THE EFFECT OF NATURAL ENEMIES OF *MYZUS PERSICAE* SULZER UPON ITS POPULATION TRENDS IN POTATO CROPS IN SOUTH AUSTRALIA

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SUMMARY

A two-year study of potato aphids and their natural enemies (especially predators) was conducted in small plots at the Waite Institute and in large commercial potato fields at Milang in South Australia. The green peach aphid *Myzus persicae* Sulzer was the most important and common aphid in potato crops at both sites. *Macrosiphum euphorbiae* (Thomas) was the only other aphid found but its numbers were relatively low.

Populations of *M. persicae* declined between July and February and reached peak numbers in April-May each year. Weekly samples of the crop indicated that, of the predators, the brown lacewing, *Micromus tasmaniae* Walker (Neuroptera : Hemerobiidae) was the most abundant (ca. 90%) and important. Coccinellids, chrysopids and syrphids occurred in very low numbers but may be important when *M. tasmaniae* is scarce. Hymenopteran parasites and entomogenous fungi (*Zoopthora* sp.) were of little importance during the study period.

Predator exclusion studies were conducted from September 1979 - January 1980 to test the hypothesis that the main reason for the low numbers of *M. persicae* on potato plants in spring each year was the abundance of *M. tasmaniae*. The results confirmed that natural populations of *M. tasmaniae* almost completely suppress populations of *M. persicae* in spring - early summer. This finding was also consistent with the abundance of the predators in the weekly samples.

The numbers of *M. tasmaniae* were always relatively low, however, in late summer-autumn, and in autumn *M. persicae* attained its highest peak numbers and often caused considerable economic loss if not controlled by insecticides.

When the field relationship between *M.persicae* and *M. tasmaniae* had become clear, the main objective of this thesis was restricted to test the possibility of increasing the numbers of *M. tasmaniae* so that they could be used to control *M. persicae* in the autumn.

In order to obtain information on the behaviour of larvae of *M. tasmaniae*, laboratory studies on the minimum food requirements, survival, voracity, probability of capturing prey, and prey preference were done. And experiments on the influence of prey density and temperature on voracity were conducted in plant growth cabinets. Further experiments were conducted in a glasshouse to study the searching efficiency and prey suppression as influenced by predator density and prey spatial distribution in a more complex arena. The interrelationship between these factors that influence prey suppression are discussed.

A method of rearing *M. tasmaniae* for the production of small batches of 600-1000 eggs per day was developed. The possibility of expanding the method of mass-rearing of eggs to produce large number of eggs on a factory basis is suggested.

A special compressed air sprayer was successfully developed for spraying eggs of *M. tasmaniae*. Spraying tests conducted in the laboratory showed that eggs can be sprayed without damage at 2 kg/cm^2 pressure. A special gum (Xanthan gum) was selected as a liquid medium for suspending the eggs and making them adhere to potato foliage.

Replicated small-plot trials were conducted in the spring of 1980 and autumn of 1981 to test the efficacy of periodic releases of sprayed eggs of *M. tasmaniae* to suppress the early build-up of *M. persicae* on potatoes. Large numbers of *M. tasmaniae* when released periodically augmented the naturally occurring predator population and exerted effective early season control of potato aphids.

The possibilities of using other methods of manipulating the crop environment to increase the numbers of naturally existing *M. tasmaniae* particularly in late summer-autumn are discussed. Among others, inter-cropping and rotation between *Medicago* sp. and potatoes as well as planting of hedgerow trees near the crop to provide refuges and alternative prey are considered important. The role of *M. tasmaniae* in the integrated pest management of potato pests is also discussed.

STATEMENT

This thesis contains no material which has been accepted for the award of any degree or diploma in any University and, to the best of my knowledge and belief, this thesis contains no material previously published or written by any other person, except where due reference is made in the text of this thesis.

M. ~~Yusof~~ Hussein.

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TO MY PARENTS

CHAPTER 1

INTRODUCTION AND OBJECTIVES

The importance of natural enemies in the control of their prey or host populations has been a subject of contention. Natural enemies are viewed today by an increasing proportion of ecologists as highly significant natural control factors, but there still is, and will continue to be disagreement both as to their role and effective methods of their evaluation.

In the temperate zones, aphids are probably the most important group of crop pests and include some of the most common and destructive pests of plants. Plants may be damaged by aphids either directly by feeding or indirectly as vectors of plant viruses. The green peach aphid sometimes called the peach-potato aphid, *Myzus persicae* (Sulzer) probably is the most important pest of crop plants and of potato on a world-wide basis. Because of its abundance each season and the incidence of virus infection, *M. persicae* can be a limiting factor in the production of seed potatoes in South Australia and many other parts of the world.

Potato growers at Milang, South Australia have previously tried to grow their own seed potatoes but were discouraged by the high incidence of aphid-borne virus diseases, the most important being the potato leaf roll virus (PLRV) which is transmitted only by *M. persicae*. The rising cost of insecticides, which are ineffective in preventing the spread of PLRV, plus the increasing cost of buying, transporting and storing seed potatoes have strengthened the need for an ecological assessment of the

role played by the natural enemies in regulating the changes in the populations of potato aphids, mainly *M. persicae* in South Australia.

The extensive literature on the abundance of *M. persicae* and its natural enemies in various crops overseas indicates that natural enemies, especially predators, have often been important in limiting aphid numbers (Inaizumi, 1968; Shands *et al.*, 1972e; Mackauer and Way, 1976) and they have been judged to possess great potential in integrated pest management programs for potatoes in the United States of America (Shands *et al.*, 1972a,b,c; Whalon and Smilowitz, 1979).

I therefore investigated the phenology and abundance of the major predators, parasites (parasitoids) and entomogenous fungi attacking potato aphids, mainly *M. persicae*, in large commercial potato fields as well as small potato plots over a period of two years.

The main objectives of these field investigations were to determine:

(i) whether there was any period of the year when the abundance of *M. persicae* was usually sufficiently low to allow the growing of seed potatoes with minimal risk of infection with PLRV.

(ii) why the numbers of *M. persicae* seemed to be unusually low in the spring of each of the last five years prior to this study.

In relation to objective (ii) described above, one of the more reliable potato growers at Milang, South Australia said that when he first moved into the area and started growing potatoes in 1963, for three years he had no problems with aphid infestations and virus diseases.

From 1966 to 1973 he was troubled with varying degrees of aphid outbreaks and potato virus diseases which occurred in the spring (September, October, November) and in the autumn (March, April, May). However, in the last five years, *M. persicae* had not been troublesome in the spring (Mr. Lance Chaplin, 1978, personal communication).

To interpret the trends in numbers of aphids and predators in the field investigations, a number of related studies were done. These included:

(i) the measurement of the impact of naturally occurring predators on *M. persicae* on potted potato plants;

(ii) the measurement of the adverse effects of insecticidal sprayings on field populations of potato aphids, mainly *M. persicae* and the associated predators;

(iii) the biology and use for pest control of the brown lacewing, *Micromus tasmaniae.* (Walker).

To expand on (iii) above, among the predators of *M. persicae* in potato fields in South Australia, the brown lacewing, *M. tasmaniae* (Neuroptera : Hemerobiidae) seemed, early in the study, to be the most abundant and most important predator. The significance of hemerobiids as aphid predators seems to have been generally neglected. In California, U.S.A., *Hemerobius pacificus* Banks and *H. ovalis* Carpenter are the only predators which may help delay the aphid populations increase in alfalfa (Neuenschwander *et al.*, 1975). In Australia, *M. tasmaniae* was considered by Maelzer (1977) to be the principal predator of rose aphid, *Macrosiphum rosae* (L.) in the spring and its biology was studied by Samson and Blood (1979 and 1980).

Many other types of predators have been manipulated from pest control, e.g. periodic inundative releases of coccinellids for controlling *M. persicae* on potatoes (Shands *et al.*, 1972c) inundative releases of chrysopids for controlling *M. persicae* on glasshouse chrysanthemums (Scopes, 1969), and inundative releases of chrysopids for controlling bollworms and tobacco budworms attacking cotton plants (Ridgway and Jones, 1968 and 1969). However, the potential value of hemerobiids, particularly *M. tasmaniae*, has not been investigated. In this thesis, the possibility of utilizing insectary reared *M. tasmaniae* eggs for periodic releases to give early control of *M. persicae* attacking potatoes was investigated.

It is hoped that the results reported in this thesis will contribute towards an understanding of the role of natural enemies of *M. persicae* in potato fields and encourage their use by augmentation and/or conservation of numbers in integrated control programs so that growers in South Australia may produce their own seed potatoes.

CHAPTER 2

REVIEW OF LITERATURE

2.1 Aphids Infesting Potatoes

Worldwide, four species of aphids may occur on potatoes. These are the buckthorn aphid, *Aphis nasturtii* Kaltenbach; the foxglove aphid, *Aulacorthum solani* Kaltenbach; the potato aphid, *Macrosiphum euphorbiae* (Thomas); and the green peach aphid, *Myzus persicae* (Davies, 1932; Bald *et al.*, 1946; Shands and Simpson, 1959; Diaber, 1963; McGillivary, 1979; Byrne and Bishop, 1979).

The green peach aphid, *M. persicae* is probably the most important insect pest of potato, *Solanum tuberosum* (L.), on a worldwide basis (Mackauer and Way, 1976; Cancelando and Radcliffe, 1979). Some species of aphids infesting potato crops are encountered more often than others, depending on locality, climate, host plant distribution, and other ecological factors. In Washington, U.S.A., 95% of the aphids founds on potatoes are *M. persicae* (Tamaki and Weeks, 1972). In Australia, *Macrosiphum euphorbiae* was reported to comprise the greater part of the aphid populations on potatoes with *M. persicae* usually occurring in small numbers (Norris and Bald, 1943).

The general infestation by different species on different parts of the potato plant have been studied by many workers (Davies, 1932; Doncaster and Gregory, 1948; Broadbent, 1953; Woodford, 1973). Different species of potato aphids showed different distributions on the potato plant because of the influence of different microclimate

preferences as well as food preferences; e.g. *M. persicae* prefers growing or senescing leaves to mature ones (Kennedy *et al.*, 1959). The aphids usually begin infestations on the lower leaves (Smith, 1919; Simpson, 1932; Jacobs, 1941; Doncaster and Gregory, 1948; Bradley, 1952) or ground canopy leaves (Bald *et al.*, 1950) and spread upwards to the middle leaves as the lower leaves become senescent (Taylor, 1955 and 1962). Broadbent cited that, in France in 1951, Bonnemaison found most *M. persicae* on the middle or upper leaves (Broadbent, 1953). Other species of potato aphids also showed microclimate and food preferences. *M. euphorbiae* was found mainly on the basal leaves and the upper tips of the shoots (Bald *et al.*, 1950). Bradley (1952) noted that *M. euphorbiae* was numerous on the upper leaves in the cool morning, but was less so on hot and dry afternoons. *A. nasturtii* by contrast, usually congregated towards the base of the plant (Bradley, 1952). Fidler (1949) reported that the distribution of *M. persicae* within a potato plant in an average field to be such that 41%, 36% and 23% of the population were from the lower, middle and upper leaves, respectively.

In Australia, the two main species of aphids occurring in the potato fields near Canberra (Norris and Bald, 1943; Bald *et al.*, 1946 and 1950; Helson, 1958), in Queensland (Bartholomew, 1981) and in South Australia (F.D. Morgan, unpublished data) are *M. persicae* and *M. euphorbiae*. Another species of aphid, *Aulacorthum solani*, which is known as a major pest of potatoes overseas, has also been reported to colonise potatoes in Australia (Helson, 1958).

2.2 *M. persicae* and Potato Virus Diseases

M. persicae is reported as a major vector of well over 100 diseases of plants including crops such as beans, sugar beets, sugar cane, brassicas, citrus, tobacco and potatoes (Kennedy *et al.*, 1962; Powell and Mondor, 1973; Cancelando and Radcliffe, 1979). This aphid is also known to be a vector of several virus diseases of potatoes, the most important being potato leaf roll virus (PLRV). There is now general agreement that *M. persicae* is the species which is generally responsible for the dissemination of PLRV in potatoes (Davies, 1934; Kennedy *et al.*, 1962; Close, 1965). One or two individuals only of *M. persicae* are sufficient to transmit PLRV from an infected to a healthy plant (Smith, 1929).

Spring migrants of alate *M. persicae* usually arrive in potato crops free of potato virus (Broadbent, 1953; Close, 1965), but will spread viruses from diseased foci within the crop as they frequently fly from plant to plant feeding and depositing nymphs (Broadbent, 1953). The pattern of PLRV spread has been correlated with aphid dispersion (Bishop, 1968) and the incidence of PLRV with aphid numbers (Broadbent, 1950; Bishop, 1965; Byrne and Bishop, 1979a). Alate *M. persicae* which are bred on the crop are unlikely to move as frequently as the spring migrants (Broadbent, 1953). In general, the extent of virus transmission and spread within a crop depend largely upon the numbers and movement of aphids, which in turn depend closely on the weather (Murphy and Loughnane, 1937). In addition, the variety, age of healthy and infected plant, and fertility of the soil have been known to affect the ease with which potato

viruses spread (Ross *et al.*, 1947; Doncaster and Gregory, 1948; Broadbent, 1952; Kassanis, 1952). The same factors may operate during the dispersal of potato aphids in summer, when the virus may be spread from field to field (Davies and Whitehead, 1938; Broadbent *et al.*, 1950).

Leaf roll virus is known as a persistent or circulative virus. Persistent viruses are retained for many days; frequently for the life of the aphid. Aphids take 24-48 hours of circulation time to pick up the virus from a diseased plant and an equally long period of time to infect a healthy plant (Smith, 1929; Kassanis, 1952; Webb *et al.*, 1952; Close, 1965). The likelihood of acquisition of virus increases with increasing duration of the feeding period on diseased plants. A latent period (= circulation time), which varies considerably in duration for different viruses, occurs before transmission is possible (Swenson, 1968; Sylvester, 1980). During this latent period, the vectors may be killed with insecticides or biotic agents such as predators and transmission thus prevented (Smith, 1931; Close, 1965). On the other hand, non-persistent or stylet-borne viruses are acquired optimally in brief probes of 10-60 sec. duration. The proportion of aphids acquiring viruses decreases with a longer acquisition period. Non-persistent viruses may be transmitted immediately, i.e., without a latent period (Swenson, 1968; Sylvester, 1980).

PLRV is a tuber-borne virus and up to 35% and of the tubers of current-season plants infected with the virus may be infected, and most of these tubers will develop the symptoms of net necrosis (or phloem necrosis) (Knutson and Bishop, 1964; Bacon *et al.*, 1976). The virus disease may

reduce the quantity and/or quality of the crop produced. The yield of marketable tubers may be reduced by 50-100% in the case of plants growing from tubers infected with PLRV (Shands and Landis, 1964). Van der Wolf (1964) cited estimates of yield decreases due to leaf roll infection, as calculated by several authors, ranging from 7.5 to 84%. Leaf roll virus disease is also the cause of degeneration or breakdown of several potato varieties and the main reason for rejection of lines of these varieties for seed certification (Close, 1965).

2.3 General Biology and Host Plants of *M. persicae*

M. persicae occurs throughout the world on a wide range of host plants and is presumably adapted to a great diversity of environments. Its life cycle varies both within and between regions in relation to the widely differing climates it experiences. However, very little is known about the exact nature and significance of the intraspecific variation (van Emden *et al.*, 1969). Life cycle variation, involving differences in the method of overwintering, is a significant feature of the biology of *M. persicae* in every continent throughout the world. The aphids overwinter either as parthenogenetic forms on secondary host plants (anholocycly) or as fertilized eggs on the primary hosts (holocycly). The kind of life cycle has profound effects on the ecology and genetics of *M. persicae* populations (Mackauer and Way, 1976).

The complexities of *M. persicae's* life cycle in any one locality have been studied by many workers (Ward,1934; Ossianilsson, 1959; Cognetti, 1967; and reviewed by van Emden *et al.* (1969) and by Mackauer and Way (1976). The life cycle

involves production of oviparae, fundatrices, fundatrigenae, alate migrants on the primary host, and apterous and alate virginoparae, males and gynoparae on secondary hosts (van Emden *et al.*, 1969). In the temperate regions, winged immigrant gynoparae of *M. persicae* reach the primary host (*Prunus* sp.) at a well-defined time in autumn (Ward, 1934; Newton *et al.*, 1953; Scholl and Daiber, 1958).

In Australia, oviposition occurs in late autumn (May) on peaches and nectarines and, as in other temperate zones, the eggs overwinter in diapause (Ward, 1934; Helson, 1958). The duration of development of the eggs is approximately 55 days. Hatching occurs during mid-winter (July) and early spring (September). The newly hatched nymphs are called fundatrices, and their progeny (fundatrigenae) are born and develop to maturity on peach (*Prunus persicae).* In the third generation of the fundatrignae, winged forms of the aphid begin to occur and their frequencies increase until all adult aphids are winged. At this time, the aphids begin to fly from the primary woody hosts to secondary herbaceous plants including weeds and food plants like potatoes. Such migratory flight usually occurs in the spring and often lasts for several weeks (Davies, 1932; Ward, 1934; Helson, 1958; Heathcote, 1965). In Australia, the period of spring migration varies slightly in different places due to differences in the weather patterns. Hughes *et al.* (1964) suggested that the normal build-up of the flights of various species of aphids including *M. persicae* occurring between August and November marked the start of the spring migration period. Helson (1958) reported that *M. persicae* migrated from peaches to potatoes in Canberra in late October or early November. During the summer months the aliencolae, which are initiated by the spring migrants on the secondary food plants, give rise

to several viviparous generations. The winged males and winged sexual females do not arise until the return migration to the peach is about to take place in autumn (Davies, 1932; Ward, 1934; Helson, 1958; Heathcote, 1966).

M. persicae may also overwinter as active stages on crops, weeds or in sheltered situations such as glasshouses (Doncaster and Gregory, 1948; Broadbent, 1953) and on stored beets and potatoes (Heie, 1954) in regions with mild winters where the average monthly maximum temperature in winter exceeds 10°C (van Emden *et al.*, 1969). Anholocycly may be common for *M. persicae* populations in most parts of South Australia e.g., at Murray Bridge, where Maelzer (personal communication) found *M. persicae* on glasshouse capsicums in August. The overwintering host plants for the active stages of *M. persicae* include cruferous crops (Chamberlin, 1950; Fisken, 1959a; Lowe, 1962; Daiber, 1963); potatoes (Broadbent, 1946; Banerjee and Basu, 1956); beets (Dickson and Laind, Jr, 1962); peach nursery stock (Batra, 1953); and weeds (Heathcote, 1963).

In the warm temperate and tropical regions, the hot dry summer season, as is experienced in South Australia, is the most hazardous period for survival of *M. persicae*, both in terms of scarcity of suitable host plants and of high temperatures. Mean daily maximum temperature above 28°C will prevent development of *M.persicae* (Bald, 1943; van der Plank, 1944; Bodenheimer, 1957; Barlow, 1962). In South Africa, *M. persicae* populations almost disappeared when the mean daily maximum temperature reached 32°C (van der Plank, 1944). In Australia, aphids including *M. persicae* become scarce or disappear from potatoes with the onset of hot, dry summer weather (Helson, 1958; M.Carver, personal communication).

Small populations of *M. persicae* probably survive the summer on weeds and other wild plants (M.Carver, personal communication), or in gardens where a wide range of exotic plants are grown under irrigation (Maelzer, 1981).

2.4 Predators of *M. persicae*

Many natural enemies of *M. persicae* have been reported but there is still little quantitative data on their ecology and value in controlling the aphid. Van Emden *et al.* (1969) classified natural enemies of *M. persicae* into two categories:

1) generalized predators about which little is known, and
2) all parasites and many pathogens, for which aphids form the main or sole food of the predaceous or parasitic stage of the life cycle.

The predators of *M. persicae* are represented in 13 insect families including anthocoridae, cantharidae, ceccidomyiidae, chamaeyiidae, chrysopidae, coccinellidae, hemerobiidae, miridae, nabidae, pentatomidae, syrphidae (van Emden *et al.*, 1969; Mack and Smilowitz, 1980), malachiidae (Mackauer and Way, 1976), staphylinidae (Mack and Smilowitz, 1980), two families in the Order Araneida (Mack and Smilowitz, 1980) and one family in the Order Acarina (van Emden *et al.*, 1969). At least 21 species of arthropod predators of *M. persicae* were found on potato foliage in Pennsylvania, U.S.A. (Mack and Smilowitz, 1980).

The amount of work which has been done on different groups of predators of *M. persicae* varies widely. A survey conducted in 1972 indicated that coccinellids had been studied most, followed by Neuropterans,

Syrphids, Heteropterans, Cecidomyiids (= Itonidids), Aracnoids, Chamaemyiids and Malachiids in descending order (Mackauer and Way, 1976).

While many workers thought that predators played an important role in the regulation of *M. persicae* numbers (Stathopoulous, 1967; Inaizumi, 1968; Tamaki *et al.*, 1967; Shands *et al.*, 1972e), others were sceptical about the impact of predators on *M. persicae* populations (Evenhuis, 1968; Oatman and Planter, 1969; Dunn and Kempton, 1971; Galecka and Kajak, 1971). Shands *et al.* (1972e) concluded from the analysis of 31 populations curves of *M. persicae* and *M. euphorbiae* that predators and entomogenous fungi were chiefly responsible for initiating decreases of the aphid populations.

Some of the common predators of *M. persicae* which have been subjects of intensive studies in attempts at biological or integrated control include *Coccinella septempunctate* (Shands *et al.*, 1972e) *Propylaea quatuordecimpunctata* (Rogers *et al.*, 1972), *Harmonia axyridis* (Voronia, 1968), *Coccinella transversoguttata* (Shands *et al.*, 1972e) *Hippodamia* sp. (Hagen *et al.*, 1971; Shands *et al.*, 1972) and *Coleomegilla maculata* (Mack and Smilowitz, 1980). These species are all coccinellids. *Chrysopa carnea* is the only chrysopid predator of *M. persicae* which has received intensive studies on biological or integrated control of *M. persicae* (Shands *et al.*, 1972a). By contrast, little is known of hemerobiids as predators of aphids other than those in lucerne fields (Neuenschwander, 1975; Cameron *et al.*, 1979; Syrett and Penman, 1980), roses (Maelzer, 1977) and cotton (Samson and Blood, 1979) and very little quantitative data on their ecology are available. In particular, no previous attempts at biological or integrated control of *M. persicae*

have been made. This study on *M. persicae* on potatoes in South Australia includes an attempt to use the brown lacewing, *Micromus tasmaniae* for integrated control of the aphid.

2.5 The Brown Lacewings

The brown lacewings (Hemerobiidae) are spread over the world and occur in all major regions and continents and even on isolated islands in the oceans. More than 80 genera and 600 species have been described but several genera have fallen into synonymy (Tjeder, 1961).

Hemerobiidae have received much less attention as control agents than Chrysopidae, although both families are widely distributed in most geographical regions. Recent surveys have shown that Hemerobiidae are often more diverse than Chrysopidae, and are usually smaller and have a high proportion of 'rare' species (New, 1975).

Many hemerobiids are found on taller vegetations such as conifers and many exhibit prey specificity limiting their value for control work to similar specialized situations. On the other hand, some hemerobiids (many *Micromus* and *Drepanacra*) frequent low vegetations and could be of great value for use in many agroecosystems (Killington, 1936; Tjeder, 1961; New, 1975).

The commonly known genera include *Boriomyia, Drepanepteryx, Dyshemerobius, Hemerobius, Micromus, Notobiella, Psectra, Sympherobius, Sisyra, Drepanacra, Megalomina, Caronius, Psychobiella* and *Megalonus* (Bank, 1909; Killington, 1936; Carpenter, 1961; Tjeder, 1961; New, 1975).

The genus *Hemerobius*, particularly *H. pacificus* Banks, is the most common brown lacewing along the coast of California, U.S.A. (Neuenschwander, 1975). It is the only common and active predator in artichoke fields in California to be considered an important control agent for aphids under cooler conditions (Neuenschwander and Hagen, 1980) and has a potential for periodic releases very early inthe growing season when other predators are still inactive (Neuenschwander, 1976).

The genus *Micromus* has 19 synonyms (Tjeder, 1961). This genus has a worldwide distribution. Many species occur in Asia and are well represented in the Hawaiian islands, many islands in the Pacific and in Australia. *Micromus tasmaniae* was first described by Walker (1860). Its generic complexity was synonymised under *Micromus* by Tjeder (1961). The species is native to Australia and is also found in New Zealand, New Hebrides, New Caledonia, Chathan Island, Antipodes and Auckland Island (Wise, 1973). Hilson (1964) studied the ecology of *M. tasmaniae* in New Zealand and discussed the possibility of mass releases of the predator eggs for aphid control. Also, in New Zealand, *M. tasmaniae* is the only species of predator common through spring and summer in the lucerne fields and appeared earlier than other aphid predators (Cameron,*et al.*, 1979; Syrett and Penman, 1980).

In South Australia, *M. tasmaniae* is one of the major predators of the rose aphid, *Macrosiphum rosae* (L.) (Maelzer, 1977) in the spring, and the spotted alfalfa aphid, *Therioaphis trifolii* f. *maculata* (Buckton) (Ting *et al.*, 1978). In Queensland, *M. tasmaniae* is an important predator of *Aphis gossypii* and eggs of *Heliothis* sp. attacking cotton plants (Samson and Blood, 1979). It has also been reported as an important

predator of lucerne aphids in Tasmania (Brieze-Stegeman, 1978), in Victoria (Ridland and Berg, 1978), and in New South Wales (Waters and Dominiak, 1978; Forrester, 1978). *M. tasmaniae* has been considered to be the only species which consistently occurred earlier than other predators because it can withstand lower temperatures and can find aphids at very low prey densities (Maelzer, 1977; Milne, 1978). It has been found very abundant in the spring (Forrester, 1978) and in the summer (Brieze-Stegeman, 1978), appears to have very few natural enemies (Milne, 1978), and has the greatest potential for aphid pest control in Australia (Maelzer, 1977).

Despite these indications that *M. tasmaniae* may be an important predator of aphids in Australian crop systems, no work has previously been done to elucidate the role, or to encourage the use of *M. tasmaniae* in the biological or integrated control of insect pests in Australia.

2.6 Current Methods of Controlling *M. persicae* on Potatoes

Attempts to prevent the spread of potato viruses by controlling the aphid vectors so far have been unsuccessful or only partially successful. Chemical control, while effective on a short-term basis, has hte obvious disadvantages of producing insecticide-resistant clones when applied frequently or in large doses. There is evidence of frequent insecticide-induced aphid resurgences caused by the destruction of natural enemies as well as the aphids (Peterson, 1963; Radcliffe, 1972 and 1973).

Control of potato aphids by methods other than chemical ones are, however, difficult. Mackauer and Way (1976) concluded that data collected from all over the world suggest that economically acceptable biological

control of *M. persicae* as a virus vector by promoting the existing natural enemies after the aphids had reached the potato crop is yet to be proven. However, peak numbers can be limited by predators on occasion, especially where the aphid's rate of increase is low. Indigenous parasites, even without reduction in numbers by hyperparasites, produce rather insignificant mortality in *M. persicae* populations. Work on parasites might therefore concentrate on the potential of using 'foreign' races and/or inundative releases rather than on the preservation of existing biological control agents.

Fungal attack also appears too sporadic to hold out much hope for biological control, though the development of new strains or of new technologies for disseminating artificially introduced fungi might change the situation. There were no signs of field mortality from fungal attack early in the season, even in damp weather, and in general *M. persicae* populations were too sparse to make satisfactory targets (Mackauer and Way, 1976).

Predators, on the other hand, appear to be surprisingly important in several diverse areas. There seems a real potential here to control the size of the aphid peak by predators. Non-specific predators which can build up in numbers independent of the aphids may exert control early in the season when aphid numbers are low, or later by inundations (Shands *et al.*, 1972c; Mackauer and Way, 1976).

Mackauer and Way (1976) stressed that non-crop or alternative crop plants may be profitably used to accelerate the impact of biological agents on green peach aphid populations.

Coccinellids would appear potentially the most valuable predators, but there is a real need for more work to be done on the lesser known but important predators, in particular aphidophagous ceccidomyiids, hemerobiids, beetle larvae, predatory mites and spiders (Shands *et al.*, 1972e; Mackauer and Way, 1976).

The most important need is for the development of an integrated control program, with the main objective of reducing the numbers of virus-carrying winged aphids (Bacon *et al.*, 1976; Mackauer and Way, 1976; Cancelando and Radcliffe, 1979; Whalon and Smilowitz, 1979). The International Biological Control Program work on *M. persicae* which began in 1967 has identified two aspects of the aphid's life history and population dynamics that are relevant to control and should be examined in more detail in the light of integrated control. The first is host plant resistance and second is that of life cycle and biotype variations. However, in developing an integrated control program (integrated pest management) against *M. persicae*, natural enemies, host plant resistance, environmental manipulation, and insecticides can all be useful components.

A pilot integrated pest management program for *M. persicae* on potatoes was initiated in Pennsylvania, U.S.A. Among others, the objectives of the program included reduction of the usage of insecticides and conservation of natural enemies of *M. persicae* (Whalon and Smilowitz, 1979). From their three years of field studies on the interaction of insecticides, *M. persicae*, and natural enemies, they were able to develop a computer forecast system for predicting current year field populations of *M. persicae*. Through the use of a selective aphicide, natural enemies of *M. persicae* could also be conserved.

In New Zealand, on the other hand, prevention of spread of PLRV was achieved by controlling *M. persicae* on potatoes through a combination of available control methods such as application of granular insecticides, late planting, and roguing of diseased plants. Through the integration of these control methods, natural enemies of *M. persicae* were conserved and their actions enhanced (Close, 1965).

There is little doubt that an integrated control program developed for potato aphids in South Australia would be welcomed by the potato growers and its development could make a contribution to the ecology of *M. persicae* in South Australia and to our knowledge of the interaction of predator and prey.

CHAPTER 3

GENERAL MATERIALS AND METHODS

3.1 Growing of potato plants

Growing of potato plants from tubers (seeds) in the glasshouse

Two-three weeks prior to the start of the experiment, potato (var. Exton) seed pieces (with 2-3 eyes per piece) were planted 2-3 cm deep in 15 cm (in diameter) black plastic pots containing a recycled University of California soil mixture. The planting rate was 1 per pot. The plants were allowed to grow in a glasshouse under natural light until they reached an average height of 8-10 cm. The plants were watered once a day and when necessary. A few days before the start of the experiment the stems were thinned to one per pot.

Growing of potato plants from shoot cuttings in the plant growth cabinet

One week prior to the start of the experiment, cuttings (2.5 to 3.0 cm long) of terminal and auxillary shoots of potato plants growing in the field were obtained and rooted in the following manner. After suitable shoots had been selected, they were carefully cut as near to the base as possible, using a clean and sharp razor blade. The end of the cutting was then moistened with distilled water and dipped its lower 1.0 cm in Seradix$^{(R)}$ No.2 rooting powder [active constituent : 3 g/Kg 4-indol-3-yl butaric acid (0.3% w/w)]. Excess powder was shaken off and the cutting was planted 1.0-1.5 cm deep in a small plastic pot (5 cm x 5 cm x 6 cm) filled with vermiculite. The cuttings were then

placed in the 25°C plant growth cabinet for the roots to develop. In every case the total number of cuttings collected from the field was 25% more than the numbers required as some of the cuttings failed to root.

3.2 Culture of *Myzus persicae*

A stock culture of *M. persicae* was maintained in the insectary throughout this study. It was necessary as a source of insects of high viability and reproductive capacity for use in experiments at different times and for experiments at a time when the aphids are very scarce in the field. This method of culture was particularly useful because *M. persicae* becomes abundant on potatoes in the field in South Australia only in autumn. The insectary culture was started numerous times with field-collected apterous adult *M. persicae*. Usually, adult *M. persicae* were collected from uncrowded colonies developing on potato plants. However, at times when *M. persicae* were absent from potato plants, they were obtained from other crop plants and even weeds.

The aphids were reared on clean potato 'trifoliates' (a trifoliate here refers to a potato leaf with only the terminal and two immediate basal leaflets) c. Exton. Usually ten newly moulted apterous adult *M. persicae* were carefully placed on the surface of each leaflet by means of a camel's hair brush. To keep each trifoliate fresh for at least seven days, its petiole was submerged in water after it was inserted through a hole (10 mm diameter) in the lid of a plastic vial (35 mm x 50 mm) containing tap water. A small cotton plug was used to cushion the petiole against the side of the hole and to hold the 'trifoliate' upright.

The vial plus the 'trifoliate' were then placed inside a rearing

cage (Figure 1) which consisted of an inverted 1.5-litre round container (as the top part) and a 15 mm (diameter) plastic or glass petri dish (as the base). Two ventillation holes (45 mm diameter each) opposite to each other were made on the sides of the container. Another large ventillation hole (70 mm diameter) was made on the top. All the three holes were covered with very fine voil to prevent aphids from escaping.

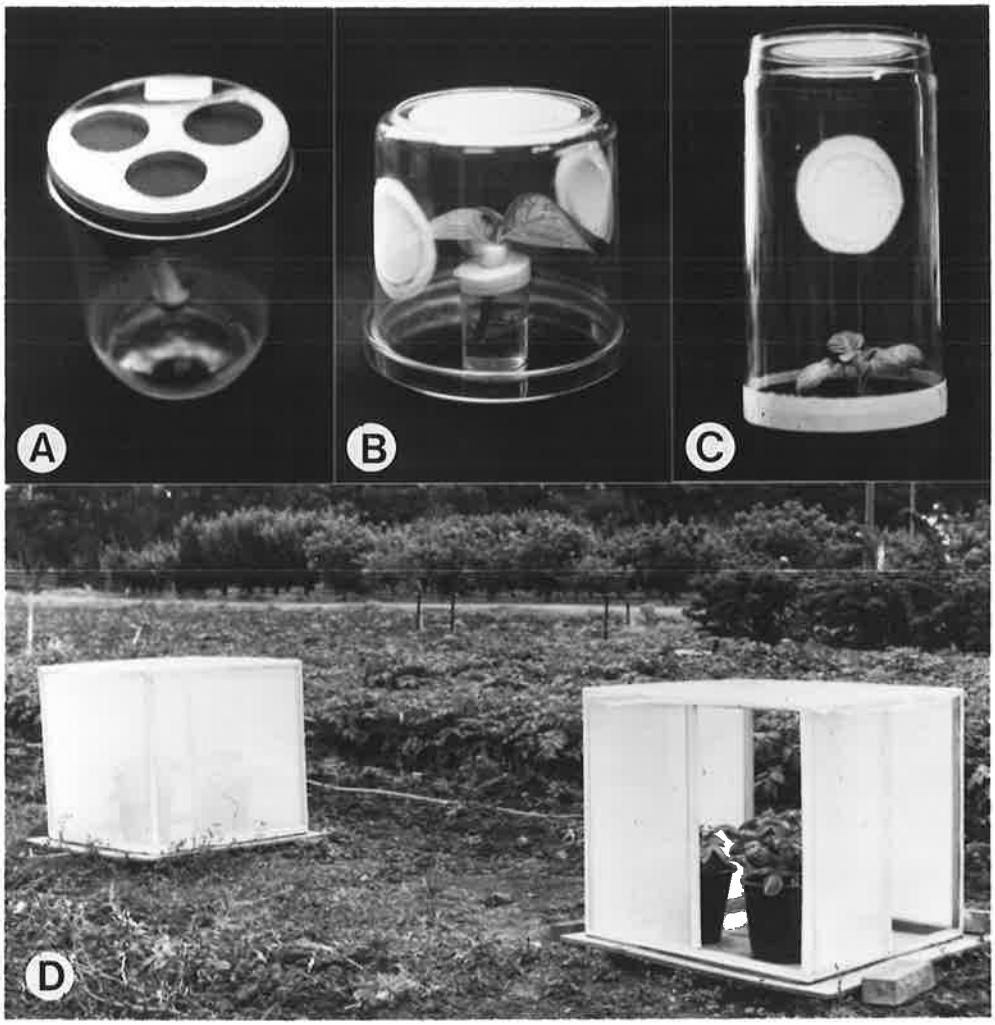
Adult aphids were transferred to a new trifoliate contained in clean rearing cages every day. All adults were discarded after seven days when they were growing less fecund and the trifoliate had started to yellow. All aphids were either discarded or used for feeding predators as soon as the trifoliates started yellowing. The water level inside each vial was maintained by adding tap water every day.

The temperature inside the insectary was maintained at 23 ± 2°C. A bank of ten 80 watt flourescent tubes and one 60 watt incandescent bulb were maintained to provide artificial lighting during the 16 : 8 LD photophase. The relative humidity ranged between 55 to 75 percent.

A routine program of maintaining an insectary culture of *M. persicae* was maintained. Frequently, adult aphids had to be removed from the leaflets to prevent crowing and to slow down deterioration of the leaflets. The insectary culture was renewed at the beginning of every autumn with new apterous adult aphids collected from the field. This was done to ensure that the problems of loss of viability and reproductive capacity in a continuous insectary rearing of insects was minimised (Beck and Chippendale, 1968; Boller, 1972). This method of rearing *M. persicae* on potato trifoliates not only allowed a continuous supply

Figure 1: Types of rearing cages used in this study:

A. Predator oviposition unit used for routine insectary production of eggs.
B. Aphid-rearing cage for routine insectary culture of aphids on potato "trifoliate".
C. A typical cage for experiments conducted in the plant growth cabinet (Section 5.5).
D. Predator and parasite exclusion cage; Closed cage (left) and open cage (right) (Section 4.3).


A
B
C
D

of aphids but also provided a large number of aphids of the desired instars at any time.

3.3 Culture of *Micromus tasmaniae*

Many species of Chrysopidae and Hemerobiidae are easily reared in the laboratory (Finney, 1948; Tulisalo and Korpela, 1973) and the major problems when rearing large numbers are cannabalism, and the provision of an adequate supply of prey.

The brown lacewing, *M. tasmaniae* was reared in the insectary on aphid prey, which was usually *M. persicae*, but other aphids were used whenever *M. persicae* became scarce. The predators were not given food other than live aphids.

The insectary culture of *M. tasmaniae* was started by first collecting adult lacewings in the field. The best time to collect adults in the field were during spring and early summer when they were most abundant. Adults were easily collected by beating potato plants and branches of bushes over a beating tray (Killington, 1937).

Individual adults were kept separately in plastic vials (45 mm x 25 mm). Each vial was closed with a plastic lid and ventilation was provided by making a circular hole (10 mm diameter) in the lid and covering it with copper-mesh. Adults kept in such a container can be transported over long distances with adverse effects. In the insectary they were transferred to oviposition units.

The insectary culture of *M. tasmaniae* served two main purposes:

a) to provide adequate supply of predators for use in various experiments, and

b) to mass-produce eggs for field release studies.

All rearings of *M. tasmaniae* were done in the same insectary room where *M. persicae* were reared.

Oviposition unit

The oviposition unit (Figure 1) consisted of a 350 ml cylindrical clean plastic cup (100 mm high x 85 mm in top diameter). At the top, a cotton cloth (usually brown) was stretched and held in place by a snug-fitting 85 mm plastic petri dish with three round holes (35 mm diameter each) cut into it. The dark coloured cloth, on which the eggs were laid, allowed the white or pinkish eggs of *M. tasmaniae* to be more easily seen. Water for drinking was supplied by placing one end of a short length of absorbent cotton roll (40 mm long x 10 mm diamter) into a wire loop and wetting it with distilled water until saturation.

Eggs which were collected on the cloth tops were incubated in a 25^{o}C constant temperature room.

Incubation unit

Eggs collected on cloth from the insectary culture were removed when needed by methods described in Section 3.2.3 below. Sometimes, in order to avoid cannabalism among the larvae, each egg was then placed individually in an incubation unit, which was a glass tube (50 mm x 5 mm diameter) plugged with cotton wool at the open end.

Larval unit

After the newly hatched larvae had left their egg shells, they were transferred to a larval rearing unit. Not more than 10 larvae were kept in each unit which consisted of a 120 ml cylindrical paper cup (50 mm x 70 mm top diameter) covered with a 75 mm glass petri dish as a lid. Every day, the larvae were carefully transferred, using a soft camel's hair brush, into a clean unit. Excess amounts of live aphids were given to the larvae by brushing the aphids off the leaves and scattering them inside the larval rearing unit.

Just prior to pupation, two pieces of 40 mm filter papers folded along the middle to form roof-like structures were placed in each unit. The folded filter papers acted as shelters and support for the pupa to climb and brace itself for the stretching process and thus reduced fatalities in rearings (Smith, 1923). A small ball of cotton wool saturated with one or two drops of distilled water was also placed inside the larval unit during the pupation period to provide enough moisture and to reduce fatalities among the pupae (*ibid*).

Adults upon emergence were removed from the larval unit and transferred to a clean oviposition unit by means of a mouth-operated aspirator. The aspirator consisted of a plastic vial (80 mm x 35 mm diameter) as a collecting chamber, a rubber stopper fitted with a 5 mm (internal diameter) and 3 mm (internal diameter) glass inlet tubing and a plastic outlet tubing respectively. Adults were supplied with live aphids in a manner described for larvae.

The following laboratory experiments and observations were carried out to ensure that the methods used for the production of eggs for use

in later laboratory, glasshouse and field experiments were reliable.

3.3.1 Dietary requirements of adult *M. tasmaniae*

Introduction

The brown lacewings are predaceous in both larval and adult stages (Smith, 1923; William, 1927; Laidlaw, 1936; Killington, 1937; Tjeder, 1961; New, 1975; Samson and Blood, 1979; Syrett and Penman, 1981). By contrast, adults of some green lacewings are not predaceous, but utilise yeats and honeydew as a staple food (New, 1975). The adult of *Chrysopa oculata* Say is predaceous and it will not mate and oviposit eggs unless the adult has consumed live prey (Tauber and Tauber, 1973). I therefore conducted the following experiment to determine whether males or females of *M. tasmaniae* require nutrients other than sugar in order to mate and whether nutrients were required mainly to promote egg development.

Materials and Methods

In this experiment, each predator, after adult emergence, was placed in a clean oviposition unit in a portion of which were two cotton rolls, one soaked in distilled water and the other in a 15 percent sucrose solution. *M. persicae*, reared on potato trifoliates, were supplied daily to the predator in the combination of treatments noted in Table 1.

All adult predators remained on their respective diets for 5 days prior to pairing. Eight hours prior to pairing, aphids

Table 1: Diets[1] given to females and males of *M. tasmaniae*

Number of pairs	Sex of each pair	Aphids given (+) or not given (-)
3	male	+
	female	+
3	male	-
	female	+
3	male	+
	female	-
3	male	-
	female	-

[1] All adults were also fed with basic diets of 15% sucrose and water.

were removed in order for the lacewings to stop feeding, thereby lessening the chance of sugar-fed adults receiving nutrients from the excrements or regurgitation of aphid-fed adults (Tauber and Tauber, 1973). Then the females and the males were paired and each pair kept together for 5 days. During this time they had access to only sugar and water. On the sixth day, a fresh supply of live aphids were fed again to the adults in all the treatments.

Eggs oviposited on the cloth of the oviposition units were counted daily and all adults were transferred to a clean oviposition unit at the same time. The adults were allowed to remain in their units for three more days before the experiment was terminated.

Results and Discussion

Results of this experiment are shown in Table 2 which shows that oviposition occurred mainly when females had access to aphids prior to pairing. Each of these females oviposited within a few hours.

Mating was observed in all replicates when females were fed on aphids previously but only two females in the other treatments mated and they then laid very few or no eggs. Depriving the males of prey did not alter the incidence of mating and egg laying (2nd diet). Females on the 3rd and 4th diets failed to oviposit any eggs even when live prey were supplied to them from the sixth day onward. The results agree very closely with those of Tauber and Tauber (1973) for *Chrysopa oculata*. Similarly, *C. perla* females require prey in order to mate but, by contrast, *C. perla*

Table 2: Number of eggs laid by females of *M. tasmaniae* per day when fed on test diets for first 5 days and fed on aphids in all treatments from Day 6 to 8 after pairing.

Diet	Rep.	Days after pairing									
		1	2	3	4	5	T[1]	6	7	8	GT[2]
Male and female with A+[3]	I	18	8	3	0	0	29	1	19	5	54
	II	1	4	0	0	0	5	5	39	6	55
	III	12	17	0	0	0	32	1	21	7	61
	Mean						22.00				56.67
Only female with A+	I	23	20	7	0	5	55	1	40	15	111
	II	9	6	11	3	2	31	1	23	11	56
	III	13	11	4	1	0	30	1	21	11	62
	Mean						38.67				76.33
Only male with A+	I	0	0	0	0	0	0	0	0	0	0
	II	0	0	0	0	0	0	0	0	0	0
	III	0	2	1	0	0	3	0	0	0	3
	Mean						1.00				1.00
Neither female nor male with A+	I	0	0	0	0	0	0	0	0	0	0
	II	0	1	0	0	0	1	0	0	0	1
	III	0	0	0	0	0	0	0	0	0	0
	Mean						0.33				0.33

[1] T = Total; [2] GT = Grand Total; [3] A+ = Aphids given.

males require protein prior to mating (Phillipe, 1970, as quoted by Tauber and Tauber (1973)). The difference in the grand total number of eggs laid by females between the 1st and 2nd diets was not significant (t test, P>.05).

3.3.2 Influence of colour of substrate on egg oviposition

Introduction

The eggs of most species of brown lacewings are easily obtained by keeping females in captivity (Smith, 1923; Killington, 1936). The eggs are glued to many substrates, such as leaves or other supports, and they adhere firmly by means of a cement secretion (Smith, 1923; Killington, 1936). Captive *Micromus vinaceus* never oviposited on the glass sides of their cages, rarely on the green leaves of sugar cane, but commonly upon cotton wool or cloth (William, 1927). So, in place of leaves, twigs, etc., loose cotton wool has been used as an oviposition substrate (Neuenschwander, 1975 and 1976; Samson and Blood, 1979 and 1980; Neuenschwander and Hagen, 1980). The disadvantages of cotton wool are that it gets soiled by aphid excretions, and counting eggs in it is more difficult if the eggs are laid deep inside. In this study, I used a piece of cotton cloth, as described in Section 3, as the oviposition substrate. Since many of the eggs may be laid on the upper part of the oviposition cage or muslin cloth, the favourite resting place for adult *Micromus variegatus* (Dunn, 1954), this method was found suitable for *Micromus tasmaniae*. I used a brown coloured cloth from the beginning because of its dark colouration in contrast to the eggs; and I

conducted an experiment to test whether the colour of the cloth had any influence on oviposition by females.

Materials and Methods

This experiment was conducted in the insectary room under L.D. 16:8 at 23 ± 2°C. Adults that were used came from the insectary culture and were 21 days old. Live rose aphids, *Macrosiphum rosae*, were fed to the adult predators because *Myzus persicae* was not easily available at that time.

At the start of the experiment, one adult female was placed in an oviposition unit the top of which was covered with cloth of four different colours namely, brown, green, red and black. Each day, starting at the same time, eggs laid on the cloth in each of the three replicates were counted and recorded. Each adult female was then transferred to a clean oviposition unit. A fresh supply of rose aphids was given to the predators every other day. The experiment was terminated after a 12-day period when egg production by the females decreased very rapidly.

Results and Discussion

Results of this experiment are presented in Table 3. Analysis of variance of number of eggs laid per female *M. tasmaniae* per day showed that there was no significant difference ($P>.05$) among the four colours of substrates tested (Appendix Table 1).

The mean number of eggs obtained in this experiment was slightly lower than usual because older females (21 days old) were

Table 3: Mean number of eggs laid by *M. tasmaniae* females on cloth substrate of one of four different colours.

Colour of cloth	Mean no. of eggs/female/day			
	Rep. I	Rep. II	Rep. III	Overall
Brown	15.7	15.6	8.6	13.3
Green	19.3	10.2	15.5	15.0
Red	15.2	13.1	13.9	14.1
Black	15.9	11.2	11.8	13.0

used. Fecundity of female *M. tasmaniae* has been observed to decline after 21 days after emergence when reared at 23°C in the insectary (see Section 3.3.3).

3.3.3 Longevity and Fecundity of Females *M. tasmaniae*

Introduction

The longest known life for adult Hemerobiidae does not exceed twelve months, and in the majority of species is considerably less than this (Killington, 1936). Imagines of many species, however, appear to live for several months in nature, and early observations in the field indicated that females live longer than males (*ibid*).

Many species have been held in captivity for many weeks e.g. *Megalomus hirtus* and *Sympherobius fuscescens (ibid)*, *Hemerobius stigma* and *Sympherobius pygmaeus* (Withycombe, 1922 and 1923), and in Australia, adult *Micromus tasmaniae* survived over 3 months at 22-26°C and 27 days at 28°C (Samson and Blood, 1979). On the other hand, Williams (1927) reported that one female *Micromus* sp. only lived for 3 days and laid 558 eggs.

Since females usually live a long time but a few individuals sometimes die after only a few days, the number of eggs laid by females varies considerably. The highest number for an individual is 619 eggs over 18 days for a female *Micromus vinaceus* Gerst (= *timidus* Hag.) (Williams, 1927) but usually the number of eggs laid seem to vary from 50 to more than 600 (Tjeder, 1961).

Samson and Blood (1979) reported that female *M. tasmaniae* continued to oviposit above 10 eggs per female per day for much of the time over 3 months in an insectary with temperatures ranging from 22°C to 26°C.

As part of the routine program of culturing *M. tasmaniae*, a simple experiment was conducted to determine the longevity and fecundity of females raised in the insectary and of females collected from the field.

Materials and Methods

Twenty insectary-reared adults were obtained from eggs produced in the insectary culture, and 5 field collected adults were obtained by beating potato plants above a beating tray in the fields at Waite Institute and Milang, South Australia.

This experiment ran between January 21 and March 18, 1979. The insectary females emerged at different times and were allotted, as they emerged, to one of the four replicates each of which had different numbers of adults. All adults in one replicate were kept in one oviposition unit. Each of the five field-collected adults were kept in similar oviposition units. Males were then introduced into each oviposition unit in the same number as females. All adults were kept in the insectary room under L.D. 16:8 at constant 23 ± 2°C.

Eggs were counted daily and clean oviposition units were used every day. Live *M. persicae* obtained from the insectary

culture were fed to adult predators. All observations were continued until the last female had died.

Results and Discussion

The results, given in Table 4 and Figure 2, show that the mean number of eggs laid per female per day for field-collected adults was more than twice those laid by females reared in the insectary. Since the ages of the field-collected females were not known, the total number of eggs produced by them would have been much higher.

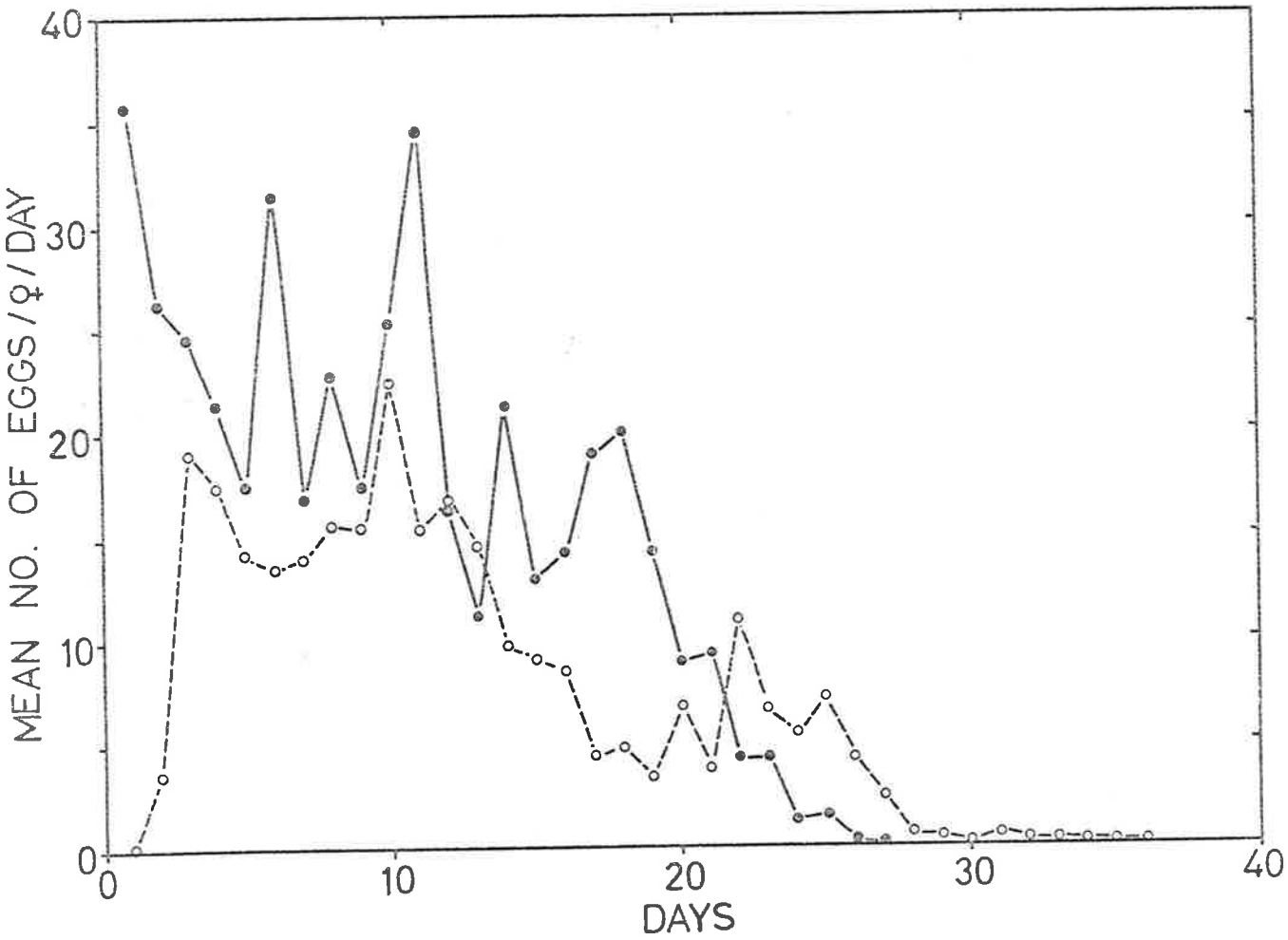
At least two reasons may be suggested for the higher number of eggs laid by the field-collected females than the insectary-reared ones. Firstly, the latter may have declined in vigour because of mass-rearing in culture in the insectary. Boller (1972) gives many such examples. Similarly Rossler (1975a) reported that field-collected females of *Ceratitis capitata* (Weid) had higher net reproductive rates than those females that had been reared in the laboratory; and laboratory males of *C. capitata* had a lower inseminating ability *(ibid)*. Secondly, the higher density of insectary reared adults per oviposition unit may have increased competition and fighting intensity between males and thus reducing the efficiency in finding mates (Boller, 1972); or else there may have been interference with oviposition.

The insectary-reared females of *M. tasmaniae* were found to live as long as 36 days but egg production declined rapidly after 2 weeks at 23°C. It was not possible to determine the actual

Table 4: Reproductive properties of field and insectary adult females of *M. tasmaniae*.

Source of females	Number of females	Mean pre-oviposition period (days)	Mean no. of eggs per female per day	Mean female longevity (days)	Mean fecundity per female
Insectary	20	1.75	7.80	27.30	271.30
Field	5	-	16.70	22.70	348.80

Figure 2: Mean longevity and fecundity of insectary reared (o---o) and field-collected (●——●) females of *M. tasmaniae*.


40
30
20
10
0
MEAN NO. OF EGGS / ♀ / DAY
0
10
20
30
40
DAYS

longevity of the field-collected females. From the trend in egg production of the field-collected females (Figure 2), the longevity of the females is estimated to be close to that of the insectary-reared females.

In this study, the insectary colony of *M. tasmaniae* was maintained for a long period in order to increase the efficiency of mass rearing. Periodic addition of newly collected adults of *M. tasmaniae* to the insectary colony and replacement of the entire insectary colony were practiced throughout the study period. These measures are necessary in order to prevent barriers to introgression that may affect every phase of the reproductive process for mating and F_2 breakdown (Rossler, 1975a).

3.3.4 Removal of eggs of *M. tasmaniae* from cloth substrate

Introduction

Normally in the field the eggs of *M. tasmaniae* and other hemerobiids are laid on the underside of leaves, twigs or bark of plants. Usually, the eggs are laid singly, but rarely two or three may be in contact. The bottom surface of the egg is placed in contact with the leaf or other support, and adheres firmly by means of a cement secreted by glands which open into the vagina (Killington, 1936).

Hemerobiid eggs are much more difficult to remove from substrates than the stalked eggs of chrysopids, and a suitable method of removing eggs of *M. tasmaniae* is vital for the production of healthy and viable eggs. Prior to this study very little has

been published on methods of removing and collecting eggs of brown lacewings. Other workers who have maintained cultures of *M. tasmaniae* (Samson and Blood, 1979 and 1980; Syrett and Penman, 1981) or other hemerobiids, e.g., *Hemerobius pacificus* (Neuenschwander and Hagen, 1980) do not mention how the eggs were removed from the oviposition substrates.

Methods have been developed for collecting the stalked eggs of chrysopids but those methods obviously do not work for *M. tasmaniae*, and so it was necessary to try methods that have been used to get other (non-stalked) insect eggs off substrates (e.g. *Heliothis virescens* on cotton leaves), such as the use of sodium hypochlorite (Hall *et al.*, 1980). Eggs of *Chrysopa* sp. have been successfully removed from cloth by immersing eggs in 21 percent sodium hypochlorite solution (NaC10) for 4 seconds at 24°C (Finney, 1950). Ridgway *et al.* (1970) replaced the cloth with brown paper which served as a site for oviposition. To remove the stalked eggs they rubbed a loose ball of nylon netting gently across the egg-bearing paper. The stalks of the eggs were thereby broken and the loose eggs were then easily collected. Similarly, the immersion of *Heliothis virescens* eggs in 0.025 percent NaC10 solution for a period of 15 minutes did not destroy the chorion of eggs (Hall *et al.*, 1980).

The following laboratory experiments were conducted with sodium hypochlorite to try to develop a safe method of removing eggs of *M. tasmaniae* from cloth or potato leaf.

Materials and General Methods

Four experiments were conducted from May 3-31, 1979 at a room temperature of 22°C. All eggs oviposited on cloth and on potato leaves were obtained from an insectary culture as described in Section 3.3.

A stock solution of NaClO (containing 13% available chlorine) was used throughout, and required test solutions were obtained by diluting the stock with distilled water.

At the end of each experiment, eggs were rinsed thoroughly in distilled water and were transferred to small glass tubes (50 mm x 5 mm diameter) and incubated at a constant 25°C under L.D. 12:12 photophase.

Before immersing the eggs in a test solution, a small piece of egg-bearing cloth or leaf with 20 eggs was cut out. A test solution was then poured into a small plastic petri dish, the egg-bearing cloth or leaf material was completely immersed in the test solution and was left submerged for a specified time. In the check (control), eggs were immersed in distilled water only.

The number of eggs removed was determined at the end of each immersion period, and the number of eggs that hatched in each treatment was determined over a period of 3 days after the first egg hatched.

Experiment 1

Aims and Design

The aim was to find out whether or not sodium hypochlorite at 0.01, 0.1 or 1.0% would remove eggs of *M. tasmaniae* from cloth and potato leaf when immersed for periods of either 1 or 3 minutes.

Results and Discussion

The results, given in Table 5, indicate that there were no obvious differences in the hatchability of eggs following immersion in any of the solutions of NaClO. However, only the 1% NaClO removed some eggs when the substrates were immersed for 3 minutes, namely 30 percent from the cloth and 10 percent from potato leaves. The percentages of egg hatch (70-100) were high for all concentrations of NaClO for both 1 and 3 minutes immersion time.

Experiment 2

Aims and Design

The highest concentration of NaClO was increased to 5% and the longest immersion time was increased to 10 minutes. The treatments were either 3 or 10 minute immersion in 0, 1 or 5% NaClO.

Results and Discussion

The results, in Table 6, show that all the eggs could be removed from the cloth by either increasing the immersion time to 10 minutes or increasing the concentration of NaClO to 5%. However, the 5% NaClO caused complete failure of all the eggs to hatch, and so was omitted in

Table 5: Numbers of *M. tasmaniae* eggs (out of 20) that were removed from cloth and potato leaf (in parenthesis), and that hatched following immersion in sodium hypochlorite solution (Expt. 1).

Immersion time	Concentration of NaClO (%)			
	0	0.01	0.1	1.0
Number of eggs removed:				
1 minute	0 (0)	0 (0)	0 (0)	0 (0)
3 minutes	0 (0)	0 (0)	0 (0)	6 (2)
Number of eggs that hatched:				
1 minute	20 (18)	17 (19)	19 (18)	17 (14)
3 minutes	17 (20)	20 (20)	16 (20)	19 (18)

Table 6: Numbers of *M. tasmaniae* eggs (out of 20) that were removed from cloth and that hatched following immersion in sodium hypochlorite solution (Expt. 2).

Immersion time	Concentration of NaClO (%)		
	0	1	5
Number of eggs removed:			
3 minutes	0	12	20
10 minutes	0	20	20
Number of eggs that hatched:			
3 minutes	20	19	0
10 minutes	20	14	0

subsequent experiments. At 1% NaClO, there was no significant reduction in hatch after 3 minutes immersion time but fewer eggs hatched (χ^2 = 4.95 with 1 d.f., P<.05) following immersion for 10 minutes. So experiments were continued with the 1% NaClO solution.

Experiment 3

Aims and Design

The 1% NaClO solution was used again and an intermediate time of immersion of 6 minutes was also tried to give either 3, 6 or 10 minutes immersion in each d.f. 0 or 1% NaClO solution. In addition, the age of eggs was also varied so that each treatment was applied to groups of 1-day and 3-day old eggs.

