus leaf disc.
(7) Pump.: butternut pumpkin.
(8) *: see Appendix Table 8.2 (1).

The total reproduction per adult red scale ranged from 38 up to 173 at temperatures between 20 and 25°C. On the other hand, it was about one for A. melinus which had not been given access to honey as food. Obviously, the very high reproductive ability of red scale makes it impossible for the A. melinus to put the population growth of red scale under control. Consequently, I believe, in the closed cage with a carbohydrate source, the parasitoids can surely put the red scale under control since the parasites have a similar daily reproduction rate to their host red scales. However, I believe DeBach-Huffaker's paired-cell technique can be modified to assess the real ability of parasites to control red scale, simply by placing a

carbohydrate food in the closed cell.

8.3. Control Strategies of *Aphytis* on Red Scale.

Some earlier studies suggest that for *A. melinus*, there is a scale size below which female eggs will not be laid (Abdelrahman 1974). Luck *et al* (1982, 1985) and Opp & Luck (1986) believed that allocating more males than females to smaller hosts is a frequent phenomenon in this species as well in other parasitic Hymenoptera (Clausen 1939, Sandlan 1979, Charnov *et al* 1981). Opp and Luck suggested: (a) a daughter's (parasitoids) body size is determined by host size, (b) body size is related to a female's potential reproductive success and (c) a female's reproductive success is more affected by its size than is that of the male. Following these, I believe that the relationship (between parasite size/sex and the size of the host scale) could be one of the important reasons for the failure of *A. melinus* to control red scale in the Waite Institute Orchard. In this orchard, the lemon trees were getting sicker and sicker throughout my experimental period due to the damage which had been done by the heavy infestation of red scale. The sicker trees offered poorer nutrition for red scales; as a result, the scales, especially the 3rd instars, became smaller than normal. The final result of this cumulative process is the disappearance of the influence of *A. melinus* on the natural control of red scale.

Since extremes of temperatures have little influence on the population regulation of red scale in the Waite Institute Orchard (see Chapter 7), I believe the natural enemy *A. melinus* is the most important factor on the natural control of red scale in Adelaide. Consequently, I suggest that future studies must be done on the relationship between reproduction and/or survival ability of this parasite and its environment. My experiments have already given some suggestion for improving the control ability of *A. melinus*, namely, (I) the improvement of the farming system by providing a carbohydrate food for *A. melinus*, e.g. artificially placing (must be protected from other insects) some honey in the orchard; periodically growing some cover herb plants to produce the flower nectar (see Chapter 6); or, possibly, releasing or infesting some citrus insect which is a honey-dew producer if this insect could be easily controlled, and (II) the rejuvenation of the quality of the parasitoid population in nature.

In my experimental orchard, the overwintering stages are 2nd, 3rd and adult female instars (see Chapter 7). So there is a certain period at the

beginning of a new annual infestation season of red scale, after all the overwintering scales have become adults, when A. melinus may have difficulty in finding host scales of a suitable size. If Luck's suggestion is true, then, during the spring period in the Waite Institute Orchard, most of the scales are too young (see Chapter 7) for parasitism or just suitable for parasites to lay male eggs; most of these young scales are suitable for host-feeding only. Killing scales by the oviposition of male parasites and by host-feeding, could delay the appearance of 3rd instars of suitable size in the spring and would further delay or even lead to the failure of the build-up of the population of the parasite itself.

So suggestion (II) could involve two strategies. The first is to release and/or kill parasites at appropriate times in the annual infestation cycle of scale to keep the natural population of the parasites remaining at the optimum condition. For instance, in the spring infestation period of red scale, kill parasites and keep the population of the parasite at a low level to reduce the host-feeding influence and also reduce the ratio between male and female parasites in the offspring of parasites; the additional parasites will not be released until summer when a certain size of the population of 3rd instar red scale have built up. The second strategy is based on the improvement of the health of trees. Trees in better condition can produce bigger 3rd instar red scales. Consequently, the bigger scales can produce a healthy population of A. melinus in summer and put red scale under control during the period of summer-autumn.

REFERENCES

Abdelrahman, I. (1974). Studies in ovipositional behaviour and control of sex in Aphytis melinus DeBach, a parasite of California red scale, Aonidiella aurantii (Mask.). Aust. J. Zool., 22:231-247.

Charnov, E. L., Los-den Hartogh, Z. L., Jones, W. T. and van den Assem, J. (1981). Sex ratio evolution in a variable environment. Nature (London), 289:27-33.

Clausen, C. P. (1939). The effect of host size upon the sex ratio of hymenopterous parasites and its relation to methods of rearing and colonization. J. N. Y. Entom. Soc., 47:1-9.

DeBach, P. and Huffaker, C.B. (1971). Experimental techniques for evaluation of the effectiveness of natural enemies. In "Biological Control", (C. B. Huffaker, ed.), pp.113-140. Plenum, New York.

Luck, R. F. and Podoler, H. (1985). The potential role of host size in the competitive exclusion of Aphytis lingnanensis by A. melinus. Ecology, 66:904-913.

Luck, R. F., Podoler, H. and Kfir, R. (1982). Host selection and egg allocation behaviour by Aphytis melinus and A. lingnanensis: Comparison of two facultatively gregarious parasitoids. Ecol. Entom., 7:397-408.

McLaren, I. W. (1971). A comparison of the population growth potential in California red scale, Aonidiella aurantii (Mask.) and yellow scale, A. citrina (Coquillet) on citrus. Aust. J. Zool., 19:189-204.

McLaren, I. W. and Buchana, G. A. (1973). Parasitism by Aphytis chrysomphali Merect and A. melinus DeBach of California red scale, Aonidiella aurantii (Mask.) in relation to seasonal availability of suitable stages of the scale. Aust. J. Zool., 21:111-117.

Opp, S. B. and Luck, R. F. (1986). Effects of host size on selected fitness components of Aphytis melinus and A. lingnanensis (Hymenoptera: Aphelinidae). Ann. Ento. Soc. Ame., 79:700-704.

Sandlan, K. (1979). Sex ratio regulation in Coccygomimus turionella Linnaeus (Hymenoptera: Ichneumonidae) and its ecological implications. Ecol. Entom., 4:365-376.

Willard, J. R. (1972). Studies on rates of development and reproduction of California red scale, Aonidiella aurantii (Mask.) (Homoptera: Diaspididae). Aust. J. Zool., 20:37-47.

Yust, H. R. (1943). Productivity of the California red scale on lemon fruits. J. Econ. Entom., 36:868-872.

APPENDIXES

Appendix Table 2.2 (1). Above-skin temperature (AS T), on both the eastern (E) and western (W) side of the canopy, in °C resulting from thermocouple sensors 1mm above the skin of lemons on a tree on a typical summer day (4/2/83). Also given are the ambient temperatures (AT) in the Stevenson Screen.

Time	AS T on :		Deviation of T between:		AT
	E	W	E and W	AS and AT	
0700	16.5	15.0	1.5	-1.5	18.0
0800	22.5	16.75	5.75	3.0	19.5
0900	32.0	19.75	12.25	11.0	21.0
1000	38.0	22.0	16.0 *	14.5	23.5
1100	38.0	24.75	13.25	12.0	26.0
1200	41.0*	26.25	14.75	15.0*	26.0
1300	39.5	27.5	12.0	12.0	27.5
1400	41.0*	29.25	11.75	11.5	29.5
1500	30.5	35.5	- 5.0	6.0	29.5
1600	28.25	40.25	-12.0	10.75	29.5
1700	28.25	40.75	-12.5	10.75	30.0
1800	28.25	43.75*	-15.5	12.75	31.0*
1900	26.5	36.5	-10.0	7.5	29.0
2000	24.5	26.5	- 2.0	-1.0	27.5

(1). *: extreme values.

(2). The extremely high temperatures in the sunlight, obtained from thermocouple sensors, were observed at time:

1125H East: 41.75°C (while West: 25.75°C)
1745H West: 45.50°C (while East: 29.25°C)

(3). The deviation between the maximum ambient temperature and the extremely high sensor-temperature was as: 12.75°C at 1800H.

Appendix Table 4.2 (1-N). Numbers of red scale of Cohort 1 on north of the canopy; started: 29/1/1983

Sampling:		Observed numbers of scales for stage:						
no.	date	W.C.	1st	2nd	male	3rd	adult	total
1	31/1	272						272
2	14/2	272						272
3	28/2	151						151
4	14/3	91						91
5	28/3	59						59
6	11/4	30						30
7	26/4	28						28
8	9/5	24						24
9	23/5	19						19
10	6/6	15						15
11	20/6	12						12
12	3/7	8						8

Appendix Table 4.2 (1-S.). Numbers of red scale of Cohort 1 on south of the canopy; started: 29/1/1983.

Sampling:		Observed numbers of scales for stage:						
no.	date	W.C.	1st	2nd	male	3rd	Adult	total
1	31/1	188						188
2	14/2	57	43	72				172
3	28/2	27	43*	18	27	27		142
4	14/3	25	43	10	27	6	21	132
5	28/3	25	43	10	27	6	21	132
6	11/4	23	43	9	27	5	21	128
7	26/4	21	43	6	27	2	21	120
8	9/5	lemon dropped off						
9								
10								
11								
12								
13								

% rates: male= 27/188 = 14.36
female= 21/188 = 11.17

Appendix Table 4.2 (1-E.). Numbers of red scale of Cohort 1 on east of the canopy; started: 29/1/1983.

Sampling:		Observed numbers of scales for stage:						
no.	date	W.C.	1st	2nd	male	3rd	Adult	total
1	31/1	343						
2	14/2	lemon dropped off						
3								
4								
5								
6								
7								
8								
9								
10								
11								
12								
13								

Appendix Table 4.2 (1-W.). Numbers of red scale of Cohort 1 on west of the canopy; started: 29/1/1983

Sampling:		Observed numbers of scales for stage:						
no.	date	W.C.	1st	2nd	male	3rd	adult	total
1	31/1	192						192
2	14/2	178						178
3	28/2	110						110
4	14/3	102						102
5	28/3	102						102
6	11/4	102						102
7	26/4	69						69
8	9/5	12						12
9	23/5	12						12
10	6/6	12						12
11	20/6	12						12
12	3/7	12						12
13	17/7	12						12

Appendix Table 4.2 (2-N.). Numbers of red scale of Cohort 2 on north of the canopy; started: 6/2/1983.

Sampling:		Observed numbers of scales for stage:						
no.	date	W.C.	1st	2nd	male	3rd	adult	total
1	8/2	77						77
2	25/2	60						60
3	11/3	22						22
4	25/3	19						19
5	15/4	14						14
6	5/5	12						12
7	26/5	12						12
8	8/6	9						9
9	22/6	7						7
10	6/7	7						7

Appendix Table 4.2 (2-S.). Numbers of red scale of Cohort 2 on south of the canopy; started: 6/2/1983.

Sampling:		Observed numbers of scales for stage:						
no.	date	W.C.	1st	2nd	male	3rd	adult	total
1	8/2	98						98
2	25/2	22	9	64				95
3	11/3	22	9	32*	15	3		81
4	25/3	19	9	32	15	0	3	78
5	15/4	15	3	42	15	0	3	78
6	5/5	15	3	42	10	0	3	73
7	26/5	lemon dropped off						
8	8/6							
9	22/6							
10	6/7							

% rate: mele= 15/98 = 15.31
female= 3/98 = 3.06

Appendix Table 4.2 (2-E.). Numbers of red scale of Cohort 2 on east of the canopy; started: 6/2/1983.

Sampling:		Observed numbers of scales for stage:						
no.	date	W.C.	1st	2nd	male	3rd	Adult	total
1	8/2	13						
2	25/2	8	0	1				
3	11/3	4	0	0	1			
4	25/3	lemon dropped off						
5								
6								
7								
8								
9								
10								

% rate: male= 1/13 = 7.69

Appendix Table 4.2 (2-W.). Numbers of red scale of Cohort 2 on west of the canopy; started: 6/2/1983.

Sampling:		Observed numbers of scales for stage:						
no.	date	W.C.	1st	2nd	male	3rd	adult	total
1	8/2	62						62
2	25/2	55	2	4				61
3	11/3	55	2	4*				61
4	25/3	45	1	4				50
5	15/4	45	1	4				50
6	5/5	41	1	2				44
7	26/5	41	1	2				44
8	8/6	33	1	2				36
9	22/6	33	1	2				36
10	6/7	33	1	2				36

Appendix Table 4.2 (3-N.). Numbers of red scale of Cohort 3 on north of the canopy; started: 15/2/1983.

Sampling:		Observed numbers of scales for stage:						
no.	date	W.C.	1st	2nd	male	3rd	adult	total
1	17/2	79						79
2	27/2	37	3	14				54
3	13/3	37	3	5	5			50
4	27/3	37	3	3*	5*	2		50
5	10/4	37	3	2	5	1	1	49
6	24/4	24	0	2	5	1	1	32
7	10/5	22	0	2	3	1	1	29
8	24/5	22	0	2	3	1	1	29
9	8/6	14	0	2	2	1	0	19
10	22/6	14	0	2	2	1	0	19
11	6/7	8	0	2	2	1	0	13
12	20/7	8	0	2	1	1	0	12

% rate: male= 5/79 = 6.33
female= 1/79 = 1.27

Appendix Table 4.2 (3-S.). Numbers of red scale of Cohort 3 on south of the canopy; started: 15/2/1983.

Sampling:		Observed numbers of scales for stage:						
no.	date	W.C.	1st	2nd	male	3rd	adult	total
1	17/2	108						108
2	27/2	11	13	72				107
3	13/3	11	13	32	20	3		90
4	27/3	13	13	29*	20*	3	2	80
5	10/4	13	13	15	9	3	2	55
6	24/4	0	9	13	9	3	2	36
7	10/5	0	9	13	6	3	1	32
8	24/5	0	9	13	6	3	1	32
9	8/6	0	9	13	6	3	1	32
10	22/6	0	6	13	6	3	1	29
11	6/7	0	4	13	6	2	1	26
12	20/7	0	4	13	6	1	0	24

% rate: male= 20/108 = 18.52
female= 2/108 = 1.85

Appendix Table 4.2 (3-E.). Numbers of red scale of Col on east of the canopy; started: 15/2/1983.