Results and Discussion

The results, shown in Table 7, indicate that the number of eggs removed at 1% NaClO was nearly as high for 6 minutes immersion as for 10 minutes immersion for both 1-day old and 3-day old eggs. But all the 3-day old eggs and nearly all the 1-day old eggs hatched after 6 minutes immersion, whereas a significantly (χ^2 = 2.98 with 1 d.f., P<.10) smaller number of 1-day old eggs hatched after 10 minutes immersion in 1% NaClO. The results suggested that 6 minutes immersion in 1% NaClO would both remove all or most of the eggs and also allow all or most of them to hatch. However, one last experiment was conducted to determine if the NaClO could be diluted further.

Table 7: Numbers of 1-day and 3-day old (in parenthesis) eggs (out of 20) of *M. tasmaniae* that were removed from cloth that hatched following immersion in sodium hypochlorite solution (Expt. 3).

	Concentration of NaClO (%)	
Immersion time	0	1
Number of eggs removed:		
3 minutes	0 (0)	15 (11)
6 minutes	0 (0)	18 (19)
10 minutes	0 (0)	20 (20)
Number of eggs that hatched:		
3 minutes	20 (18)	19 (19)
6 minutes	20 (18)	19 (20)
10 minutes	20 (19)	12 (16)

Experiment 4

Aims and Design

The treatments were 6 or 10 minutes immersion at 0, 0.25, 0.50, 0.75 or 1.00 percent NaC10.

Results and Discussion

Results, presented in Table 8, finally demonstrated that eggs of *M. tasmaniae* that were on cloth could be immersed in either 1 or 0.75% NaC10 for 6 to 10 minutes without their viability being seriously affected, but fewer eggs were removed after 6 minutes in 0.75% NaC10.

In conclusion, for the routine removal of eggs from cloth, henceforth eggs were immersed in 1% NaC10 for 6-10 minutes. They were then removed from the NaC10 solution and rinsed in distilled water.

3.3.5 Storage of eggs of *M. tasmaniae* at various temperatures

Introduction

Because of limited space, time, and labour, mass production of *M. tasmaniae* eggs, on a factory basis, was not possible in this study. Eggs could only be produced in batches of small numbers (averaging 600 per day per 30 females). With such small numbers, a method was needed to store eggs for long periods of time until the accumulated numbers were large enough for field release experiments.

Embryonic development may of course be slowed down if freshly laid eggs are kept at a temperature which is slightly above the lower threshold of development for the eggs. And eggs of many

Table 8: Number of *M. tasmaniae* eggs (out of 20) that were removed from cloth and that hatched following immersion in sodium hypochlorite solution (Expt. 4).

Immersion time	Concentration of NaC1O (%)				
	0	0.25	0.50	0.75	1.00
Number of eggs removed:					
6 minutes	0	0	4	12	17
10 minutes	0	0	11	17	17
Number of eggs that hatched:					
6 minutes	18	18	20	19	18
10 minutes	19	20	20	17	18

species of insect pests, as well as beneficial ones (parasites and predators) can be stored for 3-4 weeks at temperatures of 4-10°C without killing the embryos (Smith, 1966).

Since very little information had been published regarding the influence of temperatures on the hatching of eggs of *M. tasmaniae* when this study was begun in May, 1978, a laboratory experiment was conducted to select the appropriate temperature for long-term storage of *M. tasmaniae* eggs.

Materials and Methods

Eggs of *M. tasmaniae* were obtained from the insectary stock culture as described in Section 3.3. All eggs were 24 hours old or less.

Twenty eggs were assigned to each of the six temperature regimes namely 5°C, 10°C, 15°C, 20°C, 25°C and 30°C. All were under L.D. 12:12 photophase with the exception of the 5°C regime where eggs were incubated in darkness.

Each egg was placed in an incubation unit as previously described in Section 3.3. Individual eggs were examined once every 24 hours to see if they had hatched. When most (90%) of them had hatched, further observations on the unhatched eggs were made for only another 7 days. Since none of them in the 5°C incubator had hatched at the 40th day, they were transferred to the 25°C room for hatching.

Results and Discussion

Results, presented in Table 9, show that normal hatching of the eggs was observed at all the temperatures except 5°C. It is not known how long the eggs will remain viable at 5°C. More than half of them (out of 20) hatched when transferred to the 25°C room after 40 days.

Eggs of *M. tasmaniae* and other brown lacewings have been reported to have extremely low lower thermal thresholds. The lower thermal threshold for *M. tasmaniae* eggs varied from 0.1°C (Samson and Blood, 1979) to 4.8°C (Syrett and Penman, 1981) while for *Hemerobius pacificus* it was reported to be 0.4°C (Neuenschwander, 1975).

For future use, eggs obtained in large numbers were usually transferred immediately to 5°C and were kept at this temperature for 30 days or less.

3.4 Sampling, Trapping and Extraction Methods

3.4.1 Sampling of aphids and their natural enemies

This section deals with the methods of sampling potato aphids, mainly *M. persicae*, and their natural enemies in this study. Field samples were necessary to obtain the mean densities of aphid and natural enemy populations, and to get population trends in large commercial fields and in small plots.

Sampling of insect populations may be either extensive or intensive. Extensive sampling usually is used to survey large areas,

Table 9: Hatching of eggs of *M. tasmaniae* at different temperatures (n = 20).

Temperature (°C)	Incubation period (days)	Per cent hatched
5	40	55[1]
10	15	90
15	7-8	100
20	5	100
25	4-5	100
30	3	90

[1] indicates that eggs were hatched at 25°C.

while intensive sampling stresses the continued sampling of a population through time within a smaller area or plot (Morris, 1960; Strickland, 1961).

Several workers have concluded that no one sampling method will be suitable for all insects because of the different habitats and life stages that should be sampled. In this study, I was only concerned with intensive sampling.

Sampling of potato aphids at Milang, South Australia

Several methods have been described for estimating aphid abundance on potato plants. In most of them the aphids are counted while they are on the leaves. Davies (1934) described one of the first methods of sampling and estimating aphid populations in potato fields; he counted the aphids on lower leaves chosen at random, and expressed the population as aphids per 100 leaves. Since different species of aphids on potatoes differed in their distribution on the plant; to obtain a better estimate of the population, Simpson (1940) modified Davies' method and counted the aphids on equal number of leaves selected at random from the top, middle and bottom portions of the plant.

Other workers used various methods of selecting leaves from the sample but continued to express the population per certain number of leaves (Close, 1965; Powell and Mondor, 1973; Woodford *et al.*, 1977; Whalon and Smilowitz, 1979).

Other methods of expressing aphid numbers include numbers of aphids per 50 or 100 haulms (Woodford *et al.*,1977) or per 100 hills

(Hille Ris Lambers, 1972; Mackauer and Way, 1976; Woodford *et al.*, 1977) Bradley (1952) compared estimates of population numbers as aphids per 100 leaves, aphids per plant, and aphids per unit leaf area. He found that where the areas of leaves and number of leaves per plant were similar in all plants, populations expressed as per 100 leaves were comparable. Expressing the population as aphids per unit leaf area eliminates differences due to leaf size that occur when the population is expressed as aphids per 100 leaves, but differences in plant size and the distribution of species of aphids on the plants may make comparisons between varieties misleading (Bradley, 1952).

While most workers have been concerned with the different methods of sampling and estimating aphid populations on potatoes, Anscombe (1948) dealt with the statistical problem of estimating the changing numbers of aphids per plant in a field of growing potatoes. The 3-leaf method was found to be accurate enough for most practical purposes (Anscombe, 1948). The procedure is:

a) to classify the leaves on each plant into 3 categories namely, upper, middle and lower;

b) to select a fixed number of leaves of each category at random.

To measure the accuracy of the 3-leaf method of sampling aphids on potatoes, Anscombe (1948) produced a simple approximate expression which he called the estimation error (E):

$$E = \sqrt{\left[\frac{1}{N}\left(\frac{1}{k} + \frac{1}{m}\right)\right]}$$

where m = average aphid count per leaf; N = number of plants; and k = index of aggregation associated with the negative binomial distribution which describes the dispersion of the aphids per unit.

Using Davies (1934) data, Anscombe *(ibid)* estimated that, at a low level of aphid infestation (m = 0.4), the estimation error was ± 31%; a high infestation level (m = 2.0) gave an error of ± 22%.

Samples from South Australia

In this study, I have used the 3-leaf method of estimating populations of aphids in potato crops. Samples from a large commercial field were taken at Milang, South Australia (about 120 km south-east of Adelaide) from September 1978 to June 1980.

Samples were taken every fortnight during the period July to February and weekly during March to June. The frequency of sampling was increased in the latter period because the aphids begin to colonize the potato plants in mid-March, reach peak numbers in mid-April and decline in numbers at the end of June.

A rectangular sampling area of approximately 2 ha. in size was marked out within any field to be sampled. The area included the edge as well as the centre of the field. If the field was only slighter larger than 2 ha, the entire field was sampled. The sampling area was then sub-divided into 16 equal-sized sub-divisions or strata. From each of 15 strata, 2 plants were randomly selected, and from the 16th stratum (chosen at random

beforehand), 3 plants were randomly selected. Each sample plant was selected by using random numbers on a 2-dimensional grid. This method of stratified random sampling has been considered very efficient in minimizing variance because it ensures a satisfactory spread of sampling units over the field, and it usually leads to a gain in precision (Finney, 1941; Yates and Finney, 1942; Healy, 1962; Lyons, 1964; Kuehl and Fye, 1970; and East, 1980).

Three leaves - one upper, one middle and one lower - were taken from each plant, giving a total of 99 leaves per sample. During the early period of plant growth and very light aphid infestation, 40 or 50 plants were sampled. For these samples, I have still expressed the counts of aphids and other insects as per 99 leaves.

Sampling potato aphids at Waite Institute, Adelaide

Commercial variety 'Exton' potatoes were planted into small plots measuring 10 m x 10 m at the Waite Agricultural Research Institute (W.A.R.I.) Adelaide. Sampling of aphids and natural enemies began in June 1978 and finished in July 1980. Unlike the Milang samples, samples were taken every week throughout the potato growing period.

The same 3-leaf method of sampling and estimating aphid populations was employed as at Milang. However, smaller size samples (ranging from 30 to 60 leaves) were taken on each sampling occasion from one plot. Plants were selected at random using random numbers as described previously.

Sampling of natural enemies

Lord (1968) has suggested 'dual-purpose' samples whereby the sampling unit is common to both predator and prey species and encompasses representative proportions of the habitat of each.

In this study, counts of predators (mainly eggs), parasitized aphids and diseased aphids were necessarily made on the same sample units used for estimating numbers of aphids because of the impracticality of taking different samples for natural enemies. However, a special method of sampling adults and larvae of the brown lacewing, *M. tasmaniae*, was employed at the beginning of the second crop period (1979-80). Basically, it involved beating the plant foliage over a beating tray so that the predators fell straight into the tray and could be counted.

The beating tray consisted of a piece of clean white plastic sheet (65 cm x 65 cm). It was held below and to one side of a plant and the plant was vigorously shaken three times. Since adults of most species of lacewings, including *M. tasmaniae* will feign death and drop off the plant when disturbed, this beating tray method was very efficient for sampling adults. The larvae of *M. tasmaniae* were also easily dislodged and sampled in this manner.

3.4.2 Trapping of alate *M. persicae*

Introduction

Trapping is one of the relative methods of estimating numbers of insects. In spite of the great difficulty in interpreting

relative population estimates, such estimates are extensively used in animal ecology and economic entomology. Trapping methods, in particular, are useful because they collect specimens continuously, providing a large return of information for a relatively small amount of effort.

Basically, traps may be divided into those that attract insects in some way and those that catch insects randomly. A strict division is impossible as some traps, e.g., some water and sticky traps, are intermediate in position (Southwood, 1966). Water traps have been used extensively to trap alate aphids (Broadbent, 1948; Eastop, 1955; Lamb, 1958; Fisken, 1959b; Evand and Medler, 1966; Landis, 1972; Sandvol and Cunningham, 1975; Bacon *et al.*, 1976; Byrne and Bishop, 1979). Usually, they are simple plastic or metal bowls or trays filled with water to which a small quantity of detergent and a preservative have been added (Southwood, 1966). Omission of the detergent may reduce the total catch, e.g., of the sugar-beet root maggot, *Tetanops myopaeformis* which was reduced by more than half (Harper and Story, 1962).

The advantages of water traps as compared to sticky traps are:

a) the insects that are caught are in good condition for identification, because the catch is easily separated, and

b) when a population is sparse, a water trap will make catches when a sticky trap will not, for aphids at least (Heathcote, 1957).

Heathcote (1957) compared the efficiency of yellow cylindrical, yellow flat sticky traps, water traps and Johnson's suction traps. He found that water traps caught more aphids than sticky traps and were as effective as suction traps.

The efficiency of water traps in catching flying aphids depends on several factors such as trap background (Landis, 1972), height of traps above ground (Heathcote, 1958; Landis, 1972) and size of bowl (Costa and Lewis, 1968).

The main purpose of setting up water traps in this study was to get an indication of the general flight pattern and time of aphid immigration into the field. It was thought that the data gathered from trap catches throughout the year would be useful in alerting growers to the existence of damaging field populations in the field at the time of sampling. Such data have even been useful in predicting aphid population trends, e.g., Byrne and Bishop (1979) found that numbers of alate *M. persicae* caught in water traps in potato fields had the highest correlation with adjacent field populations because the aphids collected were migrating out of the field rather than into the field. Also, water traps have been useful in comparing relative *M. persicae* numbers among potato producing areas and among years (Sandvol and Cunningham, 1975).

The field experiment reported here was conducted to study the efficiency of the water traps as influenced by the nature of the trap background surface and crop age. Its outcome was expected to provide useful guidance for the operation of water traps throughout the field survey period.

Materials and Methods

The experiment was conducted at the Waite Institute, Adelaide. The experimental area was 10 m wide and 30 m long and was subdivided into 3 equal-sized plots, each measuring 10 m x 10 m. The three plots (A, B and C) were arranged within a row and adjacent to one another. Plot A was planted with potatoes (var. Exton) on January 22, 1979, and was designated as old crop. Plot B was planted next to Plot A with the same variety of potatoes on March 3, 1979 and was designated as young crop. Plot C which was adjacent to Plot B was bare ground.

Two yellow bowls (30 cm diameter and 12 cm deep) were placed in the middle of each plot and were 3 m apart. The distance between traps in adjacent plots was 10 m. Each bowl was supported by a metal framework which was fixed to the ground so that the base of the bowl was 30 cm from the ground. This height was chosen because water traps placed at 80 cm or lower and level with the top of the plant, consistently catch more aphids than at ground level (Heathcote, 1958). Heathcote (1958) also recommended that water traps over bare ground should be as low as possible. The chosen height was, therefore, a compromise and it further avoided the necessity of having to adjust the trap height as the plants grew.

The bowls were filled to within 4 cm from the top with water and provision for drainage of excess water was provided by two screen-covered holes (15 cm diameter) made on opposing sides and 2.5 cm below the rim. A few drops of detergent was added to the

water. All traps were emptied once a week and the aphids were collected by pouring the contents onto a fine voil sieve.

Trapping was begun on April 4, 1979 and terminated on May 25, 1979. This trapping period was selected to coincide with the major period of migration of alate *M. persicae* into potato crops.

Results and Discussion

Results of this experiment are presented in Table 10. The mean numbers of aphids caught against the 3 backgrounds over the whole 7 week period were obviously different, with bareground > young crop > old crop. The results were analysed with χ^2 to further test whether bareground > young crop and young crop > old crop for each of the 7 weeks. The χ^2 values given in Table 11 indicated that, indeed, bareground gave a higher catch than young crop for each of the 7 weeks, and young crops gave a higher catch than old crop, every week except the last one.

It may be concluded that the efficiency of yellow water traps for *M. persicae* depends in part on the nature of the trap background surface. The presence of crop plants obviously reduces the number of alate *M. persicae* alighting to the traps, with a young crop seemingly being more attractive to the aphids than the old crop because of the amount of soil surface between the plants that is exposed. Similar trends in trap catches were obtained by Landis (1972).

For future use, all water traps were located against a background as near as possible to bare soil.

Table 10: Numbers of alate *M. persicae* caught in each of two water traps (R1 and R2) placed over three different trap backgrounds; data for 7 weeks ending on the dates given.

Week ending (date)	Old crop			Young crop			Bare ground		
	R1	R2	Mean	R1	R2	Mean	R1	R2	Mean
13.4.79	15	16	15.5	66	40	53.0	103	111	107.0
20.4.79	10	8	9.0	17	20	18.5	39	52	45.5
27.4.79	0	1	0.5	11	10	10.5	23	25	24.0
4.5.79	4	9	6.5	18	9	13.5	60	73	66.5
11.5.79	27	20	23.5	41	34	37.5	100	109	104.5
18.5.79	5	4	4.5	24	17	20.5	76	65	70.5
25.5.79	13	20	16.5	17	10	13.5	35	25	30.0
Mean			10.86			23.86			64.00

Table 11: Summary of χ^2 (Chi-square) analyses to test differences in the numbers of alate *M. persicae* caught by water traps placed over three different trap background surfaces during 7 weeks ending with the given dates.

Weekending (date)	χ^2 values (1 d.f.)	
	Old crop vs Young crop	Young crop vs Bareground
13.4.79	20.52**	18.22**
20.4.79	6.56*[1]	11.38**
27.4.79	9.10**[2]	5.28**
4.5.79	4.90*	4.17*
11.5.79	6.43*	34.48**
18.5.79	10.12**	27.58**
25.5.79	0.30	6.26*
Total χ^2 (5 d.f.)	57.93**	107.37**

1* indicates significant difference ($P<.05$)

2** indicates highly significant difference ($P<.01$)

3.4.3 Extraction of *M. persicae* from potato leaves

Introduction

Live aphids are often difficult to shake from foliage, and when rapidly killed may remain attached to leaves by their stylets. They sometimes, however, can be removed with relative ease. Heathcote (1972) described several methods of extracting aphids and other small insects from leaves, stems, soil, plant roots and surface trash by using slow acting toxicants or anaesthetics, gradients of light and heat, or brushing and imprinting.

Most of these methods require special apparatus and are time-consuming. I, therefore, developed a very simple method of extracting aphids from potato leaves using heat. The method depends on aphids readily leaving leaves which have wilted.

The following laboratory experiment was conducted to determine what combination of temperature and duration of exposure would give the highest percentage of aphids leaving or dropping off the leaves without rendering the aphids unidentifiable.

Materials and Methods

Potato 'trifoliates' infested with *M. persicae* were obtained from the insectary culture. An unknown number of aphids (of mixed instars) were allowed to remain on each "trifoliate' and each trifoliate was placed in a separate brown paper bag (11 cm x 3 cm). Each treatment was replicated three times.

Four temperatures were chosen namely, 40°C, 45°C, 50°C and 55°C. The lowest temperature was selected because of the finding of

Broadbent and Hollings (1951) that the thermal death-point of *M. persicae* lay between 38°C and 41°C when exposed for 1 hour at 60% relative humidity. Five different durations of exposure were tested, namely 4, 8, 16, 32 and 64 minutes.

It was not possible to simultaneously use a different oven for each temperature, so only one oven was used and the temperatures were obtained sequentially, starting at 40°C. For each temperature, the required numbers of bags containing the aphid-infested leaves were placed in the oven and bags were removed at specified intervals according to the duration of exposure to be tested.

At the end of each test at each temperature, counts of all the aphids found inside the bags and of those that remained on the leaves were made. The aphids were also classified into dead or alive, and burnt or normal. All aphids showing movement were recorded as alive, whereas those that were blackened and rendered unidentificable were recorded as burnt.

Results and Discussion

Results, given in Table 12, show that exposure had a significant influence on percent aphids extracted from potato leaflets. As the duration of exposure increased, the percentage of aphids extracted also increased especially at 40°C and 45°C. At 50°C a big increase in percentage of extraction was obtained between 4 minutes and 8 minutes exposure time, but with exposures of 16 minutes or longer, the percentage of aphids extracted began to level off at the 3 highest temperatures.

Table 12: Mean percentages of apterous *M. persicae* extracted from potato leaves at various temperatures X durations of exposure.

Duration of exposure (minutes)	Mean % of aphids extracted at temperatures:			
	40°C	45°C	50°C	55°C
4	0.1	12.9	51.3	5.6
8	24.7	36.9	68.5^{D1}	82.1^{D*}
16	38.4	42.7^{D}	78.7^{D}	85.4^{D*}
32	33.4	70.3^{D}	82.8^{D*}	89.6^{DB*2}
64	67.4^{D}	82.2^{D*}	87.3^{D*}	87.1^{DB*}

^{1D} indicates aphids were dead but not burnt

^{2DB} indicates aphids were dead and burnt

The treatments marked with an asterisk are not significantly different.

Least significant difference between any 2 exposure times at one temperature is 6.7% (P .05)

Least significant difference between any 2 temperatures for one exposure time is 6.0% (P .05).

To test for differences between means, the data were subjected to a 2-way (exposure x temperature) ANOVA. The analysis is given in Appendix Table 1, and the LSDs are given in Table 12 to allow the comparisons of means.

The LSDs in Table 12 indicate that the means denoted by asterisks were not different from each other. However, the exposures of 32 and 64 minutes at 55^{o}C burnt many aphids and cannot therefore be used. The treatment which was likely to give the highest percentage extraction if further replicates were tested was 64 minutes exposure at 50^{o}C and so this combination was used in future as a standard method of extracting aphids from leaves.

CHAPTER 4

THE CHANGING NUMBERS OF APHIDS AND NATURAL ENEMIES IN THE FIELD

INTRODUCTION

The main emphasis of a population study of this nature is the identification of the causes of numerical changes in the populations and an explanation of how these changes act and interact to produce the observed patterns or trends. In this way it is possible to define where and when in the life cycle the key regulating processes may operate.

The study of the whole population of *M. persicae* is impractical, and it is necessary to study instead a definable part that is thought to be representative of the whole. The study of the part must then be repeated in time in at least two areas in which the climate is different so that the interactions of weather and other environmental components can be compared. The observed changes in the sub-populations may then have their own specific explanations. The usefulness of a population study of this sort depends on how representative the observed numerical changes and their causes are in both time and space.

Similar studies made on the observed changes in aphid populations in relation to various causes, have always been hampered by (a) complexities of population sampling in the field; (b) overlapping generations; (c) polymorphism; (d) unknown numerical relationships between the populations occurring on a sequence of host plants, and (e) influence of long-distance migration (van Emden *et al.*, 1969).

Aphid populations usually show a rapid increase in population size and dispersion during the vegetative growth of their host plant, followed by a more or less striking decline in numbers. This change in population size is usually accompanied by a change in population structure e.g. the age structure and the appearance of different morphs (apterae, alatae). The factors causing and influencing such changes are often investigated and discussed by workers because of their importance with respect to phytopathological problems.

Three main factors are usually regarded as being most important for the population dynamics and changing age-structure of aphid populations in the field: (1) the potential fertility of the aphids, which is modified by the physiological condition of the host; (2) density-dependent and climate-dependent production of winged morphs, and (3) the time of appearance of predators and parasites (Tomiuk and Wöhrmann, 1980).

Many workers have studied one or more of the factors causing the growth and decline of aphid population on potatoes (Davies, 1932; Broadbent, 1946; Dunn, 1949; Shands *et al.*, 1956; Helson, 1958; Klostermeyer, 1959; Daiber and Schöll, 1959; Close, 1965; Rough and Close, 1965; Powell and Mondor, 1973; Radcliffe, 1973; Sandvol and Cunningham, 1975; Mackauer and Way, 1976; Cancelando and Radcliffe, 1979; Whalon and Smilowitz, 1979). Evidence summarized by van Emden *et al.* (1969) suggests that the stability of *M. persicae* populations depends fundamentally on intraspecific interactions, especially the effects of emigration caused by density-influenced production of relatively poorly fecund alatae, most of which fail to colonize suitable new food plants. Another stabilizing factor is the aphid/plant interaction which may also affect the actions of natural enemies.

Many workers who participated in the International Biological Control Programme (IBCP) and have investigated the factors causing changes in populations of *M. persicae* on potatoes have agreed that predators, especially coccinellids, appeared surprisingly important in regulating the aphid populations. By contrast indigenous parasites, even without reduction in numbers by hyperparasites, produced rather insignificant mortality in *M. persicae* populations, and fungal attack was found to be too sporadic to hold much hope for biological or integrated control (Mackauer and Way, 1976).

The objectives of this study in South Australia are (a) to describe the seasonal trends of potato aphid populations and their associated natural enemies; (b) to determine the factors causing the changes in population growth; (c) to describe the spatial distribution of potato aphids with reference to future sampling programmes, and (d) to apply some of the findings in the development of a more effective control programme such as integrated control with special emphasis on the use of predators in combination with chemical control methods.

MATERIALS AND METHODS

4.1 Small-plot survey at the Waite Institute, Adelaide

A survey of aphid occurrence on small plots of potatoes was conducted at the Waite Agricultural Research Institute (W.A.R.I.), Glen Osmond, South Australia from June 1978 to July 1980. Certified virus-free 'Exton' seed potatoes purchased from a local supplier in Adelaide were planted in small plots 10 m x 10 m in size. Whole or cut-up potato seeds were dusted with a protectant fungicide before planting them to a

depth of approximately 5 cm and at the planting density adopted by commercial growers, namely 23 cm apart within rows and 90 cm between rows. Similar size plots of potatoes were established every 2-4 months to ensure a continuous crop of potato throughout the year.

After the land had been prepared for planting, a basal dressing of a mixture of superphosphate, sulphate of ammonia and sulphate of potash was applied as fertilizer. No insecticide or fungicide was applied throughout the study period. Hilling was routinely done a few days after sprouting of tubers and was repeated when necessary. Each crop of potatoes in the plots lasted for a period of 3-5 months depending on the time of the year they were planted. A total of eleven plots of potato plants were established during the study period. Except on two occasions, plots were distributed around the experimental orchard and the same plots were not planted with potatoes in order to minimize the risk of virus disease in the new plantings.

The experimental orchard consisted of several small blocks of fruit trees such as apple, peach, apricot and citrus and grape vines. There were also small plots of sugar cane, cruciferous vegetables, beans and roses. The rest of the area was either bare ground or covered with weeds and other wild plants. Several buildings including an insectary, glass-houses, laboratories and houses were not far from the plots.

Table 13 shows the distribution and planting dates of the various potato plots.

Table 13: Planting dates for potatotes in plots at the Waite Agricultural Research Institute, Adelaide.

Plot identification		Date of planting
1.	A-1	20 April, 1978
2.	B-1	7 July, 1978
3.	C	10 October, 1978
4.	A-2	1 January, 1979
5.	B-2	6 March, 1979
6.	D	1 April, 1979
7.	E	21 September, 1979
8.	G	12 October, 1979
9.	H	3 December, 1979
10.	I	6 March, 1980
11.	J	29 April, 1980

Sampling of aphids and natural enemies

The methods of sampling potato aphids and their natural enemies are described in detail in Section 3.4.1.

During the 1978-79 crop period, sampling of predators, especially *M. tasmaniae*, was done by direct counting of eggs, larvae and adults from sample leaves taken for aphid counts. This method had produced a rather low estimate of predator abundance, especially of that of *M. tasmaniae* larvae and adults. Larval and adult predators may have escaped from being counted in the process of removing the leaves. For 1979-80 crop period the sampling method was improved by using a beating tray as described in Section 3.3.1. for sampling larval and adult *M. tasmaniae*.

Counting of aphids and natural enemies

Aphids and all stages of natural enemies, mainly predators, were either counted in the field or were placed in plastic or paper bags and labelled when aphid numbers were gery high and brought to the laboratory for extraction and counting.

Aphids from sample leaves were classified into the following groups: apterous and alatae, diseased aphids and mummified (parasitized) aphids. The aphids were also identified to species level.

The separation of *M. persicae* into 4 nymphal instars and apterous adults was made visually and based on anatomical features such as body length, number of antennal segments, shape of antennal tubercle, rostrum length, cornicle length and shape, and caudal size and shape (Sylvester, 1964).

Identification of potato aphids and natural enemies

Identification of the different species of aphids found on potatoes was based on a pictorial field key given by MacGillvray (1979).

Some of the predators collected during the survey were identified to species level by comparing them with specimens kept at Entomology Department, W.A.R.I., South Australia. The correct identification of the brown lacewing, *Micromus tasmaniae* Walker was confirmed by Dr. T.R. New, Department of Zoology, La Trobe University, Bundoora, Victoria, from larval and adult specimens which were sent to him.

The species of primary parasites of *M. persicae* and its hyper-parasites were identified by Dr. I. Naumann, Division of Entomology, C.S.I.R.O., Canberra, A.C.T., from specimens of adult parasites, aphid mummies and hyperparasites which were sent to him.

Diseased aphids found on potato plants were given to Dr. D.E. Pinnock, Entomology Department, W.A.R.I., Adelaide, South Australia for correct identification of pathogenic fungi.

Trapping of alate aphids

The activity of alate aphids, mainly *M. persicae*, was monitored by placing a yellow plastic-pan water trap in the middle of the potato plot. Trapping by this method is described in Section 3.4.2.

4.2 Large-field survey at Milang, South Australia

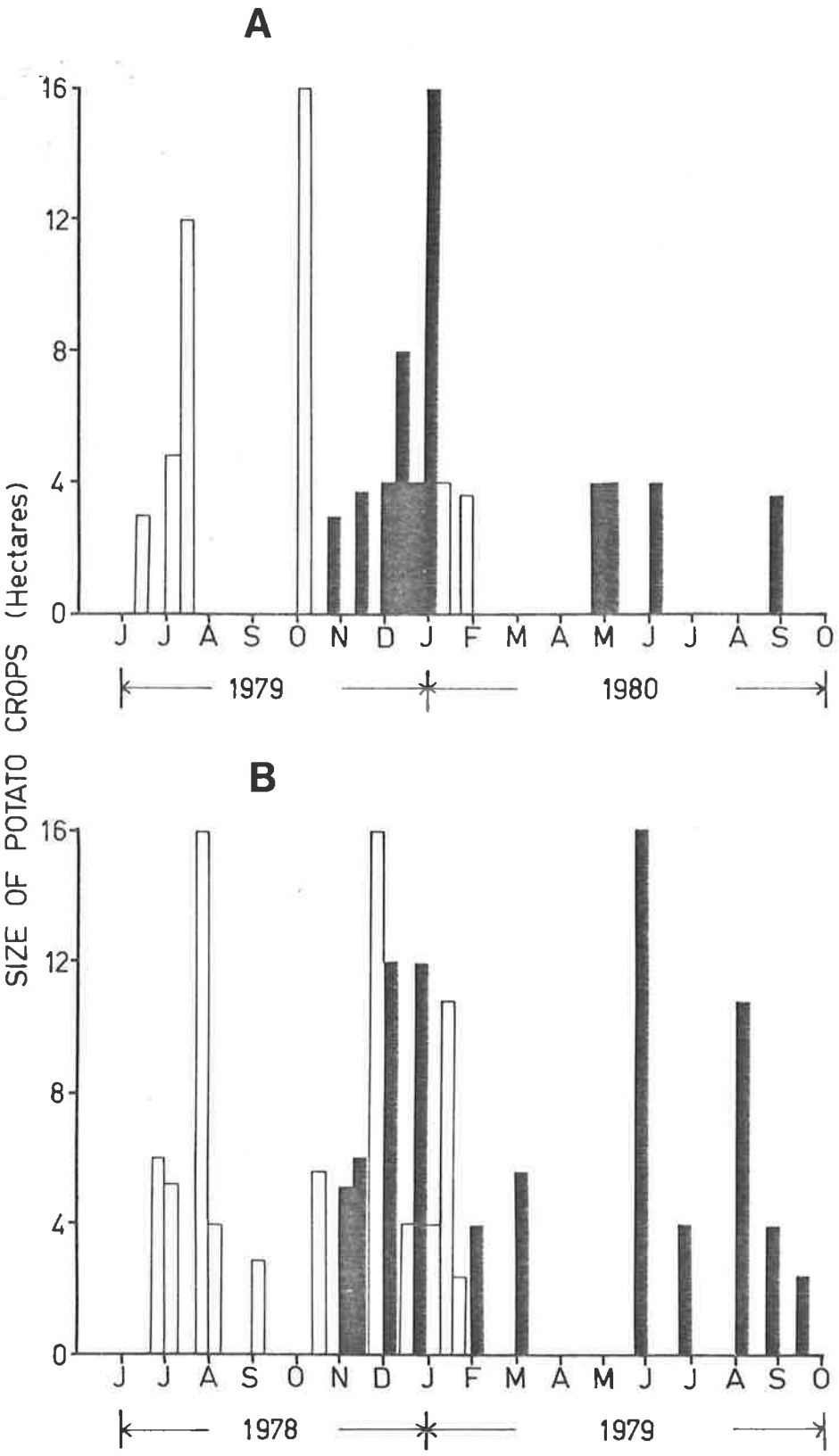
This field survey was conducted in potato fields owned by Mr. Lance Chaplin at Milang (80 km south-east of Adelaide), South Australia. Field

samplings of potato aphids and their natural enemies were carried out from September 1978 to May 1980. The entire farmland was largely planted to potatoes, but lucerne crops were also grown nearby during the spring, summer and autumn months. Potato fields were generally well distributed over the entire farm, each field ranging from 2.4 to 16.0 ha. weeds were commonly seen thriving in uncultivated fields and along ditches and roadsides.

The entire farm was very close to Lake Alexandrina and farmers believe that because of the influence of a prevailing sea-breeze off the lake, the daily maximum and minimum temperatures in this area are slightly lower than in areas several kilometers inland, such as Strathalbyn (15 km from Milang). However, the Bureau of Meteorology in Adelaide, found that differences in daily temperatures between Milang and Strathalbyn were negligible. Hence, weather data were taken from the meteorological station at Strathalbyn (since there is none at Milang).

Commercial plantings of potatoes at Miland are planted in the same field only every second year. The fields are left fallow in other years. Fourteen fields were planted to potatoes between June 1978 to February 1979 and only 10 fields were planted in the following crop period (1979-80). Potatoes were planted almost throughout the year. 'Exton' was the most common variety of potato grown by Mr. Chaplin. Other varieties such as 'Colliban' and 'Sequoia' were also planted when 'Exton' plantings were not suitable. All certified seeds were purchased from Victoria and kept at low temperatures in Adelaide until planting. Figure 3 shows the planting and harvesting dates and sizes of the fields.

Figure 3: Dates of planting (□) and harvesting (▩) of potatoes and the size of the crop for each date at Milang during the 1979-80 (A) and 1978-79 (B) crops period.


A
B
SIZE OF POTATO CROPS (Hectares)
16
12
8
4
0
J J A S O N D J F M A M J J A S O
1979
1980
1978
1979

The planting distance used was 23 cm within rows and 90 cm between rows. All fields were adequately irrigated in spring and summer by means of overhead sprinklers. Normal cultural practices including fertilizer application, pesticide application, hilling and harvesting were carried out by the grower as scheduled. In the 1978-79 crop period, five insecticides were applied at the recommended rate to control potato pests, mainly leaf-feeding caterpillars and larvae of the potato tuber moth (*Pthorimaea operculella* (Zeller)). The five insecticides used and the dates of application are shown in Table 14. Application of the insecticides was made with a tractor-mounted boom sprayer. Prior to February 1, 1979, no other insecticide was applied.

In the 1979-80 crop period, the first application of insecticides was made in two fields very close to fields F and G where samples were taken. In these fields, malathion and DDT were applied as sprays on March 27, 1980, and a second application was made on April 4, 1980. One application of metasystox to control potato aphids was made on April 10, 1980 in field G.

Sampling aphids and natural enemies

Similar methods of sampling aphids and natural enemies were used here as are described for Waite Institute in Section 3.4.1. The numbers of larvae and adults *M. tasmaniae* were estimated by the beating tray method (see Section 3.4.1.).

Counting aphids and natural enemies

When aphids numbers were low, whole-plant counts were made *in situ*; but at higher infestation rates, leaves were taken off the plants and were

Table 14: Trade names, chemical names of insecticides applied in the potato fields at different dates at Milang during the 1978-1979 crop period.

Date of application	Trade names	Chemical names
1 Feb. 1979	Nitofol	O, S - dimethyl phosphoamidothioate.
2 Feb. 1979	Nitofol	Same as above.
20 Feb. 1979	DDT	Mixed isomers of dichlorodiphenyl trichloroethane in which 1, 1, 1 - thichloro - 2, 2 - bis (4 - chlorophenyl) ethane predominates.
20 Feb. 1979	Malathion	S - 1, 2 - bis (ethoxycarbonyl)-ethyl O, O - dimethyl phosphorodithioate.
1 Mar. 1979	Metasystox	Mixture of O - 2 (ethylthio) - 1 ethyl O, O - dimethyl phosphorothiate and S - 2 - (ethylthio) ethyl dimethyl phosphorothiate.
10 Mar. 1979	Metasystox	Same as above.
10 Mar. 1979	Birlane	2 - chloro - 1 - (2, 4 - dichlorophenyl) vinyl diethyl phosphate.

carefully placed in plastic and brown paper bags and transported back to the laboratory. In 1978-79 crop period, leaves contained in plastic bags were immediately stored in the 5°C room on arrival at the laboratory and counting was done as soon as possible thereafter. Usually, counting was completed in 2-3 days after sampling. The various instars of *M. persicae* were determined under a binocular microscope.

In 1979-80, aphid populations in the insecticide-sprayed field (Field G) reached extremely high numbers. Samples leaves were placed in brown paper bags, and when they reached the laboratory, were immediately placed in a 50°C oven for 60 minutes. Details of this extraction method are described in Section 3.4.3.

Counts of predators and diseased aphids were made in the field itself, while mummified aphids were counted together with unparasitized aphids in the laboratory.

Trapping of alate aphids

Activity of alate aphids, mainly *M. persicae* was monitored by placing a yellow-pan water trap in the middle of the field. Great difficulty was encountered in servicing the trap weekly because of its great distance from the Waite Institute. This was particularly true in summer when weather was hot and dry so that the water in the trap was completely evaporated by the middle of the week. Therefore, trapping was confined to only the periods between the migration of alates into potato fields and the autumn emigration of alates out of the potato field; i.e. between mid-February to mid-May.

Spatial distribution of aphid populations

Natural distributions of insects including aphids have generally been described as following an aggregated pattern corresponding to the negative binomial model. Several workers have discussed the statistics of this distribution pattern (Fisher, 1941; Anscombe, 1949; Bliss and Fisher, 1953; Sylvester and Cox, 1961; Southwood, 1966; Walden *et al.*, 1978; Tamaki and Weiss, 1979; Ba-angood and Stewart, 1980). The negative binomial distribution has been reported in many sampling studies of various insects and has been found useful in the development of many sampling plans (Harcourt, 1960 and 1961; Latheef and Harcourt, 1973; Ng *et al.*, 1977; Tamaki and Weiss, 1979).

Data from field samples collected during the period of infestation were fitted to the negative binomial distributions. The observed data and those expected by the negative binomial model were analysed by χ^2 (Chi-square) goodness-of-fit test. The parameter k of the negative binomial distribution was computed by the maximum likelihood estimate and used to calculate the optimum sample size at the desired precision levels.

Measurement of rate of increase in aphid abundance

As a measure of the rate of increase of *M. persicae* in this study, I used the percent increase or decrease in abundance per unit time in relation to the arithmetic mean of abundance, as calculated at the beginning and at the end of the time period (Galecka, 1966). The percentages of increase or decrease in abundance (P) were calculated from the formula:

$$P = \frac{200\ (B-A)}{A+B}$$

where A = the abundance of aphids at the x^{th} week and B = the abundance at the $(x + 1)^{th}$ week.

Analysis of data

The understanding of the mutual relationship between *Myzus persicae* and *Micromus tasmaniae* populations was analysed by a graphic method based on Moran curves (Hughes, 1963; van Emden, 1972; Williamson, 1972). The method involves a simple plot of abundance of prey (on log. scale) and predator (on log. scale) on a linear paper whereby each point plotted represents the date of sampling and a curve is fitted by eye (which of course requires a certain simplification) (van Emden, 1972). This graphic method of analysis is useful since there was no way of directly measuring the aphid mortality caused by the predators observed in the samples (Hughes, 1963). This method also enabled us to demonstrate the relationship between *M. tasmaniae* and *M. persicae* showing a time-lag or time-delay which is prominent in the field as a result of the predator being relatively more abundant for a short time after aphid numbers start to decline (Hughes, 1963; Hassell, 1978).

4.3 Impact of naturally occurring predators

The field survey on the changing numbers of potato aphids and natural enemies indicated that natural enemies, especially predators, are important biotic factors. In particular the suppressive effects of naturally occurring known lacewings, *M. tasmaniae* on the field population of *M. persicae* on potatoes seemed obvious and appreciable, especially in the spring. However, experimental methods of evaluation of the impact of predators were needed to test the hypotheses suggested by the field data.

Many workers have discussed the various methods of evaluation of natural enemy effectiveness and concluded that the use of experimental

comparisons is the only really effective method (De Bach and Barlett, 1964; Huffaker and Messenger, 1976). One direct method of comparison is mechanical exclusion or substraction whereby natural enemies are excluded from a prey population by means of cages (Smith and De Bach, 1942; De Bach *et al.*, 1949; Huffaker and Kennett, 1956; Tamaki, 1974; Maelzer, 1977). An exclusion technique was therefore used in the field to determine (i) the impact of naturally occurring predators on the rate of increase of aphid populations and (ii) the influence of temperature during spring and summer on the impact of the predators on the aphids.

Methods

Three experiments were conducted in the orchard at the Waite Institute. They were chosen to cover the spring and summer periods when predators are most abundant in the field and seem to have the greatest effect on the population increase of *M. persicae*.

Experiment I was conducted between September 10, 1979 to October 4, 1979; Experiment II from November 13-30, 1979 and Experiment III from January 17 - February 2, 1980.

(i) The plants

Potato seeds (var. Exton) were planted in the glasshouse following the method described in Section 3.1. At the start of the experiment, each plant was transplanted into a 30 cm black plastic pot containing recycled University of California soil mixture. Three potted plants (bearing 6-8 expanded leaves) were used (each plant was a replicate) in each treatment.

(ii) The treatments and cages

There were only two treatments, namely:

(a) Plants with aphids only in "closed" cages which excluded parasites and predators.

(b) Plants with aphids in "open" cages, in which two sides of each cage were omitted (i.e. were open) so that parasites and predators were able to enter and leave it.

Each cage was 85 cm cube, and had a wooden frame which was covered with very fine terylene netting (6 strands/cm mesh - Experiment I; 35 strands/cm mesh - Experiment II and III). The "closed" cage had netting on all 4 vertical sides and on the top (Fig. 1); the "open" cage had netting on the left - half of each of the 4 vertical sides and on the top (Fig. 1). The bottom of the cage was wood and the three potted plants were placed in it.

The "open" cage was constructed as described above to minimise differences in the microclimate between it and the "closed" cage. Previous authors have shown that screen cages may alter the physical environment around the plant inside a cage (Peterson, 1959; Woodford, 1973). The edges of the cage were sealed with plastic adhesive tapes, and the lower surfaces of the frame which rested on the cage bottom were lined with 20 mm thick foam plastic to provide a good seal. The cage was then firmly secured to pegs in the ground by means of elastic straps.

(iii) The experimental procedure

One "open" and one "closed" cage were placed at a distance of 5 m from a potato plot and 3 m apart. There were 3 replicates

(plants) in each type of cage. At the start of each experiment, each plant was artificially infested with 5 newly moulted adult apterous *M. persicae* obtained from insectary culture (see Section 3.3). The aphids were put on with a fine brush and were spaced out on the upper, middle and lower leaves of the plants. Each aphid was then confined to the lower leaf cage (Khan, 1979) for 24 hours to ensure that it settled to feed and reproduce. Each cage was lifted off its bottom board every day to temporarily allow access to the plants for recording data, and a record was made of the total number of nymphs and adult *M. persicae*; immature and adult *M. tasmaniae* and other predators, and mummified *M. persicae* present on the plants.

Weather data were obtained from a meterological station at the Waite Institute. The experiment was terminated either when the *M. persicae* in the "open" cages had been reduced to very low numbers or when those in the "closed" cage became so numerous that further counting was impractical. The mean daily temperature during the course of each experiment was estimated as the mean of maximum plus mean of minimum divided by 2. It was estimated as 15°C, 18°C and 20°C for Experiments I, II and III, respectively.

(iv) The growth of the plants

To determine whether differences in plant growth existed between exposed and caged plants, the total leaf area of each plant was measured and compared at the start and end of each experiment. Leaf area of individual potato leaf was measured using the formula:

$$\text{Log } Y = 1.78 \log X - 0.40$$

(Epstein and Robinson, 1965)

where Y = leaf area (cm^2) and X = length of each compound leaf (cm).

Results

For purposes of discussion the plants in the open cages will hereafter be called "exposed" plants, and the plants in the closed cages will be called the "caged" (i.e. predator - excluded) plants.

Aphids

Experiment I

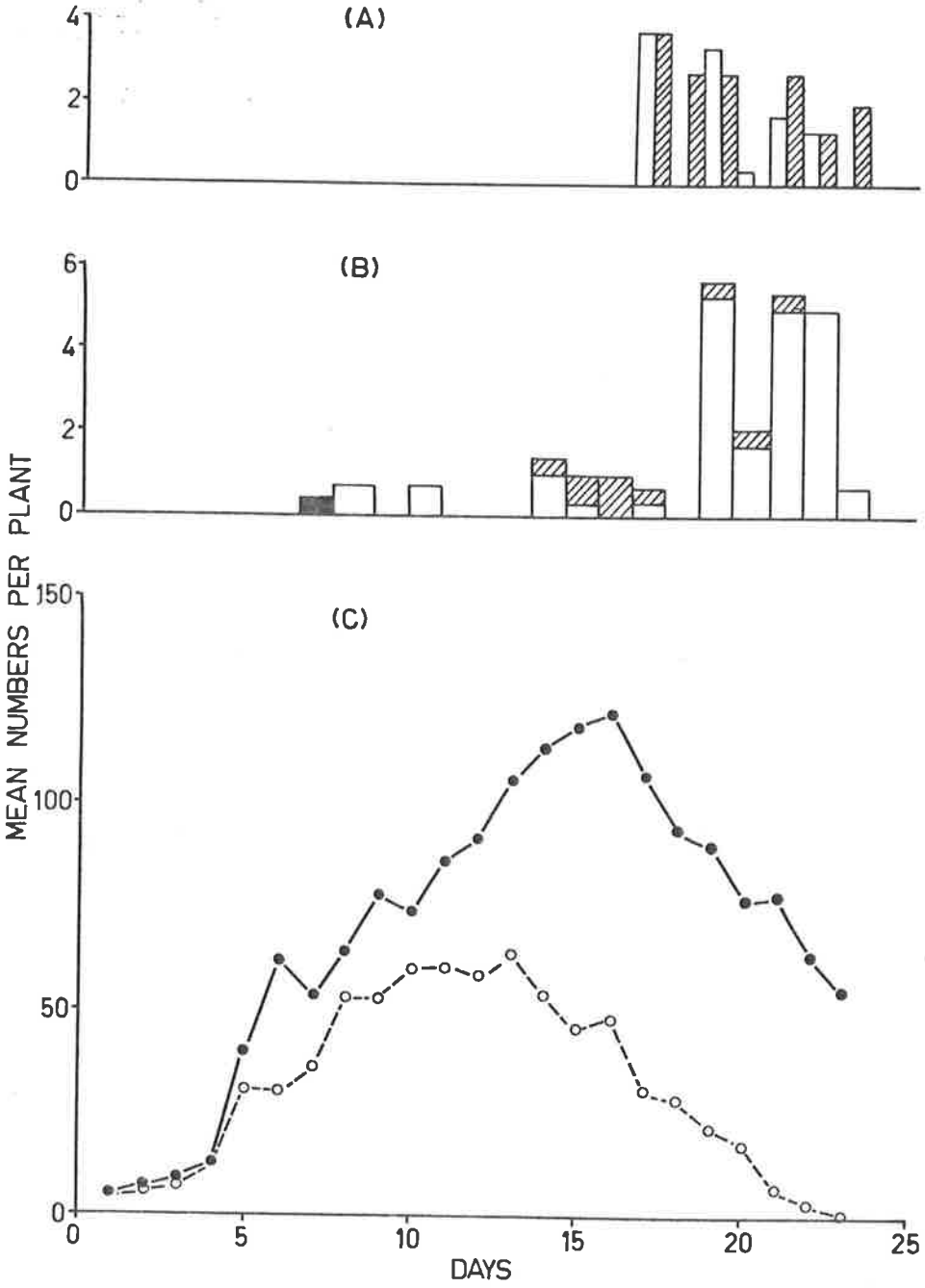
In Figure 4a, are given the mean number of mummified aphids per plant for both the caged and the exposed plants for each of the 23 days of the experiment. In Figure 4b, are given the mean number of eggs, larvae and adults of *M. tasmaniae* per plant for the exposed plants for each of the 23 days of the experiment, and in Figure 4c, are given the mean number of aphids per plant for both the caged and the exposed plants for each of the 23 days of the experiment. The number of aphids on the caged plants were significantly greater than those on the exposed plants from about day 15 onwards (a t-test for numbers on day 15 gave $t = 4.40$ with 4 d.f., $P<.05$), and on day 23 there were no aphids on the exposed plants but more than 50 aphids were on the caged plants. Nevertheless the differences were not as great as expected and in particular the numbers of aphids on the caged plants were not expected to decrease after day 16. An explanation for the relatively small difference in the numbers of aphids on the caged and exposed plants can be found in the numbers of parasitized (mummified) aphids on both sorts of plants (Figure 4a). Obviously the mesh that was used to cage the plants was not small enough

Figure 4: Mean numbers of live and mummified *M.persicae* on exposed and caged potato plants and mean number of egg, larva and adult of *M. tasmaniae* found on exposed plants between September 11 to October 4, 1979 (Experiment I).

(a) □ mummified *M. persicae* on caged plants.
▨ mummified *M. persicae* on exposed plants.

(b) □ egg, ▨ larva, ■ adult *M. tasmaniae* on exposed plants.

(c) ● live apterous *M. persicae* caged plants.
o live apterous *M. persicae* exposed plants.


(A)
4
2
0
(B)
6
4
2
0
(C)
150
100
50
0
MEAN NUMBERS PER PLANT
0
5
10
15
20
25
DAYS

to exclude parasites, although it was small enough to exclude predators, as shown by the presence of predators on the exposed plants but their absence on the caged plants (Fig. 4b).

Because of the parasites getting through the mesh to the aphids on the "caged" plants, the mesh in the next two experiments was reduced further to 35 strands/cm in an endeavour to exclude parasites as well as predators.

Experiment II

In Figure 5a are given the mean number of eggs, larvae and adults of *M. tasmaniae* per plant for the exposed plants for each of the 16 days of the experiment, and in Figure 5b are given the mean number of aphids per plant for both the caged and exposed plants for each of the 16 days of the experiment. The differences in the number of aphids between the caged and exposed plants were obvious. On the exposed plants, the aphids increased slightly in numbers up to days 5-7 and then fell to zero and stayed there, whereas on the caged plants, the aphid numbers showed a typical exponential growth trend.

For the caged plants the rate of increase of the aphid population can be approximated by the formula for exponential growth:

$$N_t = N_o e^{rt}$$

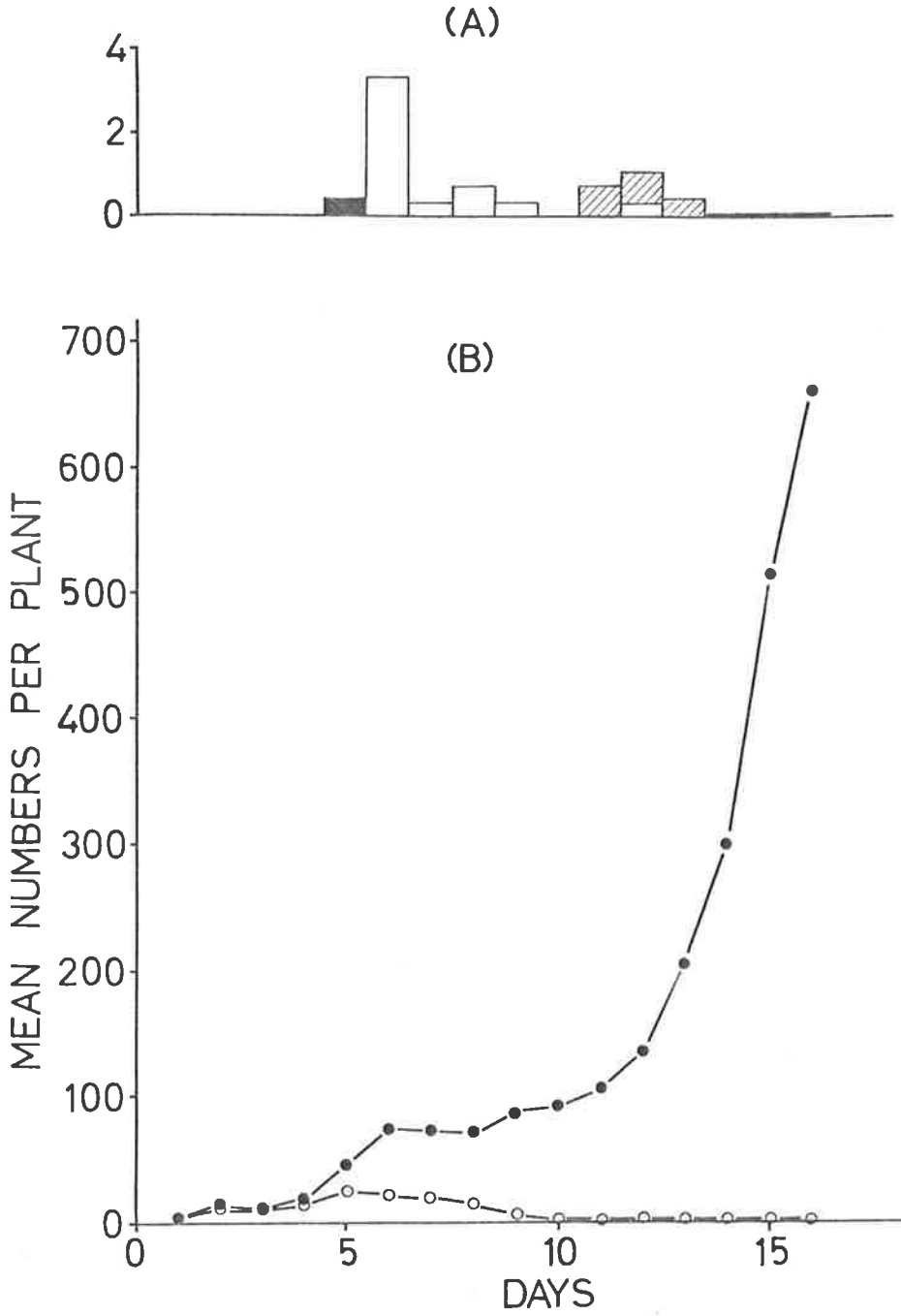
where NO = the initial number of aphids; N_t = the number of aphids at time t; and r in the aphid's rate of increase; and since N_o was 5 aphids and N_t after 16 days was 659, r can be approximated as:

$$r = \frac{\log_n 659}{(\log_n 5)(15)} = 0.27$$

Figure 5: Mean numbers of live *M. persiae* on exposed and caged potato plants and mean numbers of egg, larva and adult of *M. tasmaniae* found on exposed plants between November 13 to 30, 1979 (Experiment II).

(a) □ egg, ▨ larva, ■ adult *M. tasmaniae* on exposed plants.

(b) ● live apterous *M. persicae* on caged plants.
o live apterous *M. persicae* on exposed plants.


(A)
4
2
0
(B)
700
600
500
400
300
200
100
0
MEAN NUMBERS PER PLANT
0
5
10
15
20
DAYS

The difference between the two treatments can obviously be attributed to the actions of the predator, *M. tasmaniae* on the exposed plants (Fig.5). Adult predators were observed on the exposed plants earlier (day 4) than in Experiment I (day 6). Parasites appeared to be absent during this experimental period; no aphid mummies were observed on the exposed plants. The application of the exponential growth formula to aphid numbers on the exposed plants suggests that the rate of increase of the aphid population in the absence of predators during this period was about 0.27 per day.

Experiment III

Results, given in Figure 6, again showed that the numbers of aphids on the caged plants were obviously much smaller than on the exposed plants and their relative numbers on day 17 (966 and 119 per plant respectively), indicated a reduction of 88% in aphid numbers on the caged plants. This reduction can again be attributed to the activities of the predator of *M. tasmaniae* which were abundant on the exposed plants (Fig. 6a). Again, as in Experiment II, no parasites were observed during the period of the experiment.

An interesting feature of the experiment was that aphid numbers were not reduced to zero level in spite of the relatively greater number of predators observed in this experiment (Fig. 6). Another feature was that the aphid populations in the closed cages showed greater fluctuations than those observed in Experiments I and II.

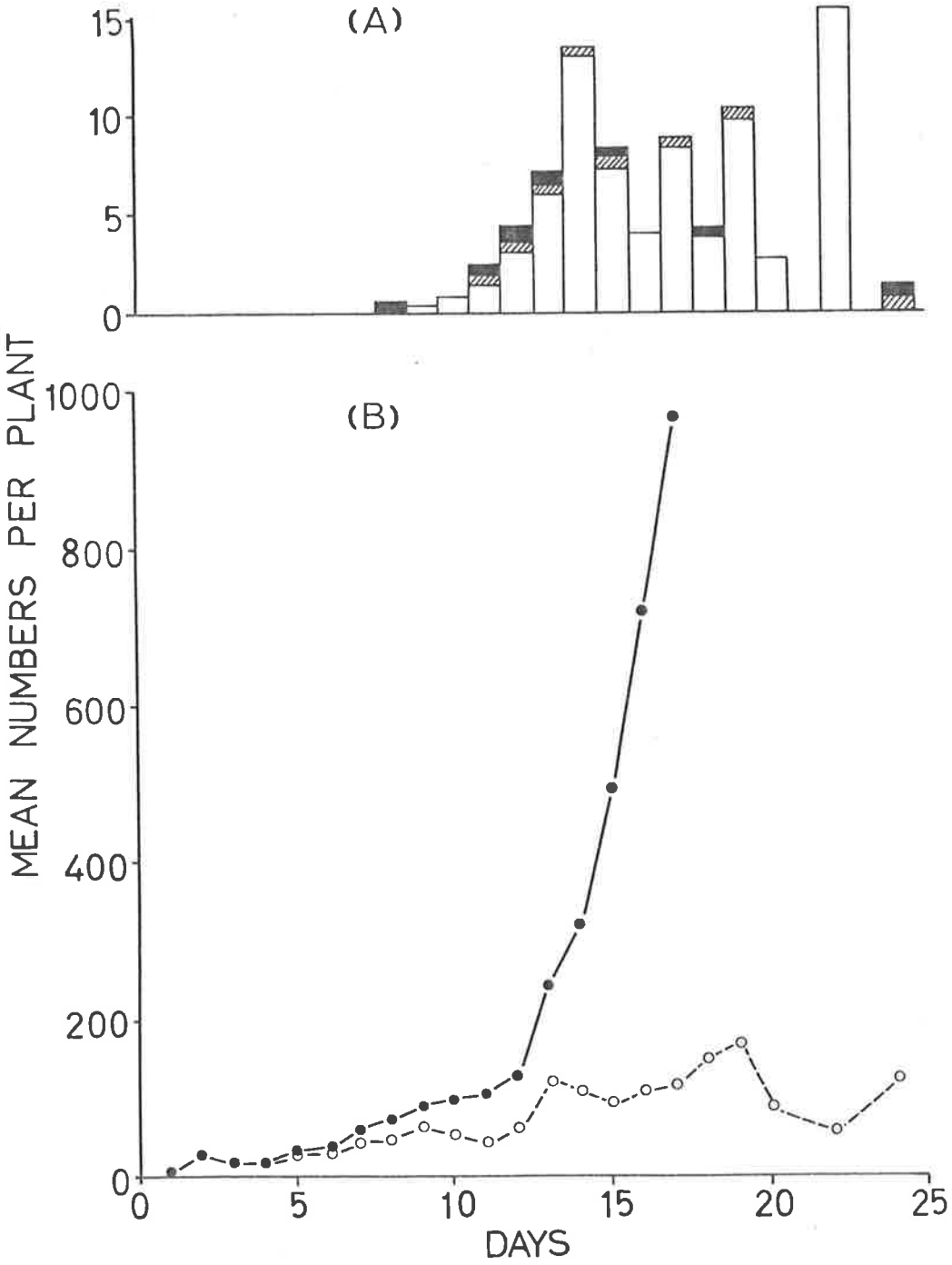
Plants

The estimated leaf areas for each plant before and after the experiment, are given in Appendix Tables 3 and 4 respectively. A series of t-tests indicated that no significant differences in the total leaf area

Figure 6: Mean numbers of live *M. persicae* on exposed and caged potato plants and mean numbers of egg, larva and adult of *M. tasmaniae* on exposed plants between January 17 0 February 2, 1980 (Experiment III).

(a) □ egg, ▨ larva, ■ adult *M. tasmaniae*.

(b) ● live apterous *M. persicae* on caged plants.
o live apterous *M. persicae* on exposed plants.


(A)
15
10
5
0
(B)
1000
800
600
400
200
0
MEAN NUMBERS PER PLANT
0
5
10
15
20
25
DAYS

of plants before any of the experiments and after Experiment II and III. However, a t-test suggested that the caged plants in Experiment I were larger than the exposed plants after the experiment ($t = 3.84$ with 4 d.f, $P<.05$). It is possible that the slight shading of the plants in the cages in spring made the leaves grow larger than they did in the exposed plants.