Sampling:		Observed numbers of scales for stage:						
no.	date	W.C.	1st	2nd	male	3rd	adult	total
1	17/2	138						138
2	27/2	4	8	82				94
3	13/3	2	8	62	17	4		93
4	27/3	2	6	56*	11*	4	2	81
5	10/4	0	6	35	10	2	2	55
6	24/4	0	6	20	9	2	2	39
7	10/5	0	6	18	8	2	1	35
8	24/5	0	6	13	7	2	0	28
9	8/6	0	6	13	7	0	0	26
10	22/6	0	6	13	7	0	0	26
11	6/7	0	6	13	7	0	0	26
12	20/7	0	4	13	5	0	0	22

% rate: male= 17/138 = 12.32
female= 2/138 = 1.45

Appendix Table 4.2 (3-W.). Numbers of red scale of Cohort on west of the canopy; started: 15/2/1983.

Sampling:		Observed numbers of scales for stage:						
no.	date	W.C.	1st	2nd	male	3rd	adult	total
1	17/2	83						83
2	27/2	76	0	6				82
3	13/3	71	0	6				77
4	27/3	71	0	6*				77
5	10/4	66	0	0				66
6	24/4	60	0	0				60
7	10/5	56	0	0				56
8	24/5	52	0	0				52
9	8/6	46	0	0				46
10	22/6	36	0	0				36
11	6/7	34	0	0				34
12	20/7	12	0	0				12

Appendix Table 4.2 (4-N.). Numbers of red scale of Cohort 4 on north of the canopy; started: 22/2/1983.

Sampling:		Observed numbers of scales for stage:						
no.	date	W.C.	1st	2nd	male	3rd	adult	total
1	22/2	84						84
2	4/3	22	3	2				27
3	14/3	15	0	1				16
4	28/3	12	0	1				13
5	14/4	9	0	0	0	1		10
6	25/4	9	0	0	0	1		10
7	12/5	6	0	0	0	1		7
8	26/5	6	0	0	0	1		7
9	9/6	6	0	0	0	1		7
10	23/6	6	0	0	0	1		7
11	7/7	6	0	0	0	1		7
12	21/7	lemon dropped off						
13	15/8							

Appendix Table 4.2 (4-S.). Numbers of red scale of Cohort 4 on south of the canopy; started: 22/2/1983.

Sampling:		Observed numbers of scales for stage:						
no.	date	W.C.	1st	2nd	male	3rd	adult	total
1	22/2	77						77
2	4/3	0	0	62				62
3	14/3	0	0	62				62
4	28/3	0	0	31	27	1		59
5	14/4	0	0	12	27	14	4	57
6	25/4	0	0	11*	27*	4	14	56
7	12/5	0	0	11	27	3	15	56
8	26/5	0	0	11	27	3	15	56
9	9/6	0	0	11	27	3	15	56
10	23/6	0	0	11	26	3	14	54
11	7/7	0	0	11	26	3	14	54
12	21/7	0	0	10	21	3	8	42
13	15/8	0	0	10	21	3	8	42

% rate: male= 27/77 = 35.06
female= 15/77 = 19.48

Appendix Table 4.2 (4-E.). Numbers of red scale of Cohort 4 on east of the canopy; started: 22/2/1983.

Sampling:		Observed numbers of scales for stage:						
no.	date	W.C.	1st	2nd	male	3rd	adult	total
1	22/2	95						95
2	4/3	2	0	78				80
3	14/3	0	0	75	1			76
4	28/3	0	0	43	22	4		69
5	14/4	0	0	32	22	8	3	65
6	25/4	0	0	26*	22*	6*	9	63
7	12/5	0	0	26	21	4	9	60
8	26/5	0	0	26	21	4	9	60
9	9/6	0	0	26	21	4	9	60
10	23/6	0	0	19	20	2	9	50
11	7/7	0	0	19	19	2	9	49
12	21/7	0	0	19	19	2	9	49
13	15/8	0	0	19	19	2	9	49

% rate: male= 22/95 = 23.16
female= 9/95 = 9.47

Appendix Table 4.2 (4-W.). Numbers of red scale of Cohort 4 on west of the canopy; started: 22/2/1983.

Sampling:		Observed numbers of scales for stage:						
no.	date	W.C.	1st	2nd	male	3rd	adult	total
1	22/2	102						102
2	4/3	51						51
3	14/3	51						51
4	28/3	47						47
5	14/4	40						40
6	25/4	23						23
7	12/5	18						18
8	26/5	18						18
9	9/6	18						18
10	23/6	18						18
11	7/7	18						18
12	21/7	12						12
13	15/8	lemon dropped off						

Appendix Table 4.2 (5-N.). Numbers of red scale of Cohort 5 on north of the canopy; started: 2/3/1983.

Sampling:		Observed numbers of scales for stage:						
no.	date	W.C.	1st	2nd	male	3rd	adult	total
1	3/3	96						96
2	13/3	1	11	76				88
3	28/3	0	10	71				81
4	14/4	0	7	34	20	2		63
5	28/4	0	6	27	27	2		62
6	16/5	0	3	16*	32*	6		57
7	26/5	0	2	15	31	1	5	54
8	9/6	0	2	15	30	1	5	53
9	23/6	0	0	12	30	1	5	48
10	7/7	0	0	12	30	1	5	48
11	21/7	0	0	12	30	1	5	48
12	15/8	0	0	12	30	1	4	47

% rate: male= 32/96 = 33.33
female= 5/96 = 5.21

Appendix Table 4.2 (5-S.). Numbers of red scale of Cohort 5 on south of the canopy; started: 2/3/1983.

Sampling:		Observed numbers of scales for stage:						
no.	date	W.C.	1st	2nd	male	3rd	adult	total
1	3/3	57						57
2	13/3	1	35	1				37
3	28/3	1	0	34				35
4	14/4	0	0	19	4			23
5	28/4	0	0	17	4	2		23
6	16/5	0	0	6*	3*	9		18
7	26/5	0	0	6	3	9	0	18
8	9/6	0	0	6	3	1	8	18
9	23/6	0	0	6	3	1	8	18
10	7/7	0	0	6	3	1	8	18
11	21/7	0	0	6	3	1	8	18
12	15/8	0	0	2	2	1	8	13

% rate: male= 4/57 = 7.02
female= 8/57 = 14.04

Appendix Table 4.2 (5-E.). Numbers of red scale of Cohort 5 on east of the canopy; started: 2/3/1983.

Sampling:		Observed numbers of scales for stage:						
no.	date	W.C.	1st	2nd	male	3rd	adult	total
1	3/3	71						71
2	13/3	6	0	63				69
3	28/3	0	0	57	4			61
4	14/4	0	0	23	29	4		56
5	28/4	0	0	11*	25*	16	2	54
6	16/5	0	0	8	25	18	2	53
7	26/5	0	0	7	25	6	14	52
8	9/6	0	0	7	25	4	16	52
9	23/6	0	0	7	25	4	16	52
10	7/7	0	0	7	25	4	16	52
11	21/7	0	0	5	23	4	16	48
12	15/8	0	0	5	21	4	16	46

% rate: male= 29/71 = 40.85
female= 16/71 = 22.54

Appendix Table 4.2 (5-W.). Numbers of red scale of Cohort 5 on west of the canopy; started: 2/3/1983.

Sampling:		Observed numbers of scales for stage:						
no.	date	W.C.	1st	2nd	male	3rd	adult	total
1	3/3	67						67
2	13/3	0	3	62				65
3	28/3	0	3	53	1			57
4	14/4	0	0	26	25			51
5	28/4	0	0	9	25	10	4	48
6	16/5	0	0	5*	22*	13	5	45
7	26/5	0	0	5	20	2	16	43
8	9/6	0	0	5	20	2	16	43
9	23/6	0	0	5	20	2	16	43
10	7/7	0	0	5	20	2	16	43
11	21/7	0	0	5	20	2	16	43
12	15/8	0	0	4	20	2	16	43

% rate: male= 25/67 = 37.31
female= 16/67 = 23.88

Appendix Table 4.2 (6-N.). Numbers of red scale of Cohort 1 on north of the canopy; started: 24/1/1985.

Sampling:		Observed scale numbers for stage:						
no.	date	W.C.	1st	2nd	male	3rd	adult	total
1	25/1	64						64
2	1/2	18	5					23
3	8/2	12	4					16
4	15/2	12	4					16
5	23/2	12	4					16
6	1/3/	10	3					13
7	8/3	8	3					11
8	20/3	8	2					11
9	25/3	8	2					11
10	1/4	0	0					0

Sampling:		Drop-off numbers of scales for stage:						
no.	date	W.C.	1st	2nd	male	3rd	adult	total
1	25/1	0						0
2	1/2	41						41
3	8/2	6	1					7
4	15/2	0	0					0
5	23/2	0	0					0
6	1/3	2	1					3
7	8/3	2	0					2
8	20/3	0	0					0
9	25/3	0	0					0
10	1/4	8	2					10
total		59	4					63

Appendix Table 4.2 (6-S). Numbers of red scale of Cohort 1 on south of the canopy; started: 24/1/1985.

Sampling:		Observed scale numbers for stage:						
no.	date	W.C.	1st	2nd	male	3rd	adult	total
1	25/1	85						85
2	1/2	44	32					76
3	8/2	20	25	4				49
4	15/2	16	24	4				44
5	23/2	16	22*	4*				44
6	1/3	13	15	3	1			32
7	8/3	11	13	3	1			28
8	20/3	8	10	3	1			22
9	25/3	8	10	3	1			22
10	1/4	6	9	3	1			19

Sampling:		Drop-off numbers of scales for stage:						
no.	date	W.C.	1st	2nd	male	3rd	adult	total
1	25/1	0						0
2	1/2	9						9
3	8/2	24	3					27
4	15/2	4	1					5
5	23/2	0	0					0
6	1/3	3	9					12
7	8/3	2	2					4
8	20/3	3	3					6
9	25/3	0	0					0
10	1/4	2	1					3
total		47	19					66

Appendix Table 4.2 (6-W.). Numbers of red scale of Cohort 1 on west of the canopy; started: 24/1/1985.

Sampling:		Observed scale numbers for stage:						
no.	date	W.C.	1st	2nd	male	3rd	adult	total
1	25/1	85						85
2	1/2	49						49
3	8/2	41						41
4	15/2	37						37
5	23/2	34						34
6	1/3	30						30
7	8/3	26						26
8	20/3	26						26
9	25/3	26						26
10	1/4	6						6

Sampling:		Drop-off numbers of scales for stage:						
no.	date	W.C.	1st	2nd	male	3rd	adult	total
1	25/1	0						0
2	1/2	36						36
3	8/2	8						8
4	15/2	4						4
5	23/2	3						3
6	1/3	4						4
7	8/3	4						4
8	20/3	0						0
9	25/3	0						0
10	1/4	20						20
total		79						79

Appendix Table 4.2 (7-N.). Numbers of red scale of Cohort 2 on north of the canopy; started: 31/1/1985.

Sampling:		Observed scale numbers for stage:						
no.	date	W.C.	1st	2nd	male	3rd	adult	total
1	1/2	92						92
2	8/2	23	43					66
3	15/2	22	19	24				65
4	23/2	21	18	21	3			63
5	1/3	20	11	7*	21	1		60
6	8/3	19	9	3	25*	1*		57
7	20/3	18	6	3	25	1		53
8	25/3	17	6	3	24	1		51
9	1/4	17	6	3	24	1		51
10	8/4	14	5	2	13	1		35

Sampling:		Drop-off numbers of scales for stage:						
no.	date	W.C.	1st	2nd	male	3rd	adult	total
1	1/2	0						0
2	8/2	26						26
3	15/2	1						1
4	23/2	1	1					2
5	1/3	1	2					3
6	8/3	1	2					3
7	20/3	1	3					4
8	25/3	1	0	0	1			2
9	1/4	0	0	0	0			0
10	8/4	3	1	1	11			16
total		35	9	1	12			57

Appendix Table 4.2 (7-S.). Numbers of red scale of Cohort 2 on south of the canopy; started: 31/1/1985.

Sampling:		Observed scale numbers for stage:						
no.	date	W.C.	1st	2nd	male	3rd	adult	total
1	1/2	65						65
2	8/2	5	30					35
3	15/2	5	9	18				32
4	23/2	5	5	8	10			28
5	1/3	5	5	2*	11	5		28
6	8/3	4	5	1	11*	6*		27
7	20/3	4	5	0	11	6	1	27
8	25/3	4	5	0	11	6	1	27
9	1/4	4	5	0	11	6	1	27
10	8/4	3	5	0	11	6	1	26

Sampling:		Drop-off numbers of scales for stage:						
no.	date	W.C.	1st	2nd	male	3rd	adult	total
1	1/2	0						0
2	8/2	30						30
3	15/2	0	3					3
4	23/2	0	4					4
5	1/3	0	0					0
6	8/3	1	0					1
7	20/3	0	0					0
8	25/3	0	0					0
9	1/4	0	0					0
10	8/4	1	0					1
total		32	7					39

Appendix Table 4.2 (7-E). Numbers of red scale of Cohort 2 on east of the canopy; started: 31/1/1985.

Sampling:		Observed scale numbers for stage:						
no.	date	W.C.	1st	2nd	male	3rd	adult	total
1	1/2	74						74
2	8/2	0	50					50
3	15/2	0	16	31				47
4	23/2	0	8	31				39
5	1/3	0	6	5*	21	5		37
6	8/3	0	5	1	22*	5*	3	36
7	20/3	0	2	1	21	4	4	32
8	25/3	0	2	1	21	4	4	32
9	1/4	0	2	0	21	4	4	31
10	8/4	0	1	0	17	4	3	25

Sampling:		Drop-off numbers of scales for stage:						
no.	date	W.C.	1st	2nd	male	3rd	adult	total
1	1/2	0						0
2	8/2	24						24
3	15/2	0	3					3
4	23/2	0	8					8
5	1/3	0	1	1				2
6	8/3	0	1	0				1
7	20/3	0	3	0				3
8	25/3	0	0	0				0
9	1/4	0	0	1				1
10	8/4	0	1	0	4	0	1	6
total		24	17	2	4	0	1	48

Appendix Table 4.2 (7-W.). Numbers of red scale of Cohort 2 on west of the canopy; started at31/1/1985.

Sampling:		Observed scale numbers for stage:						
no.	date	W.C.	1st	2nd	male	3rd	adult	total
1	1/2	105						105
2	8/2	64	15					79
3	15/2	61	7	10				78
4	23/2	60	6	9	1			76
5	1/3	55	6	8*	2			71
6	8/3	53	6	4	6*			69
7	20/3	47	4	3	7			61
8	25/3	43	4	3	7			57
9	1/4	33	4	3	7			47
10	8/4	23	3	3	7			36

Sampling:		Drop-off numbers of scales for stage:						
no.	date	W.C.	1st	2nd	male	3rd	adult	total
1	1/2	0						0
2	8/2	26						26
3	15/2	1						1
4	23/2	0	2					2
5	1/3	5	0					5
6	8/3	2	0					2
7	20/3	6	2					8
8	25/3	4	0					4
9	1/4	10	0					10
10	8/4	10	1					11
total		64	5					69

Appendix Table 4.2 (8-N.). Numbers of red scale of Cohort 3 on north of the canopy; started: 8/2/1985.

Sampling:		Observed scale numbers for stage:						
no.	date	W.C.	1st	2nd	male	3rd	adult	total
1	9/2	81						81
2	16/2	20	35					55
3	23/2	20	19	16				55
4	2/3	20	18	9	7			54
5	9/3	18	18	4	9	3		52
6	20/3	18	13	3	9*	4		47
7	25/3	17	13	3	9	3		45
8	1/4	14	12	2	8	2	1	39
9	15/4	13	10	1	8	1	1	34
10	22/4	4	5	1	6	1	1	18

Sampling:		Drop-off numbers of scales for stage:						
no.	date	W.C.	1st	2nd	male	3rd	adult	total
1	9/2	0						0
2	16/2	26						26
3	23/2	0						0
4	2/3	0	1					1
5	9/3	2	0					2
6	20/3	0	5					5
7	25/3	1	0	0	0	1		2
8	1/4	3	1	1	1	0		6
9	15/4	1	2	1	0	1		5
10	22/4	9	5	0	2	0		16
total		42	14	2	3	2		63

Appendix Table 4.2 (8-S.). Numbers of red scale of Cohort 3 on south of the canopy; started: 8/2/1985.

Sampling:		Observed scale numbers for stage:						
no.	date	W.C.	1st	2nd	male	3rd	adult	total
1	9/2	107						107
2	16/2	23	53					76
3	23/2	13	13	38				64
4	2/3	9	12	33	5			59
5	9/3	9	12	21	16			58
6	20/3	8	12	11*	21*	5		57
7	25/3	8	11	9	22	2	4	56
8	1/4	8	11	9	21	2	4	55
9	15/4	8	8	9	20	1	5	51
10	22/4	6	6	7	20	2	4	45

Sampling:		Drop-off numbers of scales for stage:						
no.	date	W.C.	1st	2nd	male	3rd	adult	total
1	9/2	0						0
2	16/2	31						31
3	23/2	10	2					12
4	2/3	4	1					5
5	9/3	0	0	1				1
6	20/3	1	0	0				1
7	25/3	0	1	0				1
8	1/4	0	0	0	1			1
9	15/4	0	3	0	1			4
10	22/4	2	2	1	0	0	1	6
total		48	9	2	2	0	1	62

Appendix Table 4.2 (8-E.). Numbers of red scale of Cohort 3 on east of the canopy; started: 8/2/1985.

Sampling:		Observed scale numbers for stage:						
no.	date	W.C.	1st	2nd	male	3rd	adult	total
1	9/2	79						79
2	16/2	21	20					41
3	23/2	18	7	12				37
4	2/3	16	7	6	6			35
5	9/3	14	7	0	11	1		33
6	20/3	2	6	0	11*	1		20
7	25/3	2	4	0	11	1		18
8	1/4	2	4	0	9	1		16
9	15/4	2	2	0	6	1		11
10	22/4	1	2	0	6	1		10

Sampling:		Drop-off numbers of scales for stage:						
no.	date	W.C.	1st	2nd	male	3rd	adult	total
1	9/2	0						0
2	16/2	38						38
3	23/2	4						4
4	2/3	2						2
5	9/3	2						2
6	20/3	12	1					13
7	25/3	0	2					2
8	1/4	0	0	0	2			2
9	15/4	0	2	0	3			5
10	22/4	1	0	0	0			1
total		59	5	0	5			69

Appendix Table 4.2 (8-W.). Numbers of red scale of Cohort 3 on west of the canopy; started: 8/2/1985.

Sampling:		Observed scale numbers for stage:						
no.	date	W.C.	1st	2nd	male	3rd	adult	total
1	9/2	109						109
2	16/2	24	49					73
3	23/2	21	15	33				69
4	2/3	18	14	24	9			65
5	9/3	14	14	9	24			61
6	20/3	9	10	6*	25*	1		51
7	25/3	5	9	6	23	0	1	44
8	1/4	2	9	6	22	0	1	40
9	15/4	2	8	6	22	0	1	39
10	22/4	2	8	5	22	0	1	38

Sampling:		Drop-off numbers of scales for stage:						
no.	date	W.C.	1st	2nd	male	3rd	adult	total
1	9/2	0						0
2	16/2	36						36
3	23/2	3	1					4
4	2/3	3	1					4
5	9/3	4	0					4
6	20/3	5	4	1				10
7	25/3	4	1	0	2			7
8	1/4	3	0	0	1			4
9	15/4	0	1	0	0			1
10	22/4	0	0	1	0			1
total		58	8	2	3			71

Appendix Table 4.2 (9-N). Numbers of red scale of Cohort 4 on north of the canopy; started: 15/2/1985

Sampling:		Observed scale numbers for stage:						
no.	date	W.C.	1st	2nd	male	3rd	adult	total
1	16/2	88						88
2	3/2	42	30					72
3	2/3	36	10	20				66
4	9/3	35	4	18	8			65
5	20/3	26	2	12	14			54
6	25/3	16	1	6*	14	6		43
7	1/4	15	1	5	14*	7		42
8	8/4	13	1	3	14	6	1	38
9	15/4	2	1	3	12	6	1	25
10	22/4	0	1	3	12	6	1	23

Sampling:		Drop-off numbers of scales for stage:						
no.	date	W.C.	1st	2nd	male	3rd	adult	total
1	16/2	0						0
2	23/2	16						16
3	2/3	6						6
4	9/3	1						1
5	20/3	9	0	2				11
6	25/3	10	1	0				11
7	1/4	1	0	0				1
8	8/4	2	0	2				4
9	15/4	11	0	0	2			13
10	22/4	2	0	0	0			2
total		58	1	4	2			65

Appendix Table 4.2 (9-S). Numbers of red scale of Cohort 4 on south of the canopy; started: 15/2/1985

Sampling:		Observed scale numbers for stage:						
no.	date	W.C.	1st	2nd	male	3rd	adult	total
1	16/2	88						88
2	23/2	6	71					77
3	2/3	3	41	30				74
4	9/3	3	16	40	14			73
5	20/3	3	15	12	42			72
6	25/3	3	14	12*	42			71
7	1/4	3	11	7	41*	5		67
8	8/4	2	10	6	41	6		65
9	15/4	1	9	5	38	6		59
10	22/4	1	7	5	38	6		57

Sampling:		Drop-off numbers of scales for stage:						
no.	date	W.C.	1st	2nd	male	3rd	adult	total
1	16/2	0						0
2	23/2	11						11
3	2/3	3						3
4	9/3	0	1					1
5	20/3	0	1					1
6	25/3	0	1					1
7	1/4	0	3	0	1			1
8	8/4	1	1	0	0			2
9	15/4	1	1	1	3			6
10	22/4	0	2	0	0			2
total		16	10	1	4			31

Appendix Table 4.2 (9-E). Numbers of red scale of Cohort 4 on east of the canopy; started: 15/2/1985

Sampling:		Observed scale numbers for stage:						
no.	date	W.C.	1st	2nd	male	3rd	adult	total
1	16/2	72						72
2	23/2	30	26					56
3	2/3	28	3	20	3			54
4	9/3	23	0	15	11			49
5	20/3	15	0	13	12			40
6	25/3	10	0	6*	12	6		34
7	1/4	10	0	5	12*	6		33
8	8/4	8	0	5	12	6		31
9	15/4	7	0	5	12	6		30
10	22/4	7	0	4	12	6		29

Sampling:		Drop-off numbers of scales for stage:						
no.	date	W.C.	1st	2nd	male	3rd	adult	total
1	16/2	0						0
2	23/2	16						16
3	2/3	2						2
4	9/3	5						5
5	20/3	8	0	1				9
6	25/3	5	0	1				6
7	1/4	0	0	1				1
8	8/4	2	0	0				2
9	15/4	1	0	0				1
10	22/4	0	0	1				1
total		39	0	4				43

Appendix Table 4.2 (9-W). Numbers of red scale of Cohort 4 on west of the canopy; started: 15/2/1985

Sampling:		Observed scale numbers for stage:						
no.	date	W.C.	1st	2nd	male	3rd	adult	total
1	16/2	152						152
2	23/2	79	28					107
3	2/3	52	18	8				78
4	9/3	43	14	11	1			69
5	20/3	24	7	8	3			42
6	25/3	13	6	5*	4	2		30
7	1/4	10	5	3	4*	4		26
8	8/4	1	4	2	4	3	2	16
9	15/4	1	2	1	4	3	2	13
10	22/4	0	1	0	4	2	2	9

Sampling:		Drop-off numbers of scales for stage:						
no.	date	W.C.	1st	2nd	male	3rd	adult	total
1	16/2	0						0
2	23/2	45						45
3	2/3	27	2					29
4	9/3	9	0					9
5	20/3	19	5	3				27
6	25/3	11	1	0				12
7	1/4	3	1	0				4
8	8/4	9	1	0				10
9	15/4	0	2	1				3
10	22/4	1	1	1	0	1		4
total		124	13	5	0	1		143

Appendix Table 4.2 (10-N). Numbers of red scale of Cohort 5 on north of the canopy; started: 8/3/1985.

Sampling:		Observed scale numbers for stage:						
no.	date	W.C.	1st	2nd	male	3rd	adult	total
1	9/3	141						141
2	20/3	88	29					117
3	25/3	83	14	14				111
4	1/4	78	12	5	9			104
5	8/4	43	6	5*	9			63
6	15/4	35	6	4	8*	1		54
7	22/4	7	3	3	8	1		22
8	29/4	4	0	0	7	4		15
9	6/5	2	0	0	7	4		13
10	13/5	1	0	0	7	4		12

Sampling:		Drop-off numbers of scales for stage:						
no.	date	W.C.	1st	2nd	male	3rd	adult	total
1	9/3	0						0
2	20/3	24						24
3	25/3	5	1					6
4	1/4	5	2					7
5	8/4	35	6					41
6	15/4	8	0	0	1			9
7	22/4	28	3	1	0			32
8	29/4	3	3	0	1			7
9	6/5	2	0	0	0			2
10	13/5	1	0	0	0			1
total		111	15	1	2			129

Appendix Table 4.2 (10-S). Numbers of red scale of Cohort 5 on south of the canopy; started: 8/3/1985.

Sampling:		Observed scale numbers for stage:						
no.	date	W.C.	1st	2nd	male	3rd	adult	total
1	9/3	105						105
2	20/3	10	63					73
3	25/3	8	12	51				71
4	1/4	6	12	23	28			69
5	8/4	4	8	5*	32	15		64
6	15/4	3	7	5	30*	15		60
7	22/4	3	7	4	30	16		60
8	29/4	2	5	3	29	11	5	55
9	6/5	2	5	3	29	2	14	55
10	13/5	2	5	3	29	2	14	55

Sampling:		Drop-off numbers of scales for stage:						
no.	date	W.C.	1st	2nd	male	3rd	adult	total
1	9/3	0						0
2	20/3	32						32
3	25/3	2						2
4	1/4	2						2
5	8/4	2	3					5
6	15/4	1	1	0	2			4
7	22/4	0	0	0	0			0
8	29/4	1	2	1	1			5
9	6/5	0	0	0	0			0
10	13/5	0	0	0	0			0
total		40	6	1	3			50

Appendix Table 4.2 (10-E). Numbers of red scale of Cohort 5 on east of the canopy; started: 8/3/1985.

Sampling:		Observed scale numbers for stage:						
no.	date	W.C.	1st	2nd	male	3rd	adult	total
1	9/3	107						107
2	20/3	16	66					82
3	25/3	11	12	35	19			77
4	1/4	8	11	16	37	1		73
5	8/4	5	8	4*	37	13		67
6	15/4	5	8	1	37*	16		67
7	22/4	5	8	1	37	16		67
8	29/4	5	4	1	35	16		61
9	6/5	4	3	1	29	16		53
10	13/5	3	3	1	29	16		52

Sampling:		Drop-off numbers of scales for stage:						
no.	date	W.C.	1st	2nd	male	3rd	adult	total
1	9/3	0						0
2	20/3	25						25
3	25/3	5						5
4	1/4	3	1					4
5	8/4	3	3					6
6	15/4	0	0					0
7	22/4	0	0					0
8	29/4	0	4	0	2			6
9	6/5	1	1	0	6			8
10	13/5	1	0	0	0			1
total		38	9	0	8			55

Appendix Table 4.2 (10-W). Numbers of red scale of Cohort 5 on west of the canopy; started: 8/3/1985.

Sampling:		Observed scale numbers for stage:						
no.	date	W.C.	1st	2nd	male	3rd	adult	total
1	9/3	85						85
2	20/3	1	58					59
3	25/3	1	29	29				59
4	1/4	0	22	14	16			52
5	8/4	0	11	13*	17			41
6	15/4	0	10	13	17*			40
7	22/4	0	10	10	19	1		40
8	29/4	0	9	3	19	8		39
9	6/5	0	9	2	19	5	3	38
10	13/5	0	6	2	15	5	3	31

Sampling:		Drop-off numbers of scales for stage:						
no.	date	W.C.	1st	2nd	male	3rd	adult	total
1	9/3	0						0
2	20/3	26						26
3	25/3	0						0
4	1/4	1	6					7
5	8/4	0	11					11
6	15/4	0	1					1
7	22/4	0	0					0
8	29/4	0	1					1
9	6/5	0	0	1				1
10	13/5	0	3	0	4			7
total		27	22	1	4			54

Appendix Table 4.2 (1.1). Hour-degrees (above 40°C) of extreme temperatures in each developmental period of the completion of 3rd instar (up to adult stage) of red scale on each aspect.

Cohort:period	Hour-degrees (>40 C) on aspect:				
	N.	S.	E.	W.	total
1983					
1 29/1 -14/3	46.5	0	118.5	125.5	290.5
2 6/2 -25/3	25.5	0	79.5	70.0	175.0
3 15/2 -10/4	15.5	0	50.0	52.5	118.0
4 22/2 -12/5	13.5	0	43.5	47.5	104.5
5 2/3 -9/6	3.0	0	13.5	13.5	30.0
1985					
1 24/1 -no adult	-	-	-	-	-
2 31/1 -20/3	29.0	0	2.5	4.0	35.5
3 8/2 -1/4	41.5	0	0	0	41.5
4 15/2 -8/4	41.0	0	0	0	41.0
5 8/3 -6/5	42.5	0	0	0	42.5

Appendix Table 4.2 (1&). Day-degrees >12°C for the development of the 1st instar red scale in each cohort.