Discussion

The results of these three experiments indicate that naturally occurring *M. tasmaniae* had the greatest impact in suppressing *M. persicae* populations in potato plants in Experiment II. During this experiment, the average daily temperature was 18°C, and the predators were able to completely suppress the aphid populations in 12 days. The good performance by *M. tasmaniae* in this experiment was not surprising because the predator is known to be most active during October-November each year (Figs.

Weather and particularly temperature during the course of these experiments, had a considerable influence on both the predator performance and on the aphid's rate of increase. Temperature influences, of course, the rate of increase of *M. persicae* through modification of its developmental time, longevity, survival rate and fecundity rate (Weed, 1927; Barlow, 1962; Sylvester, 1964; DeLoach, 1974; Wyatt and Brown, 1977; Wyatt and White, 1979). Thus in Experiments II and III, the rate of increase of the aphid populations on the caged plants was estimated to be roughly 0.270 per day (at 18°C) and 0.284 per day (at 20°C). A rate of increase could not be sensibly estimated in Experiment I.

Temperature also influences the rate of increase of a predator and is known to have a significant effect on the interaction of predator-prey.

Two reasons may be suggested to explain why the predators were not as effective at the higher temperature during Experiment III than at the lower temperature of Experiment II. Firstly, at a higher mean daily temperature (20°C) experienced in Experiment III, the aphids can build up populations at a greater rate (r = 0.284) than can be checked by *M. tasmaniae*. Also at a mean temperature of 20°C, *M. persicae* has been shown to have the highest net reproductive rate (De Loach, 1974). Secondly, the lower mean temperature (18°C) probably favours *M. tasmaniae* which prefers cooler conditions as to other hemerobiids (Neuenschwander and Hagen, 1980; Syrett and Penman, 1981), and gives it an advantage over the prey. The differential effect of temperature on prey and predator is undoubtedly a factor influencing the seasonal abundance of *M. persicae* on potatoes.

The time-relationship between the first occurrence of predators and the time the prey start to increase in numbers which van Emden (1966) called synchronization is an important factor in the suppression of the rate of increase of the aphid population. It is possible that the early appearance of some predator larvae or adults on the exposed plants especially in Experiment II at about the time that the first aphid progeny were produced resulted in complete suppression of aphid populations.

The absence of other predators such as coccinellids and chrysopids in these experiments support the indications from the field survey that *M. tasmaniae* is the most important and abundant predator of *M. persicae* on potatoes, especially in spring and early summer.

RESULTS AND DISCUSSION

Aphids and natural enemies

In this section is discussed the species involved and their relative abundances in the fields, and their phenologies taking into consideration the various factors such as feeding habits, thermal requirements for development and diapause.

Aphids

The three introduced species, the green peach aphid (*Myzus persicae*), the potato aphid (*Macrosiphum euphorbiae*) and the foxglove aphid (*Aulacorthum solani*) were all found on potato plants during the survey both at Milang and Waite Institute. *M. persicae* was by far the most common and abundant aphid at both localities. Both *M. persicae* and *M. euphorbiae* have previously been considered pests of potatoes in Australia by Norris and Bald (1943) and Helson (1958) but very little was known prior to my study of the pest status and ecology of these two aphid species in relation to the production of seed potatoes in South Australia.

Phenology of *Myzus persicae*

The relative abundance of *M. persicae* on potatoes at the two localities over the two year period is shown in Figures 7, 8, 9 and 10. Table 15 shows the relative abundance of *M. euphorbiae* at both localities.

The phenologies of *M. persicae* at both localities show maximum numbers of aphids in April-May each year, followed by a decline in numbers to near zero in June-July and an almost total absence of aphids from

Figure 7: Phenologies of *Myzus persicae*, its predators, diseased and parasitized aphids in potato plots at Waite Institute during the 1978-79 crop period.

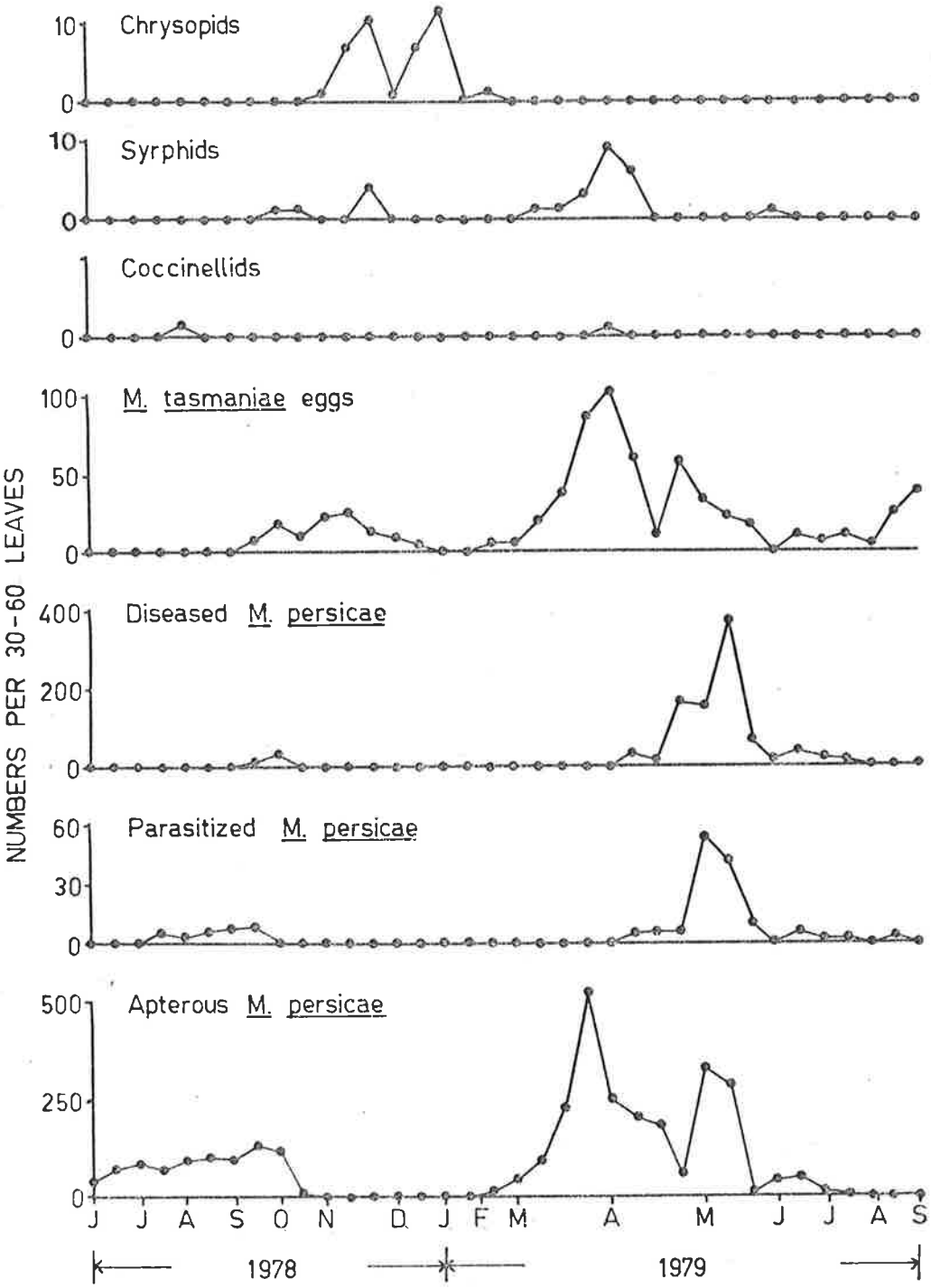

Chrysopids
10
0
Syrphids
10
0
Coccinellids
0
M. tasmaniae eggs
100
50
0
Diseased M. persicae
400
200
0
Parasitized M. persicae
60
30
0
Apterous M. persicae
500
250
0
NUMBERS PER 30-60 LEAVES
J J A S O N D J F M A M J J A S
1978
1979

Figure 8: Phenologies of *Myzus persicae*, its predators, diseased and parasitized aphids in potato plots at Waite Institute during the 1979-80 crop period.

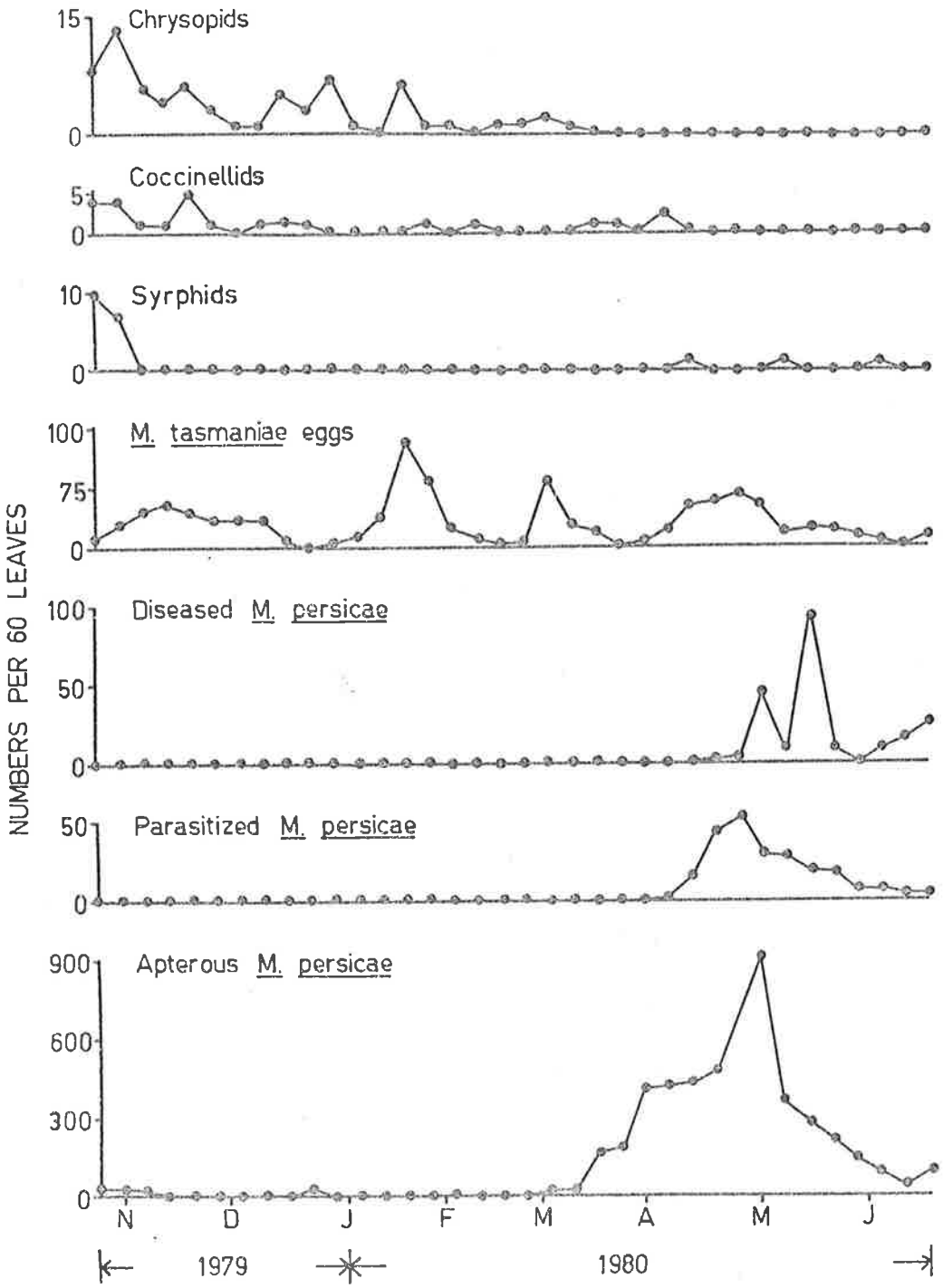

NUMBERS PER 60 LEAVES
15
Chrysopids
0
5
Coccinellids
0
10
Syrphids
0
100
75
M. tasmaniae eggs
0
100
50
Diseased M. persicae
0
50
Parasitized M. persicae
0
900
600
300
Apterous M. persicae
0
N
D
J
F
M
A
M
J
1979
1980

Figure 9: Phenologies of *Myzus persicae*, its predators, diseased and parasitized aphids in potato fields at Milang during the 1978-79 crop period.

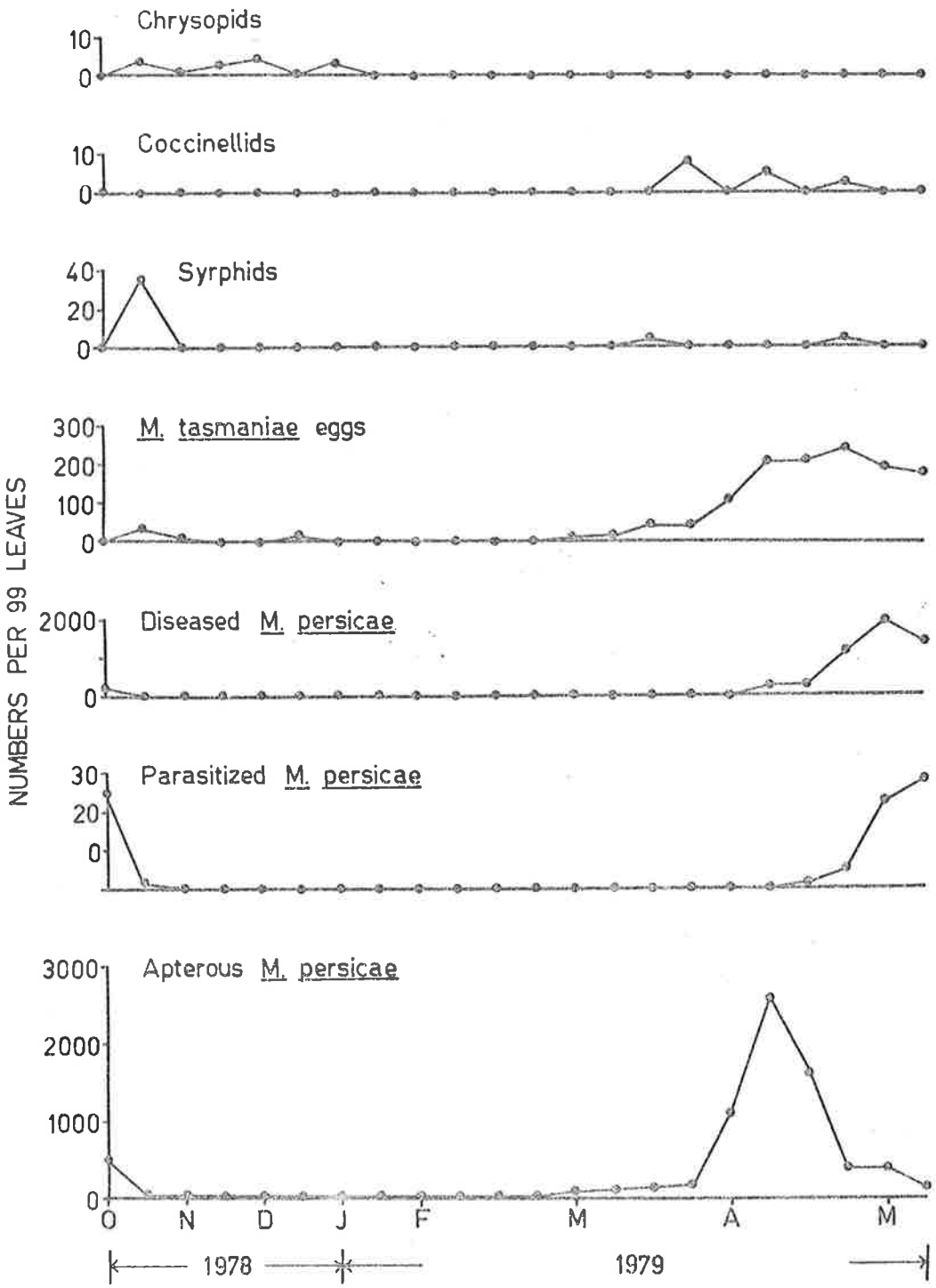

Chrysopids
10
0
Coccinellids
10
0
Syrphids
40
20
0
M. tasmaniae eggs
300
200
100
0
Diseased M. persicae
2000
0
Parasitized M. persicae
30
20
0
Apterous M. persicae
3000
2000
1000
0
NUMBERS PER 99 LEAVES
O
N
D
J
F
M
A
M
1978
1979

Figure 10: Phenologies of *M. persicae*, its predators, diseased and parasitized aphids in potato fields at Milang during the 1978-79 crop period.

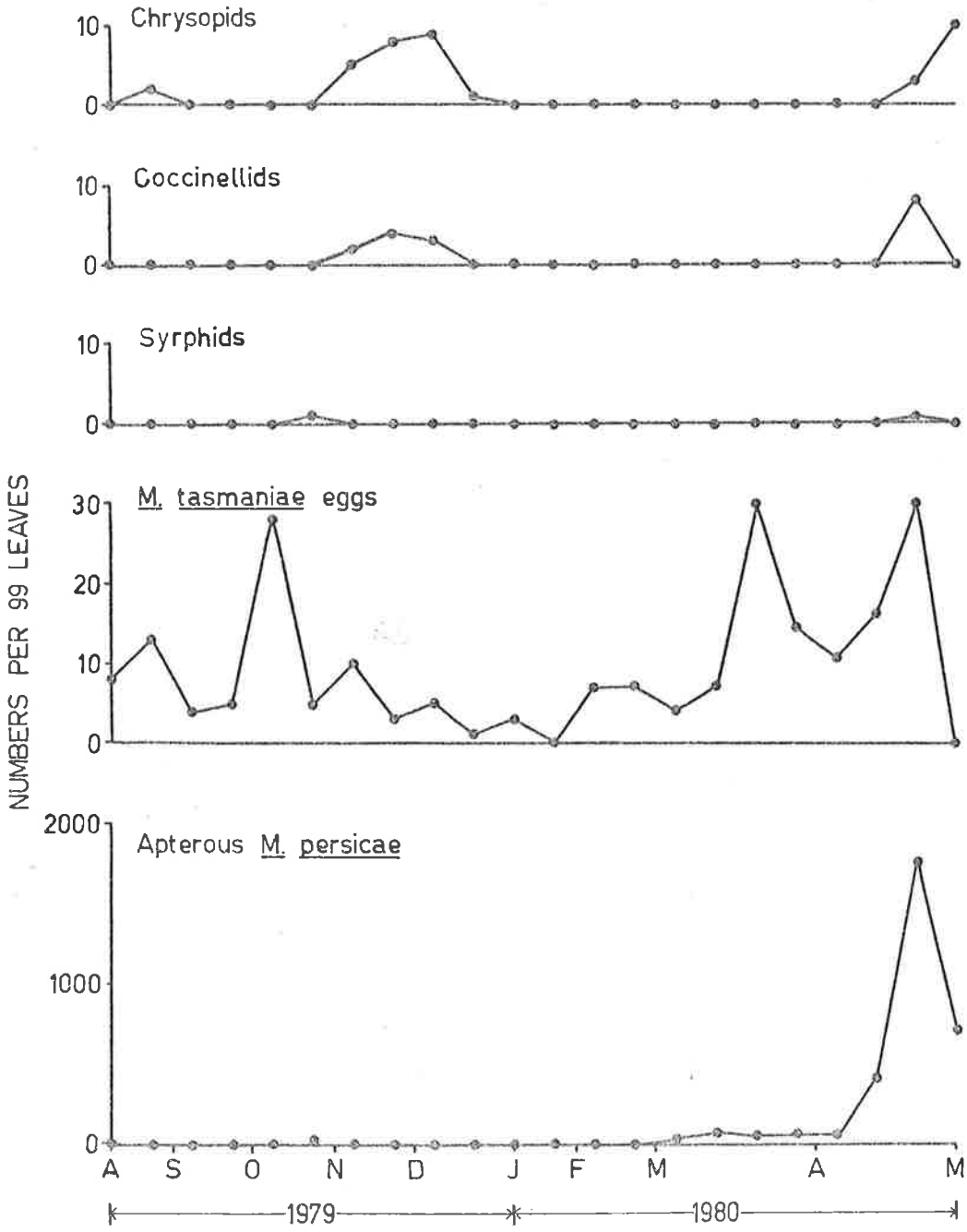

Chrysopids
10
0
Coccinellids
10
0
Syrphids
10
0
M. tasmaniae eggs
30
20
10
0
NUMBERS PER 99 LEAVES
Apterous M. persicae
2000
1000
0
A
S
O
N
D
J
F
M
A
M
1979
1980

Table 15: Numbers and percentages of *M. persicae* and *M. euphorbiae* found in samples collected at various dates from small plots at Waite Institute (1978-79) and large fields at Milang (1979-80).

Sampling date	Number of		%	
	M.persicae	*M.euphorbiae*	*M.persicae*	*M.euphorbiae*
Waite Institute:				
13. 6.78	39	19	67	33
27. 6.78	73	34	68	32
11. 7.78	83	80	51	49
25. 7.78	71	161	31	69
8. 8.78	91	403	18	82
22. 8.78	98	354	22	78
5. 9.78	95	164	37	63
19. 9.78	129	52	71	29
3.10.78	134	20	87	13
19.10.78	6	0	100	0
3.11.78	3	1	75	25
Milang:				
22.4.80	23,157	359	99	1
28.4.80	16,386	628	96	4

November to February next. Similar trends in the change of numbers of *M. persicae* in potato fields have been observed near Canberra, Australia (Helson, 1958) and in other parts of South Australia (F.D. Morgan, person. comm.).

In the Waite Institute plots (Figures 7 and 8), a small population of aphids persisted throughout the study period. Fluctuations in population size were greater at the Waite Institute, probably as a result of the presence of a wide range of host plants and overwintering refuges for the active stages of *M. persicae*. Also, *M persicae* appeared in the Waite Institute potato plots earlier than Milang.

At the Waite Institute, the population of *M. persicae* reached its maximum level on March 29, 1979 (525 aphids/51 leaves) for the 1978-79 crop period (Figure 4) and on May 1, 1980 (922 aphids/60 leaves) for the 1979-80 period (Figure 5). At Milang, the highest counts of *M. persicae* were found from samples taken on April 4, 1979 (3026 aphids/99 leaves) and on April 14, 1980 (1758 aphids/99 leaves) in the 1978-79 (Figure 9) and 1979-80 (Figure 10) crop period respectively. The similarity of the time of occurrence of the two peaks in number of *M. persicae* suggests that future peak infestations in the commercial potato fields may be predicted with precision. By contrast, the peak infestations of *M. persicae* at the Waite Institute varied considerably between the two crop periods. Predicting the date of occurrence of peak infestations at the Waite Institute is likely therefore to be more difficult.

The aphid numbers in Figures 7-10 indicate that in South Australia, on potatoes, *M. persicae* populations probably have only one peak in autumn (April-May) at Milang (Figures 9 and 10) and two peaks - a smaller and less

consistent peak in spring and a major and consistent autumn peak at Waite Institute (Figures 7 and 8). Similarly, Helson (1958) observed spring and autumn peaks of *M. persicae* on potatoes near Canberra, and the trapping data of Hughes *et al.* (1964) also showed that peak flights of *M. persicae*, which may be correlated with peak abundance of the aphids on host plants, occurred in spring and autumn at the Waite Institute and in the Adelaide Hills. Elsewhere in the eastern parts of Australia, peak flights of *M. persicae* also occurred in spring and autumn except in Merbein, Victoria where the peak flights occurred only in spring (Hughes *et al.*, 1964). In many countires around the world where *M. persicae* is known to be a pest of potato crops, peak infestations are reported to occur in spring (Daiber, 1963; Mackauer and Way, 1976).

Some variation in the patterns of infestations occurred between crop periods. At Milang, the first *M. persicae* was found in leaf samples one month earlier in 1979-80 crop period (January 28, 1980) than in 1978-79 period (March 3, 1979). Despite this difference in the time of colonization, the peak abundance of aphids occurred at nearly the same date in each year. Consequently, predictions of peak population may not be easily based on the time of colonization. However, in the Waite Institute plots the plants were colonized at about the same time in early March each year but infestations occurred at widely different dates in the two years. These different relationships between the times of colonization and times of occurrence of peak numbers at Milang and at the Waite Institute are likely to be due to the different climates at the two places and due also to different predator complexes which react differently with the growing aphid population after colonization.

Trap catches of alate *M. persicae*

The numbers of alate *M. persicae* trapped at Milang in 1979 and 1980 and at Waite Institute in 1979, 1980 and 1981 are shown in Figure 38. They show interesting differences between the two localities in relation to the times at which the crops were first colonized by *M. persicae*. At Waite Institute alates were caught 2-4 weeks earlier than at Milang. Also, at Waite Institute, alates were caught in traps 1-2 weeks before they were found on the plants whereas, at Milang, alates were always caught in the traps 3-4 weeks after the aphids had been found on the potato plants. The data thus indicate that the usefulness of water traps in determining the time of autumn migration of *M. persicae* into potato fields depends on the size of the crop and the surrounding flora and fauna.

Influence of local flora on the numbers of *M. persicae* in potato crops

In Australia, *M. persicae* was reported as anholocyclic and holocyclic in South Australia (Fowler, 1934), in Victoria (Ward, 1934), in Canberra, A.C.T. (Anonymous, 1944) and only anholocyclic in Western Australia (Norris, 1943). *M. persicae* is currently both anholocyclic and holocyclic in Australia (Dr. M. Carver, person. comm.). As in other parts of the world, *M. persicae* in South Australia survives the winter mostly as overwintering eggs on the peach trees (Fowler, 1934). However, the occurrence of aphids on potato plots at the Waite Institute in July-August 1978 and in July 1979 indicates the presence of an anholocyclic biotype. In the absence of potato crops these aphids probably survive the winter on imported weeds such as *Lenchrus* sp. (Innocent weed); *Chenopodium murale* L. (Fat hen) and *Lolium rigidum* Gaudin (Rye grass).

In spring the initial aphids on potato crops may, therefore, be migrants of either anholocyclic aphids on weeds or holocyclic aphids on peach. Both sorts of plants are more abundant around and on the Waite Institute campus than at Milang, which probably accounts for alates being found in traps at the Waite Institute before aphids are found on the plants.

The patterns of changing numbers of *M. persicae* observed in this study suggest that most *M. persicae* reproduce parthenogenetically (anholocycly), particularly at Milang, throughout the year and remain as active stages throughout the winter on weeds and other wild plants (Daiber, 1963; Heathcote, 1965). At the Waite Institute *M. persicae* may remain as active states on cruciferous crops (Fisken, 1959; Lowe, 1962; Daiber, 1963), on weeds (Daiber, 1963; Heathcote, 1965) and in glasshouses (Broadbent, 1953).

The numbers of *M. persicae* in spring were surprisingly low in both localities; in general, aphids in Australia peak in numbers during spring and autumn, presumably in response to flushes of plant growth and suitable weather (Maelzer, 1981). The low numbers may have been due to the actions of predators, mainly *Micromus tasmaniae* which is usually abundant in the spring (Maelzer, 1978). The aphid populations remained very low thereafter throughout the spring and early summer, and then became even scarcer during the rest of the summer, probably because of the hot dry weather (Helson, 1958; Maelzer, 1981). In fact, one of the major problems of aphid strategy in Southern Australia is survival over summer (Maelzer, 1981), and only very few *M. persicae* are likely to survive the summer weather that prevails at Milang and Waite Institute. The hot dry season is the most hazardous period for the survival of *M. persicae* in

terms of high temperature and scarcity of suitable host plants which prevent development of aphids above the mean daily of 28°C (Bald *et al.*, 1943; van der Plank, 1944; Bodenheimer, 1954; Barlow, 1962). The mean (over 122 years) maximum temperature for Adelaide, for the summer months (December, January and February) is above 28°C (South Australia Year Book, 1981), which accounts for the scarcity of *M. persicae* in summer.

Macrosiphum euphorbiae was the only other species of aphid on potatoes found in this study. However, it was usually in smaller numbers than *M. persicae* and accounted for 0 to 4% of the total aphids on the crop at Milang and 0 to 82% of aphids at the Waite Institute. The data in Table 15 also suggests that *M. euphorbiae* was more abundant in the Waite Institute potato plots than in the large potato fields at Miland and that the abundance of *M. euphorbiae* at Waite Institute plots tended to vary between years. In these plots *M. euphorbiae* was abundant only in winter and early spring in 1978 whereas in 1979 and 1980, the aphids were relatively scarce. On the other hand, a small percentage (1-4%) of *M. euphorbiae* was found at Milang only in April 1980. The dominance of *M. euphorbiae* over *M. persicae* at times has previously been observed by Norris and Bald (1943) in potato plots near Canberra.

Predators - Hemerobiidae

The only hemerobiid predator found at Milang and Waite Institute was the brown lacewing, *Micromus tasmaniae* (Walker) (Fig. 11). It was in fact the most common and abundant (Ca. 96%) of all species of predators found in potato fields at both localities throughout the survey period. *M. tasmaniae* is native to Australia (Walker, 1860) but seems now to feed extensively on aphids on introduced plants. Figures 12 and 13 show the relative abundance of *M. tasmaniae* eggs, larvae and adults over a two-year period at Milang. Similar data at the Waite Institute are given in Figures 14 and 15. The numbers of *M. persicae* are also shown in Figures 12-15 so that relationships between aphid numbers and predator numbers (eggs, larvae or adults) may be examined.

The numbers of adult *M. tasmaniae* at Milang in February-May, 1979 (Fig. 12) were very low and seem to have no relation to the large number of eggs laid then. In February-April, 1980 (Fig.13), there was a more obvious relation of the number of adult *M. tasmaniae* in the crop and the number of larvae (but strangely, not eggs). The most interesting peak of adults, however, was that of October-December, 1979 (Fig.13) which seems to have produced very few eggs or larvae; possibly because very few aphids were present then.

A number of interesting points arise from these data, namely:
(i) since *M. tasmaniae* was the most abundant predator, its peak numbers were expected to be related to peak numbers of aphids, probably with a time-lag, as evidenced by Hughes (1963) for example, for syrphids feeding on *Brevicoryne brassicae*. The expected relationships, with time-lags, were seen at Milang in 1979 (Fig.12) between peak numbers of *M. tasmaniae*

Figure 11: The life stages of *M. tasmaniae* -

A. Egg (X 19)

B. Larva : I - First instar (X 10)

II - Second instar (X 7)

III - Third instar (X 6)

C. Pupa (X 40)

D. Adult (X 7)

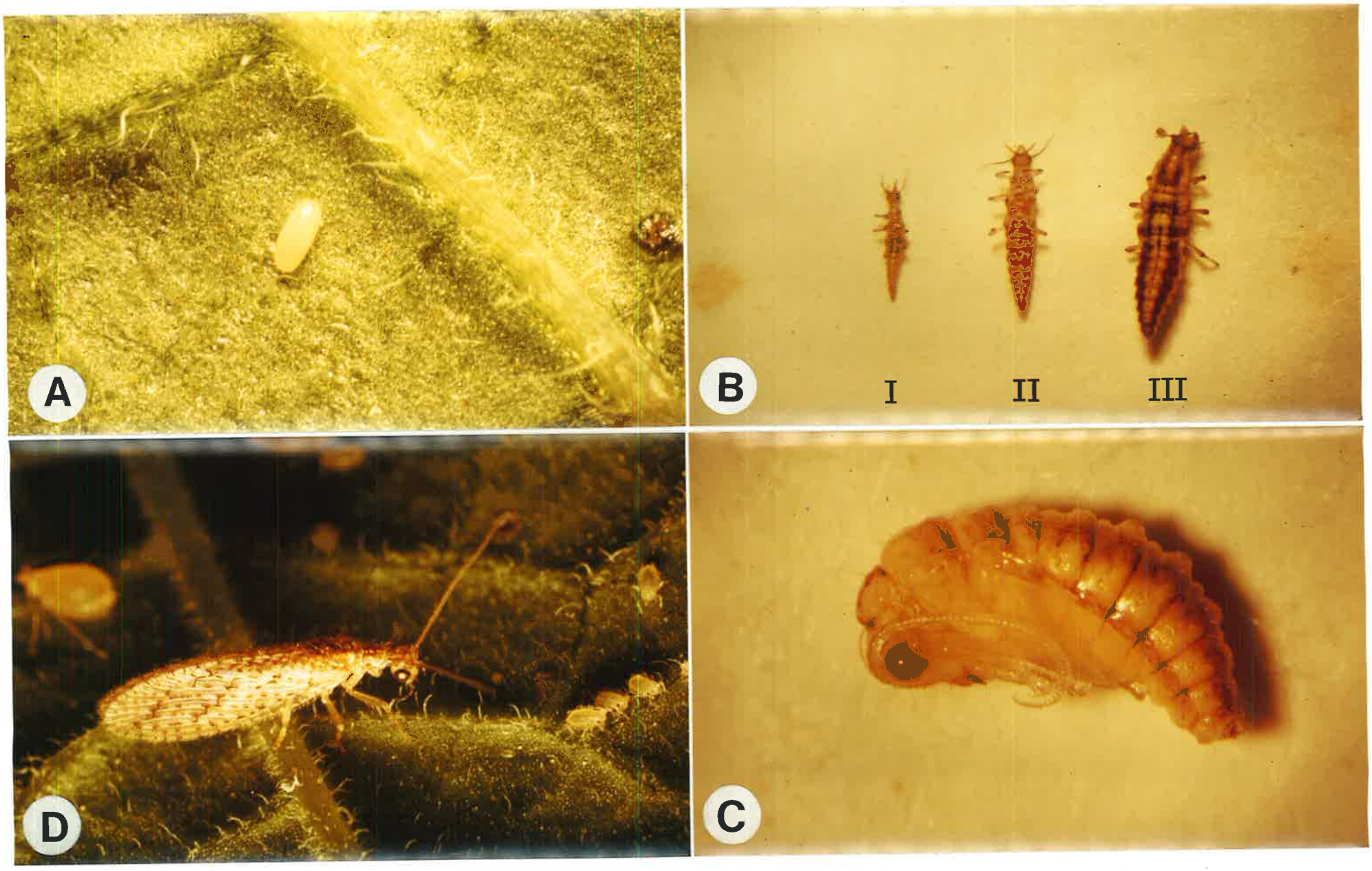

A
B
I
II
III
C
D

Figure 12: Phenologies of *M. persicae* and eggs, larvae and adults of *M. tasmaniae* in potato fields at Milang for 1978-1979 period.

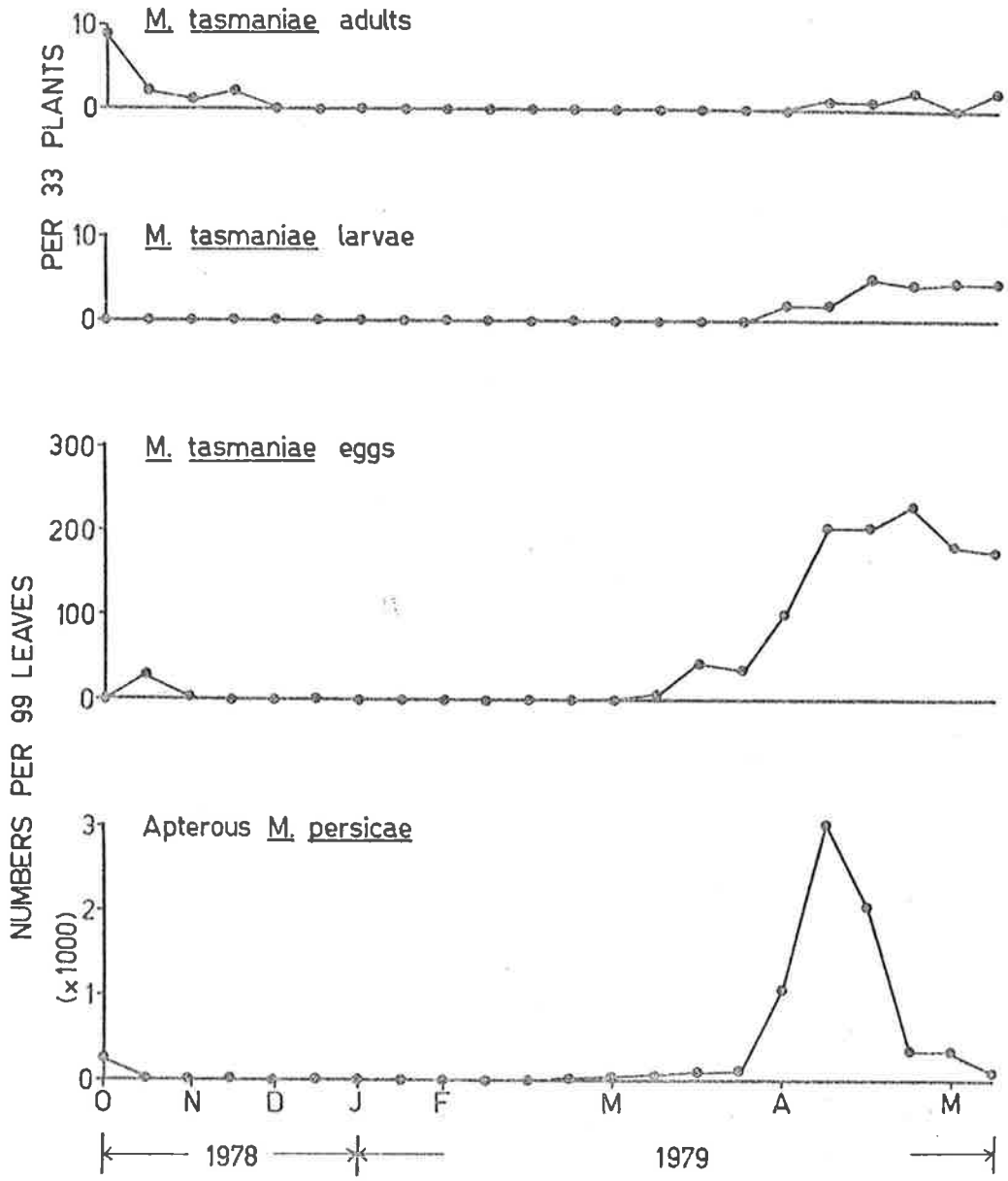

M. tasmaniae adults
10
0
PER 33 PLANTS
M. tasmaniae larvae
10
0
M. tasmaniae eggs
300
200
100
0
NUMBERS PER 99 LEAVES
Apterous M. persicae
3
2
1
0
(x 1000)
O
N
D
J
F
M
A
M
1978
1979

Figure 13: Phenologies of *M. persicae* and eggs, larvae and adults of *M. tasmaniae* in potato fields at Milang for 1979-80 period.

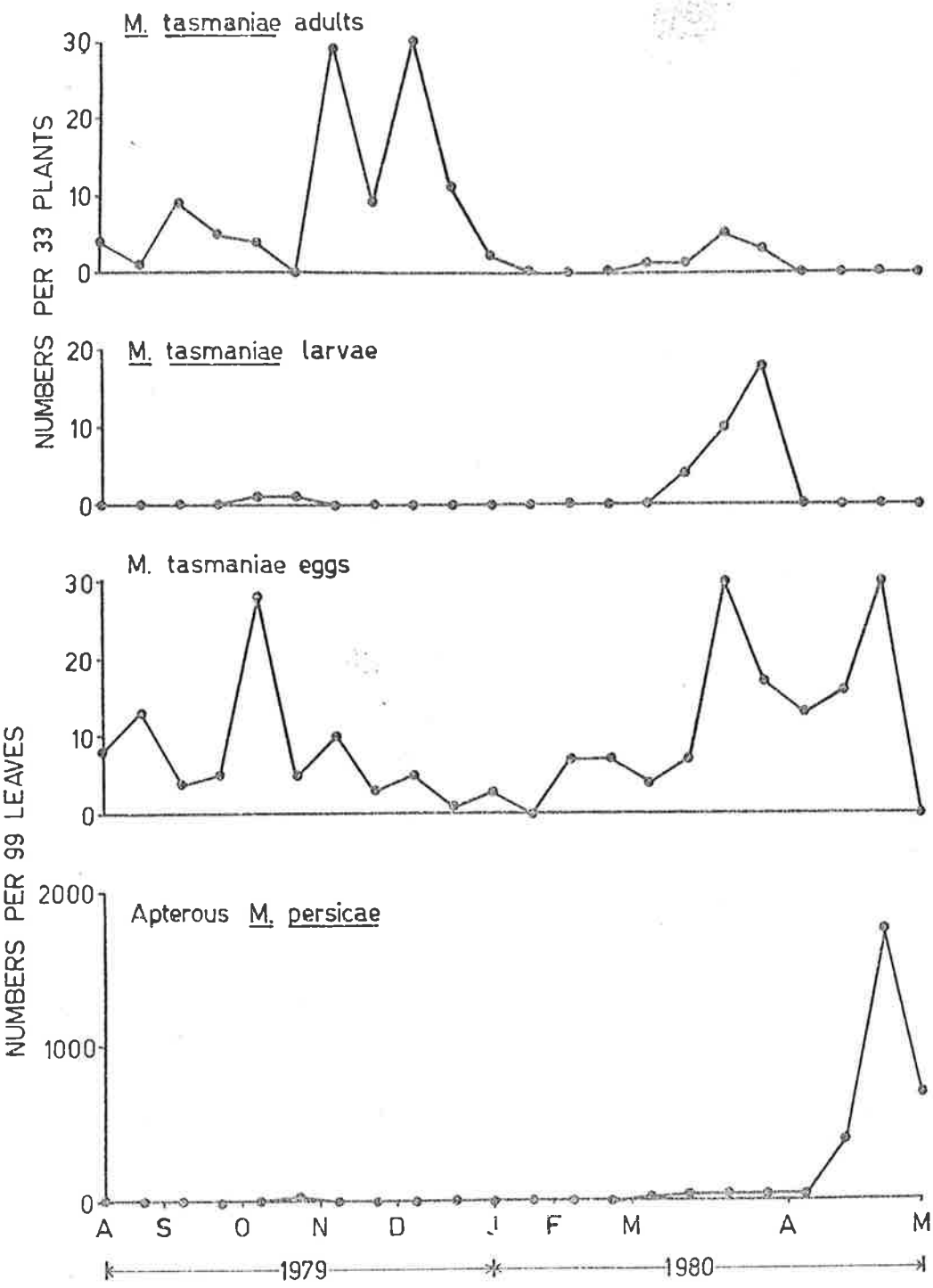

M. tasmaniae adults
30
20
10
0
NUMBERS PER 33 PLANTS
M. tasmaniae larvae
20
10
0
M. tasmaniae eggs
30
20
10
0
NUMBERS PER 99 LEAVES
Apterous M. persicae
2000
1000
0
A S O N D J F M A M
1979
1980

Figure 14: Phenologies of *M. persicae* and eggs, larvae and adults of *M. tasmaniae* at Waite Institute for the 1978-79 period.

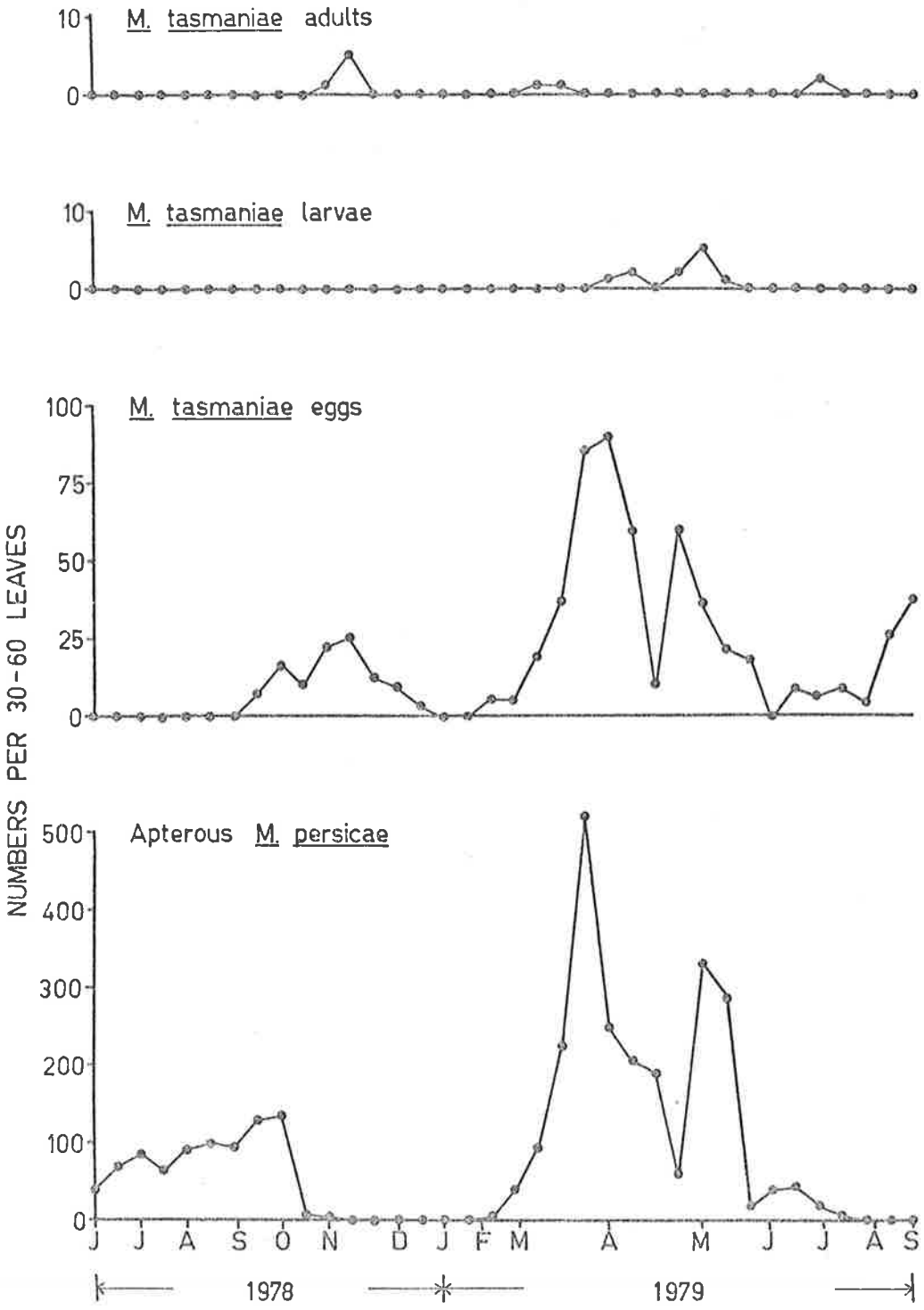
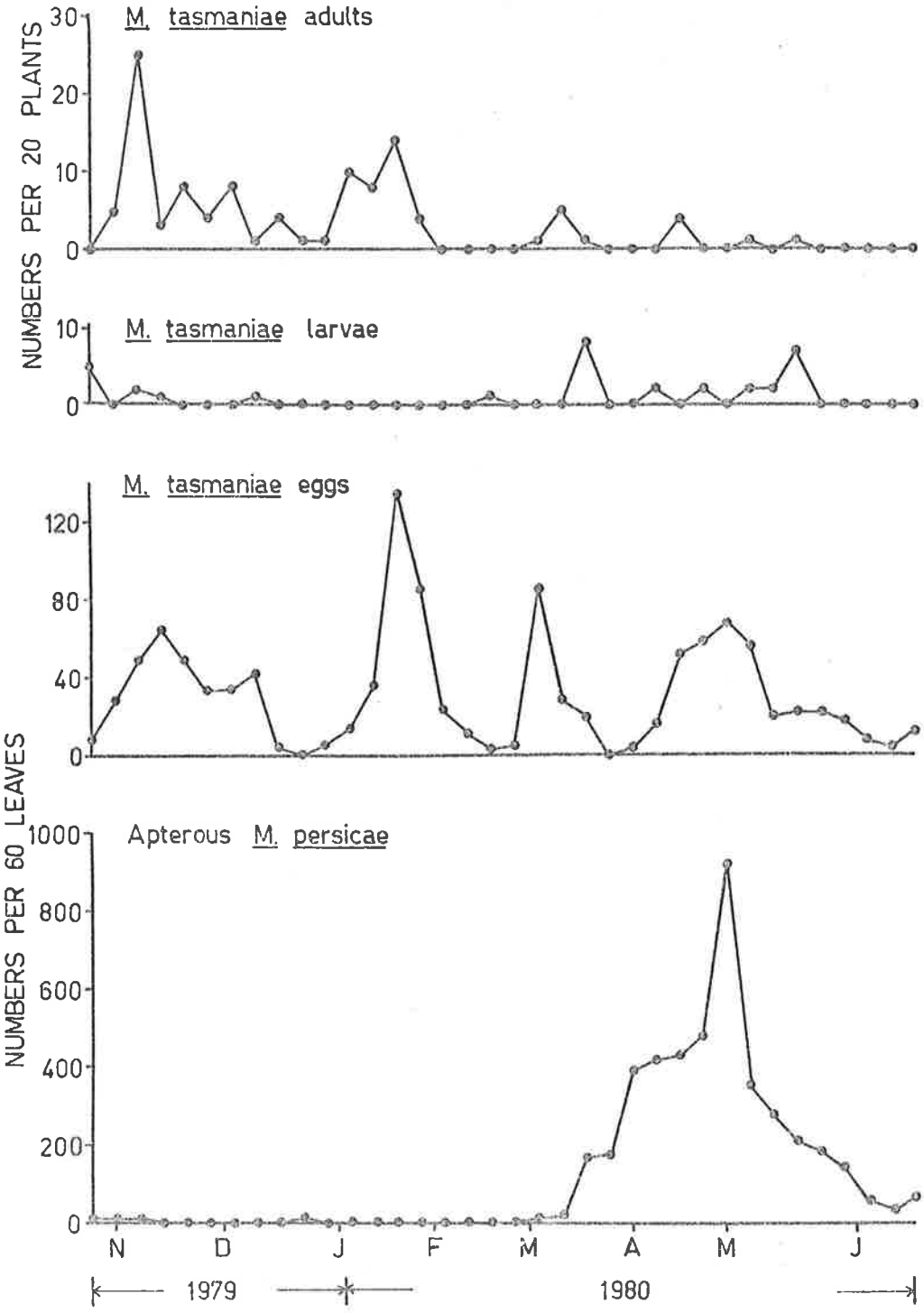

M. tasmaniae adults
10
0
M. tasmaniae larvae
10
0
M. tasmaniae eggs
100
75
50
25
0
NUMBERS PER 30-60 LEAVES
Apterous M. persicae
500
400
300
200
100
0
J J A S O N D J F M A M J J A S
1978
1979

Figure 15: Phenologies of *M. persicae* and eggs, larvae and adults of *M. tasmaniae* at Waite Institute for the 1979-80 period.


M. tasmaniae adults
NUMBERS PER 20 PLANTS
30
20
10
0
M. tasmaniae larvae
10
0
M. tasmaniae eggs
120
80
40
0
NUMBERS PER 60 LEAVES
Apterous M. persicae
1000
800
600
400
200
0
N
D
J
F
M
A
M
J
1979
1980

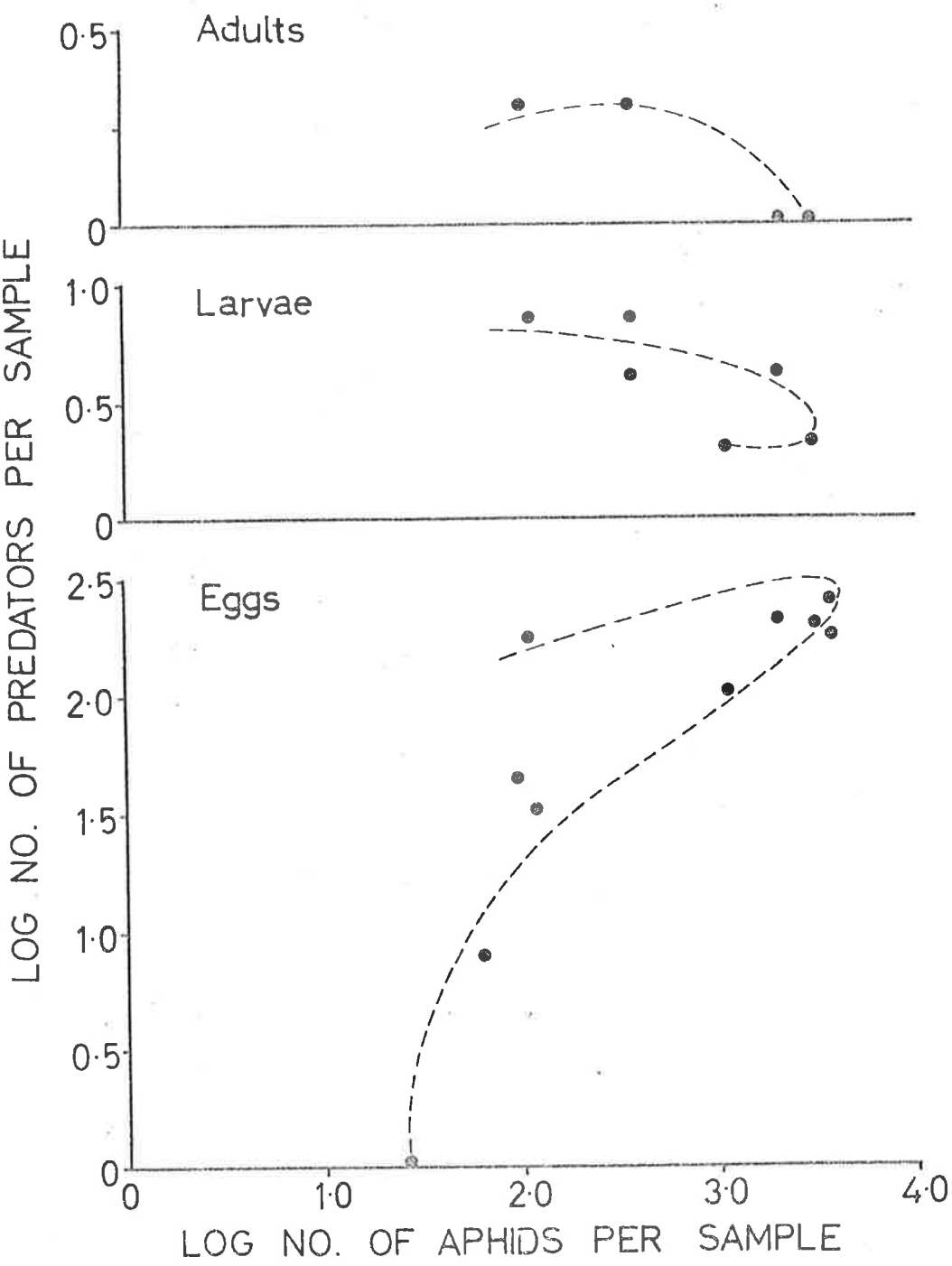
eggs, larvae and adults in relation to peak numbers of *M. persicae*. And when the data are plotted as Moran curves (Fig. 16), the relationship between predators and aphids is very similar to that obtained by Hughes (1963). However, at Milang in 1980, there was no obvious peak in *M. tasmaniae* eggs after the numbers of *M. persicae*, and there was apeak of larvae 3 weeks before the aphid peak. Indeed, it seemed that the aphids started to increase in numbers after the numbers of *M. tasmaniae* larvae had dropped. And when the data are plotted as Moran curves (Fig. 17) the relationship between predators and aphids is less obvious as that obtained in 1979.

The data at Waite Institute (Figs.14 & 15) were more consistent in that some of the peaks of *M. tasmaniae* eggs occurred in both years at, or just after, peaks of aphid abundance. The expected relationship between the predators and aphids with time-lags were also seen at the Waite Institute in 1979 (Fig. 18) and in 1980 (Fig. 19). And when the data are plotted as Moran curves, the relationship between predators and aphids is similar to that obtained by Hughes (1963).

The numbers of adult *M. tasmaniae* in February-May, 1979 (Fig. 14) were very low and appear to have no relation to the large number of eggs laid then. In March-June, 1980 again (Fig.15) very low numbers of adults as well as larvae of *M. tasmaniae* were found during peak numbers of aphids and seem to have had no relation to the large number of eggs laid then.

It is interesting to note that the shape of the Moran curves showed close similarity between the two years for each locality.

Figure 16: The time-lag relationships (on logarithmic scales) between the number of aphids (*M. persicae*) and the number of predators (eggs, larvae or adults of *M. tasmaniae*) at Milang for the 1978-79 period. The points along the curve represent the dates when the samples were taken.


Adults
Larvae
Eggs
0·5
0
1·0
0·5
0
2·5
2·0
1·5
1·0
0·5
0
0
1·0
2·0
3·0
4·0
LOG NO. OF PREDATORS PER SAMPLE
LOG NO. OF APHIDS PER SAMPLE

Fiugre 17: The time-lag relationships (on logarithmic scales) between the number of aphids (*M. persicae*) and the number of predators (eggs, larvae or adults of *M. tasmaniae*) at Milang for the 1979-80 period. The points along the curve represent the dates when the samples were taken.

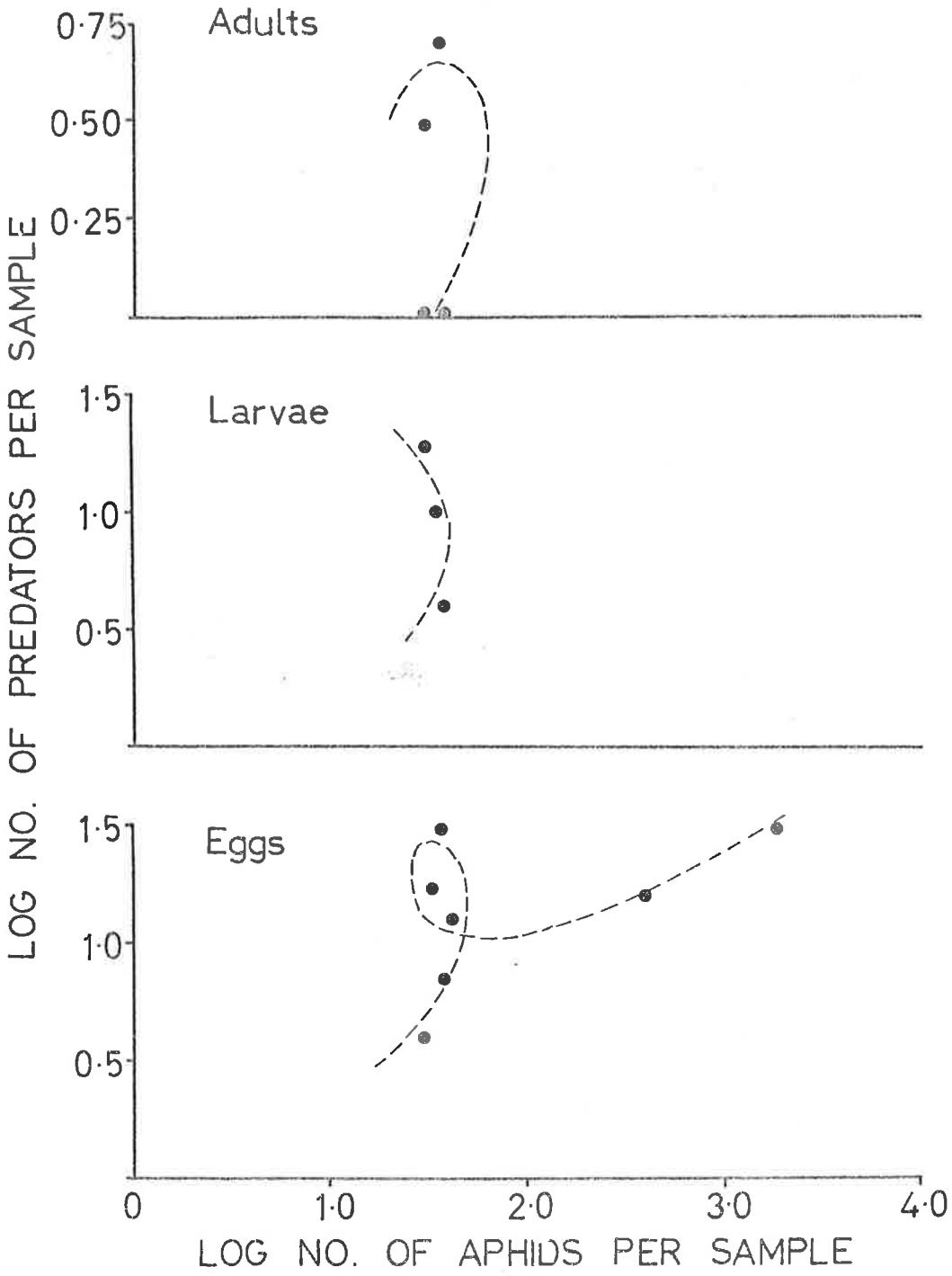

Adults
Larvae
Eggs
0·75
0·50
0·25
1·5
1·0
0·5
1·5
1·0
0·5
0
1·0
2·0
3·0
4·0
LOG NO. OF PREDATORS PER SAMPLE
LOG NO. OF APHIDS PER SAMPLE

Figure 18: The time-lag relationship (on logarithmic scales) between the number of aphids (*M. persicae*) and the number of predators (eggs, larvae or adults of *M. tasmaniae*) at Waite Institute for the 1978-79 period. The points along the curve represent the dates when the samples were taken.