Cohort	Period	Day-degrees
	1983	
1	29/1 - 14/2	188.3
2	6/2 - 25/2	206.2
3	15/2 - 27/2	140.2
4	22/2 - 4/3	146.7
5	2/3 - 28/3	211.9
	1985	
1	25/1 - 8/2	175.4
2	1/2 - 15/2	168.9
3	9/2 - 23/2	153.1
4	16/2 - 9/3	175.2
5	9/3 - 25/3	182.7

Appendix Table 4.2 (13a) The percentage rates of dead 1st instar red scales still on the host lemons and the percentage rates of dead scales already dropped off the host lemons (1983).

Cohort:Aspect :Original total numbers		% rates of dead 1st instar scales		
		On lemons	Off lemons	Total
1:north: 272		100.0	0	100.0
:south: 188		53.2	8.5	61.7
:east : -		-	-	-
:west : 192		92.7	7.3	100.0
total : 652	mean:	82.0	5.3	87.3
2:north: 77		77.9	22.1	100.0
:south: 98		31.6	3.1	34.7
:east : -		-	-	-
:west : 62		91.9	1.6	93.5
total : 237	mean:	67.1	8.9	76.0
3:north: 79		50.6	31.6	82.2
:south: 108		22.2	0.9	23.1
:east : 138		8.7	32.6	41.3
:west : 83		91.6	1.2	92.8
total : 408	mean:	43.3	16.6	59.9
4:north: 84		29.8	67.9	97.7
:south: 77		0	19.5	19.5
:east : 95		2.1	15.8	17.9
:west : 102		50.0	50.0	100.0
total : 358	mean:	20.5	38.3	58.8
5:north: 96		10.4	8.3	18.7
:south: 57		1.8	38.6	40.4
:east : 71		0	2.8	2.8
:west : 67		4.5	3.0	7.5
total : 291	mean:	4.2	13.2	17.4

Appendix Table 4.2 (13b). The percentage rates of dead 1st instar red scales still on the host lemons and the percentage rates of dead scales already dropped off the host lemons (1985).

Cohort:Aspect :Original total numbers		% rates of dead 1st instar scales		
		On lemons	Off lemons	Total
1:north: 64		25.0	75.0	100.0
:south: 85		52.9	42.4	95.3
:east : -		-	-	-
:west : 85		48.2	51.8	100.0
total : 234	mean:	42.0	56.4	98.4
2:north: 92		44.6	29.3	73.9
:south: 65		21.5	50.8	72.3
:east : 74		21.6	36.5	58.1
:west : 105		64.8	25.7	90.5
total : 336	mean:	38.1	35.6	73.7
3:north: 81		48.1	32.1	80.2
:south: 107		24.3	40.2	64.5
:east : 79		31.6	53.2	84.8
:west : 109		33.0	36.7	69.7
total : 376	mean:	34.3	40.6	74.9
4:north: 88		44.3	26.1	70.4
:south: 88		21.6	17.0	38.6
:east : 72		31.9	31.9	63.8
:west : 152		37.5	54.6	92.1
total : 400	mean:	33.8	32.4	66.2
5:north: 141		68.8	21.3	90.1
:south: 105		19.0	32.4	51.4
:east : 107		21.5	28.0	49.5
:west : 85		35.3	30.6	65.9
total : 438	mean:	36.2	28.1	64.3

Appendix Table 4.2 (14a). Hour-degrees (H.D.) >40°C during the developmental period of the 1st instar red scale in each cohort in 1983.

Cohort	Period	Aspect	H.D.>40°C
1	29/1-14/2	N.	22.5
		S.	0
		E.	54.5
		W.	61.0
		Mean	34.5
2	6/2-25/2	N.	23.0
		S.	0
		E.	71.0
		W.	68.5
		Mean	40.6
3	15/2-27/2	N.	21.0
		S.	0
		E.	53.5
		W.	51.5
		Mean	31.5
4	22/2-4/3	N.	2.0
		S.	0
		E.	35.0
		W.	38.0
		Mean	18.8
5	2/3-28/3	N.	2.5
		S.	0
		E.	14.0
		W.	13.5
		Mean	7.5

Appendix Table 4.2 (14b). Hour-degrees (H.D.) above 40°C during the developmental period of the 1st instar red scale in each cohort in 1985.

Cohort	Period	Aspect	H.D. above 40°C
1	25/1-8/2	N	11.5
		S	0
		E	6.5
		W	13.0
		Mean	7.8
2	1/2-15/2	N	7.0
		S	0
		E	2.5
		W	4.0
		Mean	3.4
3	9/2-23/2	N	8.5
		S	0
		E	0
		W	0
		Mean	2.1
4	16/2-9/3	N	9.0
		S	0
		E	0
		W	0
		Mean	2.3
5	9/3-25/3	N	26.0
		S	0
		E	0
		W	0
		Mean	6.5

Appendix Table 4.3 (3). The mortality of 2nd instar red scales after exposure to durations (durat.) of 0-8 hours at temperature (temp.) of -2°C. Also given is the mortality of scales at the (base) constant temperature of +10°C.

temp. (°C)	Durat. hrs. (X)	No. of scales		% Mortality (Y)
		dead	total	
10	24	2	135	1.48
-2	0	10	152	6.58
-2	1	76	210	36.19
-2	2	73	236	30.93
-2	4	65	170	38.24
-2	6	68	192	35.42
-2	8	48	140	34.29

$Y = 22.75+2.15X$ ($r= +0.559$; d.f.=4; $P>0.05$)

Appendix Table 4.3 (4). The mortality of 2nd moult instar red scales, male + female, after exposure to durations (durat.) of 0-8 hours at temperature (temp.) of +5°C. Also given is the mortality of scales at the (base) constant temperature of +10°C.

temp. (°C)	Durat. hrs. (X)	No. of scales		% Mortality (Y)
		dead	total	
10	24	5	171	2.92
5	0	11	119	9.24
5	0.5	17	126	13.49
5	1	29	206	14.08
5	2	19	163	11.66
5	4	31	179	17.32
5	6	79	197	40.10
5	8	54	141	38.30

$Y = 8.50+3.94X$ ($r= +0.923$; d.f.=5; $P<0.01$)

Appendix Table 4.3 (5). The mortality of male only within 2nd moult instar red scales after exposure to durations (durat.) of 0-8 hours at temperature (temp.) of +5°C. Also given is the mortality of scales at the (base) constant temperature of +10°C.

temp. (°C)	Durat. hrs. (X)	No. of scales		% Mortality (Y)
		dead	total	
10	24	0	101	0
5	0	7	52	13.46
5	0.5	14	60	23.33
5	1	24	92	26.09
5	2	17	74	22.97
5	4	24	84	28.57
5	6	68	97	70.10
5	8	47	78	60.26

$Y = 15.57+6.31X$ ($r= +0.898$; d.f.=5; $P<0.01$)

Appendix Table 4.3 (6). The mortality of the female only within 2nd moult instar red scales after exposure to durations (durat.) of 0-8 hours at temperature (temp.) of +5°C. Also given is the mortality of scales at the (base) constant temperature of +10°C.

temp. (°C)	Durat. hrs. (X)	No. of scales		% Mortality (Y)
		dead	total	
10	24	5	70	7.14
5	0	4	67	5.97
5	0.5	3	66	4.55
5	1	5	114	4.39
5	2	2	89	2.25
5	4	7	95	7.37
5	6	11	100	11.00
5	8	7	63	11.11

$Y = 3.76+0.95X$ ($r= +0.849$; d.f.=5; $P<0.05$)

Appendix Table 4.3 (7). The mortality of 3rd instar red scales after exposure to durations (durat.) of 0–8 hours at temperature (temp.) of -2°C. Also given is the mortality of scales at the (base) constant temperature of +10°C.

temp. (°C)	Durat. hrs. (X)	No. of scales		% Mortality (Y)
		dead	total	
10	24	1	92	1.09
-2	0	1	80	1.25
-2	0.5	4	78	5.13
-2	1	7	110	6.36
-2	2	15	97	15.46
-2	4	16	96	16.67
-2	6	15	74	20.27
-2	8	17	88	19.32

$Y = 5.21+2.23X$ ($r= +0.887$; d.f.=5; $P<0.01$)

Appendix Table 4.3 (8). The mortality of 1st instar red scales after exposure to durations (durat.) of 0–8 hours at temperature (temp.) of +45°C. Also given is the mortality of scales at the (base) constant temperature of +25°C.

temp. (°C)	Durat. hrs. (X)	No. of scales		% Mortality (Y)
		dead	total	
25	24	17	105	16.19
45	0	34	172	19.77
45	1	43	189	22.75
45	2	47	158	29.75
45	4	33	120	27.50
45	8	42	96	43.75

$Y = 20.33+2.79X$ ($r= +0.952$; d.f.=3; $P<0.05$)

Appendix Table 4.3 (9). The mortality of 1st moult instar red scales after exposure to durations (durat.) of 0-8 hours at temperature (temp.) of +45°C. Also given is the mortality of scales at the (base) constant temperature of +25°C.

temp. (°C)	Durat. hrs. (X)	No. of scales		% Mortality (Y)
		dead	total	
25	24	24	164	14.63
45	0	79	292	27.05
45	1	43	186	23.12
45	2	61	264	23.11
45	4	53	115	46.09
45	6	62	157	39.49
45	8	57	133	42.86

$Y = 24.23+2.68X$ ($r= +0.797$; d.f.=4; $P>0.05$)

Appendix Table 4.3 (10). The mortality of 2nd instar red scales after exposure to durations (durat.) of 0-8 hours at temperature (temp.) of +45°C. Also given is the mortality of scales at the (base) constant temperature of +25°C.

temp. (°C)	Durat. hrs. (X)	No. of scales		% Mortality (Y)
		dead	total	
25	24	25	172	14.53
45	0	27	154	17.53
45	1	26	141	18.44
45	2	24	144	16.67
45	4	38	157	24.20
45	6	41	152	26.97
45	8	43	160	26.88

$Y = 16.77+1.43X$ ($r= +0.924$; d.f.=4; $P<0.01$)

Appendix Table 4.3 (11). The mortality of 2nd moult instar red scales, male + female, after exposure to durations (durat.) of 0–8 hours at temperature (temp.) of +45°C. Also given is the mortality of scales at the (base) constant temperature of +25°C.

temp. (°C)	Durat. hrs. (X)	No. of scales		% Mortality (Y)
		dead	total	
25	24	13	154	8.44
45	0	18	230	7.83
45	0.5	22	172	12.79
45	1	19	224	8.48
45	2	39	223	17.49
45	4	48	165	29.09
45	6	51	212	24.06
45	8	75	196	38.27

$Y = 9.00+3.49X$ ($r= +0.934$; d.f.=5; $P<0.01$)

Appendix Table 4.3 (12). The mortality of male only within the 2nd moult instar red scales after exposure to durations (durat.) of 0–8 hours at temperature (temp.) of +45°C. Also given is the mortality of scales at the (base) constant temperature of +25°C.

temp. (°C)	Durat. hrs. (X)	No. of scales		% Mortality (Y)
		dead	total	
25	24	6	67	8.96
45	0	7	103	6.80
45	0.5	13	78	16.67
45	1	9	121	7.43
45	2	23	98	23.46
45	4	31	86	36.05
45	6	28	97	28.87
45	8	47	104	45.19

$Y = 10.34+4.28X$ ($r= +0.904$; d.f.=5; $P<0.01$)

Appendix Table 4.3 (13). The mortality of female only within 2nd moult instar red scales after exposure to durations (durat.) of 0–8 hours at temperature (temp.) of +45°C. Also given is the mortality of scales at the (base) constant temperature of +25°C.

temp. (°C)	Durat. hrs. (X)	No. of scales		% Mortality (Y)
		dead	total	
25	24	7	86	8.14
45	0	11	127	8.66
45	0.5	9	94	9.57
45	1	10	103	9.71
45	2	16	125	12.80
45	4	17	79	21.52
45	6	23	115	20.00
45	8	28	92	30.43

$Y = 8.12+2.60X$ ($r= +0.966$; d.f.=5; $P<0.01$)

Appendix Table 4.3 (14). The mortality of 3rd instar red scales after exposure to durations (durat.) of 0–8 hours at temperature (temp.) of +45°C. Also given is the mortality of scales at the (base) constant temperature of +25°C.

temp. (°C)	Durat. hrs. (X)	No. of scales		% Mortality (Y)
		dead	total	
25	24	1	89	1.12
45	0	4	79	5.06
45	1	2	62	3.23
45	2	5	71	7.04
45	4	4	50	8.00
45	6	9	68	13.24
45	8	7	60	11.67

$Y = 4.11+1.12X$ ($r= +0.903$; d.f.=4; $P<0.05$)

Appendix Table 4.4 (1). Experiment 1. Numbers of red scale in the "control" treatment 1 in which scale insects were shaded from the sun during the whole experimental period of 25/2-4/8, 1983.

Date of sampling	Numbers of red scales in each stage					
	W.C.*	1st	2nd	male	3rd	adult
26/2	70					
3/3	0	52				
12/3	0	9	35			
23/3	0	0	19	16		
13/4	0	0	13	22		
23/4	0	0	4	21	9	
9/5	0	0	0	21	2	9
20/5	0	0	0	21	1	10
26/5	0	0	0	17	0	10
13/6	0	0	0	15	0	10
27/6	0	0	0	15	0	10
12/7	0	0	0	15	0	8
4/8	0	0	0	15	0	8

*: white cap stage of red scale.

Appendix Table 4.4 (2). Experiment 1. Numbers of red scales in treatment 2 in which scale insects were exposed to the sun for one day. 25/2-4/8, 1983.

Date of sampling	Numbers of red scales in each stage					
	W.C.*	1st	2nd	male	3rd	adult
26/2	57					
3/3	5	18				
12/3	4	0	15			
23/3	4	0	12	3		
13/4	0	0	7	8		
23/4	0	0	3	8	4	
9/5	0	0	3	8	0	4
20/5	0	0	1	8	0	4
26/5	0	o	1	8	0	4
13/6	0	0	1	8	0	4
27/6	0	0	0	8	0	4
12/7	0	0	0	8	0	4
4/8	0	0	0	8	0	4

*: white cap stage of red scale.

Appendix Table 4.4 (3). Experiment 1. Numbers of red scales in treatment 3 in which scale insects were exposed to the sun for two days. 25/2-4/8, 1983.

Date of sampling	Numbers of red scales in each stage					
	W.C.*	1st	2nd	male	3rd	adult
26/2	97					
3/3	51	30				
12/3	38	11	19			
23/3	37	2	10	9		
13/4	37	1	9	7		
23/4	35	0	2	7	3	
9/5	35	0	0	7	2	3
20/5	32	0	0	7	2	3
26/5	23	0	0	5	1	3
13/6	23	0	0	5	1	3
27/6	27	0	0	5	0	3
12/7	23	0	0	5	0	3
4/8	23	0	0	5	0	3

*: white cap stage of red scale.

Appendix Table 4.4 (4). Experiment 1. Numbers of red scales in treatment 4 in which scale insects were treated to grow under an unshaded condition as natural as possible. 25/2-4/8, 1983.

Date of sampling	Numbers of red scales in each stage					
	W.C.*	1st	2nd	male	3rd	adult
26/2	104					
3/3	35	31				
12/3	30	2	29			
23/3	30	2	22	5		
13/4	25	1	12	14		
23/4	17	1	3	14	9	
9/5	14	1	0	12	3	4
20/5	13	0	0	12	3	4
26/5	7	0	0	6	3	4
13/6	5	0	0	5	3	4
27/6	2	0	0	5	3	4
12/7	0	0	0	5	3	4
4/8	0	0	0	5	0	4

*: white cap stage of red scale.

Appendix Table 4.4 (5). Experiment 2. Ambient temperatures (°C) of the experimental orchard and the skin-temperatures (°C) of a lemon in the sun, on 15/2/1985

Time	Ambient temperatures	skin-temperature
12:30	31.7	
:45	32.5	
13:00	32.5	
:15	33.0	
:30	33.2	
:45	33.3	
14:00	34.2	39.1 (14:03)*
:15	32.9	44.7
:30	33.6	46.0
:45	34.1	47.3
15:00	34.3	46.6
:15	33.4	47.3
:30	33.3	45.5
:45	33.6	
16:00	34.6	
:15	33.2	
:30	32.5	
:45	32.5	
17:00	31.4	

*: value measured at 14:03, 3 minutes after the host lemons had been exposed to the sun from the shaded condition.

Appendix Table 4.5 (1). Temperatures (°C) in the field, Loxton, S. Australia, 1983

Date	Minimum	Maximum	Mean
11/8	6.3	18.0	12.2
12/8	4.0	18.5	11.3
13/8	2.5	21.0	11.8
14/8	6.0	23.0	14.5
15/8	13.3	24.0	18.5
16/8	7.0	12.5	9.8
17/8	4.0	14.0	9.0
18/8	1.5	17.5	9.5
19/8	3.0	14.0	8.5
mean	5.3	18.0	11.7

Appendix Table 4.5 (2). Temperatures (°C) in the insectary room, Loxton, S. Australia, 1983

Date	Minimum	Maximun	Mean
11/8	17.0	23.5	20.25
12/8	14.0	21.5	17.75
13/8	13.0	21.0	17.00
14/8	14.0	21.5	17.75
15/8	17.0	23.5	20.25
16/8	14.0	17.5	15.75
17/8	12.0	18.0	15.00
18/8	10.5	16.0	13.25
19/8	11.0	18.0	14.50
mean	13.6	20.1	16.83

Appendix Table 5.1 (1). Experiment 3. Numbers, live and dead, and percent dead of each stage of red scales in Treatment 1 (control) with no wasps of A. melinus.

Stage of red scale	Numbers of red scales			% dead
	Alive	Dead	Toatl	
1st:				
*rep.1	36	19	55	
rep.2	39	8	47	
total	75	27	102	26.47
2nd female:				
rep.1	69	9	78	
rep.2	77	4	81	
total	146	13	159	8.18
3rd female:				
rep.1	97	3	100	
rep.2	81	5	86	
total	178	8	186	4.30
2nd male:				
rep.1	129	4	133	
rep.2	119	11	130	
total	248	15	263	5.70
Total	647	63	710	8.87

*rep.=replication.

Appendix Table 5.1 (2). Experiment 3. Numbers, alive, dead and parasitized (Para.), and percent dead of each stage of red scales respectively in Treatment 2 in which wasps of A. melinus were not provided with food.

Stage of red scale	Numbers of red scales				% death
	Alive	Dead	Para.	Total	
1st:					
*rep.1	19	12	-	31	
rep.2	28	40	-	68	
total	47	52	-	99	52.53
2nd female:					
rep.1	17	19	1	37	
rep.2	43	21	1	65	
total	60	40	2	102	39.22
3rd female:					
rep.1	71	85	5	161	
rep.2	38	23	4	65	
total	109	108	9	226	47.79
2nd male:					
rep.1	104	27	3	134	
rep.2	105	15	0	120	
total	209	42	3	254	16.54
Total	425	242	14	681	

(1). *rep.=replicaton.

(2). Total mean:

% dead = 35.54

% parasitization = 2.06

% tota dead = % (dead + parasitization) = 37.60

Appendix Table 5.1 (2a). Corrected dead of red scale by Abbott's (1925) formula** for mortality in the control Treatment 1.

Stage of red scale	Dead no. of scales due to host-feeding	Dead % rate of red scales
1st:		
*rep.1	11	
rep.2	24	
total	35	35.53
2nd female:		
rep.1	13	
rep.2	22	
total	35	33.81
3rd female:		
rep.1	73	
rep.2	30	
total	103	45.44
2nd male:		
rep.1	15	
rep.2	14	
total	29	11.50
Total		31.55

*rep.=replication.

**: $P = Pc + Pf \times (100-Pc)/100$

where, P: total observed dead in the treatment.
Pf: dead due to the treatment factor (the corrected dead).
Pc: dead in the control.

Appendix Table 5.1 (3). Experiment 3. Numbers, alive, dead and parasitized (Para.), and percent dead of each stage of red scales in Treatment 3 in which wasps of A. melinus were provided with honey as food.

Stage of red scale	Numbers of red scales				% dead
	Alive	Dead	Para.	Total	
1st:					
*rep.1	0	107	-	107	
rep.2	0	85	-	85	
total	0	192	-	192	100.00
2nd female:					
rep.1	7	91	3	101	
rep.2	0	75	3	78	
total	7	166	6	179	92.74
3rd female:					
rep.1	2	75	19	96	
rep.2	0	72	18	90	
total	2	147	37	186	79.03
2nd male:					
rep.1	7	90	1	98	
rep.2	11	71	2	84	
total	18	161	3	182	88.46
Total	27	666	46	739	

(1). *rep.=replication.
(2). Total mean:
% dead = 90.12
% parasitization = 6.22
% total dead = % (dead + parasitization) = 96.34

Appendix Table 5.1 (3a). Corrected dead of red scale by Abbott's (1925) formula** for mortality in the control Treatment 1.

Stage of red scale	Dead no. of scales due to host-feeding	Dead % rate of red scales
1st:		
*rep.1	107	
rep.2	85	
total	192	100.00
2nd female:		
rep.1	93	
rep.2	72	
total	165	92.09
3rd female:		
rep.1	75	
rep.2	70	
total	145	78.09
2nd male:		
rep.1	86	
rep.2	74	
total	160	87.76
Total		89.49

*rep.= replication.

**: $P = Pc + Pf \times (100-Pc)/100$

where, P: total observed dead in the treatment.
Pf: dead due to the treatment factor (the corrected dead).
Pc: dead in the control.

Appendix Table 5.2 (1). Experiment 1. Accumulated dead numbers and survival duration (days) of wasps of *Aphytis melinus* at 10±0.5°C and a photoperiod of L:D=14:10 hours.

Survival days	Accumulated data of:	
	number of wasps	% dead rate
3	1	2.1
4	5	10.4
5	8	16.7
6	15	31.3
7	21	43.8
8	30	62.5
9	38	79.2
10	44	91.7
11	46	95.8
12	48	100.0

Mean survival time of wasps: 7.7 ± 0.3 days

Appendix Table 5.2 (2). Experiment 2. Accumulated dead numbers and percent death of female wasps of A. melinus at 30±1°C, about 40 % R.H. and the artificial photoperiod of L:D = 14:10 hours.

Day	Dead numbers and % death of wasps in Treatment:			
	1: wasps + no food	2: wasps + water	3: wasps + honey: Numbers	% dead
0	0	0	0	0
1	30*	27*	0	0
2	32	28	0	0
3	37	29	1	2.7
4		37	,,	,,
5			,,	,,
6			,,	,,
7			2	5.4
8			3	8.1
9			,,	,,
10			,,	,,
11			14	37.8
12			,,	,,
13			20	54.1*
14			24	64.9
15			26	70.3
16			28	75.7
17			,,	,,
18			32	86.5
19			35	94.6
20			36	97.3
21			,,	,,
22			37	100.0

"*": The observed LD50's time of wasps.

Appendix Table 5.2 (3). Experiment 3. In treatment 2, accumulated percent dead of wasps at the constant temperature of 15.0°C, 75% R.H. and the photoperiod of L:D=14:10 hours.

Duration (days)	Accumulated % death of wasps
0	0
1	3.3
2	6.7
3	16.7
4	23.3
5	40.0
6	60.0
7	76.7
8	86.7
9	100.0

*: The numbers of wasps were originally as 30.

Appendix Table 5.2 (4). Accumulated dead number and percent dead of female wasps of A. melinus in each treatment on oranges on the tree in the orchard.

Day	Accumulated dead numbers and % rates in:					
	Treatment 1: wasps + no food		Treatment 2: wasps + juice		Treatment 3: wasps + scales	
	Numbers	%	Numbers	%	Numbers	%
3	6	18.75	0	0	0	0
4	10	31.25	0	0	0	0
5	18	56.25	0	0	0	0
6	21	65.63	1	3.13	2	6.25
7	23	71.88	4	12.50	4	12.50
8	,,	,,	,,	,,	7	21.88
9	,,	,,	,,	,,	,,	,,
10	,,	,,	5	15.63	10	31.25
11	,,	,,	7	21.88	,,	,,
12	24	75.00	,,	,,	,,	,,
13	27	84.38	8	25.00	,,	,,
14	29	90.63	10	31.25	13	40.63
15	32	100.00	,,	,,	,,	,,
16			12	37.50	—	—
17			,,	,,		
18			13	40.63		
19			16	50.00		
20			18	56.25		
21			23	71.88		
22			26	81.25		
23			27	84.38		
24			,,	,,		
25			28	87.50		
26			,,	,,		
27			30	93.75		
28			31	96.88		
29			,,	,,		
30			32	100.00		

Mean longevity (days) of wasps in:
Treatment 1: 7.2 ± 0.2 (S.E.).
Treatment 2: 18.1 ± 1.2 (S.E.).

Appendix Table 5.4 (1). Numbers of dead and parasitized red scales in Experiment 1: one female wasp per small cage and no honey supply for this wasp.

Density: no.of scales per lemon	Dead no. of scales in replication				Parasitized no. of scales in replication			
	I	II	III	Total	I	II	III	Total
2	5	3	5	13	0	0	1	1
4	0	1	3	4	0	0	0	0
8	0	1	1	2	0	0	0	0
16	2	1	1	4	0	0	1	1
Total	7	6	10	23	0	0	2	2

* Numbers of red scales were originally as 16 for each density within each replication.

(cont.). 2-way ANOVA among 4 densities of red scale and 3 replications for dead numbers of red scale due to host-feeding of parasites in Experiment 1

Source of variance	SS	D.F.	M.SS	F
Density	24.2500	3	8.08	7.4615
Replication	2.1667	2	1.08	1.0000
Error	6.5000	6	1.08	
Total	32.9167	11	2.99	

Appendix Table 5.4 (2). Numbers of dead and parasitized red scales in Experiment 2: one female wasp per small cage and with honey for this wasp as food.

Density: no.of scales per lemon	Dead no. of scales in replication				Parasitized no. of scales in replication			
	I	II	III	Total	I	II	III	Total
2	1	0	0	1	2	4	1	7
4	0	0	2	2	1	3	2	6
8	2	0	2	4	2	2	3	7
16	4	4	2	10	2	2	2	6
Total	7	4	6	17	7	11	8	26

* Numbers of red scales were originally as 16 for each density within each replication.

(cont.). 2-way ANOVA among 4 densities of red scale and 3 replications in Experiment 2.

(i). for dead numbers of red scale due to host-feeding of parasites.

Source of variance	SS	D.F.	M.SS	F
Density	16.2500	3	5.42	4.3333
Replication	1.1667	2	0.58	0.4667
Error	7.5000	6	1.25	
Total	24.9167	11	2.27	

(ii). for parasitism of red scale.

Source of variance	SS	D.F.	M.SS	F
Density	0.3333	3	0.11	0.1290
Replication	2.1667	2	1.08	1.2581
Error	5.1667	6	0.86	
Total	7.6667	11	0.70	

Appendix Table 5.4 (3). Numbers of dead and parasitized red scales in Experiment 3: 5 pairs, 5 males and 5 females, of wasps per small cage and with hohey for the wasps as food

Density: no.of scales per lemon	Dead no. of scales in replication				Parasitized no. of scales in replication			
	I	II	III	Total	I	II	III	Total
2	3	4	4	11	7	7	4	18
4	4	2	3	9	8	7	7	22
8	3	0	5	8	2	3	9	14
16	3	3	3	9	5	4	3	12
Total	13	9	15	37	22	21	23	66

* Numbers of red scales were originally as 16 for each density within each replication.

(cont.). 2-way ANOVA among 4 densities of red scale and 3 replications in Experiment 3.

(i). for dead numbers of red scale due to host-feeding of parasites.

Source of variance	SS	D.F.	M.SS	F
Density	1.5833	3	0.53	0.2969
Replication	4.6667	2	2.33	1.3125
Error	10.6667	6	1.78	
Total	16.9167	11	1.54	

(ii). for parasitism of red scale.

Source of variance	SS	D.F.	M.SS	F
Density	19.6667	3	6.56	1.0679
Replication	0.5000	2	0.25	0.0407
Error	36.8333	6	6.14	
Total	57.0000	11	5.18	

Appendix Table 5.4 (4). Numbers of dead and parasitized red scales in Experiment 4: one female wasp per big cage and no honey supply for this wasp.

Density: no.of scales per lemon	Dead no. of scales in replication				Parasitized no. of scales in replication			
	I	II	III	Total	I	II	III	Total
2	0	2	1	3	2	2	0	4
4	0	1	0	1	0	0	0	0
8	2	1	1	4	0	0	0	0
16	0	1	1	2	0	0	0	0
Total	2	5	3	10	2	2	0	4

* Numbers of red scales were originally as 16 for each density within each replication.

(cont.). 2-way ANOVA among 4 densities of red scale and 3 replications for dead numbers of red scale due to host-feeding of parasites in Experiment 4.