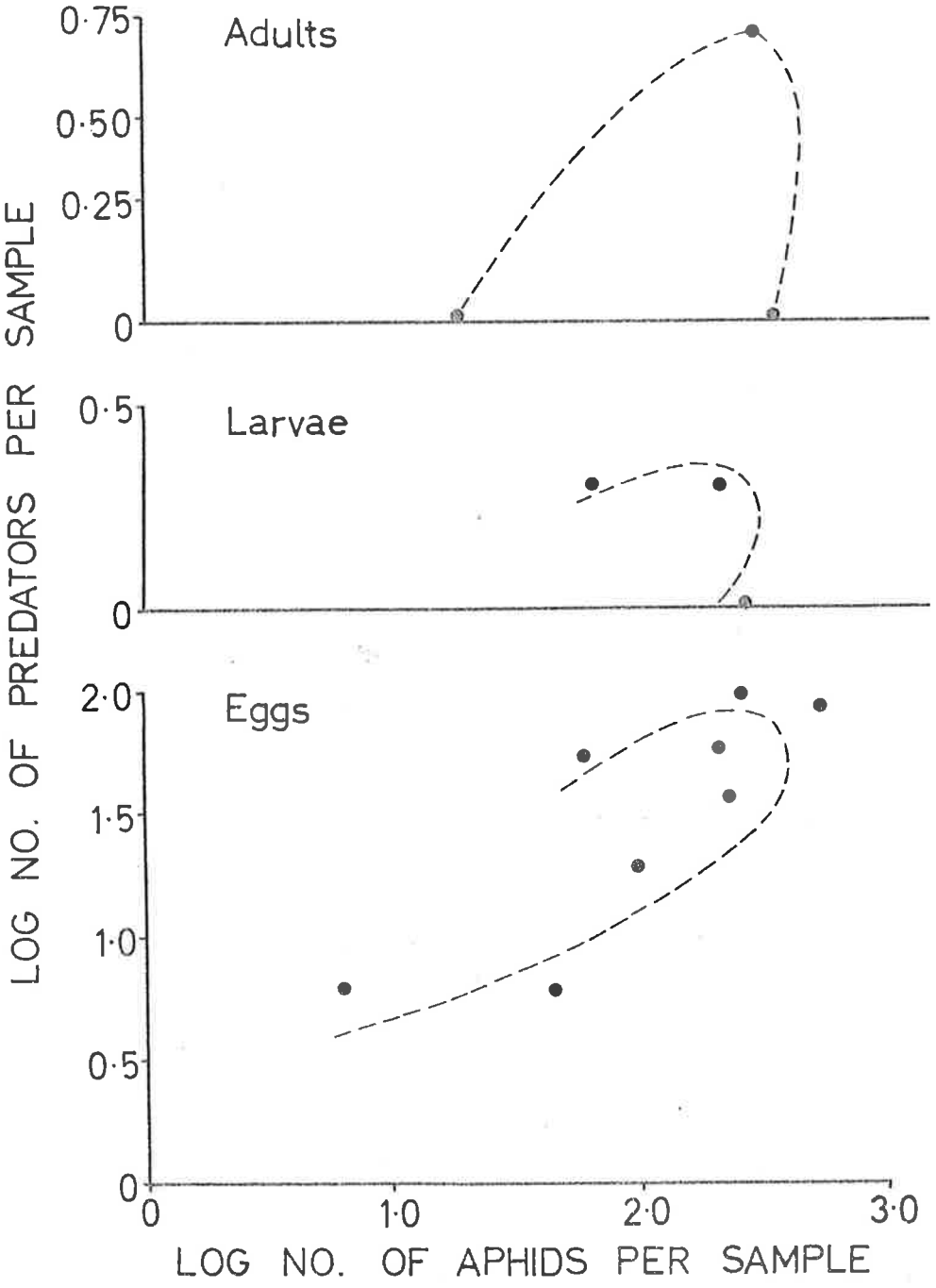
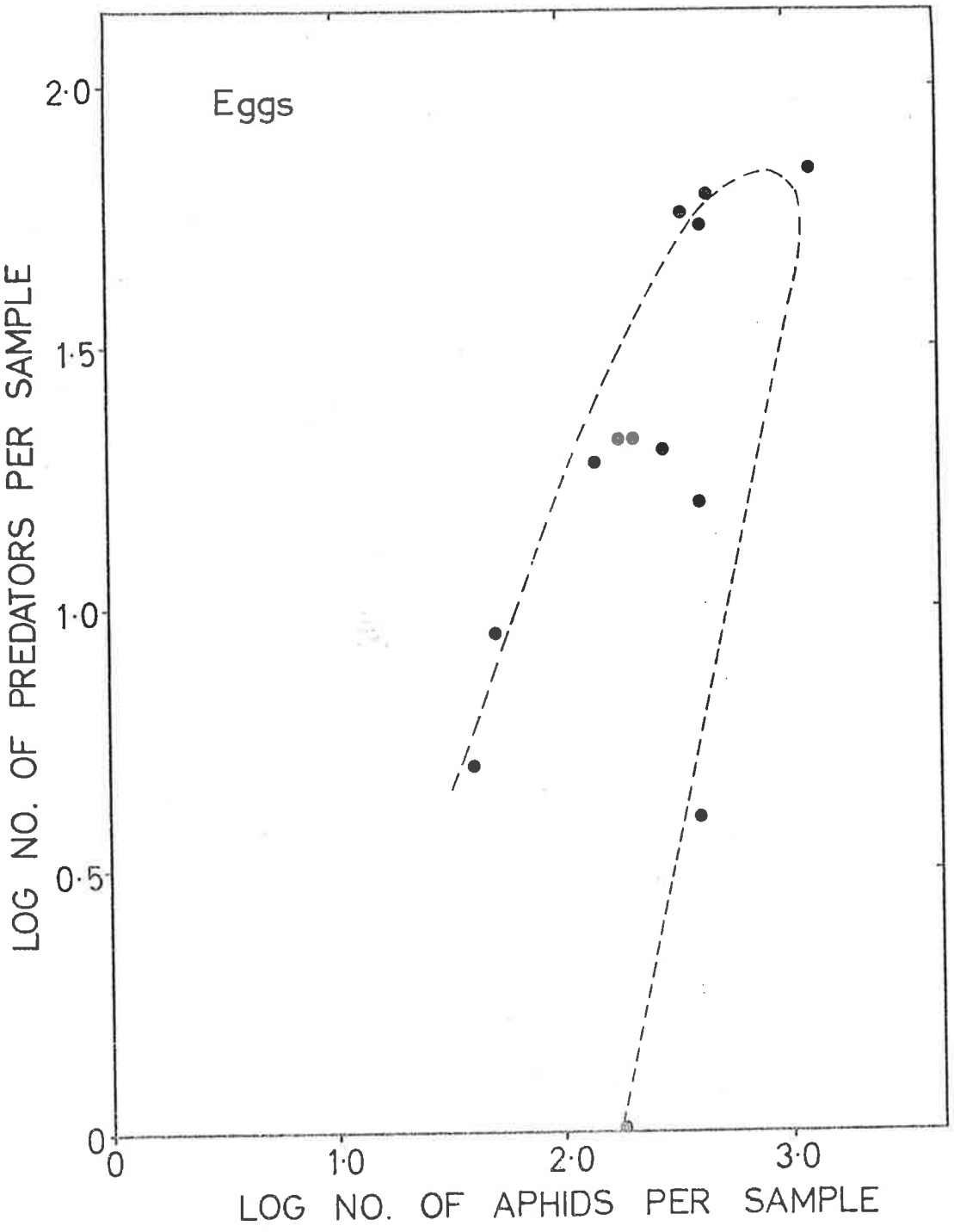

Adults
0·75
0·50
0·25
0
Larvae
0·5
0
Eggs
2·0
1·5
1·0
0·5
0
0
1·0
2·0
3·0
LOG NO. OF PREDATORS PER SAMPLE
LOG NO. OF APHIDS PER SAMPLE

Figure 19: The time-lag relationship (on logarithmic scale) between the number of aphids (*M. persicae*) and the number of predators (egg of *M. tasmaniae*) at Waite Institute for the 1979-80 period. The points along the curve represent the dates when the samples were taken.


Eggs
2·0
1·5
1·0
0·5
0
0
1·0
2·0
3·0
LOG NO. OF PREDATORS PER SAMPLE
LOG NO. OF APHIDS PER SAMPLE

Predators - Coccinellidae

Two species of Coccinellidae, *Coccinella repanda* (Thunberg) and *Leis confarmis* (Boisduval), are by far the most common coccinellid predators in potato fields at Milang and Waite Institute. The two species are native to Australia, but *Coccinella repanda* also occurs in Southern Asia (Hodek, 1967) and has not previously been reported as a predator of aphids on potatoes there. They are both considered important predators of *Heliothis* sp. in cotton in Queensland (Bishop and Blood, 1972). *C. repanda* is usually the most abundant predator in lucerne (*Medicago sativa*) fields in Australia (Waters and Dominiak, 1978; Bower and Thwaite, 1978; Brieze-Stegeman, 1978; Ridland and Berg, 1978; Forrester, 1978; Bishop *et al.*, 1980). However *L. conformis* is the major predator of rose aphids in South Australia (Maelzer, 1977) and of *M. persicae* on peaches in Victoria (Wilson, 1960).

In this study, the trends in numbers of *C. repanda* and *L. conformis* were slightly different in the unsprayed fields at Milang (Figs. 9 & 10) and in small potato plots at Waite Institute (Figs. 7 & 8). Even though numbers of coccinellids present may be related to the abundance of aphids, the total number of coccinellids was generally small in spite of the abundant supply of food to prey on.

The reverse situation was observed in small plots at the Waite Institute in which coccinellid numbers were higher and reached their peaks in early spring and only small numbers of coccinellids occurred during peak population of *M. persicae* in the autumn in both crop periods (Figs. 7 & 8).

The two factors most likely to influence coccinellid numbers are mean temperature and the availability of food. Many coccinellid species are known to be better able to control aphid populations at higher temperatures (Dunn, 1952; Hagen and van den Bosch, 1968; Maelzer, 1981); and the low numbers of coccinellids in potato fields in summer is probably due to a lack of available prey. By contrast, food is not limiting in the autumn but mean temperatures are then much lower and are probably the major constraint on the rate of increase of the coccinellids.

The slower overall rate of increase in numbers of coccinellids is explained by the fact that the thermal thresholds of development of predators are generally higher than those of their aphid prey with the exception of certain hemerobiid predators (Neuenschwander, 1975). The lower threshold for development of *M. persicae* is 6°C (Broadbent, 1953) whereas for eggs of *C. repanda* (Milne, 1978) and for eggs of *L. conformis* (Maelzer, 1981) it is 15°C. Since coccinellid populations encountered during this survey were generally very small, it is doubtful that they can be profitably ~~manipulated~~ managed and attention was concentrated on manipulating numbers of *M. tasmaniae*.

Predators - Chrysopidae

Chrysopa spp. have been previously reported as important predators of *M. persicae* on potatoes (Shands *et al.*, 1972e). They are also important predators of other aphids and of eggs and small larvae of lepidopterous insects.

The green lacewing, *Chrysopa signata* (Schneider) is the most common chrysopid predator of potato aphids found in this study. The trends in

numbers of total chrysopids shown in Figures 7-10 indicate that they were more abundant in spring and early summer but generally their numbers were rather small.

Slightly more chrysopids were recorded from small plots at Waite Institute as compared to large fields at Milang. The differences in the chrysopid populations at Milang and Waite Institute may have been due to the predators in the large fields relying heavily on one or two species of aphids found in the area. The presence of several species of aphids on many different host plants around the Waite Institute potato plots ensured a greater amount of honeydew and pollen available to the female chrysopids. Honeydew (Hagen *et al.*, 1970) and pollen (Sheldon and McLeod, 1971) have been reported to be essential to female chrysopids as a nutrient for egg production but the availability of sufficient honeydew depends on the presence of very high aphid populations. The aphid populations at Milang may have been too small to provide an adequate supply of honeydew for the predator populations to increase to large numbers. As a consequence, chrysopid populations were able to reach a relatively higher level at Waite Institute.

But, nevertheless, chrysopids were less numerous than have been reported in potato fields elsewhere e.g. in Maine, U.S.A. (Shands *at al.*, 1972e),in Italy and Switzerland (Mackauer and Way, 1976) and their relatively low numbers may have been due to the small population of aphids.

Predators - Syrphidae

Syrphids rank as major natural enemies of aphids on potatoes (Mackauer and Way, 1976), but there were found to be relatively unimportant as predators of potato aphids in this study. The relatively low numbers

of syrphids in potato fields at Milang and Waite Institute may have been due to a lack of pollen which is the main food of the adult syrphids for ovigenesis (Banks, 1959; Barlow, 1961).

All the syrphids belonged to the one species, *Melangyna viridiceps*, a native predator. This species was reported by Maelzer (1977) as one of the major predators of rose aphids in the spring in South Australia. Very little is known about its ecology and role in controlling aphid infestations in Australia.

Parasites

The only parasite recovered from parasitized mummies of aphids (mainly *M. persicae*) is in potato fields in this study was *Diaeretiella rapae* (McIntosch) (Fam. Braconidae). Two species of hyperparasites were recovered, namely *Phaenoglyphis* sp. (Fam. Cynipidae) and *Dendrocerus* sp. (Fam. Ceraphronidae), from mummified *M. persicae*. *D. rapae* has been recorded as a parasite of *M. persicae* from all the mainland states (excluding Northern Territory) of Australia, New Zealand, Hawaii, North and South America, Europe and Africa (Dr. I. Naumann, person. comm.).

The seasonal abundance of parasites (expressed as mummies) as shown in Figure 9 for Milang and in Figures 7 and 8 for Waite Institute. In general, parasitized aphids or mummies comprised an average of 6.6% in the 1978-79 and 0% in the 1979-80 crop period at Milang while at Waite Institute they comprised 7.3% (1978-79) and 13.2% (1979-80) of the total population. In spite of some variation between crop periods and localities in the number of mummies counted, the abundance of parasites seemed to be closely related to the aphid population peaks at Waite Institute potato plots. At Miland, the peak in parasite abundance

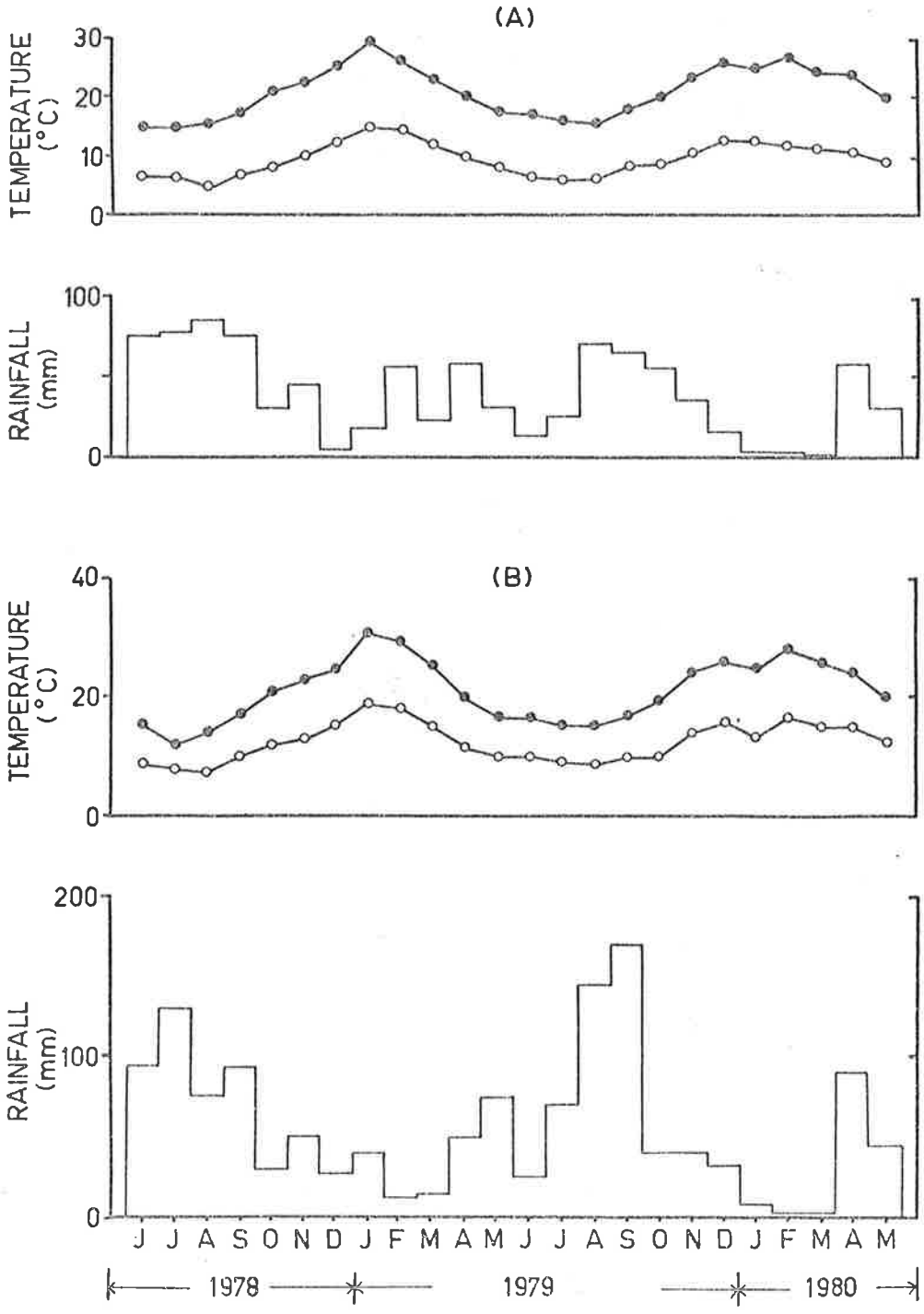
occurred after the peak in aphid populations in 1978-79 crop period, but in the 1979-80 period parasites were virtually absent.

The data in this study indicate that parasitism of potato aphids in untreated fields during the two-year period (1978-80) was neither consistent from year to year nor particularly common. Shands *et al.* (1972) arrived at a similar conclusion from the data they obtained during a 12-year period of study.

Entomogenous fungi

Figures 7, 8 and 9 show, at both localities, the magnitude of the relative abundance of the dead and diseased *M. persicae* over the two-year period on the field-growing potato plants not treated with insecticides. The fungus isolated from field specimens of *M. persicae* was identified as *Entomopthora sp.* (= *Zoopthora* sp. as from May 1981) (Dr. D.E. Pinnock, person. comm.). The data indicate that in autumn (March-May) 1979 the occurrence of fungal infection was relatively low (11.7%) at Waite Institute and that there was no infection at Milang. By contrast, in autumn 1978 38.6% and 44.4% of the aphids were infected at Milang and Waite Institute respectively. Since the development of entomogenous fungi for the initial establishment of the disease in the field is dependent on the weather, and in particulary on heavy and frequent rain (Ullyett and Schonken, 1940; Shands *et al.*, 1963), the relationship of incidence of fungal infection with rainfall was examined. At both localities, the total rainfall for March, April and May was lower in 1980 (91 mm for Miland and 119 mm for Waite Institute) than in 1979 (117 mm for Milang and 143 mm for Waite Institute) (Fig. 20), and there was a lower fungal incidence in 1979 than in 1978.

Figure 20: Climate in the two localities (A - Milang, B - Waite Institute):
Black circles and white circles show monthly mean maximum and minimum temperature respectively.
White bars indicate total monthly rainfall.


(A)
TEMPERATURE (°C)
30
20
10
0
RAINFALL (mm)
100
0
(B)
TEMPERATURE (°C)
40
20
0
RAINFALL (mm)
200
100
0
J J A S O N D J F M A M J J A S O N D J F M A M
1978
1979
1980

Other natural enemies

Other natural enemies such as birds, spiders, predaceous hemipterans and other predaceous dipterans were rarely observed and their numbers were too few and presumed to have negligible impacts on the populations of potato aphids. Nevertheless, these natural enemies have been known to suppress aphid populations including *M. persicae* in other parts of the world (Hagen and van den Bosch, 1968; Mackauer and Way, 1976).

Dispersion of aphids during further development of populations

In late summer the invasion of potato crops by migrant forms of *M. persicae* was followed by a rapid multiplication of the aphid population. The frequency distributions of aphids per leaf quickly diverged then from a Poisson series, indicating a non-random or "clumped" distribution of the population. This development of the distribution pattern of aphids has been well studied by Bald *et al.* (1953). There is little doubt that a similar pattern of development occurred for the aphids in this study.

Each sample that was taken was stratified so that, at any sampling time, differences in the number of aphids on upper, middle and lower leaves could be tested by an analysis of variance. In the early stages of infestation of the crop, aphids were most numerous on the lower leaves (Tables 16. 17 and 18), suggesting that the alate *M. persicae* settled in largest numbers on such leaves. Later there was a tendency for aphid numbers to be equal on lower and middle leaves but still fewer on upper leaves.

Table 16: Summary of the analyses of variances of the distribution of apterous *M. persicae* on upper, middle and lower leaves of potato plants in the unsprayed and sprayed fields at various sampling dates at Milang during the 1978-79 period.

Sampling date	Mean no. of aphids/leaf			F	P
	Upper	Middle	Lower		
Unsprayed fields:					
26 Mar. 1979	0.2	0.6	2.2	3.73	<.05
2 Apr. 1979	3.0	13.0	15.2	9.49	<.05
10 Apr. 1979	18.2	29.6	44.3	1.29	>.05
17 Apr. 1979	10.6	19.2	34.6	1.47	>.05
23 Apr. 1979	2.3	5.2	4.6	0.74	>.05
30 Apr. 1979	3.5	5.0	2.8	0.36	>.05
Sprayed fields:					
26 Mar. 1979	2.4	12.0	37.4	25.15	<.01
2 Apr. 1979	7.4	23.5	31.1	6.81	<.01
10 Apr. 1979	30.0	61.5	102.9	11.15	<.01
17 Apr. 1979	15.9	47.5	75.5	8.48	<.01
23 Apr. 1979	24.5	57.4	56.5	5.98	<.01
30 Apr. 1979	31.4	63.9	42.3	3.15	<.05
7 May 1979	24.3	26.1	17.3	0.38	>.05

Table 17: Summary of the analyses of variances of the distribution of apterous *M. persicae* on upper, middle and lower leaves of potato plants in the unsprayed and sprayed fields at various sampling dates at Milang during the 1979-80 period

Sampling date	Mean no. of aphids/leaf			F	P
	Upper	Middle	Lower		
Unsprayed fields:					
17 Mar. 1980	0.1	0.1	1.0	3.16	<.05
24 Mar. 1980	0.2	0.1	0.8	0.79	>.05
31 Mar. 1980	0.2	0.3	0.5	0.29	>.05
4 Apr. 1980	0.6	2.8	8.5	4.44	<.05
14 Apr. 1980	6.9	24.5	21.1	2.71	>.05
Sprayed fields:					
24 Mar. 1980	0.2	0.4	0.6	2.80	>.05
31 Mar. 1980	0.7	2.2	7.3	8.61	<.01
7 Apr. 1980	1.6	6.4	12.0	8.47	<.01
14 Apr. 1980	16.2	45.4	56.5	8.23	<.01
22 Apr. 1980	203.1	291.3	209.3	1.84	>.05
28 Apr. 1980	158.4	193.0	171.2	0.10	>.05

Table 18: Summary of the analyses of variances of the distribution of apterous *M. persicae* on upper, middle and lower leaves of potato plants in the unsprayed plots at various sampling dates at Waite Institute during the 1978-79 and 1979-80 period.

Sampling date	Mean no. of aphids/leaf			F	P
	Upper	Middle	Lower		
1978-1979:					
8 Mar. 1979	0.1	1.2	1.1	4.52	<.05
15 Mar. 1979	0.6	1.4	3.5	6.07	<.01
22 Mar. 1979	2.1	5.5	6.2	2.79	>.05
29 Mar. 1979	0.5	2.8	0.6	3.02	>.05
5 Apr. 1979	7.5	1.0	1.5	1.42	>.05
13 Apr. 1979	1.8	6.1	11.9	3.72	<.05
26 Apr. 1979	2.8	16.1	12.1	2.45	>.05
1979-1980:					
27 Mar. 1980	0.8	2.1	1.8	2.50	<.05
3 Apr. 1980	3.1	6.6	10.1	6.46	<.01
10 Apr. 1980	4.1	6.4	10.2	6.61	<.01
17 Apr. 1980	2.9	9.2	12.2	15.35	<.01
24 Apr. 1980	2.0	4.7	7.6	4.94	<.05
1 May 1980	8.1	19.8	18.6	2.97	>.05
8 May 1980	4.7	7.1	6.7	0.51	>.05

These results indicate that there is a considerable heterogeneity in the distribution of the aphid population on different parts of the plant. In relation to such heterogeneity, Bald *et al.* (1950) suggested (i) a negative correlation between the activity of aphid vectors and heterogeneity of theaphid population and (ii) a positive correlation between the activity of aphid vectors and the probability of the aphid causing leaf roll infection. Bald *et al.* (1950) believed that the less favourable the conditions such as overcrowding or poor nutritive value of leaves, the more likely were the aphids to move and wander; and provided they could feed on diseased tissues and become infective, the more likely they were to act as vectors.

Therefore, it is important that the method of sampling takes into consideration the heterogeneity in the distribution of aphids in different parts of the plant.

Sampling precision and optimum sample size

Analyses of the frequency distributions of aphids at Milang and Waite Institute by the χ^2 (Chi-square) goodness-of-fit tests showed that the distributions could be fitted by the negative binomial model in most cases (8 out of 12 sampling dates for Waite Institute and 7 out of 11 dates for Milang) at $P<.05$. The value of the parameter k of the negative binomial distribution for each sample was obtained by the method of maximum likelihood estimate (Fisher, 1953). For the calculation of optimum sample sizes a common k was computed using Anscombe's T method (Anscombe, 1949; Harcourt, 1963). Optimum sample sizes were based on the statistics of the negative binomial distribution and with the coefficient of variability used as the estimation error (Anscombe, 1948) or precision parameter

(Simonet and Pienwoski, 1979). The formula:

$$N = \frac{\frac{1}{m} + \frac{1}{k}}{E^2}$$ (Karandinos, 1976; Southwood, 1978)

was used to estimate the optimum sample size; where N = the number of leaves required, m = the sample mean, k = the dispersion parameter and E = the estimation error expressed as a decimal equivalent of the coefficient of variability. Tables 19 and 20 show the estimation errors of sampling aphids on potatoes using the 3-leaf method at Miland and Waite Institute respectively. A different k value for each sampling date was used to calculate the estimation error (E). Figures 21 and 22 show the estimates of optimum sample size (number of compound leaves) for *M. persicae* infesting potato plants in large fields at Milang (Figure 21) and in small plots at Waite Institute using common k values of 1.25 (for Milang) and 1.70 (for Waite Institute).

These curves indicate that the sample size used in the population survey (namely 99 leaves per field at Milang and 30-60 leaves per plot at Waite Institute) gave estimates of the mean number of aphids per leaf that were accurate with 20% C.V for populations of more than 0.4 aphids per leaf (for Milang) and for more than 0.5 aphid per leaf (for Waite Institute). They also indicate that the sampling precisions of 0.10 and 0.05 recommended by Southwood (1966) and (1978) respectively, usually entail sample sizes that are so large that they are impossible to obtain in practice; more usually a precision of 0.30 or so may be regarded as adequate (Maelzer, 1982).

Table 19: Estimation errors in relation to the number of leaves examined and mean number of *M. persicae* per leaf at various sampling dates for Milang during the 2-year period (1978-80).

Sampling date	Field	Mean number of aphids per leaf	Number of leaves examined	k	Estimation error (E)
26 Mar. 1979	A2	0.96	120	0.37	0.18
2 Apr. 1979	A2	8.93	102	0.39	0.16
10 Apr. 1979	A2	30.56	99	0.81	0.11
17 Apr. 1979	A2	20.69	99	0.68	0.12
23 Apr. 1979	A2	3.67	99	0.22	0.22
26 Mar. 1979	C	17.00	99	1.53	0.08
17 Apr. 1979	C	43.27	99	1.79	0.08
7 Apr. 1980	F	0.89	99	0.17	0.27
14 Apr. 1980	F	17.74	99	0.70	0.12
7 Apr. 1980	G	6.68	99	0.86	0.11
14 Apr. 1980	G	39.42	99	0.47	0.15

Table 20: Estimation errors in relation to the number of leaves examined and mean number of *M. persicae* per leaf at various sampling dates for Waite Institute during the 2-year period (1978-80)

Sampling date	Plot	Mean number of aphids per leaf	Number of leaves examined	k	Estimation error (E)
29 Mar. 1979	A2	10.20	51	1.79	0.11
5 Apr. 1979	A2	4.86	51	0.53	0.20
3 May 1979	B2	6.51	51	1.20	0.14
17 May 1979	B2	5.61	51	2.01	0.10
1 May 1980	I	15.37	60	1.09	0.13
8 May 1980	I	5.93	60	4.38	0.08
15 May 1980	I	4.67	60	0.93	0.15
8 May 1980	J	3.92	60	2.63	0.10
15 May 1980	J	4.07	60	0.99	0.14
22 May 1980	J	3.40	60	1.12	0.14
29 May 1980	J	2.63	60	0.60	0.18
5 June 1980	J	2.20	60	1.15	0.15

Figure 21: Estimation of optimum sample size for *M. persicae* on potatoes at Milang based on a common k value of 1.25.

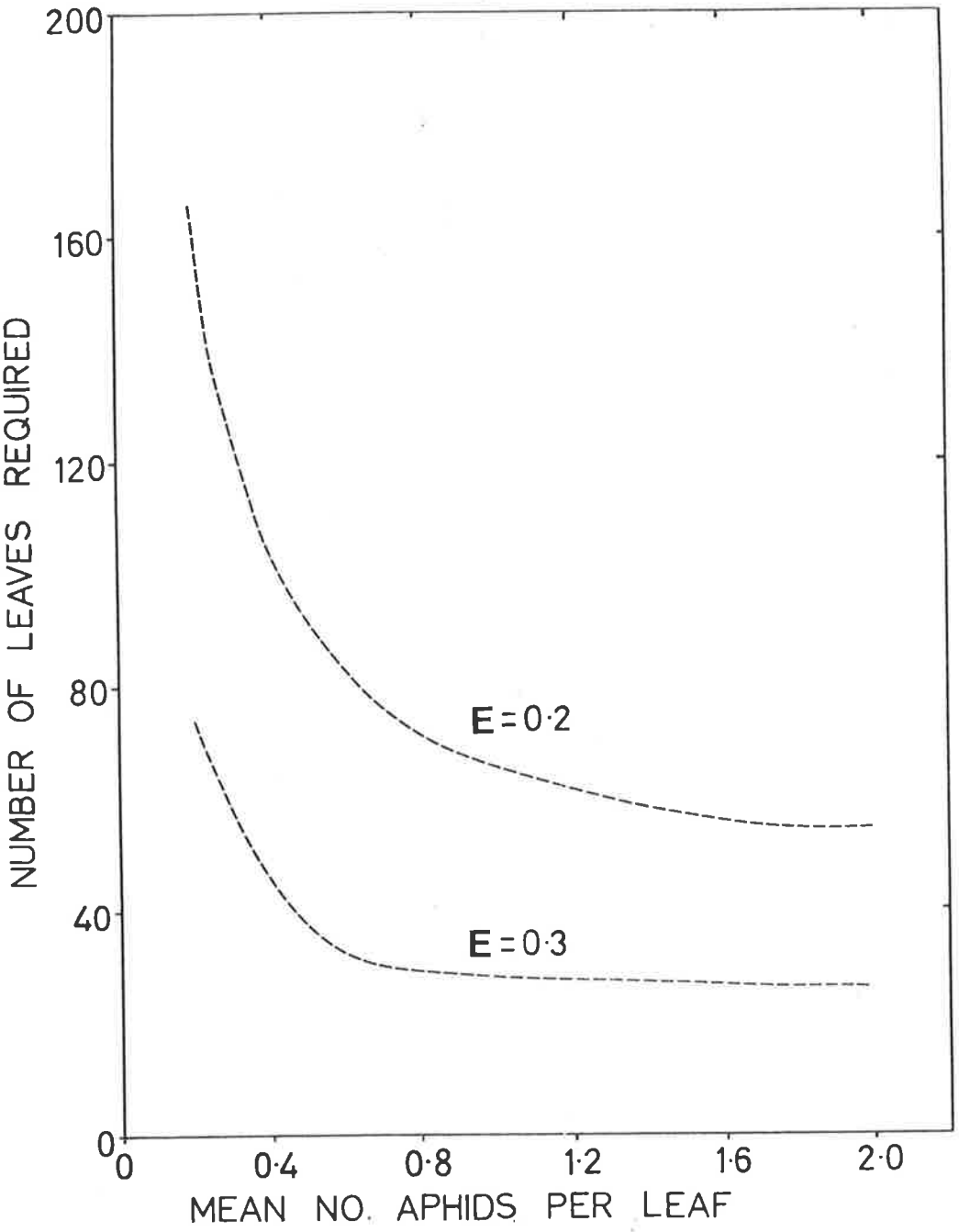
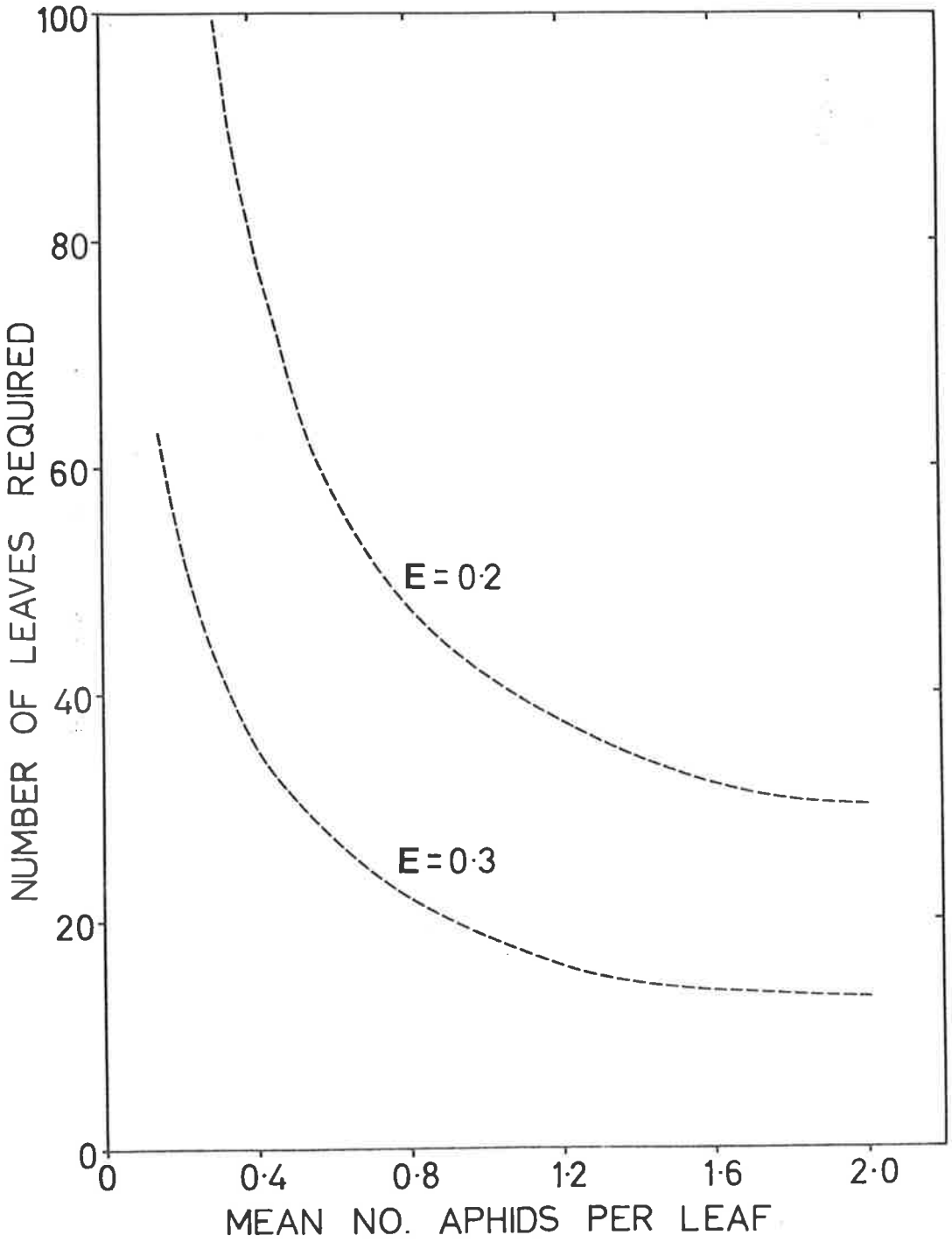

200
160
120
80
40
0
NUMBER OF LEAVES REQUIRED
E = 0·2
E = 0·3
0
0·4
0·8
1·2
1·6
2·0
MEAN NO. APHIDS PER LEAF

Figure 22: Estimation of optimum sample size for *M. persicae* on potatoes at Waite Institute based on a common k value of 1.70.


100
80
60
40
20
0
NUMBER OF LEAVES REQUIRED
E = 0·2
E = 0·3
0
0·4
0·8
1·2
1·6
2·0
MEAN NO. APHIDS PER LEAF

Impact of natural enemies on seasonal abundance of *M. persicae* on potatoes

The data in this study suggest tht the whole natural enemy complex was able to suppress the spring peak of *M. persicae* in potato fields in each of the 2 years of the study. The aphid has the potential to increase to much higher numbers and, indeed, its numbers were observed to be 3-15 fold higher in potato fields which were treated with insecticides. The effects of insecticide applications on both the natural enemy and aphid population will be discussed in the later

Suppression of potato aphid populations, mainly *M. persicae*, observed in spring of 1979 and 1980 at Milang, and in spring of 1980 at Waite Institute may be attributed to predators' actions. The aphid populations declined after the autumn peak in both periods and at both locations; these declines are probably mainly due to the increasing unfavourability of weather and its influence on the quality of the host plants (Hughes, 1963). A portion of the decline may have been due to the actions of natural enemies (Shands *et al.*, 1972e) and to the emigration of alate aphids from potato fields (van Emden *et al.*, 1969).

As is evident in Figure 7, a small peak of *M. persicae* was observed in the Waite Institute plots in spring (September-October) 1978 but not in spring 1979. I attribute the peak in spring 1978 to the influx of spring migrants of *M. persicae* which were flying from their winter hosts, especially peaches, to the nearby potato plants. The main source of the spring migrants was a block of peach trees in the vicinity of the potato plots. However, in the following summer (February, 1979), all the peach trees were cut down and removed. This removal was probably the main factor

which resulted in the disappearance of the spring peak of *M. persicae* at the Waite Institute.

Comparisons of the phenologies of the different groups of predator (Figs. 7-10) show clearly that predation by the hemerobiid, *M. tasmaniae*, is the most important, especially in the spring. *M. tasmaniae* was present in the potato fields at both localities almost all the year round with the peaks of the different stages in the life cycle occurring in succession. Not only did *M. tasmaniae* appear to be the most abundant, it was also the predator that appeared earliest in the potato fields in spring and the last to disappear in late autumn. The importance of early season predation on slowly developing aphid populations has been judged by many authors to be of great significance in delaying or preventing pest outbreaks (e.g. Neuenschwander *et al.*, 1975).

The predators seemed to be unable to prevent aphid populations increasing rapidly to a high peak in numbers in April-May. During this period the weather tended to favour the aphids more than the predators; at the lower temperature then prevailing, the predators developed more slowly, especially the coccinellids, chrysopids and syrphids which have higher thermal threshold for development than hemerobiids (Neuenschwander *et al.*, 1975; Samson and Blood, 1979). In contrast to early incidence and abundance in spring, *M. tasmaniae* appeared late in autumn each year and in relatively small numbers; suggesting that it has difficulty in surviving the hot Australian summer - at least in or near the potato fields. Similarly, coccinellids have been known to disappear in hot summer (Neuenschwander *et al.*, 1975).

Syrphid larvae were not important in the years covered by this study in the two localities, in contrast to their importance in many crops overseas (Tamaki *et al.*, 1967; Hagen and van den Bosch, 1968). The low abundance of syrphids in the study fields may have been due to the size and uniformity of the fields, particularly at Milang, which have little attraction to the pollen-feeding syrphid adults (Banks, 1959; Bombosch, 1966; Galeka, 1966).

The green lacewing, *Chrysopa* sp. became important in late spring and summer when coccinellid and syrphid numbers were beginning to decline. The coccinellids may then have been leaving the field because of diapause induction (Neuenschwander *et al.*, 1975).

In contrast to predators, parasites were of little importance in either of the two localities in the 2 years of study. Overall, parasitism of *M. persicae* never reached 50 aphids / 99 leaves.

Other causes of death included fungus diseases occurred irregularly, though they may have contributed to the aphid population crash in 1978-79 season at both localities. On the mediterranean-like climate which is typical in most parts of South Australia, the small impact of fungus on aphid populations is to be expected (Voronina, 1971).

Effects of insecticidal applications on aphids and natural enemies

In the 1978-79 crop period, aphids and natural enemies were sampled from untreated and insecticide-treated fields simultaneously from March 3, 1979 to May 7, 1979. In the 1979-80 period, similar samples were taken from March 10, 1980 to May 6, 1980. In 1978-79 the treated and untreated

fields were separated by a distance of 0.5 km whereas in 1979-80 the two fields were separated by a distance of only 100 m.

Results showing the trends in the numbers of *M. persicae*, and eggs, larvae and adults *M. tasmaniae* are shown in Figures 23 and 25. The numbers of other predators are not included because their numbers are comparatively very low. Figure 23 shows that the numbers of *M. persicae* were higher in the sprayed fields than in the unsprayed fields in both the 1978-79 period (2-fold difference at the peaks) and the 1979-80 period (13-fold difference at the peaks). The numbers of *M. tasmaniae* eggs and larvae were also higher in the unsprayed field in the 1978-79 season, while numbers of adult *M. tasmaniae* were almost equal. However, in the 1979-80 season, the situations were reversed, whereby *M. tasmaniae* eggs in the unsprayed field were fewer than those in the sprayed field. By contrast, the number of *M. tasmaniae* larvae in the unsprayed field far exceeded those in the sprayed field before the aphid populations begin to increase. No larvae were found in either field in subsequent samples. Adults of *M. tasmaniae* were generally found in low numbers in the early stages of infestation in both fields. Adults were not found in either field immediately after the insecticides were applied but they were found again in the sprayed field after the aphid numbers had passed their peak.

The evidence seems to indicate that there was an adverse effect of the insecticide application on the abundance of *M. persicae* and its predator, *M. tasmaniae*. The large number of eggs of *M. tasmaniae* found in the sprayed field during the 1979-80 period before the application of insecticide may be explained by the fact that, in the sprayed field, food for the surviving predators was plentiful and so the adult female predators were able to lay many eggs. Similarly, as the toxic effects of

Figure 23: Effects of insecticide application on abundance of *M. persicae* (per 99 leaves) and eggs (per 99 leaves), larvae and adults (per 33 plants) of *M. tasmaniae* at Milang during the 1978-79 and 1979-80 period.

●—● (Sprayed)

o--o (Unsprayed)

■ (Sprayed)

□ (Unsprayed)

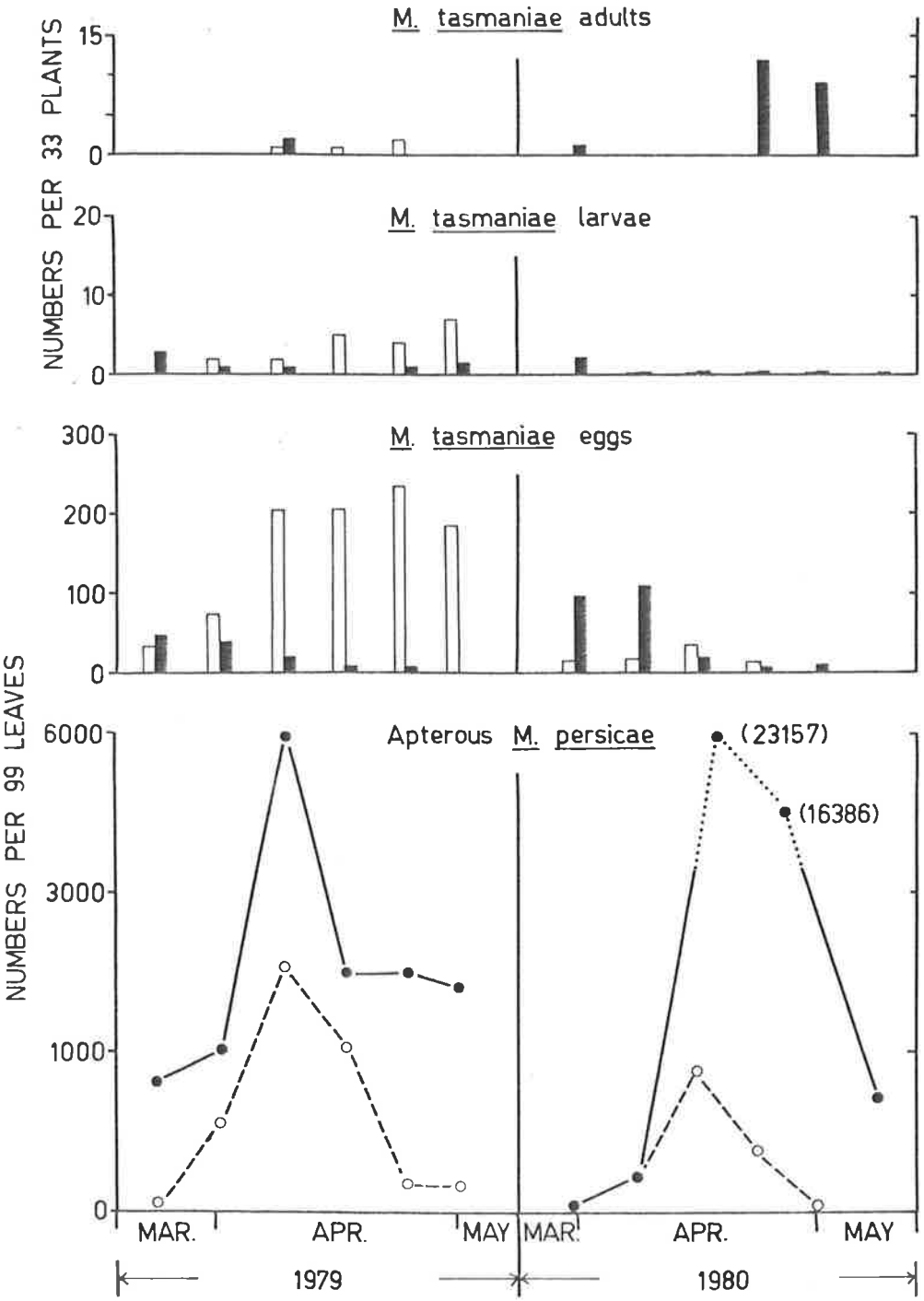
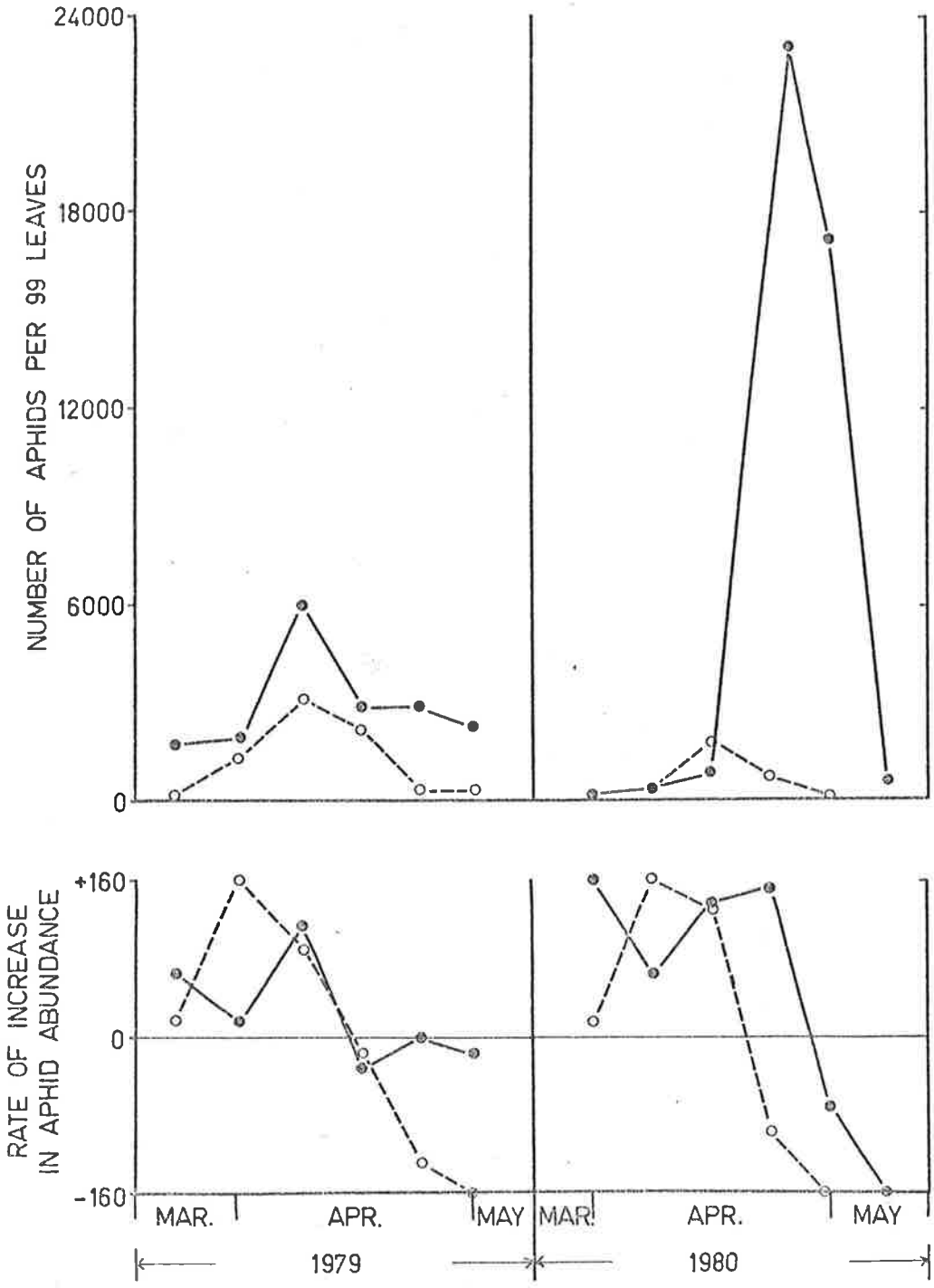

M. tasmaniae adults
M. tasmaniae larvae
M. tasmaniae eggs
Apterous M. persicae
(23157)
(16386)
NUMBERS PER 33 PLANTS
NUMBERS PER 99 LEAVES
15
0
20
10
0
300
200
100
0
6000
3000
1000
0
MAR.
APR.
MAY
MAR.
APR.
MAY
1979
1980

Figure 24: Relationship between the rate of increase in abundance and the abundance of aphids *(M. persicae)* at Milang during the 1978-79 and 1979-80 period.

●——● (Sprayed)

o--o (Unsprayed)


24000
18000
12000
6000
0
NUMBER OF APHIDS PER 99 LEAVES
+160
0
-160
RATE OF INCREASE IN APHID ABUNDANCE
MAR.
APR.
MAY
MAR.
APR.
MAY
1979
1980

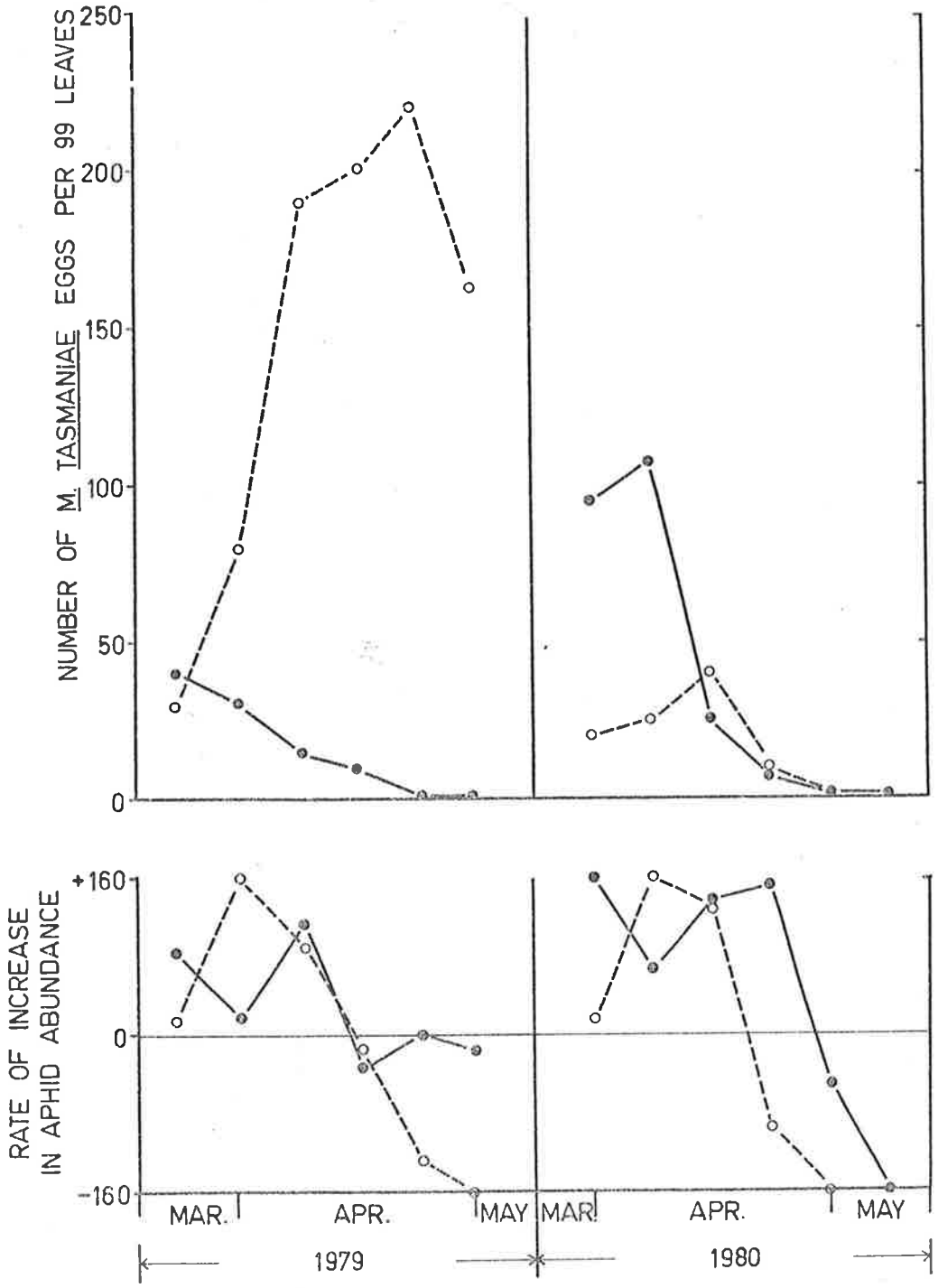
the insecticide deteriorated and at the same time food for the predator was still abundant, the predator populations increased as reflected by the high numbers of adult *M. tasmaniae* sampled in the sprayed field after the peak infestation periods.

Figure 24 presents the relationship between the abundance of *M. persicae* and the rate of increase in abundance of *M. persicae*. The value of the rate of increase in aphid abundance (P) was calculated as described in Section 4.2. The P values calculated at weekly intervals show some variation due to the fact that aphids, like *M. persicae*, are a material of great pasticity (Galecka, 1966). However, their general trends in the 1978-79 and 1979-80 crop periods appear to be similar. In the unsprayed field each trend is characterised by a rapid fall following a sharp rise. The lowering of the rate of increase in aphid abundance began when the P value was still positive. In the unsprayed field the lowering of rate of increase occurred when the abundance of *M. persicae* was still on the increase, whereas in the sprayed field, it occurred after the populations had begun to decline. The values (P) of the rate of increase in aphid abundance in the sprayed field is characterised by a slight decrease at first, then an increase and finally a very rapid fall. The rate of increase in aphid abundance may be used as a measure of the intensity of the actions of predators, mainly *M. tasmaniae* , as the population reducing factor. The relationship between the rate of increase of *M. persicae* abundance and the abundance of *M. tasmaniae* eggs ~~are~~ is shown in Figure 25. The regularity of the trends in numbers of *M. tasmaniae* eggs was observed during the 1978-79 and 1979-80 periods, even though the weather was slightly different each year.

Figure 25: Relationship between the abundance of predator (*M. tasmaniae*) eggs and the rate of increase in abundance of aphids *(M. persicae)* at Milang during the 1978-79 and 1979-80 period.

●——● (Sprayed)

O - - O (Unsprayed)


NUMBER OF M. TASMANIAE EGGS PER 99 LEAVES
250
200
150
100
50
0
RATE OF INCREASE IN APHID ABUNDANCE
+160
0
-160
MAR.
APR.
MAY
MAR.
APR.
MAY
1979
1980

In the insecticide-treated field in 1978-79 (Field C), the populations of *M. persicae* were almost doubled as compared to the untreated field (Field A2). In 1979-80 (Field G), there was nearly 13 times more *M. persicae* at peak infestations in the sprayed field as compared to the unsprayed field (Field F). The big increase in *M. persicae* populations in 1979-80 resulted in 5 times more aphids compared to those experienced in 1978-79.

Discussion

The suppressive effects of natural enemies including predators every year over a period of ten years as reported by Shands *et al.* (1972e) for Maine, U.S.A. are no doubt correct, not only for Maine but also throughout much of the distribution range of *M. persicae* (van Emden *et al.*, 1969). However, where there was no obvious catastrophic mortality, almost the only conclusive evidence of the impact of natural enemies on *M. persicae* is provided by the outcomes of applying insecticides which selectively kill natural enemies (van Emden *et al.*, 1969). Evidence presented in this study have illustrated such an undesirable outcome.

Evidence of explosive increases in *M. persicae* populations offer treatment with insecticide have previously been reported by several authors overseas. Meier (1966) in Switzerland reported an 8-fold increase in *M. persicae* populations 6 days after treatment with carbaryl. Similarly, in Minnesota, U.S.A. greater ratio of increases in *M. persicae* populations which resulted in more than 10 times more *M. persicae* in the check populations were found (Radcliffe, 1973, 1973). Several reasons have been suggested by these workers. Among these are: a) the selective

elimination of natural enemies, or b) a lag in the establishment of natural enemies (Meier, 1966; Radcliffe, 1972, 1973) and c) resistance of aphids to the insecticides, particularly the organophosphorous compounds (Radcliffe, 1972, 1973; Hrdý, 1975). Either of these reasons may have been responsible for the adverse effects of insecticidal applications upon *M. persicae* populations in this study. On the other hand, very few studies have been conducted to determine the direct effects of insecticides on both predators and their prey (Croft and Brown, 1975). Insecticides may have caused adverse effects on *M. tasmaniae* found on potato fields in this study. The fact that, sometimes numbers of *M. tasmaniae* increase again after an apparent decline caused by insecticides is probably because some of the stages are more tolerant than others. This phenomenon has recently been investigated by Syrett and Penman (1980) who reported that larvae of *M. tasmaniae* were fifteen times more tolerant to insecticide fenvalerate than the adults.

Recent evidence by Syrett and Penman (1980) that adult *M. tasmaniae* were 60-120 times more tolerant to fenvalerate than the aphids gives *M. tasmaniae* a further advantage in an integrated control programme involving fenvalerate.

CHAPTER 5

PREDATOR-PREY RELATIONSHIP

Numerical changes in the population of prey and predators obtained from sampling data are difficult to interpret in the absence of any other knowledge of the biological and ecological characteristics of the predator-prey relationship. To help interpret the field data given in the previous chapter, therefore, a series of experiments were done in the laboratory to estimate some of the properties of the predators, especially *Micromus tasmaniae*, and to determine how weather (temperature, light and % relative humidity) influenced the preadtor-prey relationship.

The experiments were conducted either in constant temperature rooms or in plant growth cabinets and included an examination of the feeding habits of larvae of *M. tasmaniae* and the determination of their minimum food requirements, voracity and weight gain as they developed. Experiments were also done to measure the mobility, searching capability and efficiency of the larvae in relation to temperature and abundance of both prey and other predators.

5.1 Minimum food requirement for *M. tasmaniae* larvae

Introduction

All adult predators require to eat a minimum number of prey for egg production. A minimum number must also be eaten in the larval stages to provide the required nutrients and energy for maintenance, searching, growth and development (Hagen *et al.*, 1976). The number of biomass of prey

required for these functions depends in part upon the size of the predator (*ibid*).

The aim of this experiment was to determine the minimum quantity of aphids required for 50% and 100% survival for each larval instar of *M. tasmaniae* and the effects of food had on the duration of the larval instar.

Materials and Methods

An experiment was conducted in a 20°C room under 12:12 LD photophase. Eggs oviposited on the same day were individually transferred into a glass tube (50 mm long x 5 mm in diameter) by means of a soft camel's hair brush and were incubated at 25°C.

First instar *M. tasmaniae* was reared on treatment number of prey as given in Table 22, then reared on an adequate number of prey as second and third instars. Second instar *M. tasmaniae* was given a surfeit of food as first instar, then given the treatments as second instar, then given a surfeit of food against as third instar. Third instar *M. tasmaniae* was given a surfeit of food as first and second instars and then given the treatments as third instars.

Each larva was kept with the appropriate number of prey in a small plastic cage (38 mm diameter x 10 mm high) which consisted of a soft plastic top of a plastic vial fitted snugly into a clean plastic petri-dish. Aeration was provided by a 10 mm hole covered with fine mesh. Before the predator and the prey were placed inside the cage, the bottom of the case was lined with two layers of filter papers. A 35 mm diameter disc of potato leaf was then placed inside the cage and was kept fresh by regularly

wetting the filter papers with distilled water. Every 24 hours, the cages were opened and the number of aphids eaten by the larvae ~~were~~ was recorded. The surviving aphids were discarded and replaced with fresh ones. The leaf disc and the filter papers were replaced every alternate day.

The duration of each larval instar of *M. tasmaniae* for different food regimes was also measured by recording, each day, when each larva moulted.

Results and Discussion

The results are presented in Table 21. The numbers of third instar or third-instar equivalents of *M. persicae* required for survival of 50% of the preadator larvae were about 3.7 for first instars, between 3.7 and 6.6 for second instars and about 33.8 for third instars.

Suboptimal amounts of prey per day obviously influenced both the survival and the duration of development. Increase in the number of larvae surviving was observed when the feeding rate was increased. Similar results have been obtained for coccinellid predators when feeding on different species of aphids (Dixon, 1959 and 1970; Wratten, 1973). Also, the duration of each successive larval instar of *M. tasmaniae* was longer than that preceeded it. The same was true for coccinellid, *Adalia bipunctata (ibid)*.

It was of interest that the mean total number of aphids eaten during the stadium changed very little when the number of prey was increased from 2 to 3 or 4 per day but then about doubled for each larval instar when 12 prey were provided. In addition, for each instar, over all treatments

Table 21: The effect of the quantity of *M. persicae* provided each day upon survival and instar duration of *M. tasmaniae*.

No. of aphids provided each day	No. of larvae tested	No. of larvae surviving	Ave. total no. of aphids eaten and TIES[1] in brackets	Ave. instar duration (days ± S.E.)
First instar larvae:				
1	35	0	0	-
2 First	20	11	12.8 (3.7)	6.9 ± 0.73
3 instar	19	14	13.6 (3.8)	4.9 ± 0.36
4 aphids	13	11	14.2 (4.1)	3.7 ± 0.14
12	10	9	29.6 (8.5)	3.0 ± 0.00
Second instar larvae:				
1	8	3	3.7	5.0 ± 2.08
2 Third	7	7	6.6	3.2 ± 0.30
3 instar	5	5	8.4	3.0 ± 0.00
4 aphids	6	6	6.8	2.7 ± 0.21
12	5	5	13.2	2.0 ± 0.00
Third instar larvae:				
1	9	0	0	-
2 Third	10	6	33.8	16.2 ± 1.28
3 instar	7	7	23.9	8.3 ± 0.52
4 aphids	4	4	25.5	6.8 ± 0.48
12	5	5	52.4	3.8 ± 0.20

[1] TIES = Third Instar Equivalents (1 third instar *M. persicae* is equivalent to 3.5 first instars *M. persicae*).

in which the mortality of larvae was very low, the mean total number of prey eaten x duration of development was about constant. So it seems that the larvae of *M. tasmaniae* can complete their development at fairly low prey densities, and at these low prey densities they eat a total of about one half the number of prey that would be eaten if prey was abundant.

5.2 Growth and voracity of larvae of *M. tasmaniae*

Introduction

The feeding rate of a predator as measured by its voracity in each of its instars, is recognized as an important characteristic (Hodek *et al.*, 1972). The only previous work done on the voracity of *M. tasmaniae* is that of Samson and Blood (1980) who used *Heliothis punctigera* Wallengren as the prey. But although *M. tasmaniae* is an important and abundant predator of aphids on roses (Maelzer, 1977) and aphids on lucerne (Bishop *et al.*, 1980) its voracity on aphids has never been measured.

This experiment was conducted to determine the numbers of *M. persicae* of different instars that were consumed by larvae of *M. tasmaniae* in each stadium, and the influence of such consumption on the change in wet weight of the larvae.

Materials and Methods

The gain in weight and voracity were measured for seven *M. tasmaniae* larvae fed on first and second instar of *M. persicae* at 20 ± 2°C and under LD 11:11. Each larva was kept in a separate cage as described in Section 5.1 and fed a controlled surfeit of aphids every 24 hours. Each larva was weighed twice daily at 10.00 a.m. and 4.00 p.m. The number of

aphids it ate every 24 hours was recorded. Larvae were fed with 1st instar *M. persicae* during the first larval instar and with 3rd instar *M. persicae* during the 2nd and 3rd larval instars. A fresh surfeit of 15 1st instar aphids was given every 24 hours to 1st instar larvae while 15 and 30 3rd instar aphids were given to 2nd and 3rd instar larvae respectively. The uneaten aphids were discarded.

Results and Discussion

Table 22 gives the number of aphids of appropriate instar eaten by larvae throughout the larval developmental periods. Only one out of seven larvae failed to complete its development. Figure 26 shows the trend in mean weight of all larvae during their development. The trend is not linear and is better expressed as a series of smooth curves which have been drawn by eye. Similar trends in mean weight of a coccinellid predator, *Leis conformis*, at 20°C has been observed by Maelzer (1978). Small decreases in the slope of the curves at day 2, 4 and 7.5 coincided with the moulting period to the next instar and the change to prepupae (Maelzer, 1978). It can be seen from Figure 22 and Table 23 that the voracity of larvae of *M. tasmaniae* similarly decreased before a moult as do other predators (Hodek, 1973). Therefore, the capture efficiency of *M. tasmaniae* is expected to vary with the stage of development of the predator within the stadium.

Figure 26: Weight of larvae of *M. tasmaniae* during development at $20^{o} \pm 0.2^{o}C$. Arrows indicate approximate weights and times at the end of the 3 larval stadia. P marks the change to prepupa.

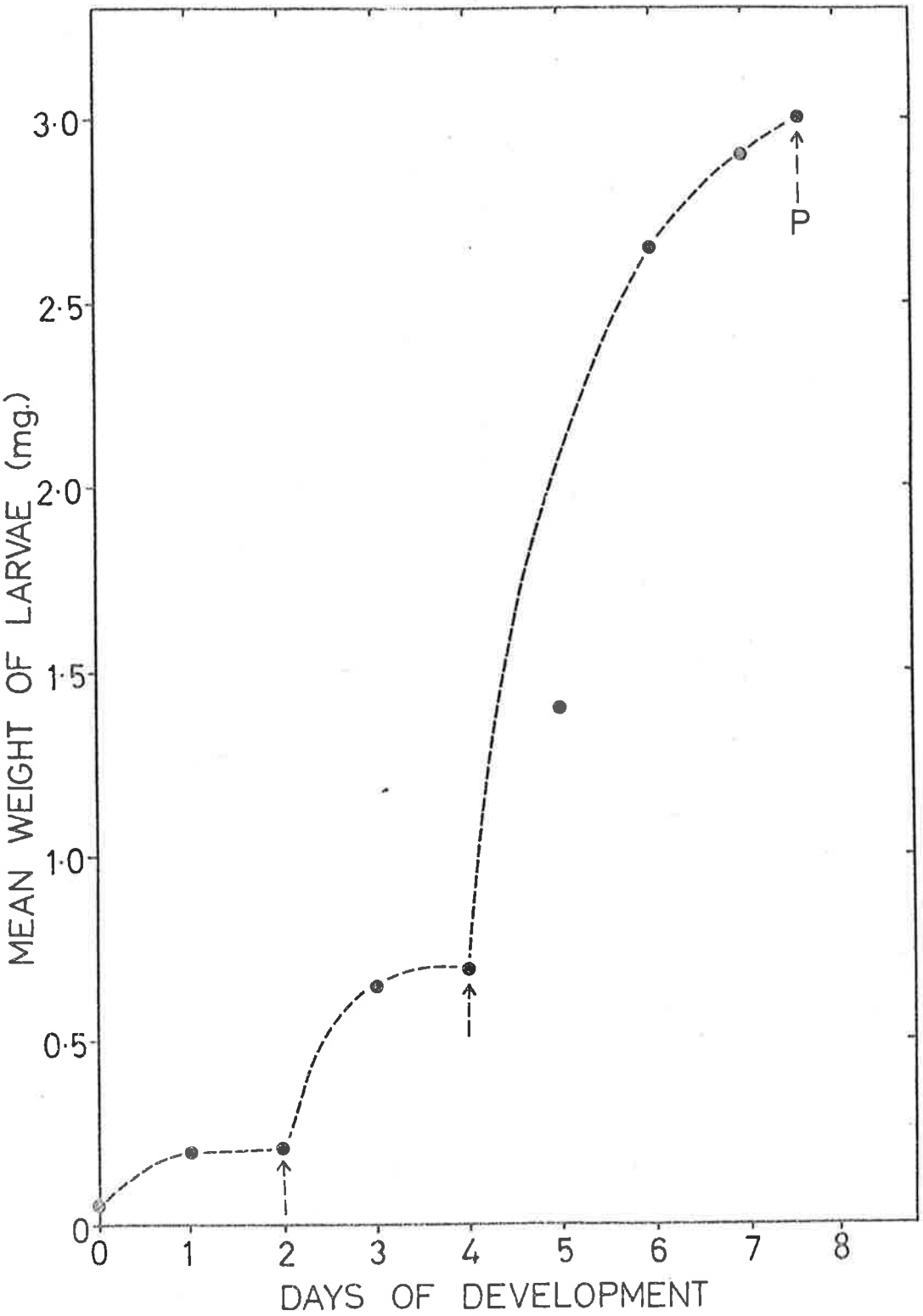

MEAN WEIGHT OF LARVAE (mg.)
3·0
2·5
2·0
1·5
1·0
0·5
0
P
0
1
2
3
4
5
6
7
8
DAYS OF DEVELOPMENT

Table 22: Observed mean weights of *M. tasmaniae* larvae during eight days of their development at 20°C

Days after feeding	Observed mean weight (mg ± S.E.)	Mean number of aphids eaten	
		Instar I	Instar III
0	0.045 ± 0.003	-	-
1	0.205 ± 0.002	3.0	-
2	0.208 ± 0.007	1.0	-
3	0.648 ± 0.046	10.8	-
4	0.687 ± 0.029	-	0.5
5	1.331 ± 0.164	-	5.2
6	2.604 ± 0.188	-	13.2
7	2.894 ± 0.253	-	10.7

5.3 Probability of capturing prey and prey preference by larvae of *M. tasmaniae* at different temperatures

Introduction

The processes of encounter and capture appear basic to every predator-prey interactions. In all situations, the predator must first of all encounter the prey. It must then capture the prey and its ability to do so will depend on properties of both the predator and the prey. A predator may exhibit preferences for some prey over others because they are more readily encountered or more readily captured or both. In the field, predators usually have a choice between more than one age group or type of prey. Which prey they choose under various circumstances may have important consequences for both the predator and prey populations. Changes of preference in response to prey frequency may result in the maintenance of polymorphisms within a species or coexistence of different prey species (Murdoch and Marks, 1972). Also, a predator's preference for older adult aphids which had already reproduced or whose death had little impact on the population may result in ineffective control (Clark and Brown, 1962).

The aims of this experiment were to (a) measure the probability of capture of larvae of *M. tasmaniae* in capturing different instars of *M. persicae* and (b) determine whether there was any preference by larvae of *M. tasmaniae* for different aphid instars at different temperatures.

Materials and Methods

The predators and aphids used in this experiment were obtained from insectary culture. Larvae of *M. tasmaniae* were taken out of the incubation units within 24 hours after they had hatched.

The experiment was conducted in constant temperature rooms at 15°C, 20°C and 25°C under LD 12:12 and was divided into two blocks because limited resources were available, particularly labour and test insects. The second block of the experiment was conducted immediately following the completion of the first. There were four treatments in each block consisting of different combinations of instars of *M. persicae* which were fed to each of the two larvae (two replicates) on each day of their larval development (Table 24). The aphids were fed to the predators on potato leaf discs inside small cages as described in Section 5.1. The treatments were randomized each day amongst the 8 larvae.

The bottom numbers of Table 23, show that on each of the days during the 1st larval instar, the 8 larvae were given a total of 120 aphids in the ratios 7:2:2:1 (first:second:third:fourth instars); and on each of the days during the 2nd and 3rd larval instars a total of 280 aphids were given in the ratios 2:1:1 (second:third:fourth instars). These ratios were converted to percentages of the total prey presented. The proportion of any aphid instar eaten on one day was similarly estimated by totalling the numbers of that instar eaten that day by each of the 8 larvae and dividing the total then by the total number of prey presented. The proportions were expressed as percentages.

It should be noted that this experiment was designed to be analysed, as did Maelzer (1978), by pooling the results of all treatments for each day rather than by treatments. The treatments were included to test preference over a range of probabilities of occurrence of different aphid instars (Maelzer, 1978).

Table 23: Number of *M. persicae* of different instars fed to larvae of *M. tasmaniae*.

Treatment number	No. of aphids given to 1st instar larvae				No. of aphids given to 2nd & 3rd instar larvae		
	Instar I	Instar II	Instar III	Instar IV	Instar II	Instar III	Instar IV
1	10	5	-	-	15	5	15
2	10	-	5	-	15	15	5
3	10	-	-	5	20	10	5
4	5	5	5	-	20	5	10
Total	35	10	10	5	70	35	35

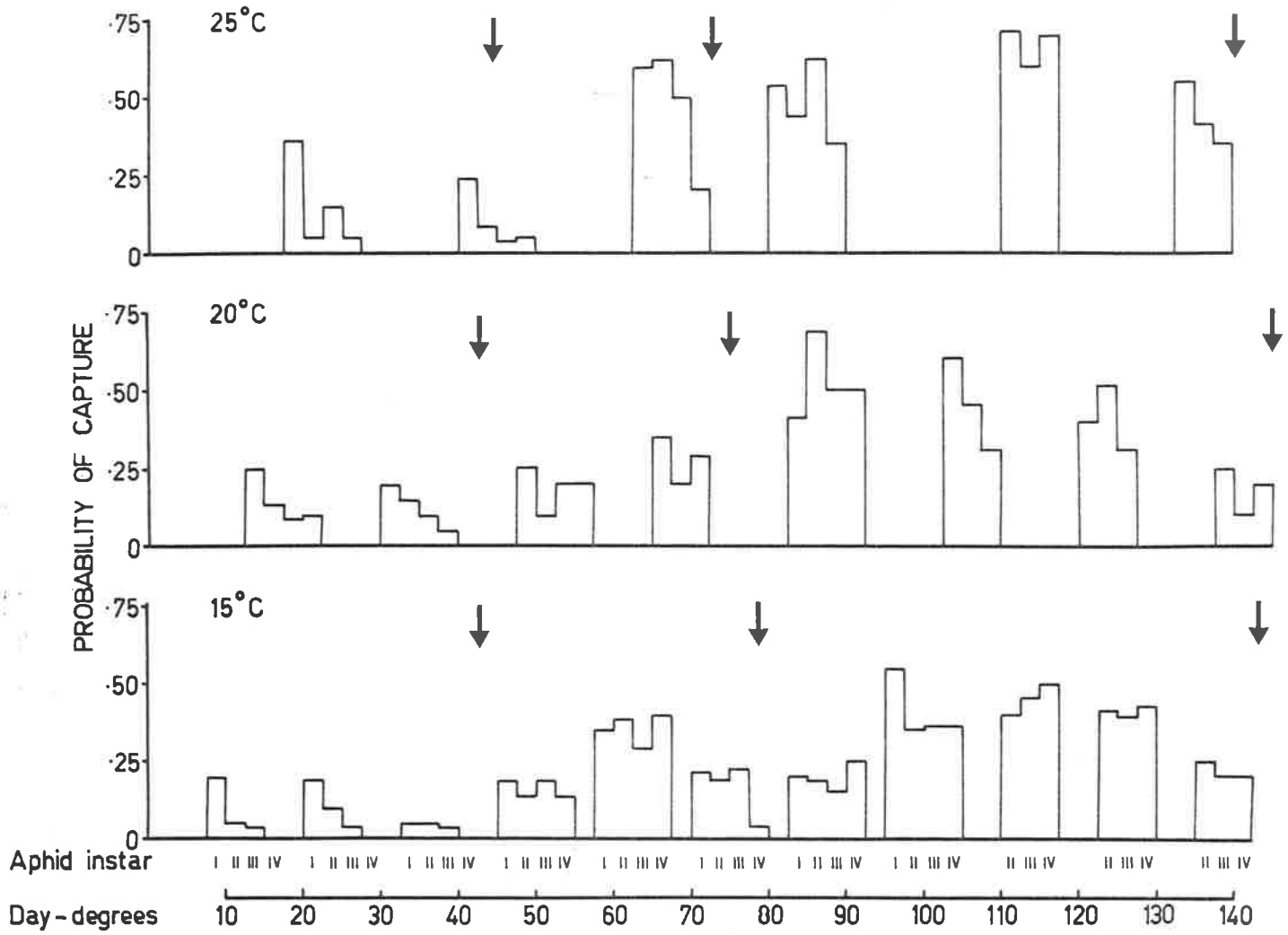
The probability of capturing prey was calculated from the ratios of (percentage of instar eaten) / (percentage of total prey) for each larval instar. The ratios have been found often to be of the same relative magnitude to each other as the probabilities estimated by Chesson (1978) and Maelzer (1978).

For larvae to show preference for certain prey instars, the percentages of prey eaten should be dissimilar to the percentages presented (Maelzer, 1978).

Results and Discussion

To compare the prey preference of larve of different ages within a stadium and at different temperatures, the temperatures have been converted to day-degrees above 2.6°C required for development so that the duration of development of larvae at each temperature have then been expressed in the appropriate interval of day-degrees with the predator's stadium (Fig. 28). The data suggest that, at each temperature, there was a distinct trend in the probability of capture of *M. persicae* by larvae of *M. tasmaniae* namely an increase in the probability of capture after each moult to a peak and a decline just before moulting (Dixon, 1959; Wratten, 1973). The trend is most marked at 15°C. The marked decreases (as indicated by arrows in Figure 27) in the probability of capture correspond with the decreases in slope of the growth and voracity curve shown in Section 5.2 (Fig. 26). Again these decreases are most marked at 15°C. The data also indicate that the efficiency of *M. tasmaniae* larvae in capturing *M. persicae* increases with age and with each moult.

Figure 27: Probabilities of capturing different instars of *M. persicae* by larvae of *M. tasmaniae* at three different temperatures. Arrows indicate approximate marked decrease in probabilities of capture and the end of the 3 larval stadia.


25°C
20°C
15°C
·75
·50
·25
0
PROBABILITY OF CAPTURE
Aphid instar
I II III IV
Day-degrees
10 20 30 40 50 60 70 80 90 100 110 120 130 140

Similar results have been obtained for coccinellid predator preying on sycamore aphid (Dixon, 1959, 1970), wheat aphid (Brown, 1972), lime aphid (Wratten, 1973) and rose aphid (Chesson, 1974), but their methods of estimating probability of capture were different. Dixon (1959, 1970) also found that all instars of *Adalia bipunctata* and *A. decempunctata* were more efficient in capturing small aphids than large ones. However, in this experiment, except during the early stages of larval development, larvae of *M. tasmaniae* seemed to be able to capture efficiently both small and large *M. persicae*.

The efficiency of *Adalia* larvae in capturing large lime aphids was because of the aphid showing a variety of effective escape responses when encountered (Wratten, 1973). Whether or not *M. persicae* shows effective escape responses when encountered by larvae of *M. tasmaniae* is not known. The data of Figure 27 also indicate that the probability of capture of prey by *M. tasmaniae* larvae increases with temperature. So too the probability of 1st instar *M. rosae* being captured by 2nd instar *Leis conformis* increased with temperature with a marked increase at 25°C (Chesson, 1974); and the increased voracity with temperature recorded for coccinellids by Dunn (1952), Sundby (1968), Maelzer (1978), and others is probably also due partly at least, to increased probability of capture resulting from greater mobility of predator larvae as temperature increases. With regards to chrysopid predators, Sundby (1968) found that *Chrysopa carnae* consumed 25% more aphids at 21°C than at 16°C indicating an increase in predator voracity with increase in temperature. Because of marked influence of temperature on various aspects of the predator-prey relationship, the effectiveness of *M. tasmaniae* may vary considerably in different climates (Hodek, 1961; Smith and Hagen, 1966).

Variations in the abundance of the hemerobiid predator, *Hemerobius pacificus*, which prefers cool conditions, have been studied by Neuenschwander (1975). In relation to this Carpenter (1940) found that *H. pacificus* was more common in the north and along the cool coast and in the south it occurred more in mountainous area of western North America. In California, U.S.A., the relative number of adult *H. pacificus* was higher in winter (January and February) in the coastal areas while in the valley, the adults responded to the late spring (May) peak of the aphids occurring in the alfalfa fields (Neuenschwander *et al.*, 1975). The lower numbers of *H. pacificus* adults in the valley was attributed to heavy mortality suffered by the eggs, larvae and pupae under higher summer and early autumn temperatures occurring from July through September (*ibid*). Comparison between the phenologies of *H. pacificus* in the two areas suggested that the coastal areas constitute a stable zone of permanent occupancy (Huffaker and Messenger, 1964), where the adult predators showed a high degree of density-dependence in relation to the aphids. The prevailance of *H. pacificus* and possibly other hemerobiids under cooler conditions in the field may be because they can be reproductively active at the same extremely low temperature that is sufficient for the normal development of their immatures (Neuenschwander, 1975; Syrett and Penman, 1981).

Prey preference

Previous experience of the predator may affect hunger level which in turn may cause significant relative changes in probability of capture (Hassell, 1976). Since estimates of relative probabilities of capture of *M. persicae* of different instars of *M. tasmaniae* larvae were obtained over much longer periods than those used to estimate probabilities of capture by

successful encounters (Dixon, 1959; Wratten, 1973; Chesson, 1974) and spanned a number of periods of hunger and non-hunger, hunger level is less likely to have caused complication in this experiment.

To illustrate the preference that may have occurred in these experiments, the percentages of presented prey of each aphid instar that were eaten are expressed in Figure 28 as percentage differences from expected (solid black areas). Also given in Figure 28 are the percentages of prey of each instar that were presented to the predators.

The data of Figure 28, indicate that the young predator larvae showed some preference for smaller prey as illustrated by large, positive percent differences from expected, whereas the older larvae of *M. tasmaniae* exhibited very little or no preference. And temperature seemed to have no independent effect on preference.

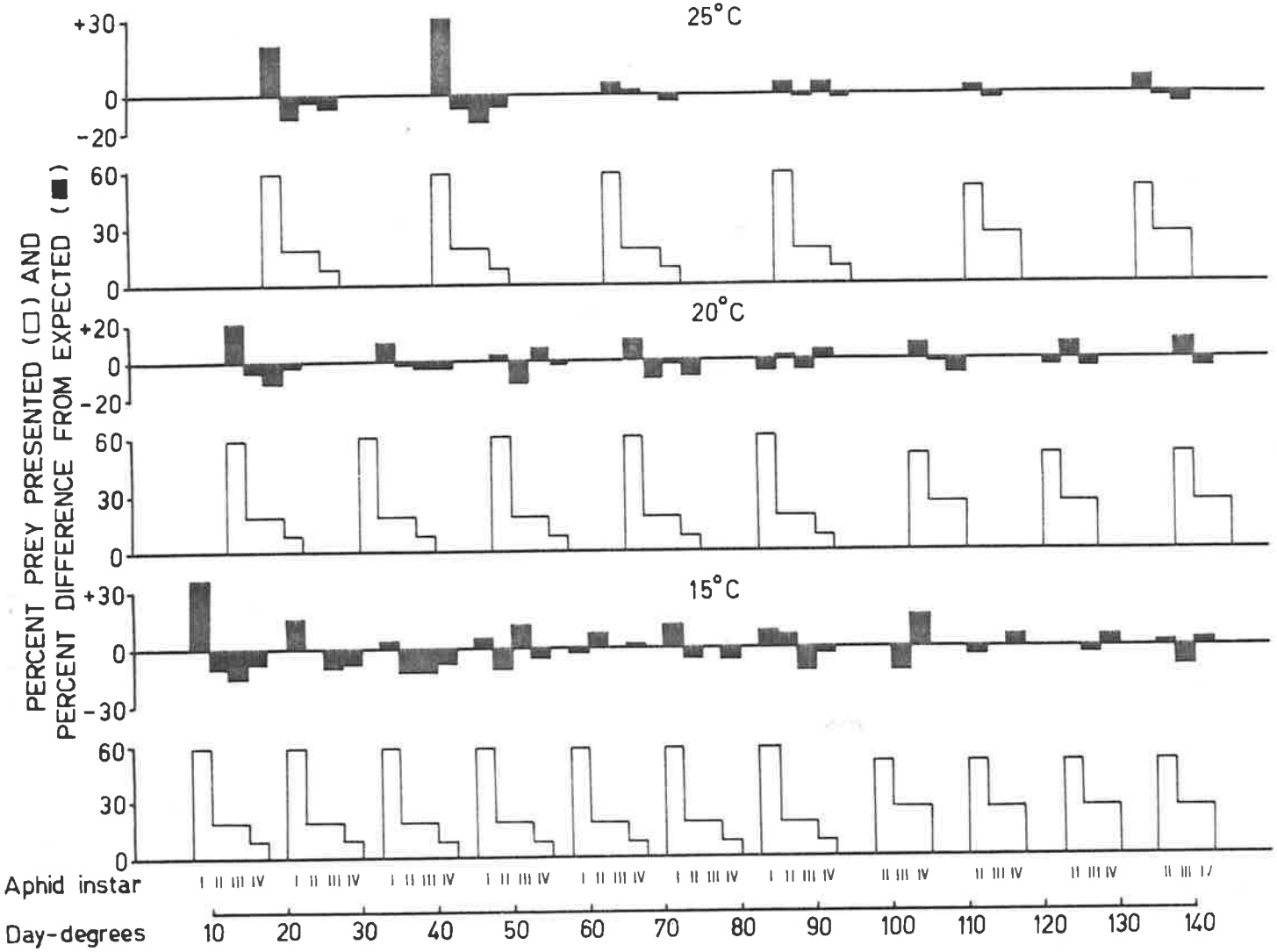
Studies on some species of coccinellid predator have shown that larvae changed preference for different aphid instars from day to day (Dixon, 1959; Wratten, 1973; Chesson, 1978; Maelzer, 1978). The changing preference of different prey size has been attributed to different probabilities of capture (Chesson, 1978). Since larvae of *M. tasmaniae* have been shown in this experiment to be more efficient than coccinellids in capturing both small and large *M. persicae*, they are less likely to show any preference for certain sized prey.

5.4 Influence of temperature and prey density on predation by larvae of *M. tasmaniae*

Introduction

Temperature may have an overwhelming importance on the whole predation process (Gilbert *et al.*, 1976). The likelihood of temperature having a

Figure 28: Percentages of different instars of *M. persicae* presented (□) and of the difference from expected (■) (i.e. the difference between percent presented and eaten by larvae of *M. tasmaniae*) at three different temperatures.


25°C
20°C
15°C
+30
0
-20
60
30
+20
-30
PERCENT PREY PRESENTED (□) AND
PERCENT DIFFERENCE FROM EXPECTED (■)
Aphid instar
I II III IV
Day-degrees
10 20 30 40 50 60 70 80 90 100 110 120 130 140

dominant influence on the interaction between *L. conformis* and *M. rosae* in South Australia has been suggested by Maelzer (1978). Similarly, the interactions of *M. tasmaniae* and *M. persicae* on potatoes may be greatly influenced by temperature.

However, properties of the environment (e.g. temperature) are only one of many sorts of factors that can affect the predation process. Holling (1961) classified the sorts of factors into five main groups namely: 1) prey density; 2) predator density; 3) characteristics of environment; 4) characteristics of prey, and 5) characteristics of the predator. He stressed that prey and predator density are inevitable features of every predator-prey situation; so that the basic components of predation will arise from these universal variables.

In this experiment the influence of prey density on predation by *M. tasmaniae* larvae was studied. Its aims were a) to determine at what prey density can the introduction of first instar predator larvae suppress the prey population and b) to evaluate the influence of temperature on the predation process.

Materials and Methods

The method of evaluating predator-prey interaction was more realistic and hence more complex than that employed in Section 5.3. The experiment was conducted with whole plants in plant growth cabinets at 16 ± 0.35°C, 21 ± 0.31°C, 26 ± 0.29°C under LD 16:8 photophase. The predators and prey were obtained from insectary culture. Potato seedlings grown in 15.0 cm black plastic pots were used as described in Section 3.1.

Due to a lack of space in the growth cabinets, the experiment was divided into two blocks or stages. In the first block two plant growth cabinets at 16 and 20°C were used; in the second block, one of the cabinets was run at 26°C. At each temperature there were three treatments (with two replicates) representing 3 levels of initial prey density namely 2, 4 and 6 newly moulted adult apterous *M. persicae*. Each treatment was further replicated 3 times (= 18 plants per temperature) to allow for destructive sampling of numbers of prey and predators on each of 3 dates during the course of the experiment. The interval between sampling dates varied according to the length of the larval developmental period at each temperature.

The experiment was started when the plants were 18 cm tall. Each plant was seeded with adult *M. persicae* (see Section 4.2) at one of the required prey densities. Twenty four hours later one 1-day old first instar larva of *M. tasmaniae* was placed onto the plant. The plant was immediately covered with a cylindrical, clear perspex cage (Fig.1) (14.5 cm in diameter and 26.0 cm high) having two side-ventillation holes (6.0 cm in diameter) and one top-ventillation hole (9.0 cm in diameter). The ventillation holes were covered with very fine mesh cloth. A 2.5 cm wide plastic adhesive tape was used to seal the opening joining the cage and the pot.

On each sampling date, 6 plants from each treatment were removed one at a time from the cabinet and brought to the laboratory. After the cage was removed, the plant was searched for the predator larvae and its presence or absence was recorded as dead or alive. Each of the leaves on the plant was then cut off and the total number of aphids were counted.

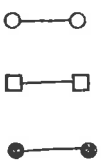
Results and Discussion

In Figure 29 are given the number of aphids per plant in each treatment (initial aphid density per plant) on the 3 sampling dates after the start of the experiment. It can be seen that the numbers of aphids were suppressed at all initial prey densities at all temperatures but as expected aphid numbers were lowest when only two aphids were initially put on the plant. At the highest initial aphid (6 per plant) the numbers of aphids increased considerably before being reduced by the predators. And the peak aphid number and subsequent reduction occurred earlier at the higher temperatures.

On the 3rd sampling date there was an indication that aphid population growth was either not being reduced any more (at 26°C) or was positive again (at 21°C). By this date, at each temperature, the predator larva was entering the pre-pupal stage and the reduced voracity of the predator before pupation was allowing the few aphids that has escaped predation to start increasing in number without further check.

The results clearly indicate that the variation in the ability of larvae of *M. tasmaniae* to suppress aphid population growth was a function of the initial prey density and of the temperature which have an obvious effect on the larval rate of growth and voracity (Gilbert *et al.*, 1976). The response shown by larvae of *M. tasmaniae* is called developmental response (Murdoch, 1971), and is a type of predator response which is not numerical but operates on a time scale longer than the functional response (Solomon, 1949). The developmental response takes into account the growth of predators over time, as was done in this experiment. Temperature, a subsidiary component of predation, has often been shown to influence not only the predator response but also the predator rate of

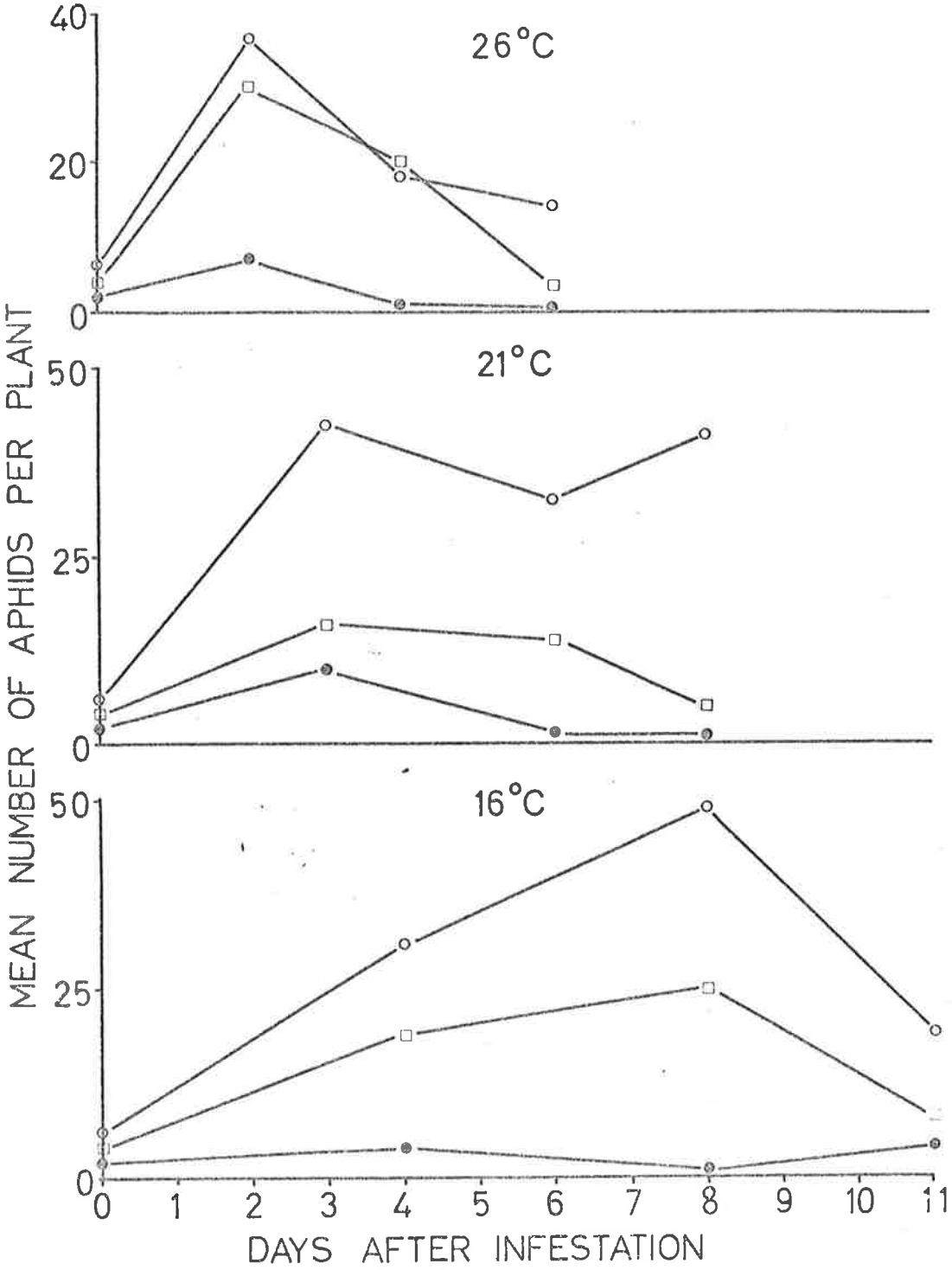
Figure 29: Trends in numbers of *M. persicae* per plant at each of 3 temperatures when each plant was seeded initially with 2, 4 and 6 adult aphids and one 1st instar *M. tasmaniae* larva.



6 initial adult aphids per plant

4 initial adult aphids per plant

2 initial adult aphids per plant


26°C
21°C
16°C
40
20
0
50
25
0
50
25
0
MEAN NUMBER OF APHIDS PER PLANT
0 1 2 3 4 5 6 7 8 9 10 11
DAYS AFTER INFESTATION

increase (Hollings, 1961). Its importance in aphid-ladybird interactions has been shown by Dunn (1952), Gilbert *et al.* (1976) and Maelzer (1978).

CHAPTER 6

GLASSHOUSE EXPERIMENTS ON THE INFLUENCE OF PREDATOR DENSITY AND PREY DISTRIBUTION ON SUPPRESSION OF PREY POPULATIONS

INTRODUCTION

The influence of natural enemies on their prey population is still one of the most difficult aspects of population ecology to study (Kiritani and Dempster, 1973). This is particularly true for predation because the prey are completely consumed, or are partially eaten and the remnants are hard to find in the field *(ibid)*. We are still a long way from having reliable techniques for studying all predator prey situations *(ibid)*.

In Chapter 4 is discussed field survey and field-cage studies to assess the impact of *M. tasmaniae* on *M. persicae* populations. Field studies have the obvious advantages of reality, but their usual disadvantages are inaccuracy and difficulty of disentanglement of the interacting factors. On the other hand, laboratory experiments, such as those described in Chapter 5 suffer from the typical defects of simplification and lack of realism.

In this chapter, I describe two experiments which were conducted in the glasshouse. The conditions provided in the glasshouse were intermediate between those in the field and in the laboratory. The glasshouse provides some control over the experimental conditions whilst providing an opportunity to study the process of predation under fluctuating temperatures that are similar to those that occur in the field and

that have a dominating influence on the outcome of the interaction of predator and prey (Dunn, 1952; Gilbert *et al.*, 1976; Frazer and Gilbert, 1976). In particular, glasshouse experiments allow experiments on the efficiency of predators and on simple Bombosh-type predator prey interactions (see Bombosh, 1963; van Emden, 1966; Gurney and Hussey, 1970) under "realistic" fluctuating temperatures.

Searching is one of the functions performed by a predator in finding its prey. The ease with which the required amount of prey can be found is dependent, among other factors, upon predator searching efficiency, predator density and spatial distribution of the prey (Hagen *et al.*, 1976). The efficiency of a predator or parasite is linked to its searching ability more so than any other property (De Bach, 1974). Only an enemy that has a high searching ability can find prey when they are scarce, and is able to regulate the prey population *(ibid)*. De Bach (1974) further states that thus far we do not know how to measure with any accuracy the searching ability of a natural enemy or its potential effectiveness except by the effect it has in prey population suppression.

The main objective of these glasshouse experiments were to investigate (i) some of the factors influencing searching efficiency of *M. tasmaniae* larvae and (ii) the ability of *M. tasmaniae* larvae to suppress populations of *M. persicae*.

6.1 Influence of predator numbers on the ability of *M. tasmaniae* larvae to suppress prey populations

Predation theory usually refers to the searching efficiency of predators as the ability of the predator to perceive, by some means, the

location of the prey in a given universe (Fleschner, 1950). Here it will be useful in the following experiments to talk instead of the searching "capacity" of a predator which I will define as the effective distance a predator larva may travel or search as measured from the site of introduction to the perimeter of the arena in which it is allowed to search for prey.

Materials and Methods

The experiments were conducted in a glasshouse cubicle (2.6 m x 2.6 m) under fluctuating temperatures (15 - 30°C) and fluctuating humidities (55-100%) during February 5 to March 6, 1981. No artificial lighting was provided. The walls and roof of the glasshouse were painted white on the outside to help reduce the temperature inside. Potato plants used in these experiments were grown in the plant growth cabinets from shoot cuttings described in Section 3.1.

Two experiments (1 and 2) were conducted at different periods inside the same glasshouse cubicle. In each, there were three treatments representing 3 different predator-prey ratios, plus a control (no predator). Ideally, when space or numbers of insects are insufficient for a whole experiment, the experiment may be divided into "blocks" in each of which is included one or more replication of each "treatments", including any control or standard that may also be part of the experiment (Fig. 30). An analysis of variance can usually then take at the variation between blocks and allow the comparison of treatments in the usual way. In this study, blocking by the above method was not possible because: a) it was considered that the minimum number of plants per tray

Figure 30: Diagramatic representation of the ideal design of an experiment with 3 treatments and a control each with two replicates and treatments x replicates divided into two "blocks".

BLOCK 1

CONTROL REP. 1	TREAT. 1 REP. 1	TREAT. 2 REP. 1	TREAT. 3 REP. 1

BLOCK 2

CONTROL REP. 11	TREAT. 1 REP. 11	TREAT. 2 REP. 11	TREAT. 3 REP. 11

should not be less than 16 in order to include a treatment in which only every 4th (corner) plant is infested with the prey to give a particular spatial distribution of prey (Section 6.2); b) with 16 plants per tray (72 cm x 72 cm x 9 cm) a maximum of 6 trays could be placed inside the glasshouse cubicle, and c) it was not possible to use an additional glasshouse cubicle. So, two different experiments were done to accommodate all the treatments.

Experiment 1 consisted of two treatments (Treat. 1 and 2) and the control, each replicated twice. Experiment 2 similarly included two treatments (Treat. 2 and 3) and a control, each replicated twice (Appendix Table 5).

Experiment 1

The experiment was conducted from February 5-18, 1981. At the start of the experiment, 16 potato plants (var. Exton) growing in plastic pots were placed in each of the wooden trays and spaced 15 cm apart and 13.5 cm from the edge of the sides of the tray. The open spaces between the pots were filled with soil (potting mixture) up to the rim of the pots. The plants were kept in their pots so that they could be removed temporarily from the soil while the aphids were counted. The top surface of the side (12 mm wide) of the tray was painted with Stickem(R), a sticky, colourless and non toxic material, for preventing the predator larvae and aphids from crawling out. The plants were watered twice daily.

Each plant was infested with two newly-moulted apterous adult *M. persicae* obtained from the insectary culture. Twenty four hours later, 4 1-day-old first instar larvae of *M. tasmaniae* were introduced into the

tray of treatment 1 (to give a predator-prey ratio of 1:8) and 8 larvae were introduced into the tray of treatment 2 (to give a predator-prey ratio of 1:4). The larvae were carefully introduced by placing them on the soil surface in the center of the tray. In the control, the aphids were allowed to develop unimpeded.

The number of aphids found on each plant were counted on days 3, 6, 9 and 12. These data allowed changes in the dispersion of aphids to be estimated together with changes in size of the aphid population.

Dispersion of the prey population is of considerable ecological importance when interpreting population changes (Southwood, 1978). In its own right, a measure of dispersion is a description of the condition of the population. I used Morisita's index of dispersion ($I\delta$), computed as:

$$I_\delta = q \frac{\sum_{i=1}^{q} \chi_i \quad (\chi_i - 1)}{T \ (T-1)}$$

where χ_i = 1,2,3 ... q) = The number of individuals in the ith sample unit q = number of sample units, and $T = \sum_{i=1}^{q} \chi_i$ (Morisita, 1962).

This index was used because it is relatively independent of the type of distribution, the mean number of samples and of the size of the mean (Morisita, 1962; Southwood, 1966).

Experiment 2

This experiment was conducted 3 days after the completed of Experiment 1 from February 21 to March 6, 1981. Similar procedures as described for Experiment 1 were followed. There were two treatments comprising 8

and 16 predator larvae respectively, and a control; each was replicated twice. Since there again, 32 aphids per replicate, the two predator treatments gave predator prey ratios of 1:4 and 1:2.

Similarly, the number of aphids on each plant were counted on day 3, 6, 9 and 12. Changes in the dispersion of aphid counts were measured using Morisita's index of dispersion.

Results and Discussion

In Table 24 are given for both experiments, the numbers of aphids in each treatment (with predators) and in the control (no predators) over 12 days after the start of each experiment. The results indicated that larvae of *M. tasmaniae* were able to suppress populations of *M. persicae* in all treatments with predators.

In Experiment 1 (Table 24), the introduction of 4 and 8 first-instar larvae of *M. tasmaniae* caused 39% and 64% overall reduction in the number of aphids as compared to the control. When the data for each sampling date were analysed independently (ANOVA 2-way classification, Appendix Table 4) significant differences between treatments and the control were found. The mean numbers of aphids per plant between any two treatments or between a treatment and the control were then compared (Table 26) and significant difference estimated by calculating least significant difference (LSD) using the usual formula:

$$LSD = t_{.05} \times S.E.$$

where $t_{.05}$ is the value of t with 90 d.f., and S.E. is the standard error of the difference between any two treatment means computed as:

Table 24: Mean number of *M. persicae* per plant in each treatment (with predators) and in the control (no predators) over 12 days period for Experiments 1 and 2.

Predator-prey ratio	Sampling date				
	0	3	6	9	12
Experiment 1:					
Control	2.00[a1]	4.88[a]	6.90[a]	11.50[a]	38.75[a]
1:8	2.00[a]	3.00[a]	1.31[b]	3.75[b]	16.06[b]
1:4	2.00[a]	1.78[a]	0.81[b]	1.22[b]	3.38[c]
LSD[2]		2.37	1.83	3.02	5.59
Experiment 2:					
Control	2.00[a]	7.41[a]	13.88[a]	17.78[a]	35.25[a]
1:4	2.00[a]	1.13[b]	1.19[b]	1.84[b]	3.47[b]
1:2	2.00[a]	1.09[b]	0.13[b]	0.50[b]	0.71[b]
LSD		2.53	4.60	5.69	8.76

[1] Means within columns followed by the same letter do not differ significantly at P = 0.05.

[2] Between any two treatment means or any one treatment mean and control.

$$S.E. = \sqrt{\frac{2(MS)}{n}}$$

where MS is the mean square value for the error term in the ANOVA, and n is the number of observations on which the treatment means are based. LSDs are given along with the treatment means in Table 26 and indicate that there is significant differences between the control and the treatment means on days 6, 9 and 12 but not on day 3. And the treatment means differed only on day 12.

In Experiment 2, the introduction of 8 and 16 first-instar larvae of *M. tasmaniae* caused 89% and 95% overall reduction in the number of aphids as compared to the control. LSDs based on an ANOVA (2-way, Appendix Table 6) are given in Table 24 along with the means of each treatment and the control; they indicate significant differences ($P<.05$) on day 3, 6, 9 and 12 between the control and each of the treatments, but the treatments were never different from each other.

The application of Bombosch's model

From the data obtained in those experiments and a knowledge of the rate of development of the aphid, it is possible to estimate the predator-prey ratio at which suppression of the aphid population's occurred, and after how many days it was achieved.

Estimates of the expected number of aphids both in the absence of predators and when subjected to different predator-prey ratio were obtained by using a formula by Bombosch (1962) (as quoted by van Emden, 1966; Scopes, 1969; Tamaki, 1974):

$$A_n = A_o \cdot q^n - kq \frac{(q^n-1)}{(q-1)} s$$

where A_n = number of aphids at the ninth day.

A_o = the initial number of aphids i.e. at day zero;

q = daily rate of increase for aphid populations in the absence of predators;

k = number of aphids eaten per day by one predator larva;

n = number of days from the start of the growth of the aphid population i.e. from day zero;

and s = the number of days lapsed between aphid infestation and predator introduction (i.e. synchronization).

In the absence of predation, the increase of the aphid population is estimated as:

$$A_n = A_o q^n$$

$$\text{or } \log q = \frac{\log A_n - \log A_o}{n}$$

so that in Experiment 1,

$$\log q = \frac{\log 620 - \log 32}{12}$$

$$= \frac{2.7924 - 1.5052}{12}$$

$$= 0.1073$$

$$q = 1.28$$

Since the mean daily temperature for the periods of both Experiments 1 and 2 was 20.5°C, the k values were obtained from the experiment on larval voracity at 20°C described in Section 5.2, and were changed for each instar of *M. tasmaniae* larvae as the voracity was likely to increase

with successive instars during the experiment (Scopes, 1966). Thus, for first, second and third instar larvae, the k values wer 0.5, 2.0 and 9.0 third instar aphid equivalents (TIES), and these values were used for 0-2, 3-5 and 6 days after the start of the experiment to allow for the growth of the predator larvae.

In Table 25 are given the expected numbers of aphids each day in the absence of predators, and the observed numbers on days 3, 6, 9 and 12. In Tables 26 and 27 are given numbers of aphids expected to be eaten by predators; the expected number of aphids left each day in the presence of predators, and the observed numbers of aphids on days 3, 6, 9 and 12 in the presence of predators with a predator-prey ratio of 1:8 and 1:4 respectively.

Table 28 shows a relatively good fit of expected numbers of aphids to observed ones for a predator prey ratio of 1:8. This is really surprising because Bombosch's model is simplistic and other good reasons can be thought to explain why the fit should not be good e.g. (a) the voracity of the predator larva is expressed in TIES and for a comparison the numbers of live aphids in the population, both expected and observed, should similarly be expressed TIES, and (b) the voracity of the predator is taken from an experiment in which there was an overabundance of prey; whereas in this experiment prey may have been in relatively short supply. It is of interest to see that the data in Table 29 for a predator prey ratio show a much worse fit between expected and observed aphids, with the latter more abundant than expected. The data of both tables considered together suggest therefore that (a) at the predator-prey ratio of 1:4, there was definitely a shortage of food and that fewer

Table 25: Numbers of *M. persicae* developing on 16 potato plants in the absence of predators each day (expected) and each of day 3, 6, 9 and 12 (observed). Experiment 1.

	Number of aphids	
Day no.	Expected	Observed
0	32	32
1	41	
2	52	
3	67	78
4	86	
5	110	
6	141	111
7	180	
8	231	
9	295	184
10	378	
11	484	
12	619	620

Table 26: Number of *M. persicae* developing on potato plants per predator in the treatment with a predatory-prey ratio of 1:8 each day (expected) and each of days 3,6,9 and 12 (observed). Experiment 1.

Day no.	Expected number of aphids	eaten (k)	left	After multiplication (X1.28)	Observed no. of aphids (÷4)
0	8.00	0.50	7.50	9.60	
1	9.60	0.50	9.10	11.65	
2	11.65	0.50	11.15	14.27	
3	14.27	2.00	12.27	15.71	12.00
4	15.71	2.00	13.71	17.55	
5	17.55	2.00	15.55	19.90	
6	19.90	9.00	10.90	13.95	5.20
7	13.95	-	13.95	17.86	
8	17.86	-	17.86	22.86	
9	22.86	-	22.86	29.26	15.0
10	29.26	-	29.26	37.45	
11	37.45	-	37.45	47.94	
12	47.94	-	47.94	61.36	64.00

Table 27: Number of *M. persicae* developing per predator in potato plants in the treatment with a predator-prey ratio of 1:4 each day (expected) and each of days 3,6,9 and 12 (observed) Experiment 2.

Day no.	Expected number of aphids	eaten (k)	left	after multiplication (X1.28)	Observed no. of aphids (÷8)
0	4.00	0.50	3.50	4.48	
1	4.48	0.50	3.98	5.09	
2	5.09	0.50	4.59	5.88	
3	5.88	2.00	3.88	4.97	7.00
4	4.97	2.00	2.97	3.80	
5	3.80	2.00	1.80	2.30	
6	2.30	9.00	<0		3.25
7					
8					
9					5.00
10					
11					
12					13.00

aphids than expected were found and eaten by the predators, and (b) at the predator-prey ratio of 1:8 the predator was possibly behaving as it did in the earlier voracity experiment and did not, in fact, suffer from a relative shortage of food.

The data for experiment two are given in Tables 28-30; in Table 28 are given the expected number of *M. persicae* each day in the absence of predators and the observed numbers of aphids on days 3, 6, 9 and 12. Tables 29 and 30 present the number of aphids expected to be eaten by predators, the expected number of aphids left each day in the presence of predators, and the observed number of aphids on days 3, 6, 9 and 12 in the presence of predators of a given predator-prey ratio.

The data in Table 29 and 30 show that the expected numbers of *M. persicae* do not fit the observed numbers with the latter more abundant than expected. The data of both tables considered together again suggest that at predator-prey ratio of 1:4 and 1:2 there were definitely a shortage of food and also fewer aphids than expected were found and eaten by the predators.

Table 28: Expected and observed numbers of *M. persicae* developing on potato plants in the absence of predators up to each of days 3,6,9 and 12 after the start of Experiment 2.

Day no.	Number of aphids	
	Expected	Observed
0	32	32
1	41	
2	52	
3	66	119
4	83	
5	106	
6	134	222
7	171	
8	217	
9	275	284
10	349	
11	444	
12	564	564

Table 29: Numbers of *M. persicae* developing on potato plants in the treatment with a predator-prey ratio of 1:4. Expected and observed numbers of aphids are given for each of days 3,6,9 and 12 after the start of Experiment 2.

Day no.	Expected number of aphids	eaten (k)	left	after multiplication (X1.27)	Observed no. of aphids (÷8)
0	4.00	0.50	3.50	4.45	
1	4.45	0.50	3.95	5.02	
2	5.02	0.50	4.52	5.74	
3	5.74	2.00	3.74	4.75	2.25
4	4.75	2.00	2.75	3.49	
5	3.49	2.00	1.49	1.89	
6	1.80	9.00	<0		2.38
7					
8					
9					3.63
10					
11					
12					6.88

Table 30: Number of *M. persicae* developing on potato plants in the treatment with a predator-prey ratio of 1:2. Expected and observed numbers of aphids are given for each of days 3,6,9 and 12 after the start of Experiment 2.

Day no.	Expected number of aphids	eaten (k)	left	after multiplication (X1.27)	Observed no. of aphids (÷16)
0	2.00	0.50	1.50	1.91	
1	1.91	0.50	1.41	1.79	
2	1.79	0.50	1.29	1.64	
3	1.64	2.00	<0		1.06
4					
5					
6					0.13
7					
8					
9					0.50
10					
11					
12					0.75

The dispersion of aphids within the treatments and the control

In Tables 31 and 32 are given the means and variances of aphids per plant and the mean values of Morisita's index of dispersion (I_δ) for each treatment and the control at different sampling days for Experiments 1 and 2 respectively.

When the distribution of animals is random and can be fitted by a Poisson series, Morisita's index gives a value of unity; when the distribution is contagious (e.g. negative binomial), the index is greater than one, and when the distribution is regular (e.g. binomial) the index is less than one (Southwood, 1978). The significance of the departure from a random distribution, as shown by the index, is tested by computing F_o calculated as:

$$F_o = \frac{I\delta(T-1) + q-T}{q-1}$$

where $I\delta$ - Morisita's index of dispersion, q = total samples (plants); and T = the sum of the number of aphids found in all the samples, with the value of F in tables, with $N_1 = q-1$ and $N_2 = \infty$.

The significance or otherwise of the departure ($P<.01$) from a random distribution of each value of Morisita's index is given in the 2nd last columns of Tables 31 and 32 From this column we may infer that after day zero, all the distributions of aphids were contagious except for the treatment with a predator-prey ratio of 1:2 on day 6

Table 31: Mean number and variance of *M. persicae* per plant and mean values of Morisita's index of dispersion in each treatment and the control at different sampling days in Experiment 1.

Predator-prey ratio	Sampling day	Mean	Variance	I_δ [1]	F_o [2]	P
Control	0	2.00	0	0.52	<1.00	>.05
	3	4.88	18.18	1.93	4.30	<.01
	6	6.90	26.47	1.63	4.42	<.01
	9	11.50	66.86	1.50	5.89	<.01
	12	38.75	659.71	1.37	16.25	<.01
1:8	0	2.00	0	0.52	<1.00	>.05
	3	3.00	39.39	3.77	2.85	<.01
	6	1.31	5.46	3.31	3.49	<.01
	9	3.75	43.30	1.94	6.74	<.01
	12	16.06	489.27	2.14	22.21	<.01
1:4	0	2.00	0	0.52	<1.00	>.05
	3	1.78	10.82	4.30	5.94	<.01
	6	0.81	4.43	3.21	3.82	<.01
	9	1.22	12.07	7.60	9.37	<.01
	12	3.38	35.48	3.56	10.73	<.01

[1] I_δ = Morisita's index of dispersion

[2] F_o tests the departure from a random distribution.

Table 32: Mean numbers and variances of *M. persicae* per plant and mean values of Morisita's index of dispersion in each treatment and the control at different sampling days in Experiment 2.

Predator-prey ratio	Sampling day	Mean	Variance	I_δ [1]	F_o [2]	P
Control	0	2.00	0	0.52	<1.00	>.05
	3	7.41	66.53	2.06	7.92	<.01
	6	13.88	79.22	2.02	13.61	<.01
	9	27.78	363.70	1.90	14.93	<.01
	12	35.25	175.82	1.65	21.55	<.01
1:4	0	2.00	0	0.52	<1.00	>.05
	3	1.13	6.66	5.06	5.64	<.01
	6	1.19	8.02	7.02	6.43	<.01
	9	1.84	24.77	2.28	7.49	<.01
	12	3.47	47.82	2.66	8.69	<.01
1:2	0	2.00	0	0.52	<1.00	>.05
	3	1.09	4.49	3.97	2.96	<.01
	6	0.13	0.10	0	0	<.05
	9	0.50	2.07	2.07	2.07	<.01
	12	0.71	5.73	2.88	3.99	<.01

[1] I_δ = Morisita's index of dispersion

[1] F_o tests the departure from random distribution.

(Table 32 where the distribution was regular ($I_\delta = 0$). We may also infer that the degree of dispersion increased as the predator-prey tatio decreased, and within each treatment there was a tendency for the degree of dispersion to at first increase os that it was maximal on day 3 or 6 and then decreased till day 12. In the control in each treatment the I_δ values decreased slightly each day up to day 12. The index (I_δ) also suggested that marked changes in dispersion occurred at predator-prey ratio of 1:2. However, the I_δ values of different replicates were very variable (see Appendix Tables 9 and 10), and one has to be cautious in interpreting and using these values.

The results of Experiments 1 and 2 indicated that the distribution of aphids tended to remain contagious when the aphid populations were being suppressed by predators. So, the size of prey aggregation and the changes in the distribution could have marked influences on the predator's ability to suppress prey populations (Waters, 1959). And the changes in the distribution of aphid population and the parameters of these distributions may also be affected by the plant-to-plant movement Shiyomi and Nakamura (1964) found that the more plant-to-plant movement in response to an increase in aphid populations, the less dispersed the distribution becomes as more aphids tended to move from plants with higher densities to plant with lower ones. In this study, the plant-to-plant movement of *M. persicae* have been limited as the mean numbers of aphids per plant decreased or tended to remain very low, and marked changes in the pattern of prey dispersion occurred.

It is evident from Experiments 1 and 2 that the introduction of larvae of *M. tasmaniae* caused changes in the I_δ values or prey spatial

distribution from a regular to a random type. Thus the influence of prey spatial distribution on the predator-prey interaction and the suppression of prey population by larvae of *M. tasmaniae* was further examined in the following experiments (Experiments 3 and 4).

6.2 Influence of prey spatial distribution on the ability of *M. tasmaniae* larvae to suppress prey populations

The dispersion of an organism within its habitat is an important aspect of the characteristic of the population. The dispersion of a prey species in relation to that of the predator, or *vice-versa*, may have profound effects on the predator-prey interaction. For any predator to extend its maximum effects on the prey it should be present and active in all places inhabited by the prey (Chant, 1961). A permanent control of the prey population may not be possible if there are areas or patches where prey is free from attack by predators, because continuous re-infestation may occur from these areas, upsetting the balance *(ibid)*.

A predator has an obvious advantage if it tends to spend most of its searching time where prey are plentiful. Such behaviour is important because of its effects on the stability of the predator-prey interaction (Hassell, 1976 and 1978). In effect, predator aggregation where prey are abundant provides a partial refuge for the prey in patches of low density. The importance of such heterogeneity in the spatial pattern of the prey has been investigated by Huffaker (1958) and Huffaker *et al.* (1968).

The aim of this experiment was to investigate the influence of the spatial pattern of *M. persicae* on the searching ability and suppression of prey population by larvae of *M. tasmaniae*.

Materials and Methods

The experiments were conducted in the same glasshouse cubicle as described in Section 6.1. Similar procedures were followed as described in Section 6.1.

Two experiments (Experiment 3 and 4) were conducted from March 10 to April 8, 1981. There were three treatments representing 3 different types of prey spatial distribution, plus a control (no predator). The three treatments were spread over two experiments for the same reasons given in Section 6.1. Again there were 16 plants in each treatment.

Experiment 3

The experiment was conducted from March 10 to 23, 1981. The treatments were:

1) each plant infested with 2 aphids and no predators (control);
2) each plant infested with 2 aphids and a total overall plants of 8 predators;
3) every 2nd (alternate) plant infested with 4 aphids and a total over all plants of 8 predators.

Each treatment with predators therefore had a predator-prey ratio of 8:32 or 1:4 which was selected on its ability to drastically suppress aphid population in the previous experiment (Section 6.1). As before the 8 predators were 1-day-old first instar larvae of *M. tasmaniae* which were carefully placed on the soil in the center of the tray of plants 24 hours after the plants were infested with aphids.

Aphids remaining on the plants were counted on day 3, 6, 9 and 12 after the introduction of the predators. The locations of the predators

were also noted. As in the previous experiment, the changing spatial patterns of the aphids in each treatment were analysed using Morisita's index of dispersion (Morisita, 1962).

Experiment 4

This experiment was conducted 3 days after the completion of Experiment 3 from March 26 to April 8, 1981. Similar procedures as described for Experiment 3 were followed. The treatments were:

1) Each plant infested with 2 aphids and no predators (control);
2) every 2nd (alternate) plant infested with 4 aphids and a total overall plants of 8 predators;
3) every 4th (corner) plant infested with ~~8 predators~~ 4 aphids and a total over all plants of 8 predators.

The methods etc. were identical otherwise to those of Experiment 3.

Results and Discussion

In Table 33 are given the numbers of *M. persicae* in each treatment (with predators) and in the control (without predators) over the 12 days period after the start of the experiment. The results indicated that suppression of *M. persicae* populations on potato plants was achieved in all treatments where predators were introduced.

In Experiment 3 (Table 33a) the introduction of 8 first instar larvae of *M. tasmaniae* caused 82% and 93% overall reduction in the number of aphids when each plant and every 2nd plant were infested respectively. When the means for each treatment were analysed by ANOV 2-way (Appendix Table 7) independently for each sampling day (Table 33a), and LSDs

Table 33: Mean number of *M. persicae* per plant in each treatment (with predators) and in the control (no predators) over a 12-day period for Experiment 3(A) and 4(B).

Prey spatial distribution	Sampling day				
	0	3	6	9	12
Experiment 3(A):					
Each plant (control)	2.00[a1]	7.59[a]	18.81[a]	37.34[a]	91.50[a]
Each plant	2.00[a]	3.78[b]	2.46[b]	1.88[b]	4.59[b]
Every 2nd plant	2.00[a]	1.63[b]	0.72[b]	0.19[b]	0.09[b]
LSD[2]		2.73	3.96	7.56	17.93
Experiment 4(B):					
Each plant (control)	2.00[a]	11.31[a]	23.25[a]	61.13[a]	131.66[a]
Every 2nd plant	2.00[a]	7.22[a]	3.16[b]	8.13[b]	29.66[b]
Every 4th plant	2.00[a]	9.94[a]	3.34[b]	6.69[b]	19.81[b]
LSD		5.59	6.19	11.72	26.47

[1] Means within columns followed by the same letter to not differ significantly at P = 0.05.