Source of variance	SS	D.F.	M.SS	F
Density	1.6667	3	0.56	1.1756
Replication	1.1667	2	0.58	1.2353
Error	2.8333	6	0.47	
Total	5.6667	11	0.52	

Appendix Table 5.4 (5). Numbers of dead and parasitized red scales in Experiment 5: one female wasp per big cage and with honey for this wasp as food

Density: no.of scales per lemon	Dead no. of scales in replication				Parasitized no. of scales in replication			
	I	II	III	Total	I	II	III	Total
2	2	3	4	9	3	3	4	10
4	2	4	2	8	2	1	1	4
8	2	1	2	5	1	1	1	3
16	1	1	1	3	2	1	1	4
Total	7	9	9	25	8	6	7	21

* Numbers of red scales were originally as 16 for each density within each replication.

(cont.). 2-way ANOVA among 4 densities of red scale and 3 replications in Experiment 5.

(i). for dead numbers of red scale due to host-feeding of parasites.

Source of variance	SS	D.F.	M.SS	F
Density	7.5833	3	2.53	3.2500
Replication	0.6667	2	0.33	0.4286
Error	4.6667	6	0.78	
Total	12.9167	11	1.17	

(ii). for parasitism of red scale.

Source of variance	SS	D.F.	M.SS	F
Density	10.2500	3	3.42	13.6667
Replication	0.5000	2	0.25	1.0000
Error	1.5000	6	0.25	
Total	12.25	11	1.11	

Appendix Table 5.4 (6). Numbers of dead and parasitized red scales in Experiment 6: 5 pairs, 5 males and 5 females, of wasps per big cage and with honey for the wasps as food.

Density: no.of scales per lemon	Dead no. of scales in replication				Parasitized no. of scales in replication			
	I	II	III	Total	I	II	III	Total
2	0	2	2	4	3	5	8	16
4	2	3	2	7	1	7	7	15
8	0	1	0	1	1	5	1	7
16	1	0	1	2	0	0	0	0
Total	3	6	5	14	5	17	16	38

* Numbers of red scales were originally as 16 for each density within each replication.

(cont.). 2-way ANOVA among 4 densities of red scale and 3 replications in Experiment 6.

(i). for dead numbers of red scale due to host-feeding of parasites.

Source of variance	SS	D.F.	M.SS	F
Density	7.0000	3	2.33	4.0000
Replication	1.1667	2	0.58	1.0000
Error	3.5000	6	0.58	
Total	11.6667	11	1.06	

(ii). for parasitism of red scale.

Source of variance	SS	D.F.	M.SS	F
Density	48.6667	3	16.22	4.9076
Replication	19.5000	2	9.75	2.9496
Error	19.8333	6	3.31	
Total	88.0000	11	8.00	

Appendix Table 5.4 (7). Numbers of dead and parasitized red scales in Experiment 7: one female wasp per medium cage and no food supply for this wasp.

Density: no.of scales per lemon	Dead no. of scales in replication				Parasitized no. of scales in replication			
	I	II	III	Total	I	II	III	Total
2	0	2	1	3	0	0	0	0
4	1	0	0	1	0	0	0	0
8	1	1	1	3	0	0	0	0
16	1	1	1	3	0	0	0	0
Total	3	4	3	10	0	0	0	0

* Numbers of red scales were originally as 16 for each density within each replication.

(cont.). 2-way ANOVA among 4 densities of red scale and 3 replications for dead numbers of red scale due to host-feeding of parasites in Experiment 7.

Source of variance	SS	D.F.	M.SS	F
Density	1.0000	3	0.33	0.8000
Replication	0.1667	2	0.08	0.2000
Error	2.5000	6	0.42	
Total	3.6667	11	0.33	

Appendix Table 5.4 (8). Numbers of dead and parasitized red scales in Experiment 8: one female wasp per big cage and with a small flowering orange tree in each cage.

Density: no.of scales per lemon	Dead no. of scales in replication				Parasitized no. of scales in replication			
	I	II	III	Total	I	II	III	Total
2	5	3	1	9	3	2	2	7
4	2	5	2	9	1	4	0	5
8	5	2	1	8	2	5	1	8
16	4	2	1	8	2	2	1	5
Total	16	12	5	33	8	13	4	25

* Numbers of red scales were originally as 16 for each density within each replication.

(cont.). 2-way ANOVA among 4 densities of red scale and 3 replications in Experiment 8.

(i). for dead numbers of red scale due to host-feeding of parasites.

Source of variance	SS	D.F.	M.SS	F
Density	0.9167	3	0.31	0.1549
Replication	15.5000	2	7.75	3.9296
Error	11.8333	6	1.97	
Total	28.2500	11	2.57	

(ii). for parasitism of red scale.

Source of variance	SS	D.F.	M.SS	F
Density	2.2500	3	0.75	0.5294
Replication	10.1667	2	5.08	3.5882
Error	8.5000	6	1.42	
Total	20.9167	11	1.90	

Appendix Table 6.1 (1). Mean height (cm) of 5 Phacelia sp. plants at different constant temperatures, with an artificial photoperiod of L:D=16:8 hours, in relation to growing durations (days). (started: 30/11/84).

Duration: days (X)	Height (Y) at temperture (°C) of:			
	15	20	24	28
1	16.4	16.6	14.4	20.6
6	28.0	32.0	36.4	37.8
9	34.6	46.4	49.4	47.2
12	44.2	57.2	61.8	53.8
15	53.4	66.8	68.6	56.4
18	64.0	72.6	72.0	56.8
21	72.8	77.2	74.2	57.6
24	77.4	79.2		
27	82.4			
30	89.2			
33	90.2			

Regression equations:

At 15°C, $Y = 106.384/[1 + \exp(1.679-0.109X)]$

At 20°C, $Y = 83.305/[1 + \exp(1.556-0.193X)]$

At 24°C, $Y = 80.656/[1 + \exp(1.453-0.200X)]$

At 28°C, $Y = 59.740/[1 + \exp(0.595-0.203X)]$

Appendix Table 6.1 (2). Mean accumulated numbers of flowers per main stem (mean of 5 plants) at 3 constant temperatures, with an artificial photoperiod of L:D=16:8 hours, in relation to the duration (days) of each flowering period.

Day after the 1st flower	Numbers of flowers at temperature: 20°C	24°C	28°C
3	21.8	6.2	12.4
5	60.6	32.0	30.4
7	113.4	94.0	73.2
9	192.0	163.4	140.0
11	281.8	278.6	212.8
13	367.6*	411.6*	295.6*
15	438.4	515.0	368.0
17	515.2	579.4	394.8
19	570.0	627.4	419.2
21	635.6	672.4	466.6
23	689.2	726.2	502.8
25	726.4	781.8	527.0
27			536.2

*: day of 50% of the total numbers of flowers.

Appendix Table 6.1 (3). Mean numbers of flowers maintaining fresh per main stem (mean of 5 plants) of Phacelia sp. at each observation day at different constant temperatures, with an artificial photoperiod of L:D=16:8 hours.

Day after 1st flower	Mean no. of flowers at temperature (°C): 20	24	28
1	0.4	0.4	3.2
3	14.4	6.2	11.4
5	35.0	28.0	21.2
7	49.0	58.4	40.0
9	90.0	83.2	57.0
11	107.2*	116.6	73.8*
13	85.4	126.4*	73.6
15	76.8	108.2	44.6
17	95.2	81.6	24.2
19	69.4	43.2	22.6
21	93.4	53.6	48.6
23	48.6	45.8	43.4
25	26.8	72.8	25.6
27			5.4

*: Maxima of fresh flowers.

Appendix Table 6.1 (4). Mean volume (micro-liter) of the nectar (mean of 7 flowers) per flower of Phacelia sp. in relation to time (in hours) after sunrise at different constant temperatures (°C), with an artificial photoperiod which was started (so-called sunrise) at 0800, of L:D=16:8 hours.

Sampling time	Hours after sunrise	Volume of nectar at temperature: 15	20	24	28
0812–0900	1	1.67	1.07	1.50	0.85
1035–1101	3	1.45	0.75	1.14	0.66
1230–1305	5	1.33	1.02	1.64	0.53
1500–1546	8	0.98	1.12	1.23	0.55
1707–1805	10	0.59	0.62	0.95	0.36
Total		6.02	4.58	6.46	2.95

Linear regression equations of the relationship between the mean volumes (Y) of flower nectar and durations of hours (X) after sunrise at tmeperature:

15°C: $Y = 1.82 - 0.11\ X$ ($r=-0.9848$; d.f.=3, $P<0.01$)

20°C: $Y = 1.03 - 0.02\ X$ ($r=-0.3611$; d.f.=3, $P>0.05$)

24°C: $Y = 1.54 - 0.05\ X$ ($r=-0.5986$; d.f.=3, $P>0.05$)

28°C: $Y = 0.84 - 0.05\ X$ ($r=-0.9295$; d.f.=3, $P<0.05$)

Appendix Table 6.2 (1). The observed dead numbers each day (No.D.D.) and the percentage accumulated dead rates (% Ac.D.) (Y) of female wasps of A. melinus in the "control" Treatment 1 (T1) in which wasps were provided with water only and in Treatment 2 (T2) in which wasps were provided with flower nectar of Phacelia sp. as food in relation to the durations of days (X) at 25°C and 60 % R.H.

Day (X)	In T1, with water only: No. D.D	% Ac.D. (Y)	In T2, with nectar: No. D.D.	% Ac.D.(Y)
0	0	0	0	0
1	17	53.13*	0	0
2	14	96.88	0	0
3	1	100.00	0	0
4-5	-	-	0	0
6			1	3.13
8			0	3.13
10			2	9.38
12			1	12.50
14			2	18.75
16			5	34.38
18			4	46.88*
20			7	68.75
22			3	78.13
24			4	90.63
26			1	93.75
28			2	100.00
Total	32		32	

(i). In Treatment 1: LD50=1.5±0.1 days (range, 1-3 days)

(ii). In Tretment 2: LD50=18.8±0.9 days (range, 6-28 days)

$$Y=115.510/[1 + \exp(5.256-0.266X)]$$

Appendix Table 6.2 (2). Details of the death and the parasitism of red scale within the densities and replications (cages): 5 pairs, 5 males and 5 females, of wasps of A. melinus per big cage and with one flowering Phacelia sp. plant in each cage

Density: no.of scales per lemon	Dead no. of scales in replication				Parasitized no. of scales in replication			
	I	II	III	Total	I	II	III	Total
2	0	3	3	6	4	2	3	9
4	0	1	2	3	0	1	0	1
8	0	2	1	3	0	1	1	2
16	0	2	1	3	0	0	0	0
Total	0	8	7	15	4	4	4	12

* The numbers of red scales were originally as 16 for each density within each replication (cage). The total numbers of red scales were originally as 16 (no. in each desity) x 4 (desities) x 3 (replications)=192.

Appendix Table 7.2 (1). Mean numbers of red scale per observation circle (15mm in diameter) on lemons from the interior part of the canopy

Height	Aspect	No. of observation circle on each lemon	Numbers of scales	
			Total	Mean (per circle)
Top	N.	35	228	6.51
	S.	24	238	9.92
	E.	24	75	3.13
	W.	29	283	9.76
Medium	N.	20	314	15.70
	S.	22	142	6.45
	E.	30	85	2.83
	W.	26	234	9.00
Bottom	N.	28	41	1.46
	S.	28	47	1.68
	E.	35	41	1.17
	W.	25	454	18.16

Appendix Table 7.2 (2). Mean numbers of red scale per observation circle (15mm in diameter) on lemons from the outer part of the canopy

Height	Aspect	No. of observation circle on each lemon	Numbers of scales	
			Total	Mean (per circle)
Top	N.	27	103	3.81
	S.	25	98	3.92
	E.	27	129	4.78
	W.	22	228	10.36
Medium	N.	29	192	6.62
	S.	24	164	6.83
	E.	24	42	1.75
	W.	28	203	7.25
Bottom	N.	22	49	2.23
	S.	27	88	3.26
	E.	29	149	5.14
	W.	21	112	5.33

Appendix Table 7.2 (3). Mean numbers of red scale per observation circle (15mm in diameter) on lemons from different aspects (north, south, east and west), heights (top, medium and bottom) and parts (interior and outer) of the canopy

Height	Aspect	Mean numbers of red scale of:		
		interior canopy	outer canopy	total
Top	N.	6.51	3.81	
	S.	9.92	3.92	
	E.	3.13	4.78	
	W.	9.76	10.36	
	Total	29.32	22.87	52.19
Medium	N.	15.70	6.62	
	S.	6.45	6.83	
	E.	2.83	1.75	
	W.	9.00	7.25	
	Total	33.98	22.45	56.43
Bottom	N.	1.46	2.23	
	S.	1.68	3.26	
	E.	1.17	5.14	
	W.	18.16	5.33	
	Total	22.47	15.96	38.43
	Total	85.77	61.28	147.05

Appendix Table 7.3 (1). Log (x+1) of total numbers (sum of live and dead) of each stage of red scale per 100 observation circles (1.5cm diameter for each) on lemons at each sampling date; 3/5/84-12/3/86.

No.	Date	W.C.	1st instar	1st moult	2nd instar	2nd moult	3rd instar	adult	male	Total
1	3/5/84	0.9998	2.0427	2.0043	1.8813	1.4730	2.0043	1.3445	2.1507	2.7670
2	22/7	0.3228	2.3383	1.6916	2.0043	1.3192	1.9963	0.9923	1.8723	2.7540
3	4/10	0	1.9599	0	1.6998	0.3203	1.8501	0.8562	1.1600	2.3633
4*	23/10	0	1.8257	0	1.4839	0.3585	1.5799	0.4970	0.9484	2.1646
5	8/11	0	1.6914	0	1.2680	0.3966	1.3097	0.1377	0.7367	1.9658
6	19/11	0.3179	1.8477	0.2354	1.2946	0	1.4412	0.7541	1.0150	2.1192
7	6/12	1.0888	1.9461	1.5630	1.7531	0.6878	1.3013	0.7730	1.2355	2.3707
8	16/12	1.2546	2.0739	1.1976	1.5388	1.2889	1.5829	1.1075	1.3712	2.4402
9	28/12	0.8310	2.0211	1.2716	1.4806	1.1784	1.5651	0.9852	1.5900	2.4050
10	11/1/85	1.0056	2.0996	1.1982	1.3731	1.1607	1.6264	1.3311	1.4727	2.4413
11	19/1	1.0442	1.9483	1.5593	1.6856	1.3674	1.6692	1.5550	1.8155	2.5120
12	26/1	1.0007	2.4598	1.5234	1.5878	1.6231	1.8365	1.8233	2.0096	2.8081
13	3/2	0.6259	2.2908	1.4947	1.1431	1.4282	1.7593	1.6755	1.7244	2.6257
14	13/2	0.5560	2.3476	1.9043	1.2628	1.5921	1.7378	1.8876	1.8105	2.7430
15	24/2	0.5735	2.2265	1.9147	1.8150	1.3756	1.3222	1.5503	1.8354	2.6641
16	9/3	1.6670	2.5533	2.0307	1.4574	1.7887	1.5135	1.8676	2.0402	2.9087
17	17/3	0.4915	2.4040	2.2522	2.0133	1.7645	1.8624	1.8035	2.2995	2.9663
18	30/3	0.8481	2.0891	1.9938	2.1351	1.5763	1.8163	1.5809	2.3415	2.8803
19	14/4	0.9408	2.4404	2.0482	2.3645	1.8457	2.2583	1.6543	2.4956	3.0901
20	4/5	1.4219	2.2157	1.6467	2.1103	1.6343	2.1103	1.1688	2.1492	2.8355
21	25/8	0	1.6037	0.8802	1.9417	1.5687	1.5909	0.2492	1.6550	2.4017
22	6/10	0	1.2060	1.0651	1.5165	1.3194	1.8200	0.8948	1.2060	2.2185
23	29/10	0	1.3344	0.9687	1.2924	0.9366	1.6321	1.6549	1.3344	2.2081
24	12/11	1.3418	1.7593	0.4171	0.9416	0.5130	1.4822	1.4177	0.9253	2.1818
25	1/12	0.5664	2.1582	1.5300	1.3949	0.6042	1.5427	1.2580	1.0026	2.4256
26	18/12	0.3996	2.2531	1.7187	1.6510	1.5664	1.5881	0.5138	1.7218	2.6056
27	3/1/86	0.6884	2.0467	1.8229	1.8201	1.8528	1.7816	1.3695	2.0272	2.7013
28	15/1	0	2.2072	1.6376	1.7219	1.7155	1.7898	1.5884	1.9932	2.6583
29	27/1	0.6724	1.7609	1.2736	1.4914	1.5585	1.8208	2.7921	1.8467	2.5313
30	7/2	2.0890	2.2413	1.4053	1.0817	1.2945	1.8664	1.9031	1.7297	2.7439
31	16/2	1.0150	2.6849	2.4632	1.5965	1.4842	1.8131	1.8940	1.8455	3.0259
32	2/3	1.7623	2.9355	2.7232	2.3134	2.1177	2.0673	2.2812	2.6266	3.3997
33	12/3	2.0093	3.0304	2.5500	2.4189	2.3660	2.3993	2.1364	2.8610	3.4962

4*: means of data of No.3 and No.5 for the missing ones.

Appendix Table 7.3 (2). Log (x+1) numbers, live only, of each stage of red scales per 100 observation circles (1.5cm diameter for each) on lemons at each sampling date; 3/5/84-12/3/86.

No.	Date	W.C.	1st instar	1st moult	2nd instar	2nd moult	3rd instar	adult	male	Total
1	3/5/84	0	1.7001	1.7563	1.6215	1.3958	1.5386	1.0146	2.0373	2.5075
2	22/7	0.2394	1.7715	1.4778	1.6136	1.0385	1.2874	0.4530	1.6648	2.3103
3	4/10	0	0	0	0.3203	0.2374	1.4732	0.7579	0.8337	1.6242
4*	23/10	0	0.7473	0	0.4798	0.2398	1.2357	0.4478	0.4857	1.6389
5	8/11	0	1.4945	0	0.6393	0.2421	0.9981	0.1377	0.1377	1.6535
6	19/11	0.1334	1.6278	0.2354	0.1334	0	0.3872	0.7541	0.5886	1.7314
7	6/12	0.7730	1.4091	1.1010	1.0215	0.4410	0.1310	0.5817	0.4410	1.7664
8	16/12	0.1364	1.5829	1.0349	1.1976	1.1435	1.0682	0.4541	1.2721	2.0275
9	28/12	0	1.6501	0.8954	1.2275	1.0987	1.3821	0.5474	1.5058	2.1324
10	11/1/85	0	1.3568	0.9866	1.0901	1.0056	1.3650	1.2327	1.3131	2.0402
11	19/1	0	1.1972	1.0581	0.9672	1.2070	1.3871	1.3252	1.7197	2.1599
12	26/1	0.5876	1.6102	0.9438	1.1859	1.4479	1.3939	1.5690	1.8689	2.3533
13	3/2	0	1.7743	1.0285	0.6655	1.1172	1.4474	1.4082	1.6605	2.2583
14	13/2	0.5003	1.9572	1.6420	1.1180	1.2524	1.3870	1.7514	1.7547	2.4761
15	24/2	0	2.1087	1.8124	1.7505	1.2796	1.0336	1.3057	1.8098	2.5542
16	9/3	0	2.4491	1.9443	1.4133	1.7225	1.2917	1.6744	2.0060	2.7854
17	17/3	0	2.1579	2.0834	1.9121	1.6379	1.5890	1.5747	2.2673	2.8099
18	30/3	0.4794	1.6204	1.8028	1.9606	1.4776	1.6488	1.2234	2.2659	2.6706
19	14/4	0.7575	1.9698	1.8039	2.0153	1.7477	1.8322	1.1808	2.3709	2.8015
20	4/5	1.0881	1.6857	1.4150	1.5760	1.4855	1.4674	0.9502	1.9630	2.4442
21	25/8	0	0.8080	0.6881	1.4551	1.5105	1.3848	0.1423	1.5105	2.0943
22	6/10	0	0	0.2266	0.1279	1.0249	1.6927	0.8552	1.1019	1.8828
23	29/10	0	0	0.2266	0	0	1.2899	1.6549	1.2375	1.8736
24	12/11	1.3354	1.6908	0.4171	0.3599	0.1214	0	1.3017	0.7897	1.9873
25	1/12	0.5664	2.0809	1.4847	1.2416	0.4278	0.6391	0.7806	0.9234	2.2661
26	18/12	0.3996	2.1374	1.6654	1.5044	1.5483	1.4259	0.1390	1.7060	2.5080
27	3/1/86	0.1557	1.7002	1.5656	1.6570	1.8395	1.7112	1.3363	1.9427	2.5496
28	15/1	0	1.6120	1.4309	1.6321	1.6732	1.6732	1.5105	1.9398	2.5030
29	27/1	0.2407	1.5630	1.0265	1.2472	1.4809	1.6948	1.7200	1.7773	2.4010
30	7/2	2.0626	2.1471	1.3110	0.8517	1.0952	1.6773	1.7596	1.6703	2.6441
31	16/2	0.9838	2.6593	2.4338	1.4994	1.4059	1.6451	1.8203	1.7960	2.9824
32	2/3	1.7358	2.7552	2.5877	2.1409	2.0823	1.8063	2.1780	2.5857	3.2701
33	12/3	1.9223	2.9476	2.4907	2.3858	2.3180	2.3423	1.9570	2.8436	3.4364

4*: means of data of No.3 and No.5 for the missing ones.

Appendix Table 7.3 (3). Mean number per 100 observation circles (1.5cm diameter for each) and percentage dead of white-cap (W.C.) instar, 1st instar and 1st moult instar red scale at each sampling date; 3/5/84-12/3/86.

Sampling: No.	Date	W.C.		1st instar		1st moult	
		No.	% dead	No.	% dead	No.	% dead
1	3/5/84	9	100.00	109	55.06	100	43.94
2	22/7	1	33.33	217	73.22	48	39.69
3	4/10	0	0	90	100.00	0	0
4	23/10	-	-	-	-	-	-
5	8/11	0	0	48	37.21	0	0
6	19/11	1	66.67	69	38.86	1	0
7	6/12	11	56.25	87	71.77	36	67.33
8	16/12	17	97.83	119	68.73	15	32.50
9	28/12	6	100.00	104	57.99	18	61.22
10	11/1/85	9	100.00	125	82.58	15	41.18
11	19/1	10	100.00	88	83.20	35	70.41
12	26/1	9	68.18	287	86.16	32	75.95
13	3/2	3	100.00	194	69.92	30	68.00
14	13/2	3	16.67	222	59.57	79	45.90
15	24/2	3	100.00	167	23.89	81	21.26
16	9/3	45	100.00	357	21.40	106	18.22
17	17/3	2	100.00	253	43.43	178	32.39
18	30/3	6	66.67	122	66.56	98	35.95
19	14/4	8	38.89	275	66.41	111	43.41
20	4/5	25	55.74	163	70.92	43	42.31
21	25/8	0	0	39	86.14	7	41.18
22	6/10	0	0	15	100.00	11	93.55
23	29/10	0	0	21	100.00	8	92.00
24	13/11	21	1.54	56	14.86	2	0
25	1/12	3	0	143	16.43	33	10.20
26	18/12	2	0	178	23.52	51	11.76
27	3/1/86	4	88.89	110	55.47	66	45.39
28	15/1	0	0	98	59.29	43	40.18
29	27/1	4	80.00	57	37.25	18	45.83
30	7/2	122	5.96	173	19.60	24	20.31
31	16/2	9	7.69	483	5.73	290	6.58
32	2/3	57	6.02	861	34.01	528	26.87
33	12/3	101	18.32	1071	17.37	358	13.81

Appendix Table 7.3 (4). Mean number per 100 observation circles (1.5cm diameter for each) and percentage rates of death (D.) and parasitism (P.) of 2nd instar and 2nd moult instar female red scale at each sampling date; 3/5/84-12/3/86.

Sampling: No.	Date	2nd instar				2nd moult	
		No.	% P.	% D.	Total %	No.	% D.
1	3/5/84	75	3.69	41.94	45.63	29	16.87
2	22/7	100	8.46	51.47	59.93	20	50.00
3	4/10	49	0	97.78	97.78	1	33.33
4	23/10	–	–	–	–	–	–
5	8/11	18	0	80.85	80.85	1	50.00
6	19/11	19	0	98.08	98.08	0	0
7	6/12	56	0	82.91	82.91	4	54.55
8	16/12	34	0	56.04	56.04	18	30.00
9	28/12	29	0	45.68	45.68	14	17.95
10	11/1/85	23	3.85	46.15	50.00	13	32.26
11	19/1	24	3.03	62.12	65.15	22	32.26
12	26/1	38	0	61.96	61.96	41	34.00
13	3/2	13	0	71.88	71.88	26	53.13
14	13/2	17	0	30.00	30.00	3	55.68
15	24/2	64	0	14.02	14.02	23	20.69
16	9/3	28	0	10.00	10.00	60	14.38
17	17/3	102	2.06	18.93	20.99	57	25.74
18	30/3	135	0.60	32.74	33.34	37	20.88
19	14/4	230	3.72	51.77	55.49	69	20.50
20	4/5	128	3.91	67.42	71.33	42	29.70
21	25/8	86	2.24	65.92	68.16	36	12.90
22	6/10	32	0	98.92	98.92	20	51.72
23	29/10	19	0	100.00	100.00	8	100.00
24	13/11	8	0	16.67	16.67	2	85.71
25	1/12	24	0	30.99	30.99	3	44.44
26	18/12	44	0.86	28.45	29.31	36	4.21
27	3/1/86	65	0	31.79	31.79	70	3.07
28	15/1	53	1.47	19.12	20.59	52	11.19
29	27/1	30	0	44.44	44.44	35	16.84
30	7/2	11	6.90	37.93	44.83	19	38.78
31	16/2	38	0	20.56	20.56	29	17.07
32	2/3	205	0	32.94	32.94	130	7.89
33	12/3	261	0	7.39	7.39	231	10.52

Appendix Table 7.3 (5). Mean number per 100 observation circles (1.5cm diameter for each) and percentage rates of death and parasitism (Para.) of 3rd instar female red scale at each sampling date; 3/5/84–12/3/86.

Sampling: No.	Date	No. of red scale	% rate of: Para.	Dead	Total
1	3/5/84	100	44.98	21.45	66.43
2	22/7	98	37.08	44.19	81.27
3	4/10	70	8.33	50.52	58.85
4	23/10	-	-	-	-
5	8/11	19	1.92	51.92	53.84
6	19/11	27	4.05	90.54	94.59
7	6/12	19	1.85	96.30	98.15
8	16/12	37	0.99	70.30	71.29
9	28/12	36	2.02	33.33	35.35
10	11/1/85	41	6.32	40.00	46.32
11	19/1	46	9.45	39.37	48.82
12	26/1	68	1.82	63.03	64.85
13	3/2	56	0.71	51.43	52.14
14	13/2	54	0.81	55.65	56.46
15	24/2	20	11.76	39.22	50.98
16	9/3	32	3.75	37.50	41.25
17	17/3	72	10.53	36.84	47.37
18	30/3	105	21.15	37.31	58.46
19	14/4	180	22.38	40.48	62.86
20	4/5	128	22.80	55.05	77.85
21	25/8	38	4.08	34.69	38.77
22	6/10	65	1.05	24.74	25.79
23	29/10	42	9.52	47.62	57.14
24	13/11	29	6.59	93.41	100.00
25	1/12	34	2.97	87.13	90.10
26	18/12	38	0.06	26.00	26.06
27	3/1/86	59	2.90	12.32	15.22
28	15/1	62	5.03	20.13	25.16
29	27/1	65	11.36	14.20	25.56
30	7/2	73	7.37	28.42	35.79
31	16/2	64	1.69	30.90	32.59
32	2/3	116	2.37	43.20	45.57
33	12/3	250	8.19	4.17	12.36

Appendix Table 7.3 (6). Mean number per 100 observation circles (1.5cm diameter for each) and percentage rates of death and parasitism (Para.) of adult instar female red scale at each sampling date; 3/5/84-12/3/86.

Sampling: No.	Date	No. of red scale	% rate of: Para.	Dead	Total
1	3/5/84	21	54.10	1.64	55.74
2	22/7	9	79.17	0	79.17
3	4/10	6	5.88	17.65	23.53
4	23/10	-	-	-	-
5	8/11	0	0	0	0
6	19/11	5	0	0	0
7	6/12	5	21.43	21.43	42.86
8	16/12	12	62.50	21.88	84.38
9	28/12	9	50.00	20.83	70.83
10	11/1/85	20	14.89	6.38	21.27
11	19/1	35	28.89	13.40	42.27
12	26/1	66	20.00	25.00	45.00
13	3/2	46	36.52	10.43	46.95
14	13/2	76	10.23	17.05	27.28
15	24/2	35	31.82	12.50	44.32
16	9/3	73	32.07	4.35	36.42
17	17/3	63	32.89	8.72	41.61
18	30/3	37	43.48	14.13	57.61
19	14/4	45	46.15	22.12	68.27
20	4/5	14	30.30	12.12	42.42
21	25/8	1	50.00	0	50.00
22	6/10	7	10.00	0	10.00
23	29/10	43	0	0	0
24	13/11	25	2.56	21.79	24.35
25	1/12	17	5.88	64.71	70.59
26	18/12	2	16.67	66.67	83.34
27	3/1/86	22	3.85	3.85	7.70
28	15/1	39	14.00	5.00	19.00
29	27/1	62	13.77	2.99	16.76
30	7/2	79	22.71	5.80	28.51
31	16/2	77	8.84	6.98	15.82
32	2/3	190	14.77	6.49	21.26
33	12/3	136	30.68	3.41	34.09

Appendix Table 7.3 (7). Mean number per 100 observation circles (1.5cm diameter for each) and percentage rates of death and parasitism (para.) of male red scale at each sampling date; 3/5/84-12/3/86.