[2] Between any two treatment means or any one treatment mean and the control.

applied to treatment means, significant ($P<.01$) differences were found in the number of aphids between the control and each of the treatments on days 3, 6, 9 and 12. There were, however, no significant differences between the two treatments on any day.

In Experiment 4 (Table 33b), the introduction of 8 first instar *M. tasmaniae* larvae caused 72% and 68% overall reduction in the number of aphids in treatments where every 2nd plant and every 4th plant were infested with aphids. Differences in the number of aphids per plant were significant (ANOV, 2-way, Appendix Table 8) and when LSDs were applied to the treatment means (Table 33b), there were significant differences between the control and each treatment on days 6, 9 and 12 but not on day 3. Again, there were no significant differences between the means of the two treatments on any sampling day.

The results also indicated that the two treatments that were common to both experiments, namely the control and the treatment where every 2nd plant was initially infested had much higher aphid numbers in Experiment 4 than in Experiment 3. The lower numbers in Experiment 3 may be attributed to the higher mean daily temperature experienced in Experiment 3 ($23 \pm 0.7^{o}C$) than in Experiment 4 ($21 \pm 0.6^{o}C$). This is consistent with with other studies on the effects of temperature on the rate of multiplication of *M. persicae*. Thus, Barlow (1962) and De Loach (1974) found that the R_o (rate of multiplication per generation) for *M. persicae* tended to decrease with increases in temperature above $20^{o}C$.

Application of Bombosch's Model

Bombosch's model was similarly applied to the results of Experiments 3 and 4 to determine whether it could predict the degree of suppression of the aphid population by the predator larvae.

Experiment 3

In Table 34, are given the expected numbers of aphids each day in the absence of predators, and the observed numbers on each of days 3, 6, 9 and 12. Table 34 shows a relatively good fit of expected and observed numbers. The rate of multiplication of *M. persicae* was similarly estimated as described in Section 6.1 and was found to be 1.376.

The k values for first, second and third instar predator larvae were again estimated as 0.5, 2.0 and 9.0 third instar equivalents respectively, and these values were used for 0-2, 3-5 and 6 days as described in Section 6.1. A k value of 9.0 was not used after day 6 because the predator larvae had pupated. In Table 36 are given for the predator treatments, the expected number of aphids eaten by predators; the expected number left each day; and the observed numbers of aphids on days 3, 6, 9 and 12. It can be seen from the results that the observed numbers were higher than that expected because of probable food being relatively in short supply and fewer aphids than expected were found and eaten by the predators. Similarly, there was no fit between the expected and observed number of aphids for both treatments (Table 35) indicating that it is not possible to predict the outcome of the results.

Table 34: Expected and observed numbers of *M. persicae* developing on potato plant in the absence of predators up to each of days 3,6,9 and 12 after the start of Experiment 3.

Day no.	Number of aphids	
	Expected	Observed
0	32	
1	44	
2	61	
3	83	128
4	115	
5	158	
6	217	304
7	299	
8	411	
9	566	592
10	779	
11	1071	
12	1474	1462

Table 35: Numbers of *M. persicae* developing on potato plants in the treatments: (a) where each plant and (b) every 2nd plant was initially infested with 2 and 4 aphids respectively; and each treatment had 8 predators. Expected and observed numbers of aphids are given for each of days 3,6,9 and 12 after the start of Experiment 3.

	Expected number				Observed no. of aphids in treatment (÷8)	
Day no.	aphids	(k)	left	after multiplication (X1.37)	Each plant	Every 2nd plant
0	4.00	0.50	3.50	4.80		
1	4.80	0.50	4.30	5.89		
2	5.89	0.50	5.39	7.38		
3	7.38	2.00	5.38	7.37	3.78	1.63
4	7.37	2.00	5.37	7.36		
5	7.36	2.00	5.36	7.34		
6	7.34	9.00	<0		2.46	0.72
7						
8						
9					1.88	0.19
10						
11						
12					4.59	0.09

Experiment 4

Similarly the observed and expected numbers of aphids in the absence of predators are given in Table 36. The value of q was estimated to be 1.42. And in Table 39 are given the usual data of expected number of aphids eaten etc. for Experiment 4. Table 36 shows a relatively good fit of expected numbers of aphids to observed ones. Similarly, there was relatively good agreement between the expected and observed numbers of *M. persicae* for both the treatments where every 2nd and 4th plant was initially infested with aphids (Table 37). Therefore, it is quite possible to predict the number of aphids in the control (no predators) and the treatments (with predators) under the assumptions and conditions of this experiment.

The dispersion of aphids within treatments and the control

In Tables 38 and 39 are given the means and variances of aphids per plant and the mean values of Morisita's index of dispersion (I_δ) in each treatment and the control for each sampling day. For variation in the values of I_δ within replicate see Appendix Tables 11 and 12.

From the values of F_o given in the 2nd last column of Tables 39 and 40 it can be said that all the distributions of *M. persicae* were contagious except in Experiment 3, on day 9 where the departure from a random distribution was not significant ($P>.05$) and on day 12 where the distribution was regular ($I_\delta = 0$). Within each treatment a similar trend in which the I_δ values first increased then decreased and increased again on day 12 as was observed in Experiment 3. The results of both experiments (3 and 4) also indicated that the distribution of aphids per

Table 36: Expected and observed numbers of *M. persicae* developing on potato plants in the absence of predators up to each of days 3,6,9 and 12 after the start of Experiment 4.

Day no.	Number of aphids	
	Expected	Observed
0	32	
1	45	
2	65	
3	92	181
4	130	
5	185	
6	262	372
7	372	
8	529	
9	751	978
10	1066	
11	1515	
12	2151	2107

Table 37: Numbers of *M. persicae* developing on potato plants in the treatments: (a) where every 2nd plant and (b) every 4th plant was initially infested with 4 and 8 aphids respectively; and each treatment had 8 predators. Expected and observed numbers of aphids are given for each of days 3,6,9 and 12 after the start of Experiment 4.

Day no.	Expected number of aphids	Eaten (k)	left	after multiplication (X1.42)	Observed no. of aphids in treatment (÷8) Every 2nd plant	Every 4th plant
0	4.00	0.50	3.50	4.97		
1	4.97	0.50	4.47	6.35		
2	6.35	0.50	5.85	8.31		
3	8.31	2.00	6.31	8.96	7.22	9.94
4	8.96	2.00	6.96	9.88		
5	9.88	2.00	7.88	11.19		
6	11.19	9.00	2.19	3.11	3.16	3.34
7	3.11	-	3.11	4.42		
8	4.42	-	4.42	6.28		
9	6.28	-	6.28	8.92	8.13	6.69
10	8.92	-	8.92	12.67		
11	12.67	-	12.67	17.99		
12	17.99	-	17.99	25.55	29.66	19.81

Table 38: Mean numbers and variances of *M. persicae* per plant and mean values of Morisita's index of dispersion in each treatment and the control at different sampling days for Experiment 3.

Prey spatial distribution	Sampling day	Mean	Variance	I_δ [1]	F_o [2]	P
Control	0	2.00	0	0.52	<1.00	>.05
	3	7.59	53.33	1.58	6.08	<.01
	6	18.81	193.66	1.41	9.47	<.01
	9	37.34	653.89	1.40	17.25	<.01
	12	91.50	3757.67	1.38	40.80	<.01
Each plant	0	2.00	0	0.52	<1.00	>.05
	3	3.78	27.35	2.26	5.93	<.01
	6	2.46	28.31	5.86	11.70	<.01
	9	1.88	37.92	3.12	10.92	<.01
	12	4.59	140.20	3.27	16.76	<.01
Every 2nd plant	0	2.00	4.27	1.55	2.13	<.01
	3	1.63	8.30	2.52	4.14	<.01
	6	0.72	2.47	3.59	2.98	<.01
	9	0.19	0.33	1.60	0.87	<.05
	12	0.09	.08	0	<1.00	>.05

[1] I_δ = Morisita's index of dispersion.

[2] F_o tests the depature from random distribution.

Table 39: Mean numbers and variances of *M. persicae* per plant, and the mean values of Morisita's index of dispersion in each treatment and the control at different sampling days for Experiment 4.

Prey spatial distribution	Sampling day	Mean	Variance	I_δ [1]	F_o [2]	P
Control	0	2.00	0	0.52	<1.00	>.05
	3	11.31	81.36	1.53	6.97	<.01
	6	23.25	401.83	1.72	17.85	<.01
	9	61.13	1513.35	1.38	24.95	<.01
	12	131.66	7608.89	1.35	53.75	<.01
Every 2nd plant	0	2.00	4.27	1.55	2.13	<.01
	3	7.22	48.88	1.69	6.20	<.01
	6	3.16	17.33	0.85	2.77	<.01
	9	8.13	51.17	1.99	3.86	<.01
	12	29.66	198.89	3.35	7.08	<.01
Every 4th plant	0	2.00	12.80	3.61	6.40	<.01
	3	9.94	248.12	3.30	24.35	<.01
	6	3.34	45.44	3.83	11.57	<.01
	9	6.69	103.26	2.19	10.76	<.01
	12	19.81	679.93	2.37	28.65	<.01

[1] I_δ = Morisita's index of dispersion.

[2] F_o tests the departure from random distribution.

plant tend to be more contagious in the presence of predators. In addition, when the prey were aggregated, there was a marked change in the distribution which in turn influenced the predator's ability to suppress prey population (Waters, 1959).

The level of prey suppression in this study was thus dependent partly on prey spatial distribution and searching rate (Hassell, 1978). In relation to this, Hassell (1978) suggested that the higher and lower limit of prey abundance associated with prey aggregation and spatial distribution may be determined in part by the relative protection of the prey in low density areas and the greater susceptibility to predation in high prey density areas. That the aphid population in Experiment 4 was lowest in the presence of predators when every 4th (corner) plant was initially infested may be due to the changes in the searching behaviour of *M. tasmaniae* larvae after they have found and attacked their prey (Fleschner, 1950; Waters, 1959; Hodele, 1967). After a predator larva has consumed its prey in a high density area, it tends to make thorough search for prey in that particular area to increase the chance of the predator coming in contact with a neighbouring prey (Fleschner, 1950). In a high-prey density area, larvae of *Chrysopa* sp. exhibited greater twisting movement in the searching pattern especially in restricted areas *(ibid)*. A similar behaviour may have been true for *M. tasmaniae* larvae preying on *M. persicae* in the treatment where every 4th plant was initially infested and the aphids were initially most dispersed.

CHAPTER 7

SPRAYING OF M. TASMANIAE EGGS ON TO POTATO CROPS

One of the main objectives of my field studies described in Chapter 4 was to gain information necessary for consideration in biological control of *M. persicae* and to enable us to determine whether we need to emphasize importation of new enemies, conservation, or augmentation of established enemies, or all three. In addition, basic research carried out through laboratory and glasshouse experiments (Chapters 5 and 6) on the biology of the natural enemy is aimed at providing the key to successful biological control.

It was evident from the results of the field studies conducted in large commercial potato fields and small potato plots (Chapter 4) that *M. tasmaniae* is the most abundant and important natural enemy of the potato aphids and was present almost all the year round. However, the populations of *M. tasmaniae* were much lower than expected prior to the autumn peak in aphid populations and hence they were ineffective in suppressing the aphid outbreaks. Some of the possible reasons for the ineffectiveness of *M. tasmaniae* in suppressing *M. persicae* population in autumn are: (i) the predators are not synchronised with the prey or (ii) their numbers are not adequately high to give early control. Therefore, one way to improve the predator's impact is to enhance its effectiveness.

There are various possible ways of enhancing the effectiveness of natural enemies, depending on the leads provided by the basic studies (De Bach, 1964). One of the ways is by augmentation of natural enemies involving

direct manipulation by mass production and periodic colonization (De Bach and Hagen, 1964). In the case of *M. tasmaniae* for the control of *M. persicae* in potato crops, I proposed augmentation by releasing mass produced eggs of *M. tasmaniae* in late March or in early April to coincide with the onset of the migration of alate *M. persicae* into the potato fields.

Periodic releases of eggs of *C. carnea* in the field had been successfully demonstrated to suppress populations of the bollworm, *Heliothis zea* (Boddie) and the tobacco budworm, *Heliothis virescens* (F.) in Texas, U.S.A. (Ridway and Jones, 1969). Shands *et al.*, (1972b) pioneered the work on mass releases of predator eggs for the control of potato aphids in Maine, U.S.A. with some success. So, too, manually introduced predators have shown promise for controlling damage caused by certain insect pests on certain crop plants on a field basis (Ridway and Jones, 1968, 1969; Shands and Simpson, 1972a, b; Shands *et al.*, 1972a, b, c, d, e). However, a suitable method of distributing large number of eggs of predators in large field plantings of certain crops is yet to be developed. So, one of the preliminary investigations which needs consideration is a method for field distribution of *M. tasmaniae* eggs. Because of the cannibalistic nature of *M. tasmaniae* larvae and adults, releasing the eggs provides a number of advantages.

The following laboratory and glasshouse tests were conducted to provide the basic information for later field-plot trials.

7.1 Development of a sprayer designed for spraying eggs

Introduction

A special compressed air sprayer was developed by Shand *et al.*(1972a) for spraying eggs of *Chrysopa* sp., and *Coccinella septempunctata* and

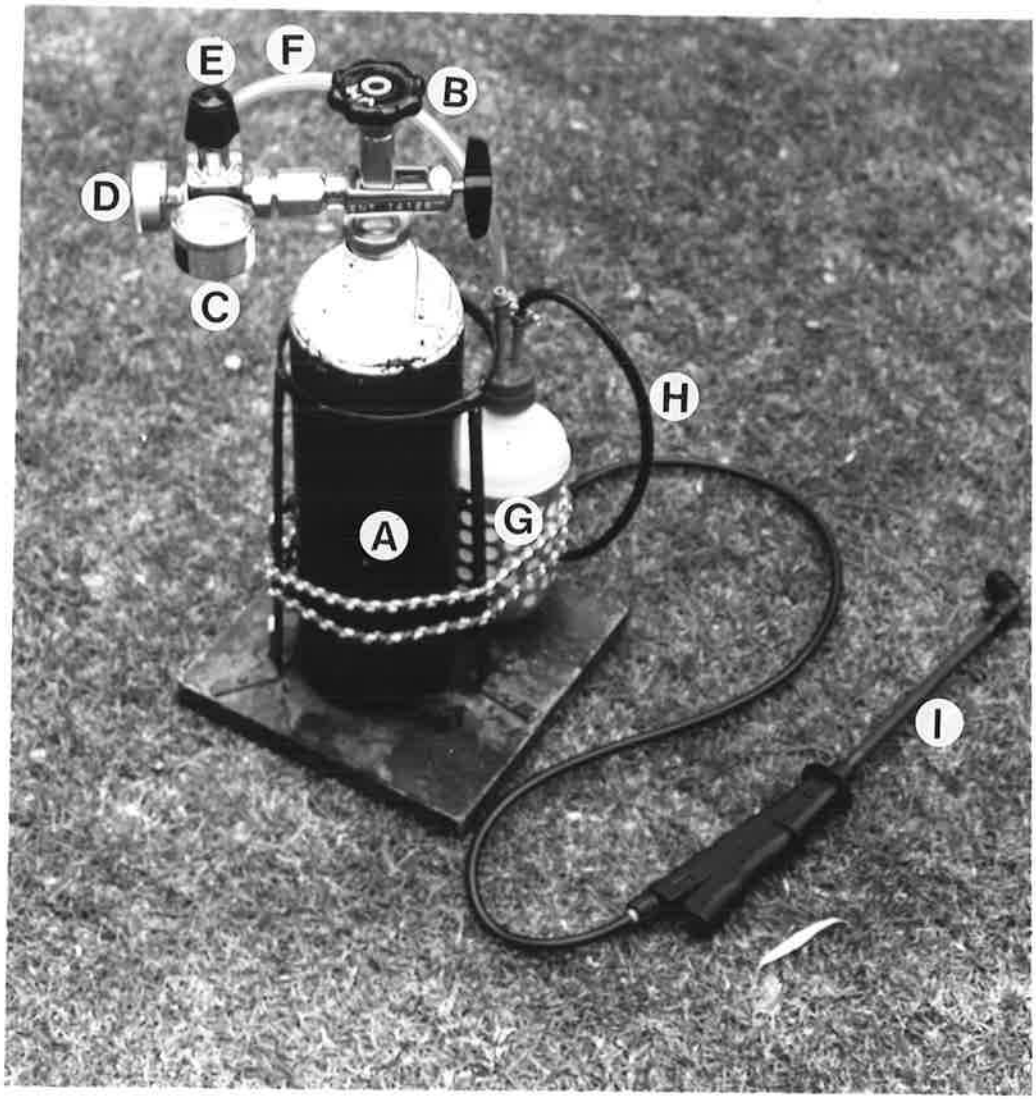
C. transverroguttata satisfactorily on to potato foliage. Whether or not such a sprayer is suitable for spraying *M. tasmaniae* eggs, which are different in size, shape and texture, is yet to be proven.

The sprayer and its operation

The general design and assembly of the sprayer that we used was similar to that developed by Shands *et al.* (1972a). It consisted of the following components as shown in Figure 31. The assembled sprayer weighed 5.0 kg with the spray tank full. The air-storage tank was a medical air type size 'C' metal cylinder (40 cm high x 11 cm in diameter), rated by the manufacturer to withstand pressures of 10,000 kPa. The required line pressure was obtained by adjusting the twin-gauge gas-pressure regulator (comet sprint RJ Series made by C.I.G., Australia) after opening the cylinder air valve, then opening the cut-off mechanism in the distal end of the lance by pressing the attached hand operated spray-gun lever. The air released from the air-storage tank entered and built up the pressure over the liquid in the spray tank. The spray tank was fitted into a cup-shaped metal casing specially constructed to protect the spraying tank from breakage. The air pressure over the liquid then forced the liquid from the bottom of the tank into the aluminium uptake tube (5 mm internal diameter) into the rubber tubing (5 mm internal diameter) and through the nozzle on the tip of the lance. The cone nozzle had a centered, circular orifice of 1.37 mm diameter, the swirl plate, and produced a hollow cone spray. The strainer was removed for spraying eggs of *M. tasmaniae*, leaving inside the disc only the 2-hole swirl plate. A 30 mm mouth polystyrene, ACI$^{(R)}$, one litre bottle was used as thespray tank. The spray tank rested on a metal support lashed to the air tank with rubber strapping, and was held in place by a metal strap around it.

Figure 31: The compressed air sprayer developed for spraying eggs of *M. tasmaniae*.

A. Air-storage tank
B. Air-intatake valve
C. Air tank pressure gauge
D. Delivery air pressure gauge
E. Delivery air pressure regulator
F. Spray tank air-inlet plastic tubing
G. Spray tank
H. Spray mixture-outlet rubber tubing
I. Spray lance


E
F
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C
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Both the pressure gauges were oriented in such a manner so that the operator could see them while in operation. The operating line pressure never exceeded 2.06 kg/cm^2.

7.2 Techniques of spraying eggs

7.2.1 Influence of nozzle size and application pressures on egg recovery, egg hatch, spray patterns and droplets size

Introduction

The quantity discharged by a sprayer depends to a great extent on the size of the nozzle orifice. Changing the diameter of the orifice does not only alter the amount discharged but also the distance carried and the angle of the spray cone (Hough and Mason, 1951). On the other hand, pressure is the principal factor controlling the spray droplets or particles. Increasing the pressure with a given nozzle size, will decrease the spray droplet size. The finer the spray droplets the further they will be carried. The greater the pressure also, the greater the included angle of the spray cone *(ibid)*.

In spraying liquid mixtures containing viable eggs of insects, the nozzle size needs also to be large enough to allow the eggs to pass through without causing damage. Damage to the eggs may also be caused by the impact of the eggs landing on leaf surfaces. The impact could vary according to the application pressure. Before the sprayer is tested in the field, a knowledge of the influence of nozzle size and application pressure on *M. tasmaniae* eggs must first be gathered.

The aim of these experiments was to determine the effects of nozzle size and application pressures on the percentage of egg recovered, and on egg hatch after spraying.

Materials and Methods

a). Water as the spray medium

Two hundred eggs of *M. tasmaniae* obtained from the insectary culture were added to 600 ml of distilled water in a 1-litre beaker, then poured into the spray tank and gently swirled to evenly disperse throughout the spray medium.

The eggs were sprayed at six different air pressures namely, 0.34, 0.68, 1.02, 1.36, 1.72 and 2.06 kg/cm^2 using two different sizes of nozzle orifice - 1.00 mm diameter and 1.375 mm diameter. The spray nozzle was directed half-way into a 1-litre beaker which was needed for collecting the sprayed eggs together with the water. The spray was agitated continously during spraying. In order to know the verticle distribution of eggs while being dispersed in the spray tank, the first, second and third 200 ml of the mixture were collected in three separate 1-litre beakers. The first 200 ml collected was designated as the bottom, the second 200 ml the middle and the third 200 ml the top.

After each spraying, the inside of the spray tank was thoroughly washed by adding some water and pouring out the contents into a large (15 cm) petri dish. In this manner, any

eggs that were retained in the bottle could be counted and recorded as unsprayed eggs. The nozzle was also searched for any eggs or remnants of eggs trapped during spraying. Collapsed eggs or empty egg shells were classified as damaged eggs. Their numbers were also recorded. Finally, 50 eggs were sampled from among the recovered eggs, placed individually in incubation units, and incubated in the 25°C room. The percent egg hatch after 4-5 days of observation was calculated.

b). Using Xanthan gum as the spray medium

A test was also conducted to determine the influence of nozzle size on the spray pattern using xanthan gum solution instead of distilled water.

Four concentrations of xanthan gum solutions namely, .03%, .06%, 0.125% and .25% were prepared in distilled water. Using two size nozzle orifices, 1.00 mm and 1.375 mm in diamter, the solution was sprayed at an air pressure of 2.06 kg/cm^2. The pattern of the spray, the size of the cone spray and the spray droplets size were observed and compared.

Results and Discussion

The overall recovery rate when sprayed using 1.00 mm and 1.375 mm nozzle were 90.6% (Table 40) and 89.3% (Table 41) respectively. The results indicated that nozzle size had no significant effects on egg recovery. The overall percent egg hatch after spraying through 1.00 mm and 1.375 mm nozzle were 93.3 (Table 42) and 89.7 (Table 43).

Table 40: Recoveries (out of 200) of eggs of *M. tasmaniae* when sprayed through a 1.0 mm nozzle at 6 different air pressures using distilled water as the spray medium.
(T = top, M = middle, B = bottom (lots of 200 ml solutions)

Air pressure (kg/cm^2)*	Vertical distribution	Number of eggs: Recovered	Left in spray bottle	Trapped in nozzle	Damaged	Egg recovery (%)	Egg hatch (out of 50) (%)
0.34	T	110	2	0	0	95	88
	M	50			3		
	B	30			0		
0.68	T	98	7	0	1	91	98
	M	62			5		
	B	21			3		
1.02	T	96	3	0	0	92	90
	M	53			2		
	B	35			2		
1.36	T	45	6	0	5	94	96
	M	78			0		
	B	65			0		
1.72	T	30	6	0	2	81	100
	M	60			0		
	B	60			2		
2.06	T	126	4	2	0	91	88
	M	49			3		
	B	6			0		

* 1 kg/cm^2 = 14.5 lb/in^2

Table 41: Recoveries (out of 200) of eggs *M. tasmaniae* when sprayed through a 1.375 mm nozzle at 6 different air pressures using distilled water as the spray medium.
(T = top, M - middle, B = bottom (lots of 200 ml solutions)

Air pressure (kg/cm^2)	Vertical distribution	Number of eggs: Recovered	Left in spray bottle	Trapped in nozzle	Damaged	Egg recovery (%)	Egg hatch (out of 50) (%)
0.34	T	73			0	97	94
	M	76	0	0	3		
	B	45			0		
0.68	T	30			1		
	M	98	5	0	2	87	92
	B	46			9		
1.02	T	23			1		
	M	83	15	0	0	89	92
	B	72			5		
1.36	T	43			2		
	M	54	16	0	0	85	90
	B	73			2		
1.72	T	80			6		
	M	53	10	0	4	81	92
	B	29			1		
2.06	T	2			0		
	M	136	10	0	3	78	78
	B	17			0		

Since, with n = 50, a χ^2 test can pick up a significant difference of only 30% or more, none of the percent hatches in Tables 40 and 41 are different from each other - showing that the pressure which the eggs were sprayed had no influence on their hatching percentage. Similarly, the percent hatchings of eggs sprayed through a 1.375 mm nozzle (Table 41) were no different from those sprayed through a 1.00 mm nozzle. There was, however, a rather poor vertical distribution of the eggs whilebeing dispersed inside the spray tank (bottle). This may be attributed to the use of distilled water as a spray medium. The eggs were expected to be more poorly dispersed and suspended and to settle down more rapidly if the spray mixture was not agitated continously.

Table 42 shows the results of the influence of nozzle size on spray pattern and size of spray droplets at 2.06 kg/cm^2. At 0.25% the spray tended to be shaped into a jet; and at 0.125% not only was the cone narrowed but the droplet size also becomes larger. At the lower end of the range of concentrations, only at 0.03% with the 1.375 mm nozzle was a normal cone-shape pattern of spray obtained which lasted until the spraying ended. For this combination of concentration and nozzle size, the spray droplets began to get bigger only at the very end of the spraying period.

7.2.2 Selection of suitable spray medium

Introduction

Several materials have been tested including agar, Dacagin, sucrose (Shands *et al.*, 1972a; Jones and Ridgway, 1976), Methocel, Decagin plus sucrose, corn starch plus sucrose (Jones and Ridway, 1976), Plantgard (Nordlund *et al.*, 1974) and xanthan gum (McWilliams, 1979; Hall *et al.*, 1980) as spray media for immersing dispersing

Table 42: Effects of size of nozzle orifice on the spray pattern and droplets size at 2.06 kg/cm^2.

Concentration of Xanthan gum	Diameter of nozzle orifice			
	1.00 mm		1.375 mm	
	Spray pattern	Droplets size	Spray pattern	Droplets size
.25%	Jet	-	Jet	-
.125%	Narrow cone cone	Large	Narrow cone	Large
.06%	Normal cone but narrowed at the end of spraying	Fine	Normal cone but narrowed at the end of spraying	Finer
.03%	Normal cone but narrowed at the end of spraying	Fine	Normal cone	Fine but larger droplets at the end

eggs of insects while in the spray tank and for adhering the eggs to plant foliage after being sprayed. Since different spraying equipments were employed in the above works using different concentrations, of the spray media, different application pressures and nozzle sizes and different groups of insects, there is little basis for comparing the results. A separate test was thought necessary for testing selected spray media against *M. tasmaniae* eggs.

These laboratory experiments were conducted to select from a range of selected materials, which have been used in the past, a suitable one as liquid medium of good immersion, dispersion and adherence properties.

Materials and Methods

a). Agar, gelatin and sucrose

A preliminary laboratory experiment was conducted at room temperature to evaluate several materials for immersing *M. tasmaniae* eggs in them. Materials investigated were 0.15% agar, 1.0% gelatin, and 5.0% sucrose.

The immersing agents were dissolved in distilled water, using heat when required. The test solutions were tested for their immersion ability by completely soaking 20 *M. tasmaniae* eggs in 5 ml of the solution contained in a small plastic petri dish (35 mm in diameter and 10 mm deep). The eggs were then left submerged for a period of 30, 60, 120 and 240 minutes. At the end of each immersion period, the eggs were removed and individually placed inside an incubation unit. The eggs were placed in a 25^{o}C room for hatching.

Egg hatching was observed daily for a period of 6 days. The percentage of eggs that hatched for each treatment was calculated. Test solutions were also tested at 20°C for their suspension ability by estimating the speed of egg settling down as each egg is allowed to sink through a distance of 5 cm of a test tube (15 mm long and 10 mm in diameter) filled with the solution.

b). Plant glue

A plant glue called Plantgard(R) (Polymetrics International, New York) designed for use in the protection of ornamental trees and shrubs against water loss and air pollution, was tested at room temperature for its immersion effects on *M. tasmaniae* eggs. Similar procedures as described in Section 7.2.1a was followed using four different concentrations namely 0, 10, 20 and 30% solutions in distilled water. Similar observations as described in Section 7.2.1a were taken.

c). Xanthan gum[1]

Xanthan gum was then tested for its effects on *M. tasmaniae* eggs following poor performance by plant glue. In addition its

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[1]A cream coloured, odorless, free flowing powder. Dissolved readily in water with stirring to give highly viscous, solution at very low concentrations. Forms strong film on evaporation of aqueous solutions. Resistant to heat degradation. Aqueous solutions are highly pseudo plastic. Used in foods, non-foods cosmetics as stabilizer and emulsifying agent. (The Merck Index, 1976).

ability to adhere eggs on to potato leaves was evaluated.

Five concentrations (0, 0.03, 0.06, 0.125 and 0.25%) of xanthan gum in distilled water were prepared. For testing its ability to suspend the eggs, the solution was poured into a 100 ml graduated cylinder. The cylinder was positioned in front of a dark brown cloth so that the eggs inside the cylinder could be easily seen. One hundred eggs were added into the solution and agitated gently. The mixture was then observed periodically for 1 hour at intervals of 5 minutes for eggs suspension results. At the end of the 1 hour period, the number of eggs settling at the bottom of the cylinder were counted.

In the egg submergence experiment, four concentrations of xanthan gum solution namely 0, 0.06, 0.125 and 0.25% were tested. The solution was poured into a small plastic petri dish (35 mm diameter) to fill up to 1-2 cm of its rim. Twenty eggs were placed on the centre of a square piece (5 cm x 5 cm) of fine-mesh black voil. The voil was then carefully lowered into the dish until all the eggs had been submerged. The piece of voil was needed to contain and remove the eggs as quickly as possible. The eggs were submerged in the test solution and the control (only distilled water) for a period of 30, 60, 120, 180 mins. Eggs were removed and placed individually in an incubation unit at the end of each immersion period. Eggs were kept in the 25^{o}C room for hatching.

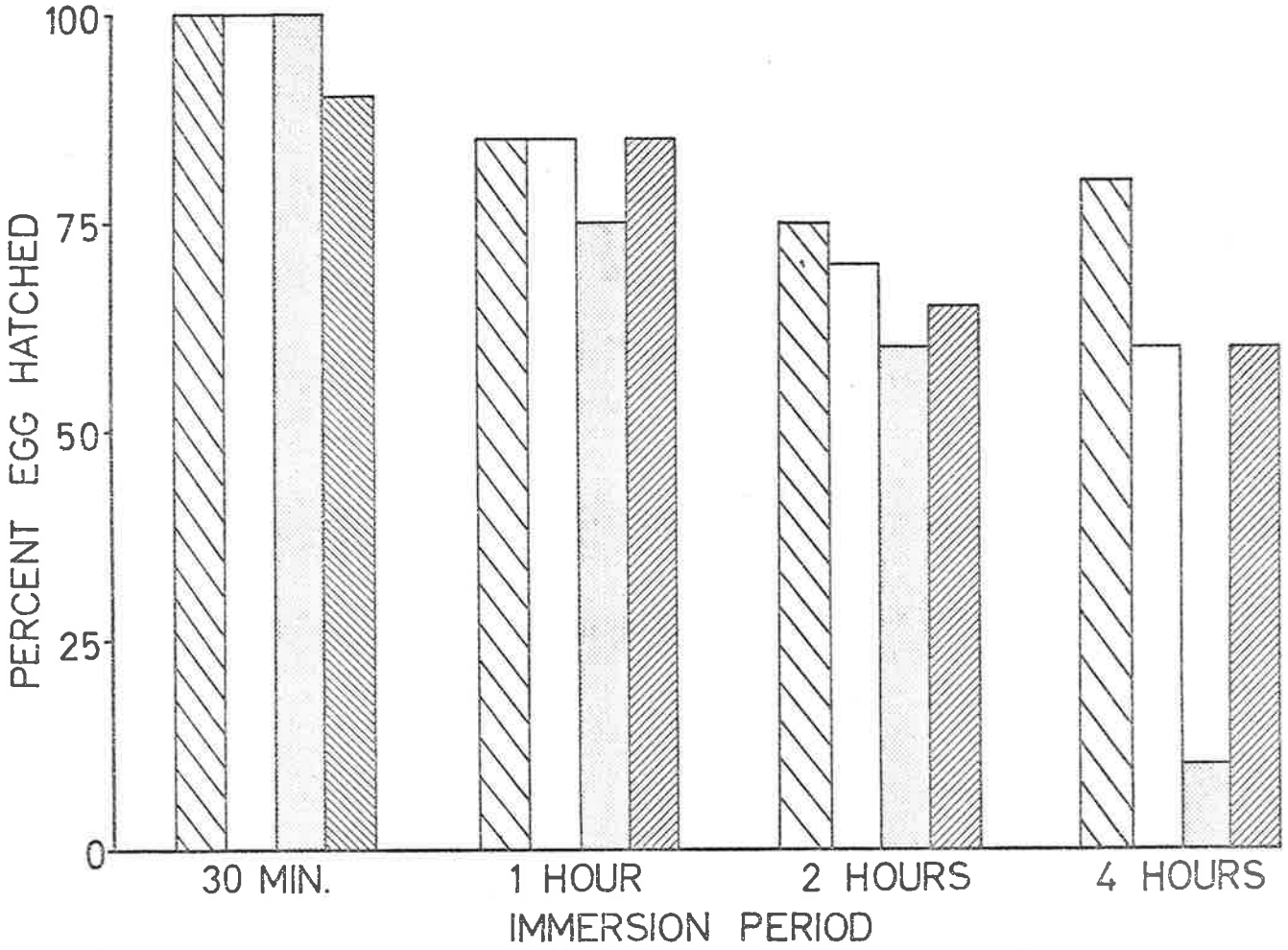
To determine the adherence properties of the eggs a solution of 0.03% and 0.25% xanthan gum in distilled water were prepared.

About 100 *M. tasmaniae* eggs were added to 100 ml of the gum solution contained in a 100 ml beaker. The mixture was agitated and left standing for 30 minutes. At the end of the submergence period, the mixture was poured out into a large petri dish (15 cm diameter) so that the eggs could be taken out easily. The eggs were taken out of the mixture and placed individually on a potato leaf disc (30 mm diameter) contained in a 35 mm plastic dish. To keep the leaf disc fresh a layer of moist filter paper was placed under it. To determine whether the egg has been glued on to the potato leaf, the egg was gently brushed three times using a very soft camel's hair brush at intervals of 15 minutes for 1 hour. The egg could only be categorised as "glued on" if it remained stationery when brushed. The experiment was conducted at 15, 20, 25 and 30^{o}C.

Results and Discussion

Figure 32 presents the results of immersing *M. tasmaniae* eggs in water solutions of 5% sucrose, 1% gelatin and 0.15% agar. There was a general reduction in egg hatch with increasing periods of egg immersion. Gelatin at 1% concentration caused the highest reduction in egg hatch at 1 hr, 2 hr and 4 hr immersion period. After 4 hrs of immersing, the eggs in gelatin there was a reduction of 55% (as compared to control) reduction in egg hatch. The zero reduction in egg hatch caused by gelatin at 30 min immersion was in contrast to Shands *et al.* (1972a) results who reported 39% reduction in *Coccinella septempuctata* egg hatch. Shands *et al.* (1972a) did not test effects of immersion for periods longer than 30 min on egg hatch. Distilled water alone caused 25% and 20% reduction in egg hatch at 2 hrs and 4 hrs immersion periods.

Figure 32: Effects on eggs hatch after immersing *M. tasmaniae* eggs in various water solutions.


100
75
50
25
0
PERCENT EGG HATCHED
30 MIN.
1 HOUR
2 HOURS
4 HOURS
IMMERSION PERIOD

Neither the 5% sucrose nor 1% gelatin as spray media appeared to have an effect on the percent hatch of *M. tasmaniae* eggs after 30 min of immersion. However, after 1 hr of immersion, gelatin caused 25% reduction in egg hatch while sucrose only caused 5% reduction. From the results it was obvious that submerging the eggs for more than 1 hr in the various solutions was detrimental to the eggs. If ever any of the solutions tested were to be used as a spray medium, eggs would have to be sprayed within 1 hr after adding them to the spray medium.

Settling speed of eggs

The results of the suspension test are given in Table 43. If the settling speed of the egg is taken as a measure of the degree of egg suspension, then the slower the settling speed, the better is the egg suspension. No speed could be recorded for all concentrations of agar, since the eggs did not move at all after 1 hr of observation. Probably agar was too viscous even at 20°C to allow adequate dispersion and suspension (Shands *et al.*, 1972a). Eggs suspended in 5% sucrose solution settled down 58% slower than those placed in distilled water. On the other hand, 1% gelatin reduced the settling speed of the eggs by 156%. The results only indicate that eggs placed in gelatin 1% will remain suspended longer (more than twice) than those placed in sucrose 5%. In spite of the good suspension property of 1% gelatin, it will not be safe to use as a spray medium because it had adverse effects on egg hatch.

Table 43: Settling speeds (sec./5 cm) of *M. tasmaniae* eggs travelling in various spray media

Solutions	Egg 1	2	3	4	5	6	7	8	9	10	Mean
Agar .05%	*[1]	*	*	*	*	*	*	*	*	*	-
Agar .10%	*	*	*	*	*	*	*	*	*	*	-
Agar .15%	*	*	*	*	*	*	*	*	*	*	-
Gelatin 1%	33.6	26.5	25.5	33.0	32.5	32.3	34.4	32.6	32.5	34.0	31.7
Sucrose 5%	18.4	17.0	18.4	19.2	21.0	21.3	19.7	17.0	22.7	21.7	19.6
Control (Distilled water)	11.7	12.6	13.0	13.5	11.5	12.3	12.7	11.8	11.8	13.0	12.4

[1] * indicates that the eggs remained stationery all the time.

Egg hatch

Figure 33 presents the results of the effects on egg hatch when *M. tasmaniae* eggs were immersed in Plantgard solutions. The general trend was that greater reduction in egg hatch was obtained with increasing concentration of Plantgard except at 2 hr immersion which produced a 6% higher percent egg hatch at 25% concentration than at 10% concentration. Plantgard not only caused greater reduction in percent egg hatch, but those larvae that hatched had then tails glued to the egg shell and only some managed to crawl out half-way. No further test was conducted on Plantgard.

The results of the egg immersion test on xanthan gum are shown in Figure 34. Except at 0.125% constant and 24 hr immersion period, xanthan gum appeared not to cause appreciable reduction in percent egg hatch as compared to other materials tested. Percent egg hatch was on the average higher at all concentrations and was maintained at 65% or higher.

Table 44 presents the results of suspending *M. tasmaniae* eggs in various concentrations of xanthan gum solution. As the concentration of the solution was increased, it became more viscous and that permitted good suspension of *M. tasmaniae* eggs. Even at concentrations as low as 0.03%, the eggs remained in good suspension for 20 mins.

Egg adherence

Results of the experiment on egg adherence to the potato leaf disc at four different temperatures and at two concentrations of

Figure 33: Effects on egg hatch after immersing *M. tasmaniae* eggs in various concentrations of glue solution.

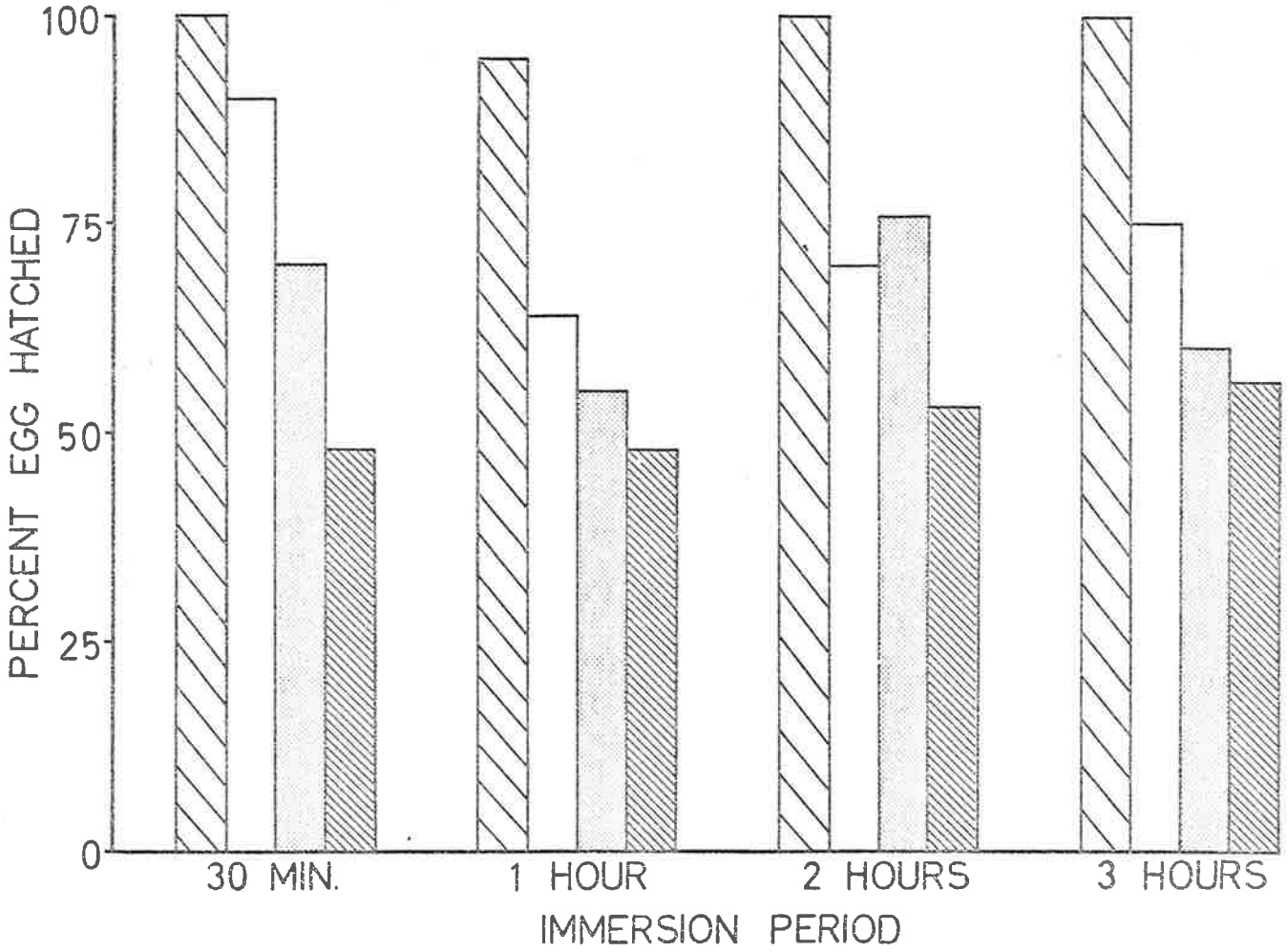
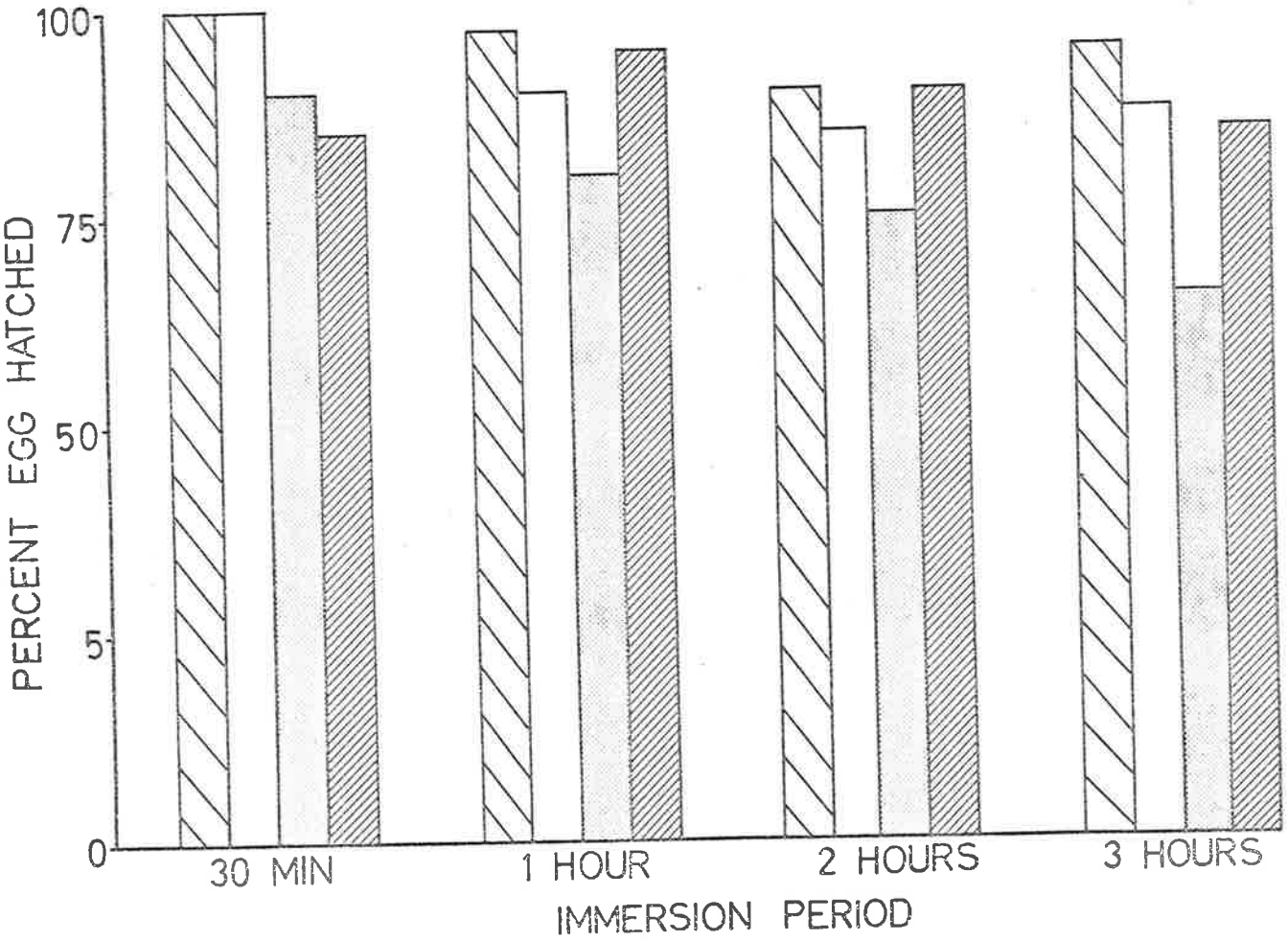

100
75
50
25
0
PERCENT EGG HATCHED
30 MIN.
1 HOUR
2 HOURS
3 HOURS
IMMERSION PERIOD

Table 44: Results of suspending *Micromus tasmaniae* eggs in various concentrations of Xanthan gum solution.

Conc. of Xanthan gum (%)	No. eggs observed for hatch	Percent of hatch	No. seconds(s) or minutes(m) or hours(h)		
			50% of eggs were suspended	75% of eggs were suspended	100% of eggs were suspended
0	100	95%	30s	40s	1m
.03	100	96%	20m	35m	45m
.06	100	93%	25m	40m	50m
.125	100	90%	1h	2h	3h
.25	100	90%	*[1]	*	*

[1] * indicates that the eggs have remained in suspension for >3 hours.

Figure 34: Effects on egg hatch after immersing *M. tasmaniae* eggs in various concentrations of Xanthan gum solution.


100
75
50
5
0
PERCENT EGG HATCHED
30 MIN
1 HOUR
2 HOURS
3 HOURS
IMMERSION PERIOD

xanthan gum solution are given in Table 45. The overall mean percentage of *M. tasmaniae* eggs glued to the potato leaf discs 1 hr after the eggs had been taken out of the .25% xantha gum solution was 80.6%. Slightly higher overall mean percentage (92.5%) of eggs glued on to the leaf was found in the case of 0.03% gum solution.

Temperature seems to have very little effect on the percent eggs glued. A significant difference ($P<.05$) in the percentage of eggs glued was found among the temperatures in the case of .03% gum solution. Between 15 and 30 mins. after the eggs were placed on the leaf seemed to be the critical period governing the percent egg glued. The eggs were well glued on to the leaf discs after the 30 min duration.

7.2.3 Distribution of sprayed eggs on a flat surface with and without potato plants

Introduction

Once a method of distributing the eggs has been developed, the next step is to study the distribution of the eggs when sprayed on to the plants in the field. Shands *et al.* (1972a) experienced difficulty in getting uniform dispersion of eggs of *Coccinella septempunctata* in the spray mixture which eventually resulted in less uniform distribution of the eggs when sprayed in the field. A large percentage of eggs sprayed in the field may be lost because they become soil- or mud-covered, both in the open and beneath a plant canopy, as experienced by Shands *et al.* (1972a).

The following experiments were conducted to study the distribution of *M. tasmaniae* eggs when sprayed under simulated field conditions, and to estimate the percentage of egg caught on the foliage and those lost on the ground.

Table 45: Percent eggs glued on to potato discs at different temperatures after being taken out of the Xanthan gum solutions and placed on the leaf discs.

Minutes later	Percent eggs glued on leaf disc (n=10)			
	15°C	20°C	25°C	30°C
0.25% Xanthan gum solution:				
15	60	90	70	70
30	60	90	80	70
45	90	90	80	90
60	90	90	80	90
0.03% Xanthan gum solution:				
15	100	100	90	90
30	100	100	90	90
45	100	100	90	90
60	100	100	90	90

Materials and Methods

a). Distribution of eggs sprayed on to a flat surface

One hundred and fifty eggs of *M. tasmaniae* were added to 200 ml of 0.03% (w/v) xanthan gum solution. The eggs were thoroughly dispersed throughout the gum solution by gently pouring the mixture back and forth between two 500 ml beakers. The mixture was then poured into the spray tank and was ready for spraying.

The experiment was conducted in a wind-free environment provided by a glasshouse with the temperature maintained at 23°C. One hundred and five black plastic pots (each with a diameter of 15 cm) were placed upside down, touching one another and so arranged to create a rectangular block of 15 pots long and 7 pots wide. A rectangular piece of black voil fabric (300 cm x 150 cm) was placed over the block of pots which acted as support. This type of arrangement of pots and the fabric was designed to be used in subsequent spraying tests.

The eggs were sprayed, from a height of 45 cm from the fabric. The air pressure was maintained at 2.06 kg/cm^2 and the diameter of the cone nozzle orifice was 1.375 mm. A spray swath of 60 cm wide was obtained when sprayed from a height of 45 cm. The sprayer was moved down the middle of the spray area at a speed of approximately 1.6 km/hr (= 2 m.p.h.) and it was moved back and forth along the spray area four times before the spray tank was emptied.

After the spraying was completed, eggs left in the mixing beaker, the spray tank and on the black fabric were counted. Also, the position of individual eggs on the fabric were marked on a paper, thus

showing digramatic representation of the distribution of the eggs. The spraying test was repeated 3 times.

b) Distribution of eggs on to a row of potato plants

Similar procedures as described in 7.2.3(a) were followed. The only difference between this experiment and the previous one was the presence of a row of 3 potted potato plants on the centre of the black fabric. By removing three empty pots on rows 5,8 and 11 of the middle column, the 3 plants spaced at 15 cm apart were then positioned. Each plant had an average canopy diameter of 40 cm, an average height of 20 cm, and an average of 13 leaves (excluding those leaves less than 2 cm long) per plant.

The number of *M. tasmaniae* eggs left in the mixing beaker, in the spray tank, on the fabric and on the plants were similarly counted. The spraying test repeated 3 times.

c). Distribution of sprayed eggs on to two rows of plants

Similar procedures to those used in the two previous experiments were followed. Instead of having one row in the middle of the spray area, two rows of 5 potato plants, with the leaves between the adjacent plants touching, were used (Fig 35). Eggs were sprayed on to the plants by keeping the spray nozzle in a straight line in between the two rows. Eggs left in the mixing beaker, in the spray tank, on the fabric and on the foliage were counted. The spraying test was replicated three times.

Figure 35: A typical layout of potted potato plants protruding through a black cloth for the spraying tests in the glasshouse.

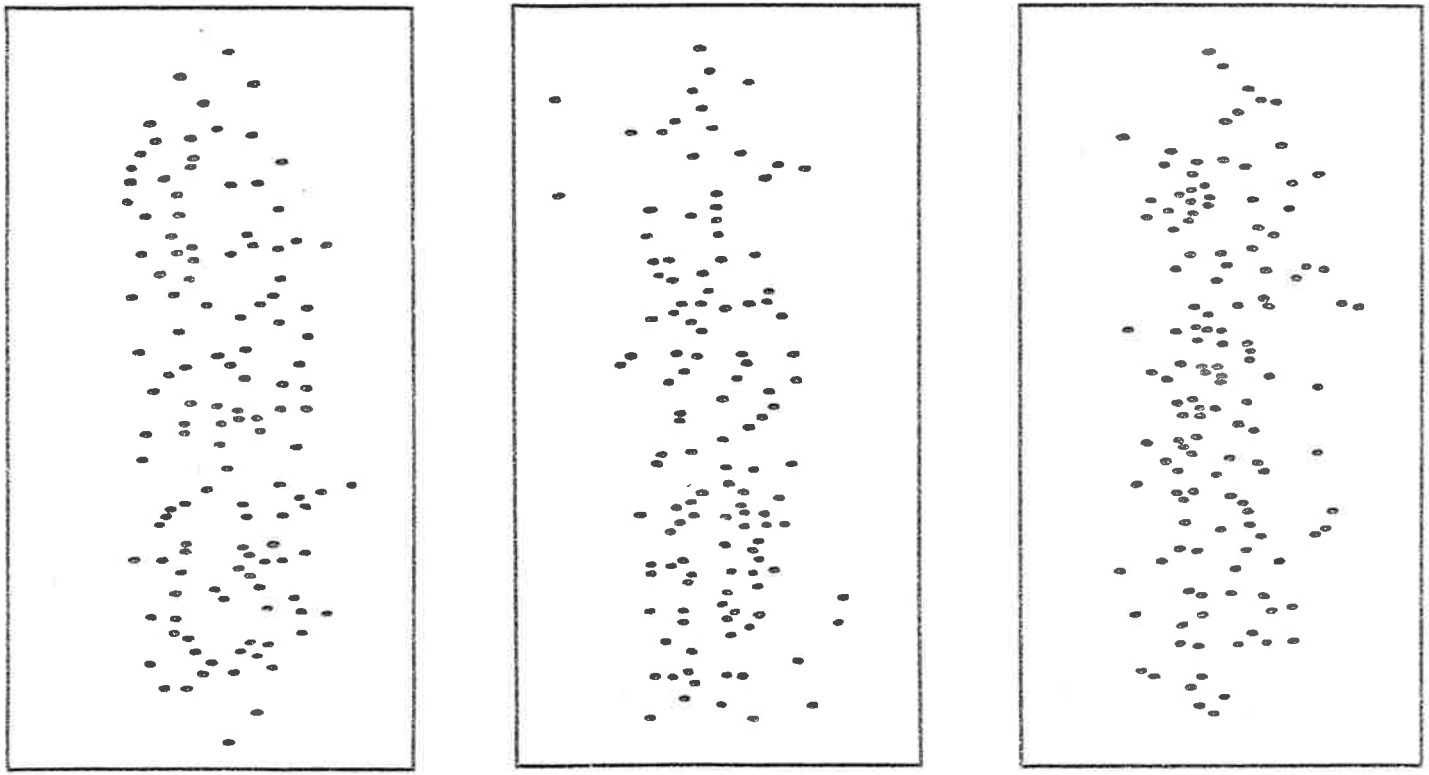
Results and Discussion

Results of spraying eggs on the black fabric without plants on it are shown in Figure 35 and Table 46. It can be seen in Table 46 that the average percentage of the eggs sprayed on to the fabric was 86%. Most of the eggs that were not sprayed were left in the spray tank. The number of eggs retained inside the spray tank may vary according to the gap created between the lower end of the uptake tube and the bottom of the spray tank. Very few eggs were lost or drifted away during spraying. The distribution of the sprayed eggs on the fabric appeared to be quite even with very few eggs going outside the spray swatch boundary (Fig. 36).

Table 47 presents the results of the experiment on spraying the eggs on a row of 3 potato plants spaced at 15 cm apart. An average of 21 eggs (14.0%) of *M. tasmaniae* landed and stuck on the leaves. More than half of the eggs sprayed (58.2%) landed on the black fabric. Unsprayed eggs which were retained inside the spray rank amounted to 10.7% which compared favourably with that detailed in the previous experiment (10.0%). Each plant had an average of 4.2 eggs. So, quite a substantial quantity of eggs were actually landing on the fabric when plants were spaced out. This is true in the field in the early stages of the growth of the potato plants where the leaves of plants within and between rows are still not tocuhing one another.

When the palnts were moved closer together with their leaves tocuhing the number of eggs landed on the plant were almost doubled as shown in Table 48. Since in this case there was 50% less open

Figure 36: Distribution of eggs of *M. tasmaniae* after being sprayed on to a flat piece of black fabric for each of the 3 replicates.



REPLICATE 1 REPLICATE 2 REPLICATE 3

Table 46: Number of *M. tasmaniae* eggs lost and recovered in mixing beaker, spray tank, black fabric and potato plants after spraying.

	No. of Eggs (n=150)		
	Replicate I	Replicate II	Replicate III
Mixing beaker	1	0	1
Spray tank	20	16	9
Black fabric	128	125	136
Lost	1	9	4

Table 47: Number of *M. tasmaniae* eggs lost, and recovered in mixing beaker, spray tank, black fabric and on potato plants after being sprayed.

	No. of Eggs (n=150)		
	Replicate I	Replicate II	Replicate III
Mixing beaker	2	3	6
Spray tank	14	13	21
Black fabric	83	93	86
Plant 1	5	1	5
" 2	2	5	3
" 3	4	6	4
" 4	6	7	3
" 5	2	4	6
Total	19	23	21
Lost	32	19	16

Table 48: Number of *M. tasmaniae* eggs lost and recovered in mixing beaker, spray tank, black fabric and potato plants after being sprayed.

	No. of Eggs (n=150)		
	Replicate I	Replicate II	Replicate III
Mixing beaker	3	0	1
Spray tank	14	17	21
Black fabric	63	64	50
Plants 1-6	2-0	4-2	3-1
" 2-7	7-5	3-3	3-3
" 3-8	5-4	3-4	6-7
" 4-9	5-9	4-3	2-5
" 5=10	3-5	3-3	4-5
Total	40	32	39
Lost	30	38	39

area on the black fabric, the percentate of eggs landed on the fabric was reduced from 58% to 39%. The percent of eggs retained in the spray tank was 11.3% which is still within the range of those obtained in previous experiments (Section 7.2.2). The percent of egg lost, probably due to spray drift or eggs bouncing off the leaf surface and thrown off the edge of the fabric in Experiment 7.2.3a, b and c were 4.6%, 22.0% and 35.6% respectively. There was obviously an increase in the percent egg lost. More eggs were lost in the presence of plants on the fabric than otherwise. Even more eggs were lost if more plants were present. Whether or not the number of eggs that bounced off the leaves and were lost is related to the area covered by the leaves is not known. Since the air inside the glasshouse was still, egg loss due to spray drift was very unlikely.

CHAPTER 8

SMALL-PLOTS FIELD STUDIES ON INUNDATIVE RELEASES OF M. TASMANIAE EGGS

Introduction

In the direct manipulation of entomophagous insects through either innoculative or inundative releases, the natural enemy is first selected as a candidate for release. The selection is based on three strategies: a) innoculative releases made with the expectation that the species will survive permanently in the system and regulate the pest at a new and lower density; this is classical biological control; b) innoculative releases made with the expectation that the species will survive and reproduce only for a limited number of generations and prevent the pest density from rising above the economic threshold during that period and c) periodic, inundative releases for immediate control of a pest population, with an expectation of immediate prey mortality but not long term regulation. The third strategy refers to the use of'biological insecticides' with thresholds which may differ from those established for chemical usage (Rabb *et al.*, 1976; De Bach, 1964).

In this thesis, a hypothesis based on stragety c) mentioned above was formulated. The hypothesis states that when large numbers of *M. tasmaniae* eggs are periodically released to the potato crops in late March to coincide with the period of migration of alate *M. persicae*, an early suppression of the developing initial aphid populations may be achieved, thus maintaining the aphid population at a very low level and preventing the incidence and spread of potato leaf roll virus infection.

Past work on inundative releases of insect predations for the control of aphids, melaly bugs, mites and lepidopterous pests have been successful on an experimental basis. Doutt and Hagen (1950) reported the successful suppression of *Pseudococcus* sp. on pears in U.S.A. through periodic releases of *Chrysopa* eggs. More recently, experimental releases of *Chrysopa* sp. have been effective against *Heliothis* sp. on cotton (Ridgway and Jones, 1968 and 1969) and aphids on potatoes (Shands *et al.*, 1972). Experimental releases of coccinellid predators also have shown promise against aphids on potatoes (Shands *et al.* 1972a,b,c, d and e).

Two experiments with inundative releases were done in this study. Their main purpose was to evaluate the effectiveness of periodic inundative releases by spraying of eggs of *M. tasmaniae* in the suppression of *M. persicae* populations developing on potato plants in late March.

Materials and Methods

8.1 Experiment 1; potato plants artificially infested with aphids

This first experiment was conducted in December 1980 at the Waite Agricultural Research Institute's orchard at Glen Osmond, South Australia, and was timed to coincide with the period of the year when *M. persicae* are scarce in the potato fields. The absence then of natural populations of *M. persicae* and of their predators enabled the artifical infestation of plants with insectary-reared colonies to be made without the necessity to enclose the experimental populations in large field cages.

This experiment was done to test the methods etc. before the 2nd experiment was done with naturally infested plants at the critical time in

March when aphid populations are starting to build up and need to be controlled.

a). Plants

Healthy certified seed pieces of the 'Exton' variety of potatoes were planted on September 29, 1980 in 90 cm rows. Spacing of seed-pieces were 30 cm apart in the small plots, consisting of four 5 m rows. The plots were arranged 2 x 3 completely randomized design with 2 treatments and 3 replicates. The two treatments were sprayed and unsprayed (control). The soil surface was kept bare in the 4 m alley and 2 m alleys between columns and rows. A 4 m wide soil surface bordering the plots was also kept bare.

Cultural practices on growing potatoes for this experiment were those normally followed in commercial plantings except that no insecticide and other pesticides were applied. The plots were irrigated by furrow-flood, rather than by the overhead sprinklers usually in commercial crops so that the eggs of *M. tasmaniae* that were sprayed on to the leaves would not be washed off during irrigation. The first furrow irrigation was done one day prior to spraying and the second one was done 5 days later. The 5-day interval between irrigations allowed those eggs that were sprayed on the ground to hatch before the next irrigation.

One day prior to infestation by aphids 30 leaves (3 leaves x 10 plants) were randomly sampled from each replicate in the sprayed and control plots. Total numbers of *M. persicae* and other aphids (if any) and natural enemies were counted directly from the leaves.

b) Infestation with aphids

Potato plants were infested on December 2, 1980 in the late afternoon by placing 6 fourth instar and adult apterous *M. persicae* on every 3rd plant. A total of 34 plants were infested with 204 aphids.

On December 3, a few hours before eggs of *M. tasmaniae* were sprayed on to the plants, 30 leaves were again randomly sampled from each replicate, and aphids and natural enemies were counted.

c) Spraying of eggs of *M. tasmaniae*

Eight hundred eggs suspended in 1000 mls of 0.03% xanthan gum solution were sprayed on to plants in each replicate of the treated plots with a specially designed compressed air sprayer equipped with a cone-type nozzle at 2.06 kg/cm^2 pressure. The eggs varied in age from 24 hours to 2 weeks (held at $5^{o}C$). First the two inner rows of plants, and then the two outer rows of plants were sprayed in succession. Spraying was done at a distance of not more than 45 cm between the nozzle and the top of the plant.

The first assessment of the effectiveness of the release of *M. tasmaniae* eggs was made 5 days after spraying to allow most of the eggs, particularly those fallen to the ground to hatch out.

The potato plants at the time of spraying were already matured with 2-3 stems per hill and 10-12 leaves per stem. The lower leaves of some of the plants were senescing and the plants lying prostrate on the ground towards the end of the experiment. The experiment

could not be conducted earlier when the plants were smaller and younger because of the difficulty in synchromizing the production of *M. persicae* and of *M. tasmaniae* eggs at the critical time for field infestation.

8.2 Experiment 2 ; potato plants naturally infested with aphids

a) The plants

Healthy certified seed pieces of 'Exton' variety of potatoes were planted on February 10, 1981 in 90 cm rows. Spacing of the seed pieces was 90 cm between rows and 30 cm with rows (Fig. 37) Each of the six plots consisted of five 6 m rows. The plots were arranged 2 x 3 completely randomized design with two treatments, i.e. 1) Sprayed with eggs, and 2) Not sprayed with eggs (control). Each of the treatments was replicated three times. The soil surface was kept bare in the 4.8 m alley between columns and rows of plots. A 10 m wide soil surface bordering experimental area was also kept bare. Similar cultural practices described in Section 8.1 were followed. The plots were furrow-irrigated beginning one day prior to the spraying of eggs.

b) The timing of sprays of eggs

Activity of alate *M. persicae* was monitored by placing a yellow pan water trap 45 cm above the bare soil surface in the centre of the experimental area. The timing of the first spraying of the eggs of *M. tasmaniae* was based on the time of migration of alate *M. persicae* into the potato plots with the trends in numbers of alate *M. persicae* in the trap being used to indicate the time of migration.

Figure 37: Small plots of potatoes separated by bare ground used for the trials on field spraying of eggs of *M. tasmaniae* for control of *M. persicae*.

Data on the number of winged *M. persicae* caught by water had been collected over a 3-year and 2-year period at Waite Institute and Milang respectively. The graphs of numbers per trap given in Figure 38, show that winged *M. persicae* flew into potato crops between end of February to end of March. Thus, in order to achieve early season control of the aphids, the predators need to be released during the early part of the migration period.

The first spraying of eggs was therefore made on March 24, 1981 and other sprays were applied twice weekly over a period of 4 weeks.

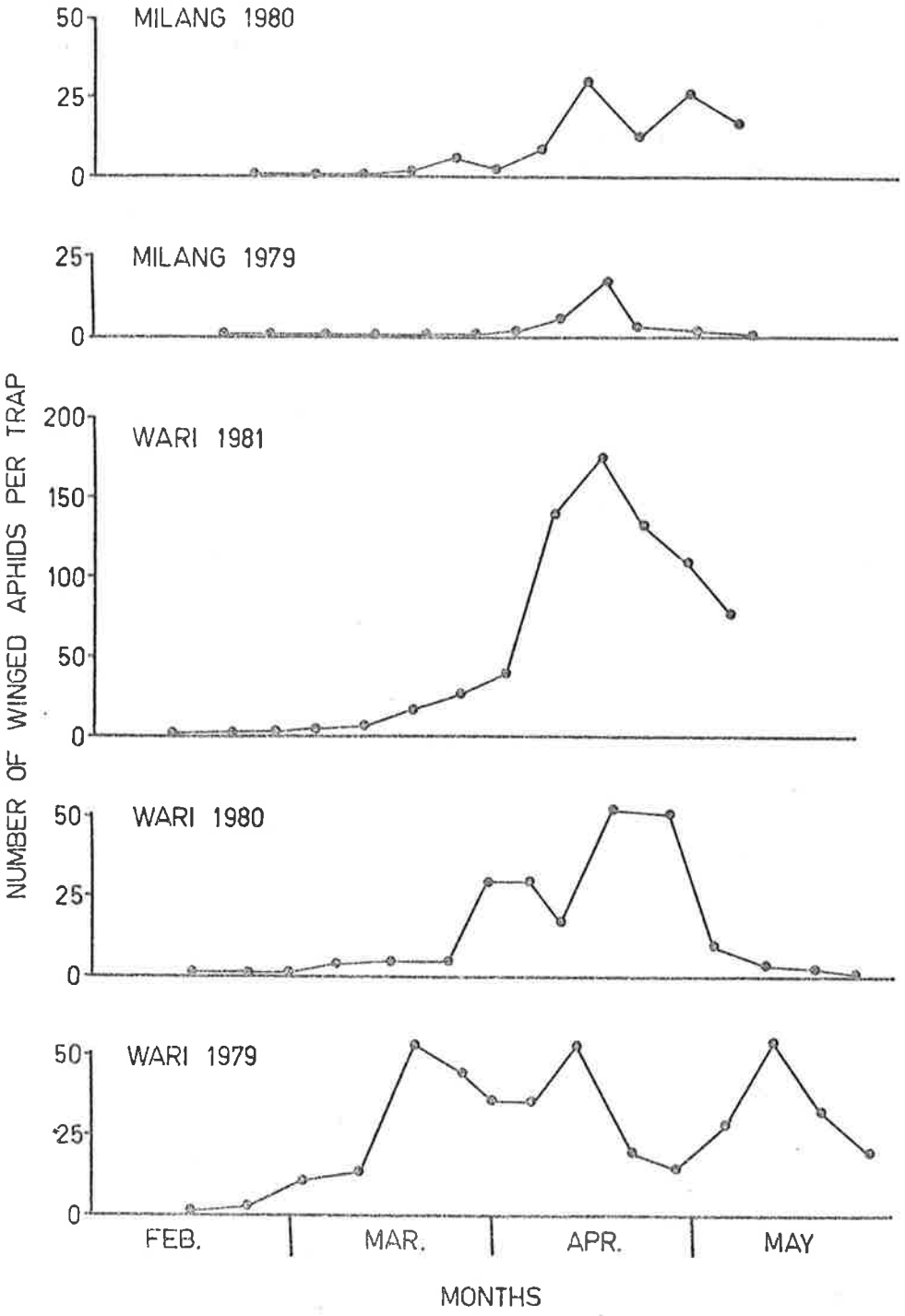
d) The spraying of eggs

The treatments were randomly assigned to each of the plots. At the time of first spray, the plants were relatively young. The leaves of plants between rows were not touching. Based on the average of 14 plants per row, the average number of plants per plot was ca. 70. Low rates of spraying made initially was due mainly to unavailability of eggs.

The initial 900-1000 eggs sprayed on each plot was based on the expected final density of 3 eggs per plant. Approximately 80% of the sprayed eggs were expected to be lost or killed due to the following factors: 1) spray drift; 2) eggs sprayed to the ground; 3) poor egg hatch and larval survival on soil, and 4) other unforseen causes of mortality.

The potato tubers from each plot were dug out on May 5, 1981 and the yields were recorded as wet weight of tubers.

Figure 38: The number of winged *M. persicae* caught per trap at Waite Agricultural Research Institute (WARI_ in 1979, 1980 and 1981, and at Milang in 1979 and 1980.


MILANG 1980
50
25
0
MILANG 1979
25
0
WARI 1981
200
150
100
50
0
WARI 1980
50
25
0
WARI 1979
50
25
0
NUMBER OF WINGED APHIDS PER TRAP
FEB.
MAR.
APR.
MAY
MONTHS

Results and Discussion

Experiment 1

Figure 39 shows the population trends of *M. persicae* and natural enemies before and after the plants were sprayed with eggs of *M. tasmaniae*. In spite of a rapid increase in the populations of *M. persicae* up to five days after infestation, the aphid populations in both sprayed and unsprayed plots crashed to zero 8 days later. The population crash coincided with the unexpected and unfortunate rise in the air temperature with the daily maximum temperature staying at 40°C for 2 days (days 7 and 8). The high temperature caused the plants to wilt and some of them to die. The 40°C was in excess of the 37.5°C thermal death point for *M. persicae*; above 37.5°C, no *M. persicae* are expected to recover and reproduce when exposed for one hour or longer (Broadbent and Hollings, 1951).

On the other hand, a surprising number of chrysopid eggs were laid quite early on the plants in both the treatment and the control (Fig. 39) and the crash of the aphid population may have been due partly to the activity of chrysopid larvae. More larvae of *Chrysopa* sp. were found after the heat wave indicating that they may be more tolerant of high temperatures than *M. tasmaniae* larvae (Neuenschwander, *et al.*, 1975).

The populations of *M. persicae* were significantly higher ($P>.05$) in the sprayed plots than in the sprayed plots prior to the population crash.

The experiment was then terminated because most of the plants were in very poor condition.

The number of *M. tasmaniae* eggs on sprayed plants were 100 % higher than that of unsprayed plants. Only 1 egg was found on every 10

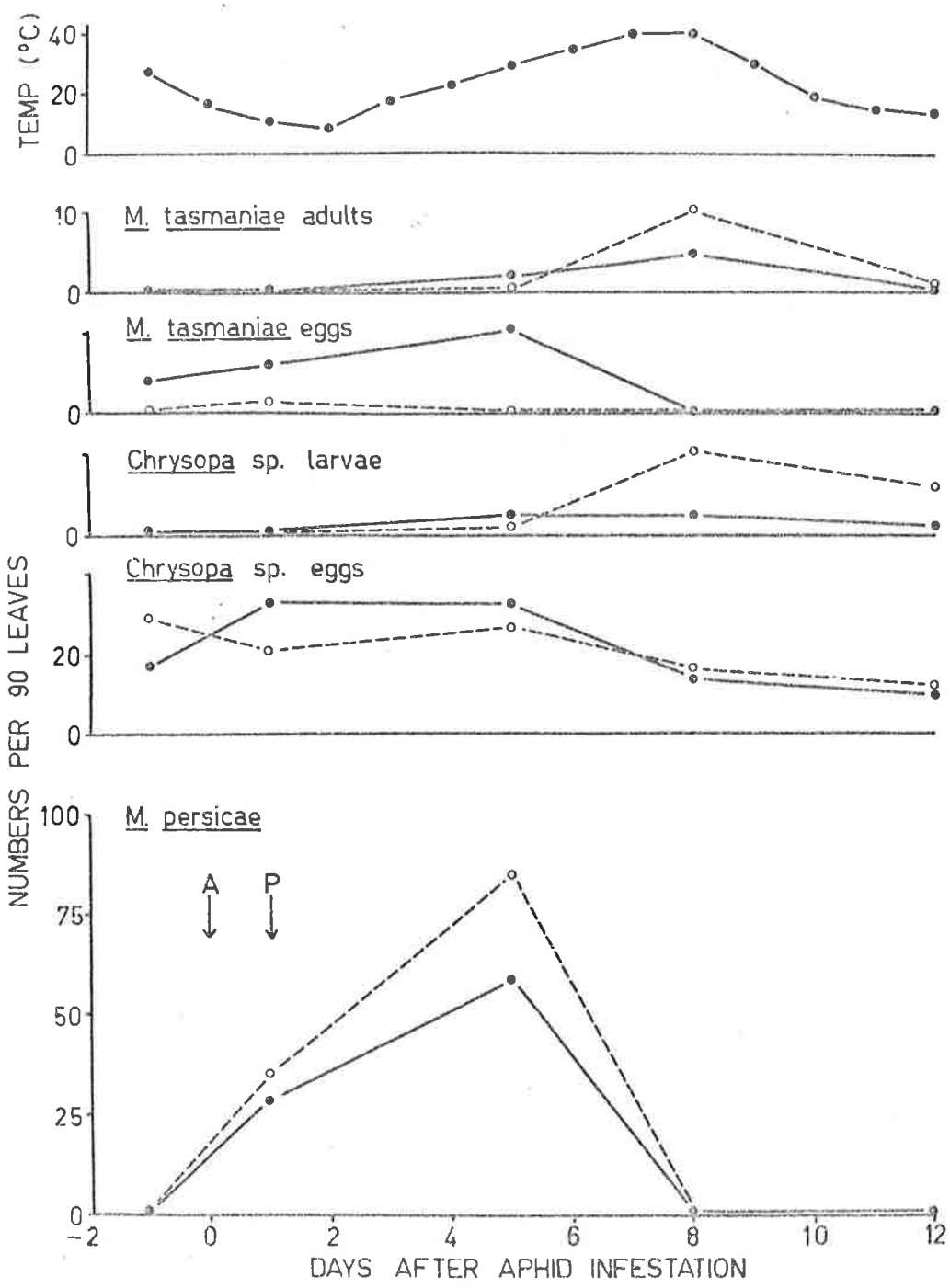
Figure 39: Population trends of apterous *M. persicae*, *Chrysopa* sp. eggs and larvae and *M. tasmaniae* eggs and adults; and the daily mean air temperature in small potato plots where eggs of *M. tasmaniae* were sprayed.

A - indicates when the potato plants were artifically infested with *M. persicae*.

B - indicates when eggs of *M. tasmaniae* were sprayed.

●—● (Sprayed)

o--o (Unsprayed - Control)


TEMP (°C)
40
20
0
M. tasmaniae adults
10
0
M. tasmaniae eggs
0
Chrysopa sp. larvae
0
Chrysopa sp. eggs
20
0
NUMBERS PER 90 LEAVES
M. persicae
100
75
50
25
0
A
P
-2
0
2
4
6
8
10
12
DAYS AFTER APHID INFESTATION

leaves on the sprayed plants representing less than 1 egg per plant (on the basis of 12 leaves per plant). The very low number of eggs found on the plants was expected because of the windy conditions at the time of spraying. A very high proportion of the eggs sprayed may have drifted away with the wind. The sharp drop in the number of eggs found on the leaves after a few days was due to the difficulty of finding egg-shells of eggs in the field after the eggs had hatched. Some eggs of *M. tasmaniae* found on the plants before spraying were obviously oviposited by naturally occurring adult *M. tasmaniae*. But no adult *M. tasmaniae* were found in samples from either the sprayed or unsprayed plots until after the rise in air temperature. Perhaps the higher air temperature forced the adults to actively search for aphids.

No conclusive evidence could be drawn as to whether or not the release of *M. tasmaniae* had effectively suppressed the populations of *M. persicae* in this experiment.

Experiment 2

Figure 40 gives the trends in the mean numbers of apterous *M. persicae* and eggs of *M. tasmaniae*. The ladybird *Coccinella repanda* also occurred and Figure 40 are also given the numbers of all its stages found on plants in the sprayed and unsprayed plots. Finally, Figure 40 records the times at which sprays of eggs (as indicated by arrows) of *M. tasmaniae* were applied to the (treated) potato plants.

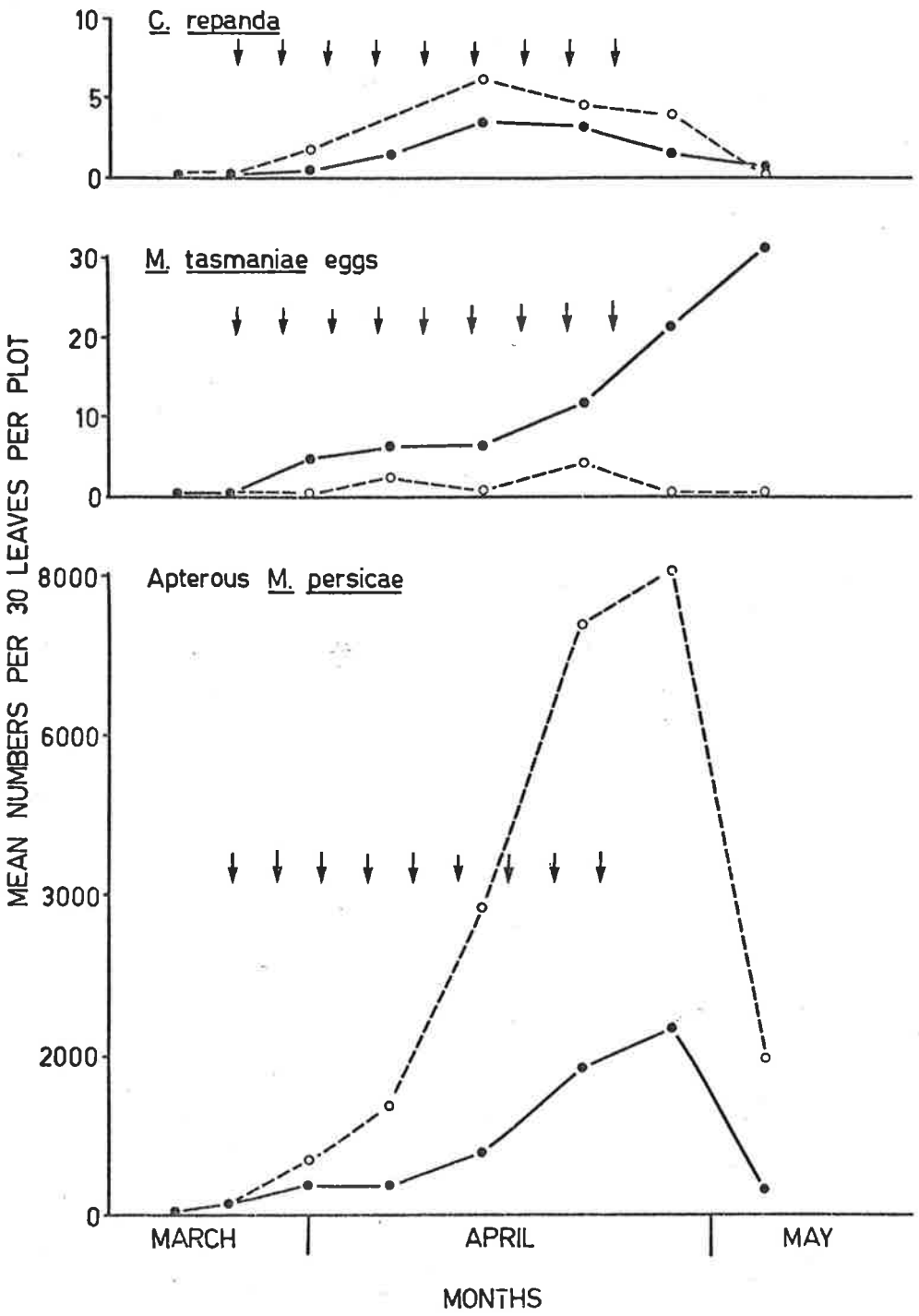
There was obvious differences in the number of aphids in the treated as opposed to the untreated (control) plants, with a peak of aphids of 8071 per 30 leaves in the control and 2354 aphids per 30 leaves in the

Figure 40: Population trends of apterous *M. persicae*, eggs of *M. tasmaniae* and all stages of *C. repanda* in small potato plots where sequential sprayings of eggs of *M. tasmaniae* were to control *M. persicae*.

Arrows indicate the date of spraying of eggs.

●—● (Sprayed)

o--o (Unsprayed - Control)


C. repanda
10
5
0
M. tasmaniae eggs
30
20
10
0
Apterous M. persicae
8000
6000
3000
2000
0
MEAN NUMBERS PER 30 LEAVES PER PLOT
MARCH
APRIL
MAY
MONTHS

treated plots. So the peak number of aphids in the treated plots was reduced by 70%.

The number of *C. repanda* were relatively low so the reduction in the numbers of aphids in the treated plots was almost certainly due to the *M. tasmaniae* that were added to the treated plots.

The populations of *M. persicae* in the unsprayed plots were much higher than in the similar plots in previous years (peaks of 500 aphids per 40 leaves in 1979, and 900 aphids per 60 leaves in 1980), and the unusually high numbers of aphids may have increased substantially the predator-prey ratio which enabled most prey to escape from predation. The suppression of the aphid population's in the treated plots would obviously have been easier if the numbers of aphids in the control plots were as low as those in previous years. Another reason for the relative inadequacy of control of *M. persicae* in the treated plots may have been due to the delay of one week before the first spray was applied. The delay in spraying was due to very hot dry weather which prevented early planting and normal growth of the plants. Moreover, when the eggs were ready for spraying in early March, the potato plants were just emerging from the ground and were too small for effective spraying.

Counts of *M. tasmaniae* eggs verified the increase in the egg and larval populations in the treated plots (Fig. 40), though the numbers found were considerably less than the numbers sprayed. Larvae of *M. tasmaniae* were rather difficult to find in the field. Similarly, Ridgway and Jones (1969) found only a small percentage of *C. carnea* larvae actually present after releasing them into cotton plots.

No adult *M. tasmaniae* were found in samples taken weekly. However, the presence of *M. tasmaniae* eggs in samples taken from the unsprayed plots indicated that there were indeed some naturally occurring adult of *M. tasmaniae*.

The only other predator found in the plots was *C. repanda* which was found in both the sprayed and unsprayed plots. The total number of *C. repanda* of all stages seemed to increase in response to the increase in the prey populations. Other aphidophagous insects such as chrysopids and syrphids were not found in the course of the experiment.

As shown in this study, an overall 70% reduction ($P>.05$) of the population of *M. persicae* in the plots sprayed with eggs of *M. tasmaniae* clearly demonstrated the potential of inundative releases for pest control. The releases also increased the yield of tubers in the treated plots by 38% ($P\leq.05$) (Table 49). Nevertheless, practical application of periodic inundative releases of *M. tasmaniae* for control of *M. persicae* in commercial plantings of potato crops will require further research concerning the timing of releases, the numbers required, economics of mass production and methods of distribution.

Some of the major factors which need consideration on conducting predator release programmes are plot barrier, spatial distribution of sprayed eggs (Shands and Simpson, 1972a, b), size and shape of plot and number of eggs and schedule for release (Shands *et al.*, 1972b,c and d). One or more of these factors may have influenced to a greater or lesser extent the success of the predator release reported in this chapter. No estimates were made of the amount of interplot movement of aphids or of the predators released. However, the relative lack of variability

Table 35: Yield of potato tubers from plots sprayed and unsprayed with *M. tasmaniae* eggs.

Plot (replicate)	Wt. of tubers (kg)	
	Sprayed	Unsprayed
1	29.6	17.9
2	35.0	21.5
3	14.5	9.7
Total	79.1	49.1

between replicates of the treatments, and the distribution patterns of the aphids and of the predators lead me to believe that there were reasonably separate populations of both by treatments. The effects of interplot movement may be sufficiently reduced, as suggested by Shands and Simpson (1972a, b), by using large plots (e.g. 0.04 ha) separated by alleys of bare ground 4.5-6.0 m wide.

How the eggs are placed on the potato plant is also of great importance in achieving effective reductions in pest abundance (Shands and Simpson, 1972a, b). In small plots, such as those used in this study, uniform placement of eggs is best obtained by placing eggs on every row. However, in a large plot or a small field, the pattern of placement of the released eggs depends on the mobility of the larvae and economics of the operation. Shands and Simpson (1972a, b) found that in a small field (0.1-0.2 ha in size), *Chrysopa* eggs were best placed in areas 3 m diameter centred 15 m apart and *Coccinella* eggs on every row to give the best reductions of aphid population on potatoes.

Timing and frequency of release could also have marked influence on predator performance. Usually the frequency of release will depend on the availability of eggs, but ideally, perhaps, the numbers of eggs released may be increased in proportion to the increase in the aphid density per unit of sample (Shands *et al.*, 1972c). On the other hand, rapid accumulations of predator numbers for greater early suppression of aphid populations is more important if the economic threshold level is extremely low. A very low economic threshold is important, particularly when the pest, like *M. persicae* is a vector of important potato virus diseases.

The trick however, is to maintain a low level of prey that is adequately controlled by the predator without the predator dying out. The small aphid population will then minimize inter-plant movement of infected aphids and the spread of the virus may be prevented. Such control of aphid population at a very low level may not be possible but further experimentation is needed to explore its possibility.

CHAPTER 9

GENERAL DISCUSSION

(A) *M. tasmaniae* as a biological control agent

In natural aphid populations at the Waite Institute and Milang in South Australia, aphid predators seemingly have little impact upon the huge increase in aphid numbers which occur each autumn. However, the results of a predator-exclusion study (Chapter 4, Section 4.3) showed that the hemerobiid predator, *M. tasmaniae* did much to suppress the rate of increase of *M. persicae* in spring and early summer before other predators such as coccinellids, chrysopids and syrphids became active later on. And in the absence of *M. tasmaniae*, peak numbers of *M. persicae* were 2.5 - 900 times as high as in natural populations. Hence, *M. tasmaniae* has been suggested (Chapter 8) as a biological control agent to control *M. persicae* in autumn.

Overseas, the hemorobiids have been shown to have great potential for biological control and have been suggested for controlling early season aphid infestations when prey numbers are still low (Neuenschwander, 1975; Syrett and Penman, 1981; Hagen and Neuenschwander, 1980). Similarly, *M. tasmaniae* has many advantages as a biological control agent for *M. persicae*, namely:

(a) the larvae have high probability of capture of prey and are probably more efficient at low prey density than are most other insect predators (Hagen and Neuenschwander, 1980; Maelzer, 1981; Syrett and Penman, 1981).

(b) eggs and larvae have lower thermal threshold for development than either *M. persicae* or other predators;

(c) the adult females are phytozetic i.e. the plant is of paramount stimulus in seeking aphids (Chandler, 1968);

(d) the adult females mate and oviposit readily in the laboratory and have a relatively high mean fecundity (220-300 eggs).

(e) it has no diapause in winter (Milne, 1978);

(f) adults can be kept alive easily and are long lived;

(g) it seemingly has no significant natural enemies;

(h) the species is abundant in nature throughout Southern Australia at least.

Mass releases of *M. tasmaniae* eggs for controlling aphids in New Zealand was suggested by Hilson (1964) but he made no attempt to implement the proposal in the field. In U.S.A., Shands *et al.* (1972a) and Shands and Simpson (1972c) have conducted pilot spraying tests of eggs of the coccinellids *Coccinella septempunctata* L. and *C. transversogutata* Faldermann, and found that early-season applications were best but that none of the treatments gave satisfactory control of the aphids. On the other hand, Ridgway and Jones (1968) have demonstrated excellent control of the bollworm and *Heliothis* on cotton in Texas, U.S.A. by mass releases of the green lacewing *Chrysopa carnea* Stephens. These releases reduced bollworm larvae by 96% and resulted in a 3-fold increase in yield of seed cotton.

In this thesis I have described preliminary spraying tests (Chapter 8) to mass release eggs of *M. tasmaniae* for the possible control of potato

aphids, mainly *M. persicae* in autumn.

(B) The problem of seed potatoes

Potato growers in South Australia can grow seed potatoes with little difficulty in spring and early summer in most parts of South Australia because *M. persicae* is then in very low numbers (Chapter 4). However, such seed potatoes would need to be stored for 8-7 months before being planted in the following spring; and considerable problems arise if potatoes are stored for so long, e.g. (i) seed rotting and (ii) increase in cost of production.

Growers are most anxious, therefore, to grow crops for seed which can be harvested in winter and stored for a minimal time at the relatively low temperatures of late winter before being used for planting in spring and early summer. But such crops are most susceptible to damage by *M. persicae* and leaf roll virus because aphid numbers are highest in autumn each year (Chapter 4). Hence, the need to control *M. persicae* in autumn, and the attempt to do so by augmenting numbers of *M. tasmaniae*.

(C) Augmentation of predator numbers

The problems that inhibit the more frequent use of mass releases of natural enemies for pest control are economic rather than ecological (Stinner, 1977). Largely for such reasons, augmentation of natural enemy numbers (by means of periodic releases should in general be given the lowest priority in biological control endeavours and not resorted until it has been determined that the solution does not lie in foreign exploration and importation of new natural enemies or conservation of natural enemies

(De Bach, 1974). Furthermore, augmentation attempts should usually be restricted to those natural enemies which have been demonstrated by research, such as in this thesis, to be inherently effective in prey suppression but are prevented from doing so (*ibid*).

The strategy behind the periodic releases of *M. tasmaniae* is to control *M. persicae* and prevent the introduction and spread of the potato leaf roll virus infection. The primary objective is to suppress as early as possible the aphid colonies established by the first few adult alate aphids which usually migrate into the crop at the beginning of the major flight period i.e., between late February and early March. During this period, the level of infestation of aphids on potato plants is low and the use of insecticides for vector control to prevent rapid increase in aphid numbers has often found to be ineffective and uneconomical (Bacon *et al.*, 1976; Powell and Mondor, 1973). Unfortunately aphid enemies are generally too few early in the season (probably with the exception of *M. tasmaniae*) and act too late to provide economically acceptable control once the virus vectors are present on the crop (Mackauer and Way, 1976). The release of *M.tasmaniae* a few days prior to the predicted time of alate migration into the crop would be most desirable because of the favourable qualities of *M. tasmaniae* mentioned earlier. As such, the timing of release of predators in relation to the time of late summer migration of alate aphids appeared to be the crucial factor in determining the success of early suppression of the subsequent aphid populations.

(D) The difficulties of timing of releases

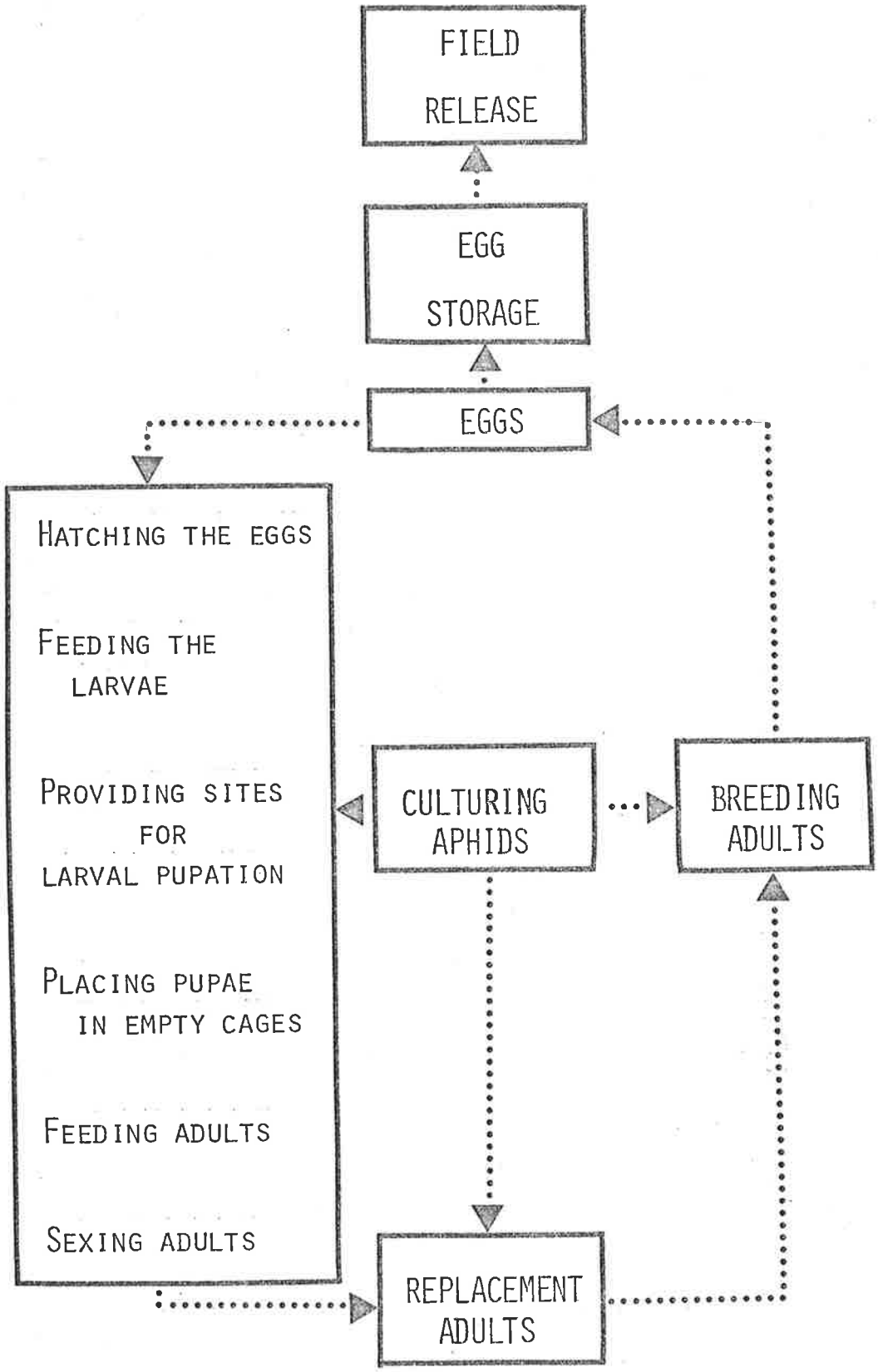
In this study, the time of alate migration varied considerably between localities (Milang and Waite Institute) and to a lesser extent between years for each locality (Chapter 4). Variations in the weather patterns, species of host plants and the complexity of the phenologies of the predators and prey species are some of the factors which will have a marked influence in the correct timing of predator releases.

Correct timing between alate migration and predator releases depends very much on the ability to precisely predict the time of alate migration. Perhaps, in order to improve the precision of trap data catches of alate *M. persicae*, data needs to be collected over several years (rather than the two years of this study).

(E) The problems of mass production of *M. tasmaniae*

After sufficient data have been collected to enable us to predict the time of alate migration, the feasibility of mass production of eggs of *M. tasmaniae* needs serious consideration. The method of producing eggs in this study was only capable of producing small batches of eggs for usage in small plot trials, but the scale of egg production can, undoubtedly, be expanded given the required space, labour and equipment. To produce eggs in more or less a factory basis, a systematic and efficient production system with the necessary subdivision of activities is vital. Such a production system is presented diagrammatically in Figure 41, which shows a simple flow of activities at the various stages of rearing procedures to ensure a smooth running of the production system.

Fig. 41: A schematic diagram to represent the divisions of activities and stages involved in the mass-production of *M. tasmaniae* eggs for field releases.


FIELD RELEASE
EGG STORAGE
EGGS
HATCHING THE EGGS
FEEDING THE LARVAE
PROVIDING SITES FOR LARVAL PUPATION
PLACING PUPAE IN EMPTY CAGES
FEEDING ADULTS
SEXING ADULTS
CULTURING APHIDS
BREEDING ADULTS
REPLACEMENT ADULTS

When in operation the proposed system is expected to produce large numbers of eggs ready for storage and field releases.

(F) Getting the eggs to the site of action

Once a suitable method of producing eggs has been found, the eggs have to be delivered to the plants with minimal loss. In this study, eggs were successfully sprayed using a specially designed compressed air sprayer for even distribution. The spraying method of distributing the eggs hold promise for it to be adapted and upgraded to a more mechanised assembly and be mounted on to a tractor or an aircraft for spraying in large fields.

If the mass production and the distribution problems can be solved, the spraying of eggs of *M. tasmaniae* may have a great potential for use in commercial plantings.

(G) Other possible methods of control

(i) The importation of parasites

Only one species of parasite *(Diaeretiella rapae)* was recorded parasitizing *M. persicae* and was absent at Milang (1979-80) and was in relatively low numbers at Milang (1978-79). However, the abortive predto--exclusion experiment (Section 4.3, Experiment I) indicated that the species had some effect in suppressing aphid numbers. *D. rapae* is also known as a prasite of the cabbage aphid *Brevicoryne brassicae*, and it has been shown by Hughes and Gilbert (1968) to also have little influence on the numbers of that aphid species.

Other more specialized parasites of *M. persicae*are available overseas, and it may be arranged that despite the potential of *M. tasmaniae* for pest control, the introduction of new parasite species into South Australia and if necessary mass releases of one of them, may offer a quicker, cheaper and easier path to the control of *M. persicae*.

If new parasites are introduced, should they be specific or generalized species?. Arguments in favour of each kind have often been advanced for biological control (Huffaker *et al.*, 1976). Because of the difficulty of an introduced species surviving the Australian summer (Maelzer, 1981) perhaps a generalized parasite would offer more chance of success because it would have a wider range of refuges to choose from in summer.

(ii) Conservation of native predators

Another possible method of controlling *M. persicae* is by conservation of native predators which may be achieved by (a) manipulating the environment to favour biotic agents through plant diversification; (b) provision of alternative prey and shelter and (c) addition of supplemental food or supplemental host resources (Knipling, 1979). These alternative methods of manipulation of predator numbers for aphid control may be vital if biological control through periodic mass releases of predators or parasites fails.

One of the ways to manipulate the environment to encourage predators, such as *M. tasmaniae*, to appear earlier in potato crops in

summer is to provide them with alternative food or refuges near the crops. For example, in South Australia, *M. tasmaniae* occurs in relatively small numbers in autumn in potato crops because food is initially scarce, but it may breed slowly over summer and attained sufficiently large numbers in late summer or early autumn on interplanted crops of *Medicago* sp. infested with the blue-green aphid, *Acrythosiphon kondoi*. Similarly, wind breaks or border rows etc. of *Casuarina stricta* and other trees that harbour natural prey for *M. tasmaniae* over winter and summer may possibly have a great impact on numbers of potato aphids if such species are planted in sufficient numbers over wide areas (Maelzer, 1981).

Addition of supplemental foods or supplemental host resources to increase reproduction and survival of *M. tasmaniae* and other predators holds promise of enhancing the efficacy of predators. The addition of Wheast and/or sugar or pollen has been found to increase the effectiveness of some chrysopid predators in many crops (Hagen and Hale, 1974; Rabb *et al.*, 1976; Tassan *et al.*, 1979). Supplementary feeding of *M. tasmaniae* could be profitably experimented in potato crop in South Australia.

(H) Integrated control of *M. persicae* in South Australia

Evidence is presented in this thesis that *M. persicae* is not an economic problem on potatoes in spring - early summer because of the abundance and efficacy of the predator *M. tasmaniae* (Chapter 4) and no additional pest control measures are required then. However, the

predator is less abundant and less effective in the late summer and autumn and it is then, and particularly in the autumn, that supplemental pest control measures must be considered i.e. an integrated control approach is indicated.

I have determined the reasons why *M. tasmaniae* is prevented from exerting effective control of *M. persicae*, and also considered ways to augment, complement or otherwise improve its performance. Among those factors known to reduce the effectiveness of *M. tasmaniae* is the use of insecticides. The types of insecticides used by the grower involved in this study cover some of the most harmful to beneficial insects e.g. DDT. Even though there were no reports of widespread problems resulting from insecticide interference in potato fields around South Australia, a move towards the integrated control of potato pests at the earliest possible time will give a long term benefit to potato growers in South Australia.

I hereby propose a practical integrated control programme for potato pests, particularly *M. persicae*, in areas similar to those in this study. The biological control component in such a programme is a central and important element for reasons of economy, all round effectiveness and environmental harmlessness. Often enough, pesticide usage cannot be reduced without a corresponding increase in the efficiency of natural control agents. Increased effectiveness of natural enemies can be brought about by various methods such as periodic inundative releases of natural enemies. If periodic releases are not yet possible conservation of natural enemies by cultural manipulations should be encouraged and integrated with current systems of insecticidal applications.

Integrated control simply requires the involvement of compatible use of appropriate methods of pest control. Integration is therefore crucially important as a means of minimising incidental harm by chemicals to beneficial natural enemies. Nevertheless, the definition of integrated control has now been expanded (Way, 1977) to cover situations where several methods are used which do not necessarily require conscious integration (*ibid*). For example, the integrated control of spread of potato leaf roll virus of potatoes in South Australia, would involve a combination of timely removal of overwintering sites of viruliferous *M. persicae*, separation of the seed crop from the non-seed crop, chemical control of aphids overwintering in seed crop, intercropping or rotation of lucerne (*Medicago* sp.) with potatoes and restricting insecticidal application to emergency situations or to selectively use insecticides (e.g. soil application of granular insecticides) to conserve naturally occurring predators. Each method contributes towards decreasing introduction or spread of the virus disease in the seed crop and are mutually compatible.

As was mentioned earlier, the agronomic or cultural practices utilized in growing the crop can also determine why a natural enemy is prevented from exerting effective control. This point is important in relation to the system of growing potatoes in South Australia and the success of an integrated control programme to be implemented. At Milang, where potatoes are grown in small blocks of land every 2-3 weeks potato crops can be found almost all year round. So a more stable environment is available to increase the number of predators and parasites by the provision of a continuity of prey in successive

crops. In other areas (e.g. Adelaide Hills, Virginia) where the crop is only planted in the spring-summer over a very wide area, the natural enemies may not be able to persist over long periods in nature. The strategy involved in the integrated control programme in the Adelaide Hills will be expected to be different therefore from the one proposed for Milang.

Therefore, despite the complexities of the dynamics of almost all pest species there is usually one, or a few, mortality factors that are of overriding importance to any one pest species. In this study *M. tasmaniae* was found to have that overriding importance to *M. persicae* especially in the spring. Within the potato fields, *M. tasmaniae* complements other control measures including insecticides. Outside the fields, *M. tasmaniae* may reduce the number of invading migrants developing on overwintering (Tamaki, 1973), and other weeds and crop plants (Powell and Wallis, 1974). It is by the manipulation of such key mortality factors that integrated control becomes practicable.

Integrated control of *M. persicae* overseas has been feasible under certain circumstances despite the difficulties in understanding the aphid's population dynamics (Mackauer and Way, 1976). In fact a successful integrated pest management programme for *M. persicae* has been developed with a model which is compatible with a micro-computer delivery system. This model is sufficiently accurate to forecast *M. persicae* populations as they reach economically damaging levels and it allows control action to be chosen with the following

objectives: (a) to conserve natural enemies, and (b) to reduce the total amount of insecticides used (Whalon and Smilowitz, 1979). On the other hand, successful integrated control has also been implemented by the application of relatively simple and straightforward ecological information (Close, 1965).

(I) Conclusions

Since pesticides are used mainly to control other major pests such as the potato tuber moth, *Pthorimae operculella*, the occurrence of other pests in the crop will have important bearing on the numbers of *M. tasmaniae*.

The knowledge accumulated in this thesis forms a small but important contribution in understanding the role of *M. tasmaniae* in integrated control programmes for *M. persicae* in South Australia. While the main objectives of this research were accomplished, some vital areas of research warrant further investigation. One of the more urgent is the adverse effects of pesticides used to control *M. persicae* on the reproduction, survival and abundance of *M. tasmaniae* and other aphidophagous insects. Therefore, in future one really needs to consider all the pests, the natural enemies and may be the diseases in the potato cropping system, and the ecological interrelationship among the insect species and the various cultural practices (insecticidal applications, irrigation, weed and disease control, planting dates, etc.). Only then can one develop a practical integrated pest management programme for all potato pests in South Australia.

APPENDICES

Appendix Table 1: Analysis of variance of the number of eggs laid by *M. tasmaniae* females per day on cloth substrate of four different colours (Section 3.3.2).

Source	dif.	s.s.	m.s.	F	P
Total	11	97.47	8.87		
Treatment	3	7.53	2.51	0.32	>.05
Replicate	2	43.00	21.50	2.75	>.05
Error	6	46.94	7.82		

Appendix Table 2: Analysis of variance of number of aphids extracted from potato leaves at various temperature x durations of exposure (Section 3.4.3)

Source	d.f.	s.s.	m.s.	F	P
Total	59	47826.08	810.61		
Exposures	4	18304.66	4576.16	16.56	<.01
Temperatures	3	21120.48	7040.16	25.47	<.01
Interaction	12	3316.85	276.40	2.17	<.05
Error	40	5048.09	127.10		

Appendix Table 3: Total leaf areas (cm^2) of caged and exposed potato plants at the start of the three experiments (Section 4.3)

	Exposed				Caged			
Expt.	Plant 1	Plant 2	Plant 3	$\bar{x}$	Plant 1	Plant 2	Plant 3	$\bar{x}$
I	201.9	163.1	183.1	182.7[a1]	192.8	235.1	184.5	207.5[a]
II	140.4	148.3	116.2	140.0[a]	111.1	134.0	127.6	124.3[a]
III	305.5	170.6	152.7	209.6[a]	323.2	148.4	116.3	196.0[a]

[1]Within rows means followed by the same letter do not differ significantly at P = .05 by t test (with 4 d.f.).

Appendix Table 4: Total leaf areas (cm^2) of caged and exposed potato plants at the end of the three experiments (Section 4.3)

	Exposed				Caged			
Expt.	Plant 1	Plant 2	Plant 3	$\bar{x}$	Plant 1	Plant 2	Plant 3	$\bar{x}$
I	1390,1	1116,6	1071.2	1192.6[a1]	1797.4	1593.4	1590.1	1660.36
II	1170.6	1103.0	916.2	1063.3[a]	932.0	1040.4	825.6	932.7[a]
III	1325.3	1068.2	964.6	1119.4[a]	1407.6	1149.1	940.1	1165.6[a]

[1]Within rows means followed by the same letters do not differ significantly at P = .05 by t test (with 4 d.f.).

Appendix Table 5: Table of 3 treatments with 2 replicates each for Experiments 1 and 2 (Section 6.1)

		Treatments (predator-prey ratio)		
Experiment	Control	1:8	1:4	1:2
1	Rep. 1	Rep. 1	Rep. 1	
	Rep. 2	Rep. 2	Rep. 2	
2	Rep. 1		Rep. 1	Rep. 1
	Rep. 2		Rep. 2	Rep. 2

Appendix Table 6: Analyses of variances of the number of aphids on 16 plants in two treatments (with predators) and the control (no predators) for each of days 3,6, 9 and 12 in Experiment 1 (Section 6.1)

	Source	d.f.	s.s.	m.s.	F	P
Day 3	Total	95	2390.41	25.16		
	Treatments	2	155.44	77.72	3.41	<.05
	Within replicates	3	183.41	61.14	2.68	<.05
	Error	90	2051.56	22.80		
Day 6	Total	95	2112.99	22.24		
	Treatments	2	732.52	366.26	27.03	<.01
	Within replicates	3	161.15	53.72	3.96	<.05
	Error	90	1219.31	13.55		
Day 9	Total	95	6151.99	64.76		
	Treatments	2	1836.52	918.26	27.74	<.01
	Within replicates	3	974.67	324.89	8.75	<.01
	Error	90	3340.81	37.12		
Day 12	Total	95	12409.99	130.63		
	Treatments	2	277.77	138.89	1.10	>.05
	Within replicates	3	781.65	260.55	2.07	>.05
	Error	90	11350.56	126.11		

Appendix Table 7: Analyses of variances of the number of aphids on 16 plants in two treatments (with predators) and the control (no predators) for each of days 3,6, 9 and 12 in Experiment 2 (Section 6.1)

	Source	d.f.	s.s.	m.s.	F	P
Day 3	Total	95	3707.83	39.03		
	Treatments	2	845.90	422.95	16.34	.01
	Within replicates	3	532.31	177.44	6.86	.01
	Error	90	2329.63	25.88		
Day 6	Total	95	14885.63	156.38		
	Treatments	2	3745.75	1872.88	22.03	.01
	Within replicates	3	3457.50	1152.50	13.55	.01
	Error	90	7652.38	85.03		
Day 9	Total	95	22829.83	240.31		
	Treatments	2	5914.15	1957.07	22.66	.01
	Within replicates	3	5171.07	1723.69	13.21	.01
	Error	90	11744.63	130.50		
Day 12	Total	95	63073.96	663.94		
	Treatments	2	23573.52	11786.76	38.11	.01
	Within replicates	3	11664.56	3888.19	12.57	.01
	Error	90	27835.88	309.29		

Appendix Table 8: Analyses of variances of the numbers of aphids on 16 plants in two treatments (with predators) and the control (no predators) for each of days 3,6,9 and 12 in Experiment 3 (Section 6.2)

	Source	d.f.	s.s.	m.s.	F	P
Day 3	Total	95	3789.33	39.89		
	Treatments	2	584.65	292.32	9.73	<.01
	Within replicates	3	501.56	167.19	5.57	<.01
	Error	90	2703.13	30.03		
Day 6	Total	95	12123.33	127.61		
	Treatments	2	6374.02	3187.01	50.43	<.01
	Within replicates	3	61.44	20.48	0.32	>.05
	Error	90	5687.88	63.20		
Day 9	Total	95	49275.24	518.69		
	Treatments	2	28175.65	14087.82	61.06	<.01
	Within replicates	3	335.66	111.89	0.48	>.05
	Error	90	20763.94	230.71		
Day 12	Total	95	294635.63	3101.62		
	Treatments	2	169899.19	84949.59	65.38	<.01
	Within replicates	3	7813.19	2604.40	2.00	>.05
	Error	90	116941.25	1299.35		

Appendix Table 9: Analyses of variances of the numbers of aphids on each of 16 plants in two treatments (with predators) and the control (no predators) for each of days 3,6,9 and 12 in Experiment 4 (Section 6.2)

	Source	d.f.	s.s.	m.s.	F	P
Day 3	Total	95	12409.99	130.63		
	Treatments	2	277.77	133.89	1.06	>.05
	Within replicates	3	781.65	260.55	2.07	>.05
	Error	90	11350.56	126.12		
Day 6	Ttotal	95	22983.33	241.93		
	Treatments	2	8533.90	4266.95	7.55	<.01
	Within replicates	3	511.44	170.48	1.10	>.05
	Error	90	13938.00	154.87		
Day 9	Total	95	115076.63	1211.33		
	Treatments	2	61594.75	30797.38	55.40	<.01
	Within replicates	3	3448.75	1149.58	2.07	>.05
	Error	90	50013.13	555.92		
Day 12	Total	95	533844.50	5619.42		
	Treatments	2	245439.19	122719.59	43.38	<.01
	Within replicates	3	33774.19	11258.06	3.98	<.05
	Error	90	254631.13	2829.23		

Appendix Table 10: The values of Morisita's index of dispersion for each replicate of Experiment 1 (Section 6.1)

Sampling day	Replicate no.	Treatment (Predator-prey ratio)		
		Control	1:8	1:4
0	1	0.52	0.52	0.52
	2	0.52	0.52	0.52
	$\bar{x}$	0.52	0.52	0.52
3	1	1.27	5.23	5.64
	2	2.59	2.31	2.96
	$\bar{x}$	1.93	3.77	4.30
6	1	1.24	2.62	1.60
	2	2.02	4.00	5.11
	$\bar{x}$	1.63	3.31	3.21
9	1	1.25	2.54	6.53
	2	1.74	1.33	8.66
	$\bar{x}$	1.50	1.94	7.60
12	1	1.37	2.32	2.40
	2	1.37	1.96	4.71
	$\bar{x}$	1.37	2.14	3.56

Appendix Table 11: The values of Morisita's index of dispersion for each replicate of Experiment 2 (Section 6.1)

Sampling day	Replicate no.	Treatment (Predator-prey ratio)		
		Control	1:4	1:2
0	1	0.52	0.52	0.52
	2	0.52	0.52	0.52
	$\bar{x}$	0.52	0.52	0.52
3	1	1.74	5.20	5.33
	2	2.37	4.92	2.61
	$\bar{x}$	2.06	5.06	3.97
6	1	1.72	4.26	0
	2	2.32	9.78	0
	$\bar{x}$	2.02	7.02	0
9	1	1.68	4.56	0
	2	2.11	0	4.13
	$\bar{x}$	1.90	2.28	2.07
12	1	1.46	3.13	0
	2	1.83	2.19	5.76
	$\bar{x}$	1.65	2.66	2.88

Appendix Table 12: The values of Morisita's index of dispersion for each treatment of Experiment 3 (Section 6.2)

Sampling day	Replicate no.	Treatment (prey distribution)		
		Control	on each plant	on every 2nd plant
0	1	0.52	0.52	1.55
	2	0.52	0.52	1.55
	$\bar{x}$	0.52	0.52	1.55
3	1	1.79	2.08	1.60
	2	1.36	2.44	3.43
	$\bar{x}$	1.58	2.26	2.52
6	1	1.38	3.89	3.05
	2	1.44	7.83	4.13
	$\bar{x}$	1.41	5.86	3.59
9	1	1.35	6.23	0
	2	1.45	0	3.20
	$\bar{x}$	1.40	3.12	1.60
12	1	1.31	4.35	0
	2	1.45	2.29	0
	$\bar{x}$	1.38	3.27	0

Appendix Table 13: Values of Morisita's index of dispersion for each treatment of Experiment 4 (Section 6.2)

Sampling day	Replicate no.	Treatment (prey distribution)		
		Control	on every 2nd plant	on every 4th plant
0	1	0.52	1.55	3.61
	2	0.52	1.55	3.61
	$\bar{x}$	0.52	1.55	3.61
3	1	1.42	1.67	3.61
	2	1.64	1.71	2.98
	$\bar{x}$	1.53	1.69	3.30
6	1	1.42	1.69	3.84
	2	2.01	0	3.82
	$\bar{x}$	1.72	0.85	3.83
9	1	1.31	1.32	1.89
	2	1.44	2.67	2.49
	$\bar{x}$	1.38	1.99	2.19
12	1	1.62	1.09	2.49
	2	1.08	5.61	2.25
	$\bar{x}$	1.35	3.35	2.37

Appendix Table 13: No. of aphids on each of 16 plants in each treatment and the control with two replicates over 12-day period (Experiment 1, Section 6.1)

Day	Rep		PLANT 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	Σ
Control (no predators)																			
3	1		16	12	5	11	5	3	4	5	4	3	11	5	4	15	4	2	111
	2		0	3	2	0	0	13	5	0	4	2	0	4	0	1	11	0	45
		Σx_2	16	15	7	11	7	16	9	5	8	5	11	9	4	16	15	2	156
		Σx^2	256	153	29	121	49	178	41	25	32	13	121	41	16	226	137	4	1442
6	1		18	17	10	14	10	3	6	4	2	8	14	8	9	15	4	2	99
	2		0	2	2	2	1	17	5	1	3	7	3	4	1	6	14	0	68
		Σx_2	18	19	12	16	11	20	11	5	5	15	17	12	10	21	18	2	167
		Σx^2	324	293	104	200	101	298	61	17	13	113	205	80	82	261	212	4	2368
9	1		37	23	15	24	15	9	11	7	33	12	16	21	18	17	5	3	266
	2		0	5	3	5	1	25	9	6	8	8	5	4	2	14	17	0	112
		Σx_2	37	28	18	29	16	34	20	13	41	20	21	25	20	31	22	3	378
		Σx^2	1369	554	234	601	226	706	202	85	1153	208	281	457	328	485	314	9	7212
12	1		118	54	44	78	66	39	22	21	34	34	64	93	52	22	10	9	760
	2		6	30	31	20	6	56	42	27	50	26	40	28	3	63	52	0	480
		Σx_2	124	84	75	98	72	95	64	48	84	60	104	121	55	85	62	9	1240
		Σx^2	13960	3816	2597	6484	4392	4387	2248	1170	3656	1832	5696	9433	2713	4453	2804	81	69692
Treatment 1 (Predator-prey ratio 1:8)																			
3	1		2	1	2	0	0	0	0	9	5	0	0	3	34	4	1	1	62
	2		3	2	0	0	5	0	0	0	1	0	1	1	11	2	5	1	32
		Σx_2	5	3	2	0	5	0	0	9	6	0	1	4	45	6	6	2	94
		Σx^2	23	5	4	0	25	0	0	81	26	0	1	10	1277	20	26	2	1500
6	1		1	0	12	2	4	2	4	0	4	0	0	0	4	1	0	0	34
	2		0	0	0	0	3	0	0	0	2	0	0	0	3	0	0	0	8
		Σx_2	1	0	12	2	7	2	4	0	6	0	0	0	7	1	0	0	42
		Σx^2	1	0	144	4	25	4	16	0	20	0	0	0	25	1	0	0	240

Appendix Table 13 continued/...

Day	Rep		PLANT 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	Σ
9	1		15	0	36	4	13	3	4	5	6	7	0	0	14	3	0	1	114
	2		2	1	0	0	0	0	0	0	1	0	0	2	2	0	1	0	9
		Σx_2	17	1	36	4	13	3	4	5	7	7	0	2	16	3	1	1	123
		Σx^2	229	1	1296	16	169	9	16	25	37	49	0	4	200	9	1	1	2062
12	1		39	0	124	17	36	10	24	34	33	10	0	7	47	18	0	6	405
	2		8	18	3	6	24	8	3	1	1	0	5	3	20	4	1	4	105
		Σx_2	37	18	127	23	60	18	27	35	34	10	5	10	67	22	1	10	505
		Σx^2	1585	324	15385	325	1872	164	585	1157	1090	100	25	58	2609	340	2	52	
Treatment 2 (Predator-prey ratio 1:4)																			
3	1		0	0	9	0	0	0	1	0	1	0	1	0	0	1	0	2	15
	2		0	4	0	2	0	0	0	2	0	1	2	9	0	15	4	3	42
		Σx_2	0	4	9	2	0	0	1	2	1	1	3	9	0	16	4	5	57
		Σx^2	0	16	81	4	0	0	2	4	2	1	5	81	0	226	16	13	451
6	1		0	0	0	0	0	0	0	0	1	0	1	0	0	1	0	2	5
	2		0	3	0	0	0	0	0	8	0	0	9	0	0	0	1	0	21
		Σx_2	0	3	0	0	0	0	0	8	1	0	10	0	0	1	1	2	26
		Σx^2	0	9	0	0	0	0	0	64	2	0	82	0	0	1	1	4	162
9	1		0	0	0	0	0	0	0	0	0	8	0	0	0	0	7	1	16
	2		0	2	0	1	0	0	0	0	0	0	17	1	0	0	1	1	23
		Σx_2	0	2	0	1	0	0	0	0	0	8	17	1	0	0	8	2	39
		Σx^2	0	4	0	1	0	0	0	0	0	64	289	1	0	0	50	2	412
12	1		7	3	0	0	0	4	15	0	1	8	4	0	0	0	7	2	51
	2		0	14	0	5	0	0	0	1	0	0	27	6	0	0	3	1	59
		Σx_2	7	17	0	5	0	4	15	1	1	8	31	6	0	0	10	3	108
		Σx^2	49	205	0	25	0	16	225	1	1	64	745	36	0	0	58	5	1430

Appendix Table 14: Number of aphids on each of 16 plants in each treatment and the control with two replicates over 12-day period (Experiment 2, Section 6.1).

Day	Rep		PLANT 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	Σ
Control (no predators)																			
3	1		29	10	0	2	12	27	9	25	12	1	0	0	5	29	9	2	172
	2		3	5	5	0	3	0	15	0	4	2	0	13	3	0	0	2	55
		Σx_2	32	15	5	2	15	27	24	25	16	3	0	13	8	29	9	4	227
		Σx^2	850	125	25	4	153	729	306	625	160	5	0	169	34	841	81	8	4115
6	1		26	59	4	8	19	58	19	42	16	0	12	1	15	69	9	31	389
	2		4	3	1	0	3	0	16	1	2	11	0	13	18	1	0	4	77
		Σx_2	30	62	5	8	22	58	35	43	18	11	12	14	33	70	9	35	466
		Σx^2	692	3940	17	64	370	3364	617	1765	260	121	144	170	549	4762	81	977	17893
9	1		24	59	9	24	37	76	7	56	17	0	16	0	17	74	9	61	486
	2		7	0	4	0	3	0	16	1	3	11	0	13	18	3	0	4	83
		Σx_2	31	59	13	24	40	76	23	57	20	11	16	13	35	77	9	65	569
		Σx^2	625	3481	97	576	1378	5776	305	3137	298	121	256	169	613	5485	81	3737	26135
12	1		44	70	28	75	107	106	7	107	30	7	37	4	23	77	35	109	889
	2		13	8	6	5	7	7	28	10	44	38	2	51	26	8	1	8	270
		Σx_2	57	78	34	80	114	113	35	127	74	45	39	55	49	85	36	117	1159
		Σx^2	2105	4964	820	5650	11498	11285	833	11549	2836	1493	1373	2617	1205	5993	1226	11945	
Treatment 1 (predator-prey ratio 1:4)																			
3	1		0	0	0	1	1	1	0	12	0	0	3	0	0	0	4	0	22
	2		0	0	0	0	7	0	0	0	0	0	0	2	4	0	1	0	14
		Σx_2	0	0	0	1	8	1	0	12	0	0	3	2	4	0	5	0	36
		Σx^2	0	0	0	1	50	1	0	144	0	0	9	4	16	0	17	0	242
6	1		0	0	0	7	1	0	0	13	0	0	3	0	0	0	4	1	29
	2		0	0	0	0	7	0	0	0	0	0	0	2	0	0	0	0	9
		Σx	0	0	0	7	8	0	0	13	0	0	3	2	0	0	4	1	38
		$\Sigma x2$	0	0	0	49	50	0	0	169	0	0	9	4	0	0	16	1	298

Appendix Table 14 continued/...