Sampling: No.	Date	No. of red scale	% rate of: Para.	Dead	Total
1	3/5/84	140	2.71	20.44	23.15
2	22/7	74	13.00	25.50	38.50
3	4/10	13	2.70	54.05	56.75
4	23/10	-	-	-	-
5	8/11	4	0	91.67	91.67
6	19/11	9	0	69.23	69.23
7	6/12	16	4.35	84.78	89.13
8	16/12	23	0	21.31	21.31
9	28/12	38	0	18.10	18.10
10	11/1/85	29	6.06	25.76	31.82
11	19/1	64	0.56	19.55	20.11
12	26/1	101	0.40	27.53	27.93
13	3/2	52	0	13.95	13.95
14	13/2	64	0	12.24	12.24
15	24/2	67	0	5.81	5.81
16	9/3	109	0.36	7.27	7.63
17	17/3	198	1.06	6.14	7.20
18	30/3	219	0.55	15.50	16.05
19	14/4	312	2.89	22.15	25.04
20	4/5	140	9.23	25.89	35.12
21	25/8	44	0	28.95	28.95
22	6/10	15	0	22.73	22.73
23	29/10	21	0	20.94	20.97
24	13/11	7	0	30.43	30.43
25	1/12	9	0	18.52	18.52
26	18/12	52	0	3.65	3.65
27	3/1/86	105	0	17.28	17.28
28	15/1	98	0.47	11.81	12.60
29	27/1	69	0.01	14.44	14.45
30	7/2	91	0	13.04	13.04
31	16/2	69	0	10.94	10.94
32	2/3	422	1.8	9.00	10.80
33	12/3	725	0	3.94	3.94

Appendix Table 7.3 (8). Mean numbers per 100 observation circles (1.5cm diameter for each), namely, dead (D.), live and parasitized (para.), of red scale overall stages at each sampling date; 3/5/84-12/3/86. Also given are the percentage rates of dead and total dead (dead + para.) of red scale.

Sampling: No.	Date	Number of red scale					% rates of:	
		Dead	Live	Para.*		Total	Dead	Total dead (D.+P.)
				C.	A.			
1	3/5/84	200	321	14	49	584	34.25	45.03
2	22/7	302	204	8	53	567	53.26	64.02
3	4/10	182	42	1	5	230	79.13	81.74
4	23/10	-	-	-	-	-	-	-
5	8/11	47	44	0	0	91	51.65	51.65
6	19/11	77	53	0	1	131	58.78	59.54
7	6/12	174	58	1	1	234	74.36	75.21
8	16/12	161	106	7	0	274	58.76	61.31
9	28/12	113	135	4	1	253	44.66	46.64
10	11/1/85	158	109	4	4	275	57.45	60.36
11	19/1	165	144	10	5	324	50.93	55.56
12	26/1	402	224	13	2	641	62.71	65.05
13	3/2	224	181	17	0	422	53.08	57.11
14	13/2	246	298	8	0	552	44.57	46.01
15	24/2	90	358	11	2	461	19.52	22.34
16	9/3	175	609	23	2	809	21.74	24.72
17	17/3	247	644	21	12	924	26.73	30.30
18	30/3	129	468	16	24	637	20.25	26.53
19	14/4	519	632	21	58	1230	42.20	48.62
20	4/5	355	278	4	47	684	51.90	59.36
21	25/8	124	124	0	3	251	49.40	50.60
22	6/10	88	75	1	1	165	53.33	54.55
23	29/10	83	74	0	4	161	51.55	54.04
24	12/11	52	96	1	2	151	34.44	36.42
25	1/12	80	184	1	1	266	30.08	30.83
26	18/12	78	321	0	3	402	19.40	20.15
27	3/1/86	146	354	1	1	502	29.08	29.48
28	15/1	117	318	5	5	445	26.29	28.54
29	27/1	72	250	9	8	339	21.24	26.26
30	7/2	90	440	19	5	554	16.25	20.58
31	16/2	93	959	7	1	1060	8.77	9.53
32	2/3	616	1862	28	3	2509	24.55	25.79
33	12/3	341	2731	42	20	3134	10.88	12.86

* C.: Comperiella bifasciata Howard.
A.: Aphytis melinus DeBach.

Appendix Table 7.3 (9). Obtained from Appendix Table 7.3 (2), the growth rate "r", r=log [N(t+1)/N(t)], of live red scales of each stage in each observation interval (between time t+1 and t).

Sampling:		r-values of scale of stage:							
No.	Date	1st instar	1st moult	2nd instar	2nd moult	3rd instar	adult	male	Total
2	3/5-22/7/84	0.07	-0.28	-0.01	-0.36	-0.25	-0.56	-0.37	-0.20
3	23/7-4/10	-1.77	-1.48	-1.29	-0.80	0.19	0.30	-0.83	-0.69
4*	5-23/10	0.75	0	0.16	0	-0.24	-0.31	-0.35	0.01
5	24/10-8/11	0.75	0	0.16	0	-0.24	-0.31	-0.35	0.01
6	9-19/11	0.13	0.24	-0.51	-0.24	-0.61	0.62	0.45	0.08
7	20/11-6/12	-0.22	0.87	0.89	0.44	-0.26	-0.17	-0.15	0.04
8	7-16/12	0.17	-0.07	0.18	0.70	0.94	-0.13	0.83	0.26
9	17-28/12	0.07	-0.14	0.03	-0.04	0.31	0.09	0.23	0.10
10	29/12/84-11/1/85	-0.29	0.09	-0.14	-0.09	-0.02	0.69	-0.19	0.01
11	13-19/1	-0.16	0.07	-0.12	0.20	0.02	0.09	0.41	0.12
12	20-26/1	0.41	-0.11	0.22	0.24	0	0.24	0.15	0.20
13	27/1-3/2	0.16	0.08	-0.52	-0.33	0.05	-0.16	-0.21	-0.10
14	4-13/2	0.18	0.61	0.45	0.14	-0.06	0.34	0.09	0.22
15	14-24/2	0.15	0.17	0.63	0.03	-0.35	-0.45	0.06	0.08
16	25/2-9/3	0.34	0.13	-0.34	0.44	0.26	0.37	0.20	0.23
17	10-17/3	-0.29	0.14	0.50	-0.08	0.30	-0.10	0.26	0.02
18	18-30/3	-0.54	-0.28	0.05	-0.16	0.06	-0.35	0	-0.14
19	31/3-14/4	0.35	0	0.05	0.27	0.18	-0.04	0.11	0.13
20	15/4-4/5	-0.28	-0.39	-0.44	-0.26	-0.36	-0.23	-0.41	-0.36
21	5/5-25/8	-0.88	-0.73	-0.12	0.03	-0.08	-0.81	-0.45	-0.35
22	26/8-6/10	-0.81	-0.46	-1.33	-0.49	0.31	0.71	-0.41	-0.21
23	7-29/10	0	0	-0.13	-1.02	-0.40	0.80	0.14	-0.01
24	30/10-12/11	1.69	0.19	0.36	0.12	-1.29	-0.35	-0.45	0.11
25	13/11-1/12	0.39	1.07	0.88	0.31	0.64	-0.52	0.13	0.28
26	2-18/12	0.06	0.18	0.26	1.12	0.79	-0.64	0.78	0.24
27	19/12/85-3/1/86	-0.44	-0.10	0.15	0.29	0.29	1.20	0.24	0.04
28	4-15/1	-0.09	-0.13	-0.02	-0.17	-0.04	0.17	0	-0.05
29	16-27/1	-0.05	-0.40	-0.38	-0.19	0.02	0.21	-0.16	-0.10
30	28/1-7/2	0.58	0.28	-0.40	-0.39	-0.02	0.04	-0.11	0.24
31	8-16/2	0.51	1.12	0.65	0.31	-0.03	0.06	0.13	0.34
32	17/2-2/3	0.10	0.15	0.64	0.68	0.16	0.36	0.79	0.29
33	3-13/3	0.19	-0.10	0.24	0.24	0.54	-0.22	0.26	0.17

4*: means of data of No.3 and No.5 for the missing ones.

Appendix Table 7.3 (10). The growth rate "r", r=log [N(t+1)/N(t)], of live red scale of each stage in each of the observation intervals in which the extreme temperature T<10°C. The moulting stage was denoted as "m.". Data of extreme temperatures were obtained from Table 7.3 (1) and "r" values were from Appendix Table 7.3 (9).

No. of sample	T. (°C)	Growth rate, r, of each stage of red scale							
		1st	1st m.	2nd	2nd m.	3rd	adult	male	total
2	3	0.07	-0.28	-0.01	-0.36	-0.25	-0.56	-0.37	-0.20
3	5	-1.77	-1.48	-1.29	-0.80	0.19	0.30	-0.83	-0.69
4	8	0.75	0	0.16	0.24	-0.24	-0.31	-0.35	0.01
5	9	0.75	0	0.16	-0.24	-0.24	-0.31	-0.35	0.01
7	9	-0.22	0.87	0.89	0.44	-0.26	-0.17	-0.15	0.04
16	10	0.34	0.13	-0.34	0.44	0.26	0.37	0.20	0.23
19	10	0.35	0	0.05	0.27	0.18	-0.04	0.11	0.13
20	10	-0.28	-0.39	-0.44	-0.26	-0.36	-0.23	-0.41	-0.36
21	4	-0.88	-0.73	-0.12	0.03	-0.08	-0.81	-0.45	-0.35
22	6	-0.81	-0.46	-1.33	-0.49	0.31	0.71	-0.41	-0.21
23	8	0	0	-0.13	-1.02	-0.40	0.80	0.14	-0.01
24	10	1.69	0.19	0.36	0.12	-1.29	-0.35	-0.45	0.11
25	10	0.39	1.07	0.88	0.31	0.64	-0.52	0.13	0.28
26	9	0.06	0.18	0.26	1.12	0.79	-0.64	0.78	0.24
27	10	-0.44	-0.10	0.15	0.29	0.29	1.20	0.24	0.04
28	10	-0.09	-0.13	-0.02	-0.17	-0.04	0.17	0	-0.05
29	10	-0.05	-0.40	-0.38	-0.19	0.02	0.21	-0.16	-0.10
30	10	0.58	0.28	-0.40	-0.39	-0.02	0.04	-0.11	0.24

Appendix Table 7.3 (11). The growth rate, r=log [N(t+1)/N(t)], of each stage of live red scale in each of the observation intervals in which the extreme temperature T>35°C. The moulting stages were denoted as "m.". Data of extreme temperatures were obtained from Table 7.3 (1) and "r" values were from Appendix Table 7.3 (9).

No. of sample	T. (°C)	Growth rate, r, of each stage of red scale							
		1st	1st m.	2nd	2nd m.	3rd	adult male		total
6	36	0.13	0.24	-0.51	-0.24	-0.61	0.62	0.45	0.08
7	36	-0.22	0.87	0.89	0.44	-0.26	-0.17	-0.15	0.04
8	35	0.17	-0.07	0.18	0.70	0.94	-0.13	0.83	0.26
9	36	0.07	-0.14	0.03	-0.04	0.31	0.09	0.23	0.10
10	36	-0.29	0.09	-0.14	-0.09	-0.02	0.69	-0.19	0.01
11	40	-0.16	0.07	-0.12	0.20	0.02	0.09	0.41	0.12
12	38	0.41	-0.11	0.22	0.24	0	0.24	0.15	0.20
13	41	0.16	0.08	-0.52	-0.33	0.05	-0.16	-0.21	-0.10
17	37	-0.29	0.14	0.50	-0.08	0.30	-0.10	0.26	0.02
27	35	-0.44	-0.10	0.15	0.29	0.29	1.20	0.24	0.04
30	37	0.58	0.28	-0.40	-0.39	-0.02	0.04	-0.11	0.24
31	37	0.51	1.12	0.65	0.31	-0.03	0.06	0.13	0.34
32	36	0.10	0.15	0.64	0.68	0.16	0.36	0.79	0.29
33	40	0.19	-0.10	0.24	0.24	0.54	-0.22	0.26	0.17

Appendix table 8.2 (1). Reproduction of numbers of crawlers per female adult red scale; on lemons on the tree in the Waite Institute Orchard, 1986

Day	Date	reproduction of crawlers of adult:										
		1	2	3	4	5	6	7	8	9	10	Total
1	9/2	4										4
3	11/2	10	3	0	0	0	7	0	9	9	8	46
5	13/2	8	8	0	0	0	9	0	7	6	10	48
7	15/2	8	2	0	0	0	5	0	4	0	4	23
9	17/2	5	3	0	0	0	4	0	0	0	0	12
11	19/2	2	3	0	0	12	0	0	0	0	0	17
13	21/2	2	5	0	0	6	0	0	0	0	0	13
15	23/2	3	5	0	0	6	4	0	0	0	4	22
17	25/2	4	3	0	0	14	9	0	5	1	7	43
19	27/2	0	2	0	0	4	10	0	1	0	14	31
21	1/3	0	2	0	0	0	0	0	7	0	2	11
23	3/3	3	2	2	4	4	5	8	6	1	5	40
25	5/3	3	3	2	7	6	5	10	6	1	6	49
27	7/3	1	3	0	5	2	5	8	4	0	4	32
29	9/3	1	0	0	0	0	0	1	0	0	0	2
31	11/3	3	0	0	0	1	0	0	0	0	0	4
33	13/3	0	0	0	0	0	0	1	0	3	0	4
35	15/3	1	0	0	1	2	0	2	0	0	1	7
37	17/3	2	0	0	0	0	0	0	3	1	0	6
39	19/3	0	0	0	0	0	1	0	4	2	0	7
41	21/3	0	1	0	0	0	0	0	0	0	0	1
Total		36	38	3	15	24	36	28	36	36	32	422
Mean±SE/per adult												28.4±3.6

Mean ambient tmeperature (obtained from a Stevenson Screen):
(a) 21.8 ± 0.8 (°C) for period of 2/9-7/3.
(b) 21.7 ± 0.6 (°C) for period of 9/2-21/3.