Day	Rep		PLANT 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	Σ
9	1		0	0	0	16	1	1	0	25	1	0	3	0	0	0	5	4	56
	2		0	1	0	0	0	0	0	0	0	0	0	0	0	1	1	0	3
		Σx_2	0	1	0	16	1	1	0	25	1	0	3	0	0	1	6	4	59
		Σx^2	0	1	0	256	1	1	0	265	1	0	9	0	0	1	26	16	937
12	1		0	6	2	21	0	0	4	36	3	3	11	4	0	0	0	9	100
	2		0	4	0	1	1	0	0	0	0	0	0	0	0	3	2	0	11
		Σx_2	0	10	2	22	1	0	4	36	4	3	11	4	0	3	2	9	111
		Σx^2	0	52	4	442	1	0	16	1296	16	9	121	16	0	9	4	81	2067
Treatment 2 (Predator-prey ratio 1:2)																			
3	1		0	0	0	0	0	0	0	2	0	0	0	0	0	1	0	0	3
	2		0	3	7	0	1	0	0	0	6	0	0	3	0	3	9	0	32
		Σx_2	0	3	7	0	1	0	0	2	6	0	0	3	0	4	9	0	35
		Σx^2	0	9	49	0	1	0	0	4	36	0	0	9	0	10	81	0	199
6	1		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	2		1	1	0	0	1	0	0	0	0	0	0	0	0	0	1	0	4
		Σx_2	1	1	0	0	1	0	0	0	0	0	0	0	0	0	1	0	4
		Σx^2	1	1	0	0	1	0	0	0	0	0	0	0	0	0	1	0	4
9	1		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	2		1	1	1	0	0	0	0	0	0	0	0	0	0	3	8	1	15
		Σx_2	1	1	1	0	0	0	0	0	0	0	0	0	0	3	8	1	15
		Σx^2	1	1	1	0	0	0	0	0	0	0	0	0	0	9	64	1	77
12	1		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	2		1	1	0	0	0	0	0	0	0	0	0	0	0	13	5	3	23
		Σx_2	1	1	0	0	0	0	0	0	0	0	0	0	0	13	5	13	23
		Σx^2	1	1	0	0	0	0	0	0	0	0	0	0	0	169	25	9	205

Appendix Table 15: Number of aphids on each of 16 plants in each treatment and the control with two replicates over 12-day period (Experiment 3, Section 6.2).

Day	Rep		PLANT 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	Σ
Control (each plant infested and no predators)																			
3	1		6	0	0	12	4	1	10	11	17	31	13	9	5	0	17	7	143
	2		13	3	3	5	4	1	2	1	7	3	5	4	12	6	2	2	73
		Σx	19	3	3	17	8	2	12	12	24	34	18	13	17	6	19	9	216
		Σx^2	178	9	9	169	32	2	104	122	338	970	194	97	169	36	293	53	2775
6	1		10	6	13	28	8	6	25	12	30	37	43	18	9	3	40	30	318
	2		19	9	22	38	29	0	6	5	28	11	12	14	40	47	13	11	304
		Σx	29	15	35	66	37	6	31	17	58	48	55	32	49	50	53	41	622
		Σx^2	461	117	653	2228	905	36	661	169	1684	1490	1993	520	1681	2218	1769	1021	17606
9	1		19	7	33	53	28	14	37	16	46	45	56	52	14	10	89	35	554
	2		53	28	53	78	72	6	23	17	60	24	13	16	76	0	91	31	641
		Σx	72	35	86	131	100	20	60	33	106	69	69	68	90	10	180	66	1195
		Σx^2	3170	833	3898	8893	5968	232	1898	545	5716	2601	3305	2960	5972	100	16021	2186	64298
12	1		31	52	70	106	70	49	47	28	102	75	199	118	45	35	127	69	1223
	2		80	75	77	245	218	56	62	88	116	42	45	64	189	0	230	118	1705
		Σx	111	127	147	351	288	105	109	116	218	117	244	182	234	35	357	187	2928
		Σx^2	7361	8329	10829	71261	52424	5537	6053	8528	23860	7389	41626	18020	37746	1225	69029	18685	387902
Treatment 1 (each plant infested and 8 predators)																			
3	1		22	2	5	0	5	0	0	12	4	2	0	0	8	21	9	10	100
	2		1	0	2	8	1	1	0	1	1	1	0	3	1	0	0	1	21
		Σx	23	2	7	8	6	1	0	13	5	3	0	3	9	21	9	11	121
		Σx^2	485	4	29	64	26	1	0	145	17	5	0	9	65	441	81	101	1473
6	1		0	1	2	2	1	0	2	23	12	0	0	2	0	4	0	4	53
	2		3	0	0	3	0	1	0	0	18	1	0	0	0	0	0	0	26
		Σx	3	1	2	5	1	1	2	23	30	1	0	2	0	4	0	4	79
		Σx^2	9	1	4	13	1	1	4	529	468	0	0	4	0	16	0	16	1066

Appendix Table 15 continued/...

Day	Rep		PLANT 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	Σ
9	1		0	0	0	0	0	0	0	35	7	0	0	2	1	7	3	3	58
	2		0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	2
		Σx_2	0	0	0	0	0	1	1	35	7	0	0	2	1	7	3	3	60
		Σx^2	0	0	0	0	0	1	1	1225	49	0	0	4	1	49	9	9	1346
12	1		0	1	0	4	0	0	0	64	12	0	0	11	0	29	6	13	140
	2		0	0	0	0	1	1	1	0	0	0	0	0	0	3	1	1	8
		Σx_2	0	1	0	4	1	1	1	64	12	0	0	11	0	32	7	14	148
		Σx^2	0	1	0	16	1	1	1	4096	144	0	0	121	0	850	37	170	5438
Treatment 2 (every 2nd plant infested and 8 predators)																			
3	1		2	4	2	0	0	0	1	2	0	0	0	1	3	0	1	0	16
	2		15	5	2	0	0	2	0	1	3	0	0	6	1	0	1	0	36
		Σx	17	9	4	0	0	2	0	3	3	0	0	7	4	0	2	0	52
		Σx	229	41	8	0	0	4	0	5	9	0	0	37	10	0	2	0	345
6	1		0	0	1	0	0	0	0	0	0	0	0	0	0	1	2	3	7
	2		5	0	1	0	0	1	0	7	1	0	0	0	1	0	0	0	16
		Σx_2	5	0	2	0	0	1	0	7	1	0	0	0	1	1	1	2	23
		Σx^2	25	0	2	0	0	1	0	49	1	0	0	0	1	1	4	9	93
9	1		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	2		1	0	0	0	0	3	1	1	0	0	0	0	0	0	0	0	6
		Σx_2	1	0	0	0	0	3	1	1	0	0	0	0	0	0	0	0	6
		Σx^2	1	0	0	0	0	9	1	1	0	0	0	0	0	0	0	0	12
12	1		0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	2		1	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	3
		Σx_2	1	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	3
		Σx^2	1	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	3

Appendix Table 16: Number of aphids on each of 16 plants in each treatment and the control with two replicates over 12-day period (Experiment 4, Section 6.2).

Day	Rep		PLANT 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	Σ
Control (Each plant infested and no predators)																			
3	1		22	12	5	14	12	13	18	16	19	17	10	6	10	50	3	11	238
	2		6	11	10	26	0	1	8	4	8	20	6	4	2	5	2	11	124
		Σx_2	28	23	15	40	12	14	26	20	27	37	16	10	12	55	5	22	362
		Σx^2	520	265	125	872	144	170	408	272	425	489	136	44	104	2525	13	242	6754
6	1		51	18	6	18	3	22	35	24	47	24	16	10	25	69	10	31	409
	2		6	25	18	84	2	6	17	9	32	56	16	9	6	12	2	35	335
		Σx_2	57	43	24	102	5	28	52	33	79	80	32	19	31	81	12	66	744
		Σx^2	2637	949	360	7380	13	520	1514	657	3233	3712	338	181	661	4905	104	2186	29350
9	1		107	30	33	35	15	49	105	88	94	60	62	26	75	164	40	80	1063
	2		36	48	41	163	39	15	37	47	67	118	37	67	20	40	28	90	893
		Σx_2	143	78	74	198	54	64	142	135	161	178	99	93	95	204	68	170	1956
		Σx^2	12745	3204	2770	27794	1746	2626	12394	9953	13325	17524	5213	5165	6025	28494	2384	14500	165862
12	1		234	0	28	0	97	172	85	354	185	261	0	263	146	284	201	0	2310
	2		133	88	108	119	122	68	77	176	143	76	121	108	91	135	139	209	1903
		Σx_2	357	88	136	119	219	240	162	539	328	337	121	371	237	419	340	209	4213
		Σx^2	69885	7744	12448	14161	24293	34208	13154	15692	54674	73897	14641	80833	29597	98881	59722	43681	788111
Treatment 1 (every 2nd plant infested and 8 predators)																			
3	1		2	2	16	7	15	0	1	15	9	0	1	19	9	27	7	24	155
	2		3	0	11	16	4	0	0	5	3	0	1	4	11	6	5	7	76
		Σx_2	5	2	27	23	19	0	0	20	12	0	3	23	20	33	12	31	231
		Σx^2	13	4	377	305	241	0	0	250	90	0	5	377	202	765	74	583	3286
6	1		0	4	8	8	2	0	3	11	12	2	0	14	4	1	12	19	100
	2		3	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	4
		Σx_2	3	4	8	8	3	0	3	11	12	2	0	14	4	1	12	19	104
		Σx^2	9	16	64	64	5	0	9	121	144	4	0	196	16	1	144	361	1154

Appendix Table 16 continued/...

Day	Rep		PLANT 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	Σ
9	1		4	8	6	23	11	10	2	26	29	5	14	21	13	22	32	30	256
	2		1	0	0	0	2	0	1	0	0	0	0	0	0	0	0	0	4
		Σx_2	5	8	6	23	13	10	3	26	29	5	14	21	13	22	32	30	260
		Σx^2	17	64	36	259	125	100	5	676	841	25	196	441	169	484	1024	900	5632
12	1		52	31	66	79	81	69	25	71	72	18	60	70	37	58	71	67	927
	2		1	0	0	9	10	0	1	0	0	0	0	0	0	0	0	1	22
		Σx_2	53	31	66	88	91	69	26	71	72	18	60	70	37	58	71	68	949
		Σx^2	2704	961	4356	6322	6661	4761	626	5041	5184	324	3600	4900	1369	3364	5041	4490	56340
Treatment 2 (Every 4th plant infested and 8 predators)																			
3	1		12	0	1	18	2	0	1	0	2	4	2	0	26	3	3	47	145
	2		65	0	4	33	6	0	0	0	13	0	3	7	26	33	4	3	197
		Σx_2	77	0	5	41	8	0	1	0	15	4	5	7	52	36	7	50	309
		Σx^2	4369	0	17	1413	40	0	1	0	173	16	13	49	1352	1098	25	2218	10784
6	1		4	1	0	1	0	0	0	0	3	17	0	4	3	0	0	4	37
	2		31	0	1	1	4	0	1	0	0	0	0	0	2	17	11	2	70
		Σx	35	1	1	2	4	0	1	0	3	17	0	4	5	17	11	6	107
		Σx	977	1	1	2	16	0	1	0	9	289	0	16	13	289	121	20	1755
9	1		8	1	0	2	2	3	0	0	0	8	4	6	1	0	0	5	39
	2		0	13	0	7	0	44	18	0	10	3	0	3	20	42	5	9	174
		Σx_2	8	14	0	9	2	47	18	0	10	11	4	9	21	42	5	14	213
		Σx^2	64	170	0	53	4	1945	324	0	100	73	16	45	401	1764	25	106	5090
12	1		29	5	0	1	0	16	3	4	42	0	24	0	1	2	10	25	162
	2		0	0	5	16	0	95	22	58	0	27	0	30	90	90	19	20	633
		Σx_2	29	5	5	17	0	111	25	62	42	27	24	30	91	92	29	45	795
		Σx^2	841	25	25	257	0	351	493	3380	1764	729	576	900	8101	8104	461	1025	27002

REFERENCES

ANONYMOUS (1944). Entomological investigations. *Rep. Counc. Sic. Ind. Res. Organ., Canberra.* 1942-43, pp. 15-20.

ANSCOMBE, F.J. (1948). On estimating the population of aphids in a potato field. *Ann. appl. Biol.* 35: 567-571.

ANSCOMBE, F.J. (1949). The statistical analysis of insect counts based on the negative binomial distribution. *Biometrics* 5: 167-173.

BACON, O.G., BURTON, V.E., McLEAN, James, R.H., RILEY, W.D., BAGHOTT, K.G. and KINSEY, M.G. (1976). Control of green peach aphid and its effect on the incidence of potato leaf roll virus. *J. econ. Entomol.* 69: 410-414.

BALD, J.G. and NORRIS, D.O. (1943). Transmission of potato virus diseases. I. Field experiments with leaf roll at Canberra, 1940-41. *Commonwealth Sci. Ind. Res. Aust. Bull.* 163: 5-18.

BALD, J.G., NORRIS, D.O. and HELSON, G.A.H. (1946). Transmission of potato virus diseases. V. Aphid populations, resistance, tolerance to potato varieties to leaf roll. Coun. Sci. Industr. Res. Aust. No. 196.

BALD, J.G., NORRIS, D.O. and HELSON, G.A.H. (1950). Transmission of potato virus diseases. VI. The distribution of aphid vectors on sampled leaves and shoots. *Aust. J. agric. Res.* 1: 18-32.

BANERJEE, S.M. and BASU, A.N. (1956). Preliminary studies on the epidemiology of potato aphids in West Bengal. *Beitr. Entomol.* 6: 510-516.

BANKS, C.J. (1959). Experiments with suction traps to assess the abundance of Syrphidae (Diptera) with special reference to aphidophagous species. *Ent. exp. & appl.* 2: 110-124.

BANK, N. (1909). Hemerobiidae from Queensland, Australia. *Proc. entomol. Soc. Wash.* 11: 76-81.

BARLOW, C.A. (1961). On the biology and reproductive capacity of *Syrphus corollae* Fab. (Syrphidae) in the laboratory. *Ent. exp. & appl.* 4: 91-100.

BARLOW, C.A. (1962). The influence of temperature on the growth of experimental populations of *Myzus persicae* (Sulzer) and *Macrosiphum euphorbiae* (Thomas). *Can. J. Zool.* 40: 145-156.

BATRA, H.N. (1953). Aphids infesting peach and their control. *Indian J. Entomol.* 15: 45-51.

BECK, S.D. and CHIPPENDALE, G.M. (1968). Environmental aspects of the mass-rearing of plant feeding Lepidopterans. *In* Radiation, Radioisotopes and Rearing Methods in the Control of Insect Pests. IAEA Panel Proceeding Series.

BROADBENT, L. (1950). The correlation of aphid numbers with the spread of leaf roll and rugose mosaic in potato crops. *Ann. appl. Biol.* 37: 58-65.

BROADBENT, L. (1952). The control of potato virus diseases by the application of insecticides. *Proc. Conf. Potato Virus Diseases. Wageningeg-Lisse* pp. 23-26.

BROADBENT, L. (1953). Aphids and potato virus diseases. *Biol. Rev.* 28:350-380.

BROADBENT, L., CHAUDHURI, R.P. and KAPICA, L. (1950). The spread of virus diseases to single potato plants. *Ann. appl. Biol.* 37: 355-362.

BROADBENT, L. and HOLLINGS, M. (1951). The influence of heat on some aphids. *Ann. appl. Biol.* 38: 577-581.

BROWN, H.D. (1972). Predaceous behaviour of four species of Coccinellidae (Coleoptera) associated with the wheat aphid, *Schizaphis graminum* (Rondani), in South Africa. *Trans. Roy. entomol. Soc. London.* 124: 21-26.

BURT, P.E., HEATHCOTE, G.D. and BROADBENT, L. (1964). The use of insecticides to find when leaf roll and Y viruses spread within potato crops. *Ann. appl. Biol.* 54:13-22.

BYRNE, D.N. and BISHOP, G.W. (1979b). Comparison of water trap and leaf counts as sampling techniques for green peach aphids on potatoes. *Am. Potato J.* 56: 237-241.

BYRNE, D.N. and BISHOP, G.W. (1979a). Relationship of green peach aphid numbers to spread of potato leaf roll virus in Southern Idaho. *J. econ. Entomol.* 72: 809-811.

CAMERON, P.J., THOMAS, W.P. and HILL, R.L. (1979). Introduction of lucerne aphid parasites and a preliminary evaluation of the natural enemies of *Acrythosiphon* spp. (Hemiptera : Aphididae) in New Zealand. *Proc. 2nd Australasian Conf. on Grassland Invert. Ecol.* Eds. T.K.Grosby and R.P.Pottinger. pp. 219-223.

CARPENTER, F.M. (1961). Neuroptera : Hermerobiidae. *Insects of Micronesia* 8: 35-43.

CARPENTER, F.M. (1940). A revision of the Nearctic Hemerobiidae, Berothidae, Sisyridae, Polystoechotidae and Delaridae (Neuroptera). *Proc. Am. Acad. Arts Sc.* 74: 193-280.

CHAMBERLIN, F.S. (1950). Source of early aphid infestations in shade-grown tobacco. *Florida Entomologist* 33: 16-17.

CHANDLER, A.E.F. (1968). Some host-plant factors affecting oviposition by aphidophagous Syrphidae (Diptera). *Ann. appl. Biol.* 61: 415-423.

CHANT, D.A. (1960). Phytoseiid mites (Acarina : Phytoseiidae). Part I. Bionomics of seven species in South-eastern England. Part II. A taxonomic review of the family Phytoseiidae, with descriptions of 38 new species. *Can. Ent. Suppl.* 12: 164 pp.

BIRCH, L.C. (1948). The intrinsic rate of natural increase of an insect population. *J. Anim. Ecol.* 17: 15-26.

BISHOP, A.L. and BLOOD, P.R. (1977). A record of beneficial arthropods and insect diseases in Southeast Queensland cotton. *PANS* 23: 384-386.

BISHOP, A.L., GREENUP, L.R. and HOLTKAMP, R.H. (1980). Management of *Acrythosiphon kondoi* Shinji, blue-green aphid and *Therioaphis trifolii* (Monell) f. *maculata*, spotted alfalfa aphid, by grazing and cutting lucerne. *Aust. J. Exp. Agric. Anim. Husb.* 20: 710-716.

BISHOP, G.W. (1965). Green peach aphid distribution and potato leaf roll virus occurrence in the seed-producing areas of Idaho. *J. econ. Entomol.* 58: 150-153.

BISHOP, G.W. (1968). Potato leaf roll virus transmission as affected by plant *Am. Potato J.* 45: 366-372.

BLISS, C.I. and FISHER, R.A. (1953). Fitting the negative binomial distribution to biological data. *Biometrics* 9: 176-200.

BODENHEIMER, F.S. and SWIRSKI, E. (1957). The Aphidoidea of the Middle East. Weizmann Sci. Press, Israel. 378 pp.

BOLLER, E. (1972). Behavioural aspects of mass-rearing of insects. *Entomophaga* 17: 9-25.

BOMBOSCH, S. (1966). Distribution of enemies in different habitats during the plant growing seasons. *In* Ecology of Aphidophagous Insects. Ed. I.Hodek, Prague, Academia. 360 pp.

BOWER, C.C. and THWAITE, W.G. (1978). Results of a monitoring study of lucerne aphids at Cowra, N.S.W. *Proc. Lucerne aphids workshop, Tamworth, N.S.W. 1978.* pp. 50-52.

BRADLEY, R.H.E. (1952). Methods of recording aphid (Homoptera : Aphididae) populations on potatoes and the distribution of species on the plant. *Can. Ent.* 84: 93-102.

BRIEZE-STEGEMAN, R. (1978). Ecology of BGA and natural enemies - Tasmanian situation. *Proc. Lucerne aphids Workshop, Tamworth, N.S.W. 1978.* pp. 15-16.

BROADBENT, L. (1946). A survey of potato aphids in North West Derbyshire, 1945. *Ann. appl. Biol.* 33: 360-68.

BROADBENT, L. (1948). Methods of recording aphid populations for use in research on potato virus diseases. *Ann. appl. Biol.* 35: 551-566.

BROADBENT, L. (1949). The grouping and overwintering of *Myzus persicae* Sulz. on *Prunus* species. *Ann. appl. Biol.* 36: 334-340.

CHESSON, J. (1974). Selective predation. B.Ag.Sc. (Hons.) Thesis, University of Adelaide, South Australia. 52 pp.

CHESSON, J. (1978). Measuring preference in selective predation. *Ecology* 59: 211-215.

CLARK, R.C. and BROWN, N.R. (1962). Studies of predators of balsam woolly aphid, *Adelges piceae* (Ratz) (Homoptera : Adelgidae). XI. *Cremifania nigrocellulata* C. (Diptera : Chamaeyiidae) an introduced predator in eastern Canada. *Can. Ent.* 94: 1171-1175.

CLOSE, R.C. (1965). Control of leaf roll virus in potatoes. *Proc. 18th. N.Z. Weed Control Conf, Wellington.* pp. 197-202.

COGNETTI, G. (1967). Sexual genotypes and migratory tendencies in *Myzus persicae* Sulz. *Monit. Zool. ital (N.S.)* 1: 229-234.

COSTA, C.L. and LEWIS, T. (1968). The relationship between the size of yellow water traps and catches of aphids. *Ent. exp. & appl.* 10: 485-487.

CROFT, B.A. and BROWN, A.W.A. (1975). Responses of arthropods natural enemies. *Ann. Rev. Ent.* 20: 285-335.

DAIBER, C.C. (1963). Notes on the host plants and winged dispersal of *Macrosiphum euphorbiae* (Thomas) and *Myzus persicae* (Sulzer) in South Africa. *J. ent. Soc., S.Africa* 26: 14-33.

DAIBER, C.C. (1964). Further notes on potato aphids and leaf roll spread in South Africa. *J. ent. Soc., S.Africa* 26: 306-323.

DAIBER, C.C. and SCHOLL, S.E. (1959). Further notes on the overwintering of the green peach aphid, *Myzus persicae* (Sulzer), in South Africa. *J. ent. Soc. S.Africa* 22: 494-520.

DAVIES, W.M. (1932). Ecological studies on aphids infesting the potato crop. *Bull. ent. Res.* 23: 535-548.

DAVIES, W.M. (1934). Studies on aphids infesting the potato crop. II. Aphid survey: its bearing upon the selection of districts for seed potato production. *Ann. appl. Biol.* 21: 283-299.

DAVIES, W.M. (1935). Studies of aphids infesting the potato crop. III. Effect of variation in relative humidity on the flight of *Myzus persicae* (Sulzer). *Ann. appl. Biol.* 22: 106-115.

DAVIES, W.M. (1936). Studies on aphids infesting the potato crop. V. Laboratory experiments on the effect of wind velocity on the flight of *Myzus persicae* (Sulzer). *Ann. appl. Biol.* 23: 401-408.

DAVIES, W.M. (1939). Studies on aphids infesting the potato crops. *Ann. appl. Biol.* 26: 116-

DAVIES, W.M. and WHITEHEAD, T. (1938). Studies on aphids infesting potato crop. VI. Aphid infestation of isolated plants. *Ann. appl. Biol.* 25: 122-142.

DAVIES, W.M. and WHITEHEAD, T. (1935). Studies on aphids infesting potato crop. IV. Notes on the migration and conditions of alate *Myzus persicae* (Sulzer). *Ann. appl. Biol.* 22: 549-556.

DeBACH, P. (1974). Biological control by natural enemies. Cambridge University Press, Cambridge. 323 pp.

DeBACH, P. and BARLETT, R. (1964). Methods of colonization, recovery and evaluation. *In* Biological Control of Insect Pests and Weeds. Ed. P. DeBach. Chapman and Hall, London. pp. 402-426.

DeBACH, P., DIETRICK, E.J. and FLESCHNER, C.A. (1949). A new technique for evaluating the efficiency of entomophagous insects in the fields. *J. econ. Entomol.* 42: 546.

De LOACH, C.J. (1974). Rate of increase of populations of cabbage, green peach and turnip aphids at constant temperatures. *Ann. ent. Soc. Am.* 67: 332-339.

DICKSON, R.C. and LAIRD, Jr. E.F. (1962). Green peach aphid populations on desert sugar beets. *J. econ. Entomol.* 55: 501-504.

DIXON, A.F.G. (1959). An experimental study of the searching behaviour of the preadtory coccinellid beetle *Adalia decempunctata* *J. Anim. Ecol.* 28: 259-281.

DIXON, A.F.G. (1970). Factors limiting the effectiveness of the coccinellid beetle, *Adalia bipunctata* (L.) as a predator of the sycamore aphid, *Drepanosiphum plantanoides* (Schr.). *J. Anim. Ecol.* 39: 739-751.

DONCASTER, J.P. and GREGORY, P.H. (1948). The spread of virus diseases in the potato crop. *His Majesty's Stationery Office, Lond.* 189 pp.

DOUTT, R.L. and HAGEN, K.S. (1950). Biological control measures applied against *Pseudococcus maritimus* on pears. *J. econ. Entomol.* 43: 94-96.

DUNN, J.A. (1949). The predators and parasites of potato aphids. *Bull. ent. Res.* 40: 97-122.

DUNN, J.A. (1952). The effect of temperature on the pea aphid-ladybird relationship. *Rep. Natn. Veg. Res. Stn.* 1951, pp. 21-23.

DUNN, J.A. (1954). *Micromus variegatus* Fab. (Neuroptera) as a predator of the pea aphids. *Proc. Roy. ent. Soc., Lond., Ser.A.* 29: 76-81.

DUNN, J.A. and KEMPTON, D.P.H. (1971). Seasonal changes in aphid populations on Brussels sprouts. *Ann. appl. Biol.* 68: 233-244.

EAST, R. (1980). Sampling white-fringed weevil *(Graphognathus luecoloma)* populations. *N.Z. J. agric. Res.* 23: 581-587.

EASTOP, V.F. (1955). Selection of aphid species by different kinds of insect traps. *Nature, London.* 176: 936.

EPSTEIN, E. and ROBINSON, R.R. (1965). A rapid method for determining leaf area of potato plants. *Agro. J.* 57: 515-516.

EVANS, D.A. and MEDLER, J.T. (1966). Improved method of using yellow-pan aphid traps. *J. econ. Entomol.* 59: 1526-1527.

EVENHUIS, H.H. (1968). The natural control of the apple-grass aphid, *Rhophalosiphum insertum*, with remarks on the control of apple aphids in The Netherlands in general. *Neth. J. Pl. Path.* 74: 106-117.

FIDLER, J.H. (1949). A three years' survey of potato aphids in north-east Yorkshire. *Ann. appl. Biol.* 36: 63-75.

FINNEY, D.J. (1941). Wireworm populations and their effect on crops. *Ann. appl. Biol.* 28: 282-295.

FINNEY, G.L. (1948). Culturing *Chrysopa californica* and obtaining eggs for field distribution. *J. econ. Entomol.* 41: 719-721.

FINNEY, G.L. (1950). Mass-culturing *Chrysopa californica* to obtain eggs for field distribution. *J. econ. Entomol.* 43: 97-100.

FISHER, R.A. (1941). The negative binomial distribution. *Ann. Eugenics* 11: 182-187.

FISHER, R.A. (1953). Note on the efficient fitting of the negative binomial. *Biometrics* 9: 197-200.

FISKEN, A.G. (1959a). Factors affecting the spread of aphid-borne viruses in potato in Eastern Scotland. I. Overwintering of potato aphids, particularly *Myzus persicae* (Sulzer). *Ann. appl. Biol.* 47: 264-273.

FISKEN, A.G. (1959b). Factors affecting the spread of aphid-borne viruses in potato in Eastern England. II. Infestation of the potato crop by potato aphids, particularly *Myzus persicae* (Sulzer). *Ann. appl. Biol.* 47: 274-286.

FLESCHNER, C.A. (1950). Studies on searching capacity of the larvae of three predators of the citrus red mite. *Hilgardia* 20: 233-265.

FLUKE, C.L. (1929). The known predaceous and parasitic enemies of the pea aphid in North America. *Agric. Exp. Sta. Univ. Wisconsin, Madison, Res. Bull.* 93: 47 pp.

FORRESTER, N.W. (1978). Seasonal abundance of spotted alfalfa aphid, blue green aphid and their predators at Tamworth, N.S.W. *Proc. Lucerne aphid workshop, Tamworth, N .S.W.* 1978, pp. 53-56.

FOWLER, R. (1934). Green peach aphid (*Myzus persicae* Sulz.) and its control. *J. Dep. Agric., S.Aust.* 38: 376-82.

FRAZER, B .D. and GILBERT, N. (1976). Coccinellids and aphids : A quantitative study on the impact of adult ladybirds (Coleoptera : Coccinellidae) preying on field populations of pea aphids (Homoptera : Aphididae). *J. ent. Soc. Brit. Columbia* 73: 33-56.

GALECKA, B. (1966). The effectiveness of predators in the control of *Aphis nasturtii* Kalt. and *Aphis frangulae* Kalt. on potatoes. *In* Ecology of the Aphidophagous insects. Ed. I.Hodek. Prague, Academia, 360 pp.

GALECKA, B. and KAJAK, A. (1971). Studies on ecological mechanisms reducing population of *Myzus persicae* (Sulz.) (Hom., Aphididae). *Ekol. Pol.* 19: 789-806.

GETZIN, L.W. (1962). Mass rearing of virus-free cabbage loopers on an artificial diet. *J. Invert. Pathol.* 4: 486-488.

GILBERT, N., GUTIERREZ, A.P., FRAZER, B.D. and JONES, R.E. (1976). Ecological Relationships. W.H.Freeman and Co., San Francisco, 156 pp.

GILLIVRAY, M.E. (1979). Aphids infesting potatoes in Canada : A field guide. *Info. Serv. Agri. Canada, Ottawa. Publ.* 1676. 23pp.

GURNEY, B. and HUSSEY, N.W. (1970). Evaluation of some coccinellid species for the biological control of aphids in protected cropping. *Ann. appl. Biol.* 65: 451-458.

HAGEN, K.S., BOMBOSCH, S. and McMURTY, J.A. (1976). The biology and impact of predators. *In* Theory and Practice of Biological Control. Eds. C.B.Huffaker and P.S.Messenger. Academic Press Inc., New York. pp. 93-142.

HAGEN, K.S., SAWALL, E.F. and TASSAN, R.L. (1970). Some ecophysiological relationship between certain *Chrysopa*, honeydews and yeasts. *Boll. Lab. Entomol. Agr. "Gilippo Silvestri" Portici* 28: 113-134.

HAGEN, K.S. and HALE, R. (1974). Increasing natural enemies through use of supplementary feeding and non-target prey. *In* Proc. Summer Inst. Biol. Cont. of Plant Insects and Diseases. Eds. G.F. Maxwell and F.A.Harris, Univ. Press Miss. pp. 170-181.

HAGEN, K.S. and van den BOSCH, R. (1968). Impact of pathogens, parasites, and predators on aphids. *Ann. Rev. Ent.* 13: 325-384.

HALL, P.K., PARROTT, W.L., JENKINS, J.N. and McCARTY, Jr. J.C. (1980). Use of tobacco budworm eggs and larvae for establishing field infestation on cotton. *J. econ. Entomol.* 73: 393-395.

HARCOURT, D.G. (1960). Distribution of immature stages of the diamondback moth, *Plutella maculipennis* (Curt.) (Lepidoptera : Plutellidae) on cabbage. *Can. Ent.* 92: 517-521.

HARCOURT, D.G. (1961). Spatial pattern of the imported cabbageworm, *Pieris rapae* (L.) (Lepidoptera : Pieridae), on cultivated cruciferae. *Can. Ent.* 93: 945-952.

HARPER, A.M. and STORY, T.P. (1962). Reliability of trapping in determining the emergence period and sex ratio of the sugar beet root maggot *Tetanops myopaeformis* (Roder) (Diptera : Otitidae). *Can. Ent.* 94: 268-271.

HASSELL, M.P. (1976). The dynamics of competition and predation. Studies in Biol. No. 72, Edward Arnold. 68 pp.

HASSELL, M.P. (1978). Arthropod predator-prey systems. Princeton University Press, New Jersey. 237 pp.

HEALY, M.J.R. (1962). Some basic statistical techniques in soil zoology. *In* Progress in Soil Zoology. Ed. P.W. Murphy. Butterworth, London. pp. 3-9.

HEATHCOTE, G.D. (1957). The comparison of yellow yclindrical, flat sticky traps, water traps and of Johnson suction traps for samplhing aphids. *Ann. appl. Biol.* 45: 133-139.

HEATHCOTE, G.D. (1958). Effects of height on catches of aphids in water and sticky traps. *Plant Path.* 7: 32-35.

HEATHCOTE, G.D. (1963). The effect of coccinellids on aphids infesting insecticide-treated sugar beets. *Plant Path.* 12: 80-83.

HEATHCOTE, G.D. (1972). Evaluating aphid populations on plants. *In* Aphid Technology. Ed. H.F. van Emden. Academic Press, London, 344 pp.

HEATHCOTE, G.D., DUNNING, R.A. and WOLFE, M.D. (1965). Aphids on sugar beet and some weeds in England, and notes on weeds as a source of beet virus. *Plant Path.* 14: 1-10.

HEIE, O.E. (1954). Studies of the overwintering of *Myzus persicae* Sulzer in Danemark and the occurrence of this aphid in beet fields. *Trans. Danish Acad. Tech. Sci.* 1954, 1: 34 pp.

HELSON, G.A.H. (1958). Aphid populations : Ecology and methods of sampling aphids *Myzus persicae* (Sulz.) and *Aulacorthum solani* (Kltb.) *New Zealand Entomologist* 2: 20-23.

HILLE RIS LAMBERS, D. (1972). Viruses of potatoes and seed potato production. PUDOC, Wageningen. pp. 36-56.

HILSON, R.J.D. (1964). The ecology of *Micromus tasmaniae* (Walker). M.Sc. Thesis. Univ. of Canterbury, New Zealand. 85 pp.

HODEK, I. (1957). The larval food consumption of *Coccinella septempunctata* *Zool. Listy* 6: 3-11.

HODEK, I. (1967). Bionomics and ecology of predaceous coccinellidae. *Ann. Rev. Ent.* 12: 79-104.

HODEK, I. (1973). Biology of coccinellidae. Dr. J. Junk N.V. Publi, The Hague. 260 pp.

HODEK, I., HAGEN, K.S. and van EMDEN, H.F. (1972). Methods for studying effectiveness of natural enemies. *In* Aphid Technology. Academic Press, London, pp. 147-188.

HODEK, I., NOVÁK, K., SKUHRAVÝ, V. and HOLMAN, J. (1965). The predation of *Coccinella 7-punctata* L. on *Aphis fabae* Scop. on sugar beet. *Acta. ent. Bohemoslov.* 62: 241-253.

HOLLING, C.S. (1961). Principles of insect predation. *Ann. Rev. Ent.* 6:163-181

HOUGH, W.S. and MASON, A.F. (1951). Spraying, dusting and fumigating of plants. Principles and applications. The Macmillan Co., New York. 726 pp.

HRDÝ, I. (1975). Insecticide resistance in aphids. *Proc. 8th British Insecticide and Funaicide Conf.* 3: 737-749.

HUFFAKER, C.B. (1958). Experimental studies on predation : dispersion factors and predator-prey oscillations. *Hilgardia* 27: 343-383.

HUFFAKER, C.B. and KENNET, C.E. (1956). Experimental studies on predation: predation and cyclamen-mite populations on strawberries in California. *Hilgardia* 26: 191-222.

HUFFAKER, C.B., KENNETT, C.E., MATSUMOTO, B. and WHITE, E.G. (1968). Some parameters in the role of enemies in the control of insect abundance. *In* Insect Abundance. Edt. T.R.E. Southwood, Roy. ent. Soc. Lond.

HUFFAKER, C.B., SIMMONDS, F.J. and LAING, J.E. (1976). The theoretical and empirical basis of biological control. *In* Theory and Practice of Biological Control. Eds. C.B. Huffaker and P.S. Messenger. Academic Press, New York. 788 pp.

HUGHES, R.D. (1963). Population dynamics of the cabbage aphid, *Brevicoryne brassicae* (L.). *J. Anim. Ecol.* 32: 393-424.

HUGHES, R.D. (1964). Survey of aphids flying over eastern Australia in 1961. *Aust. J. Zool.* 12: 174-200.

HUGHES, R.D. and GILBERT, N. (1968). A model of an aphid population - a general statement. *J. Anim. Ecol.* 37: 553-563.

IGNOFFO, C.M. (1963). A successful technique for mass-rearing cabbage loopers on semisynthetic diet. *Ann. ent. Soc. Am.* 56: 178-182.

IGNOFFO, C.M. and DUTKY, S.R. (1963). The effect of sodium hypochlorite on the viability and infectivity of *Bacillus* and *Beauveria* spores and cabbage looper nuclear polyhedrosis virus. *J. Invert. Pathol.* 5: 422-426.

INAIZUMI, M. (1968). Factors affecting the infestation of aphids on potato plants. *J. appl. Ent. Zool.* 12: 567-568.

JACOB, F.H. (1941). The overwintering of *Myzus persicae* Sulzer on Brassicae in North Wales. *Ann. appl. Biol.* 28: 119-124.

JONES, S.L. and RIDGWAY, R.L. (1976). Development of methods for field distribution of eggs of the insect predator *Chrysopa carnea* Stephens. USDA ARS-S0124. 5pp.

KARANDINOS, M.G. (1976). Optimum sample size and comments on some published formulae. *Bull. ent. Soc. Am.* 22: 417-421.

KASSANIS, B. (1952). Some factors affecting the transmission of leaf roll virus by aphids. *Ann. appl. Biol.* 39: 157-167.

KAY, I.R. (1979). Toxicity of insecticides to *Coccinella repanda* Thunberg (Coleoptera : Coccinellidae). *J. Aust. ent. Soc.* 18: 233-234.

KENNEDY, J.S., DAY, M.F. and EASTOP, V.F. (1962). A conspectus of aphids as of *Myzus persicae* (Sulzer). Ann. Vectors of Plant Viruses. Commonwealth Inst. Entomol., Lond. 114 pp.

KENNEDY, J.S., IBBOTSON, A. and BOOTH, C.O. (1959). The distribution of aphid infestation in relation to leaf age. I. *Myzus persicae* (Sulz.) and *Aphis fabae* Scop. on spindle trees and sugar-beet plants. *Ann. appl. Biol.* 37: 651-696.

KHAN, M.H. (1979). Ecology of the black citrus aphid, *Toxoptera citricidus* (Kirkaldy) (Homoptera : Aphididae). Ph.D. Thesis, Univ. of Adelaide, Adelaide, South Australia. 145 pp.

KILLINGTON, F.J. (1936). A monograph of the British Neuroptera. Adlard and Son Ltd., London, Vol. I. 269 pp.

KIRITANI, K. and DEMPSTER, J.P. (1973). Different approaches to the quantitative evaluation of natural enemies. *Proc. 14th International Congress of Ent., Canberra.* 1972. pp. 323-329.

KIRKPATRICK, H.C. and ROSS, A.F. (1952). Aphid transmission of potato leaf roll virus to solanaceous species. *Phytopathology* 42: 540-547.

KLOSTERMEYER, E.C. (1959). Entomological aspects of the potato leaf roll problem in Central Washington. *Wash. Agr. Exp. Sta. Tech. Bull.* 9: 44 pp.

KNIPLING, E.F. (1979). The basic principles of insect population suppression and management. *USDA Agric. Handbook No.512.* 659 pp.

KNUTSON, K.W. and BISHOP, G.W. (1964). Potato leaf roll virus-effect of the green peach aphid, *Myzus persicae*, in southern Idaho. potato fields. *Am. Potato J.* 41: 227-38.

KUEHL, R.O. and FYE, R.E. (1970). Efficiency of grid stratification in cotton fields for cotton insect survey. *J. econ. Entomol.* 63: 1864-1866.

LAMB, K.P. (1958). Alate aphids trapped in Auckland, New Zealand, using Moericke colour traps. *New Zealand J. Sci.* 1: 579-589.

LAIDLAW, W.B.R. (1936). The brown lacewing flies (Hemerobiidae) : their importance as controls of *Adelges cooleyi* Gillette. *Ent. Monthl. Mag.* 72: 164-174.

LANDIS, B.J. (1972). The alighting response of aphids to yellow-pan water traps at different elevations. *Environ. Entomol.* 1: 473-476.

LATHEEF, M.A. and HARCOURT, D.G. (1973). A sampling plan for studies on the population dynamics of *Leptinotarsa decemlineata* (Coleoptera : Chrysomelidae) on tomato. *Ent. exp. & appl.* 16: 365-372.

LORD, F.T. (1968). An appraisal of methods of sampling apple trees and results of some tests using a sampling unit common to insect predators and their prey. *Can. Ent.* 100: 23-33.

LOWE, A.D. (1962). The overwintering of *Myzus persicae* Sulz. in Canterbury (a note). *New Zealand J. Agr. Res.* 5: 364-367.

LYONS, L.A. (1964). The spatial distribution of two pine sawflies and methods of sampling for the study of population dynamics. *Can. Ent.* 96: 1373-1403.

McWILLIAMS, J.M. (1979). *Heliothis* spp. eggs : spray application to establish larval infestation in experimental field plots of soybeans. *Environ. Entomol.* 8: 1044-1046.

MACK, T.P. and SMILOWITZ, Z. (1980). The development of a green peach aphid natural enemy sampling procedure. *Environ. Entomol.* 9:440-445.

MACKAUER, M. and WAY, M.J. (1976). *Myzus persicae* Sulz., an aphid of world importance. *In* Studies in Biological Control. Ed. V.L.Delucchi. Cambridge University Press, Cambridge, pp. 51-119.

MAELZER, D.A. (1977). The biology and main causes of changes in numbers of the rose aphid, *Macrosiphum rosae* (L.), on cultivated roses in South Australia. *Aust. J. Zool.* 25: 269-284.

MAELZER, D.A. (1978). The growth and voracity of larvae of *Leis conformis* (Boisd.) (Coleoptera : Coccinellidae) fed on the rose aphid *Macrosiphum rosae* (L.) (Homoptera : Aphididae) in the laboratory. *Aust. J. Zool.* 26: 293-304.

MAELZER, D.A. (1981). Aphids - introduced pests of man's crops. *In* The Ecology of Pests - Some Australian Case Histories. Eds. R.L.Kitching and R.E.Jones, C.S.I.R.O., Melbourne, Australia. pp 89-105.

MAELZER, D.A. (1982). The distribution of red scale *(Aonidiella aurantii)* and its parasite (*Aphytis melinus*) within and between orange trees in South Australia. *J. appl. Ecol.* (submitted for publication).

MEIER, W. (1966). Importance of aphidophagous insects in the regulation of potato aphid populations. *Proc. Symp. on Ecology of Aphidophagous Insects.* Ed.I.Hodek, Prague, Academia. pp.323-325.

MILNE, W.W. (1978). Laboratory studies on the blue-green aphid (BGA) and its predators. *Proc. Lucerne aphid Workshop, Tamworth, N.S.W.* 1978. pp. 92-93.

MILNE, W.W. (1979). The potential of lucerne aphid predators. *Proc. Aust. Appl. Entomol. Res. Conf.* Queensland Agric. College, Lawes, 1979. pp. 6.3-6.5.

MORISITA, M. (1962). Iδ-index, a measure of dispersion of individuals. *Res. Popul. Ecol.* 4: 1-7.

MORRIS, R.F. (1960). Sampling insect populations. *Ann. Rev. Ent.* 5: 243-264.

MURDOCH, W.W. (1971). The developmental responses of predators to changes in prey density. *Ecology* 52: 132-137.

MURDOCH, W.W. and MARKS, R.J. (1972). Predation by coccinellid beetles: experiments on switching. *Ecology* 54: 160-167.

MURPHY, P.A. and LOUGHNANE, J.B. (1937). A ten years' experiment on the spread of leaf roll in the field. *Sci. Proc. R. Dublin Soc.*, N.S. 21: 567-79.

NEUENSCHWANDER, P. (1975). Influence of temperature and humidity on the immature stages of *Hemerobius pacificus*. *Environ. Entomol.* 4: 215-220.

NEUENSCHWANDER, P. (1976). Biology of the adult *Hemerobius pacificus*. *Environ. Entomol.* 5: 96-100.

NEUENSCHWANDER, P., HAGEN, K.S. and SMITH, R.F. (1975). Predation on aphids in California's alfalfa fields. *Hilgardia* 43: 53-78.

NEW, T.R. (1975). The biology of Chrysopidae and Hemerobiidae (Neuroptera), with reference to their usage as biocontrol agents : a review. *Trans. R. ent. Soc. Lond.* 127: 115-140.

NEWTON, J.H., PALMER, M.A. and LIST, G.M. (1953). Fall migration of aphids with special reference to the green peach aphid. *J. econ. Entomol.* 46: 667-670.

NORDLUND, D.A., LEWIS, W.J., GROSS, Jr. H.R. and HARRELL, E.A. (1974). Description and evaluation of a method for field application of *Heliothis zea* eggs and Kairomones for *Trichogramma*. *Environ. Entomol.* 3: 981-984.

NORRIS, D.O. and BALD, J.G. (1943). Transmission of potato virus diseases. 2. The aphid population on potatoes at Canberra during 1940-41. *Coun. Sci. Industr. Res. Aust. Bull.* No. 163.

OATMAN, E.R. and PLANTER, G.R. (1969). An ecological study of insect populations on cabbage in southern California. *Hilgardia* 40: 1-40.

OSSIANNILSSON, F. (1959). Contributions to the knowledge of Swedish aphids. II. *Lantbrukshögskolans Ann.* 25: 469-470.

PATCH, E.M. (1938). Food-plant catalogue of aphids of the world including Phylloxeridae. *Maine Agr. Exp. Sta. Bull.* pp. 392-397.

PETERSON, A. (1959). Entomological Techniques. Edwards, Ann. Arbor, Michigan. 9th ed.

PETERSON, A.G. (1963). Increases of the green peach aphid following the use of some insecticides on potatoes. *Am. Potato J.* 40: 121-129.

PHILIPPE, D.M. (1970). Biologie de la reproduction de *Chrysopa perla* (L.) (Nevropteres : Chrysopidae). These, L'Universite Paul-Sabatiés de Toulouse. 133 pp.

POWELL, D.M. and MONDOR, T.W. (1973). Control of the green peach aphid and suppression of leaf roll on potatoes by systemic soil insecticides and multiple foliar sprays. *J. econ. Entomol.* 66: 170-177.

POWELL, D.M. and WALLIS, R.L. (1974). Spraying peach trees and burning weed hosts in managing green peach aphid to reduce the incidence of virus in potatoes and sugarbeets. *Proc. Tall. Timbers Conf. Ecol. Anim. Control Habitat Manage.* 6: 87-98.

RABB, R.L., STINNER, R.E. and van den BOSCH, (1976). Conservation and sugmentation of natural enemies. *In* Theory and Practice of Biological Control. Ed. C.B.Huffaker and P.S.Messenger, Academic Press, New York. pp. 233-254.

RADCLIFFE, E.B. (1972). Population responses of green peach aphid in Minnesota on potatoes treated with various insecticides. *Proc. N. Cent. Branch Ent. Soc. Am.* 27: 103-105.

RADCLIFFE, E.B. (1973). Population responses of green peach aphid on potatoes to treatment with various insecticides. *Proc. N. Cent. Branch Ent. Soc. Am.* 28: 100-102.

RIDGWAY, R.L. and JONES, S.L. (1968). Field-cage releases of *Chrysopa carnea* for suppression of populations of *Heliothis* spp. on cotton. *J. econ. Entomol.* 61: 892-898.

RIDGWAY, R.L. and JONES, S.L. (1969). Inundative releases of *Chrysopa carnea* for control of *Heliothis* on cotton. *J. econ. Entomol.* 62: 177-180.

RIDLAND, P. and BERG, G. (1978). Seasonal abundance of spotted alfalfa aphid and its natural enemies in Victoria. *Proc. Lucerne aphid Workshop. Tamworth, N.S.W. 1978*, pp. 19-24.

RIGWAY, R.L., MORRISSON, R.K. and BADGLEY, M. (1970). Mass rearing: a green lacewing. *J. econ. Entomol.* 63: 834-836.

ROGERS, C.E., JACKSON, H.B. and EIKENBARY, R.D. (1972). Voracity and survival of Propylaea 14-*punctata* prey upon greenbugs. *J. econ. Entomol.* 65: 1313-1316.

ROSS, A.F., CHUCKA, J.A. and HAWKINS, A. (1947). The effect of fertilizer practice including the use of minor elements on stem-end browning, net necrosis, and spread of leaf roll virus in the Green Mountain variety of potato. *Bull. Maine Agr. Exp. Sta.* No. 447.

ROSSLER, Y. (1975a). Reproductive differences between laboratory-reared and field-collected populations of Mediterranean fruit fly, *Ceratitis capitata. Ann. ent. Soc. Am.* 68: 987-991.

ROSSLER, Y. (1975b). The ability to inseminate : a comparison between a laboratory-reared and field-collected population of the Mediterranean fruit fly, *Ceratitis capitata* *Ent. exp. & appl.* 18:225-227.

SAMSON, P.R. and BLOOD, P.R.B. (1979). Biology and temperature relationships of *Chrysopa* sp., *Micromus tasmaniae* and *Nabis capsiformis*. *Ent. exp. & appl.* 25: 253-259.

SAMSON, P.R. and BLOOD, P.R.B. (1980). Voracity and searching ability of *Chrysopa signata* (Neuroptera : Chrysopidae), *Micromus tasmaniae* (Neuroptera : Hemerobiidae) and *Tropiconabis capsiformis* (Hemiptera : Nabidae). *Aust. J. Zool.* 28: 575-580.

SANDVOL, L.S. and CUNNINGHAM, G. (1975). Idaho green peach aphid management program. Univ. of Idaho Misc. Ser. No.23. 14 pp.

SCHOLL, S.E. and DAIBER, C.C. (1958). Notes on the coccurrence of holocyclic overwintering of the green peach aphid in South Africa. *J. ent. Soc. S.Africa.* 21: 315-322.

SCOPES, N.E.A. (1969). The potential of *Chrysopa carnea* as a biological control agent of *Myzus persicae* on glasshouse chrysanthemums. *Ann. appl. Biol.* 64: 433-439.

SHANDS, W.A., GORDON, C.C. and SIMPSON, G.W. (1972a). Insect predators for controlling aphids on potatoes. 6. Development of a spray technique for applying eggs in the field. *J. econ. Entomol.* 65: 1099-1103.

SHANDS, W.A. and LANDIS, B.J. (1964). Potato insects : their biology and biological and cu-ltural control. *USDA ARS Agric. Handbook* No. 264. 61 pp.

SHANDS, W.A. and SIMPSON, G.W. (1959). Characteristics of aphid-population growth on potatoes in north eastern Maine. *Ann. ent. Soc. Am.* 52: 117-121.

SHANDS, W.A. and SIMPSON, G.W. (1972a). Insect predators for controlling aphids on potatoes. 2. In small plots with two kinds of barriers, in small fields, or in large cages. *J. econ. Entomol.* 65: 514-518.

SHANDS, W.A. and SIMPSON, G.W. (1972b). Insect predators for controlling aphids on potatoes. 4. Spatial distribution of introduced eggs of two species of predators in small fields. *J. econ. Entomol.* 65: 805-809.

SHANDS, W.A. and SIMPSON, G.W. (1972c). Insect predators for controlling aphids on potatoes. 7. A pilot test of spraying eggs of predators on potatoes in plots separated by bare fallow land. *J. econ. Entomol.* 65: 1383-1387.

SHANDS, W.A., SIMPSON, G.W. and BRUNSON, M.H. (1972b). Insect predators for controlling aphids on potatoes. 1. In small plots. *J. econ. Entomol.* 65: 511-514.

SHANDS, W.A., SIMPSON, G.W. and GORDON, C.C. (1972c). Insect predators for controlling aphids on potatoes. 5. Number of eggs and schedules for introducing them in large field cages. *J. econ. Entomol.* 65: 810-817.

SHANDS, W.A., SIMPSON, G.W. and HALL, I.M. (1963). Importance of entomogenous fungi in controlling aphids on potatoes in north-eastern Maine. *Maine Agr. Exp. Sta. Tech. Bull. T6.* 42 pp.

SHANDS, W.A., SIMPSON, G.W. and REED, L.B. (1954). Subunits of sample for estimating aphid abundance on potatoes. *J. econ. Entomol.* 47: 1024-1027.

SHANDS, W.A., SIMPSON, G.W. and TORCH, R.H. (1972d). Insect predators for controlling aphids on potatoes. 3. In small plots separated by alluminium flashing strip coated with a chemical barrier and in small fields. *J. econ. Entomol.* 65: 799-805.

SHANDS, W.A., SIMPSON, G.W. and WAVE, H.E. (1956). Some effects of two hurricans upon populations of potato-infesting aphids in north-eastern Maine. *J. econ. Entomol.* 49: 252-53.

SHANDS, W.A, SIMPSON, G.W., WAVE, H.E. and GORDON, C.C. (1972e). Importance of arthropod predators in controlling aphids on potatoes in northeastern Maine. *Univ. of Maine, Orono. Tech. Bull.* 54. 49 pp.

SHELDON, J.K. and MACLEOD, E.G. (1971). Some studies on the biology of Chrysopidae. II. The feeding behaviour of the adult *C. carnea*. *Psyche* 78: 107-121.

SHIYOMI, M. and NAKAMURA, K. (1964). Experimental studies on the distribution of the aphid counts. *Res. Popul. Ecol.* 6: 79-87.

SIMONET, D.E. and PIENKOWSKI, R.L. (1979). A sampling program developed for potato leafhopper nymphs, *Empoasca fabae* (Homoptera : Cicadellidae), on alfalfa. *Can. Ent.* 111: 481-486.

SIMPSON, G.W. (1932). Spraying and dusting experiments for the control of potato aphids. *J. econ. Entomol.* 25: 634.

SIMPSON, G.W. (1940). Aphids and their relation to the field transmission of potato virus diseases in northeast Maine. *Maine Agr. Exp. Sta. Bull.* No.403.

SMITH, C.N. (1966). Insect colonization and mass production. Academic Press, New York. 618 pp.

SMITH, H.S. and DeBACH, P. (1942). The measurement of the effect of entomophagous insects on population densities of their hosts. *J. econ. Entomol.* 35: 845-849.

SMITH, K.M. (1929). Studies on potato virus diseases. V. Transmission of potato leaf-roll. *Ann. appl. Biol.* 16: 209-229.

SMITH, L.B. (1919). The life history of biology of the pink and green aphid *(Macrosiphum solanafolii* Ash.). *Bull. Va. Truck Exp. Sta.* No.27.

SMITH, R.C. (1923). The life histories and stages of some hemerobiids and allied species (Neuroptera). *Ann. ent. Soc. Am.* 16: 129-151.

SMITH, R.F. and HAGEN, K.S. (1966). Natural regulation of alfalfa aphids in California. *In* Ecology of Aphidophagous Insects. Ed. I.Hodek, Prague. Academia. pp 297-315.

SOLOMON, M.E. (1949). The natural control of animal populations. *J. Anim. Ecol.* 18: 1-35.

SOUTHWOOD, T.R.E. (1966). Ecological methods with particular reference to the study of insect populations. Chapman and Hall, London. 391 pp.

SOUTHWOOD, T.R.E. (1978). Ecological methods with particular reference to the study of insect populations. The English Language Society and Chapman and Hall, Cambridge. 524 pp.

STATHOPOULOS, D.G. (1976). Studies on the identification and bioecology of cotton pests. II. *Rep. Pl. Prot. agric. Res. Stn. Thessaloniki* 3: 41-9.

STINNER, R.E. (1977). Efficacy of inundative releases. *Ann. Rev. Ent.* 22:515-531.

STRICKLAND, A.H. (1961). Sampling crop pests and their hosts. *A. Rev. Ent.* 6: 201-220.

SUNDBY, R.A. (1966). A comparative study on the efficiency of three predatory insects - *Coccinella septempunctata* (Coleoptera : Coccinellidae), *Chrysopa carnea* (Neuroptera : Chrysopidae) and *Syrphus ribesii* (Diptera : Syrphidae) at two different temperatures. *Entomophaga* 11: 395-404.

SWENSON, K.G. (1968). Role of aphids in the ecology of plant viruses. *A. Rev. Phytopath.* 6: 351-374.

SYLVESTER, E.S. (1964). Insectary life history and apterous instar morphology of *Myzus persicae* (Sulzer) (Homoptera : Aphididae). *Ann. ent. Soc. Am.* 47: 397-406.

SYLVESTER, E.S. (1980). Circulative and propogative virus transmission by aphids. *A. Rev. Ent.* 25: 257-286.

SYLVESTER, E.S. and COX, E.L. (1961). Sequential plans for sampling aphids on sugar beets in Kern County, California. *J. econ. Entomol.* 54: 1080-1085.

SYRETT, P. and PENMAN, R. (1980). Studies on insecticides toxicity to lucerne aphids and their predators. *N.Z. J. agric. Res.* 23:575-580.

SYRETT, P. and PENMAN, D.R. (1981). Developmental threshold temperatures for the brown lacewing, *Micromus tasmaniae* (Neuroptera : Hemerobiidae). *N.Z. J. Zool.* 8: 281-283.

TAMAKI, G. (1973). Spring population of the green peach aphid on potatoes and the role of natural enemies in their control. *Environ. Entomol.* 2: 186-191.

TAMAKI, G., LANDIS, B.J. and WEEKS, R.E. (1967). Autumn populations of green peach aphid on peach trees and the role of syrphid flies in their control. *J. econ. Entomol.* 60: 433-436.

TAMAKI, G., McGUIRE, J.U. and TURNER, J.E. (1974). Predator power and efficacy : a model to evaluate their impact. *Environ. Entomol.* 3: 625-630.

TAMAKI, G. and WEEKS, R.E. (1972). Biology and ecology of two predators, *Geocoris pallens* Stal. and *B. bullatus* (Say). *USDA ARS Tech. Bull.* 1446. 46 pp.

TAMAKI, G. and WEISS, M. (1979). The development of a sampling plan on the spatial distribution of the green peach aphid on sugarbeets. *Environ. Entomol.* 8: 598-605.

TANADA, Y. (1963). Epizootiology of infectious diseases. *In* Insect Pathology, An Advance Treatise. Ed. E.A.Steinhaus, Academic Press, New York. Vol. 2, 689 pp.

TASSAN, R.L., HAGEN, K.S. and SAWALL, Jr. E.F. (1979). The influence of field food sprays on the egg production rate of *Chrysopa carnea*. *Environ. Entomol.* 8: 81-85.

TAUBER, M.J. and TAUBER, C.A. (1973). Dietary requirements for mating in *Chrysopa oculata* (Neuroptera : Chrysopidae). *Can. Ent.* 105: 79-82.

TAYLOR, C.E. (1955). Growth of potato plant and aphid colonization. *Ann. appl. Biol.* 43: 151-156.

TAYLOR, C.E. (1962). The population dynamics of aphids infesting the potato plant with particular reference to the susceptibility of certain varieties to infestation. *Eur. Pot. J.* 5: 204-219.

THE MERCK INDEX (1976). An encylopedia of chemical and drugs. Eds. M.Windholz, S.Bunavari, L.Y.Stroumtos and M.N.Fertig. Merck and Co. Inc., New Jersey. 9th ed. pp. 9725.

THOMAS, I. and JACOB, F.H. (1943). Ecology of the potato aphids in North Wales. *Ann. appl. Biol.* 30: 97-101.

TING, T.H., SWINCER, D.E. and WALDEN, K.J. (1978). Laboratory studies of the native predators of the spotted alfalfa aphid in South Australia. *Proc. Lucerne aphid workshop. Tamworth, N.S.W. 1978.* pp. 94-98.

TJEDER, B. (1961). The lacewings of Southern Africa. 4. The family Hemerobiidae. Zool. Rec. : *Insecta* 98: 296-408.

TOMIUK, J. and WOHRMANN, K. (1980). Population growth and structure of natural populations of *Macrosiphum rosae* (L.) (Hemiptera : Aphididae). *Sonderdruck aus Bd.* 90: 464-473.

TULISALO, U. and KORPELA, S. (1973). Mass rearing of green lacewing *(Chrysopa carnea* Steph.). *Ann. ent. Fenn.* 39: 143-144.

VAN DER PLANK, J.E. (1944). Production of seed potatoes in a hot, dry climate. *Nature* 153: 589-590.

VAN DER WOLF, J.P.M. (1964). Virus transmission and vector control in seed potatoes. *Pflanzenschutz-nachrichten* 17: 113-184.

VAN EMDEN, H.F. (1966). The effectiveness of aphidophagous insects in reducing aphid populations. *In* Ecology of Aphidophagous Insects. Ed. I.Hodek, Prague. Academia. pp. 227-235.

VAN EMDEN, H.F., EASTOP, V.F., HUGHES, R.D. and WAY, M.J. (1969). The ecology of *Myzus persicae*. *A. Rev. Ent.* 14: 197-270.

VORONINA, E.G. (1971). Entomophthorosis epizootics of the pea aphid *Acrythosiphon pisum* Harris (Homoptera : Aphidoidea). *Ent. Rev. (Translation Entomol. obozr. publ. for ent. Soc. Am.)* 4: 444-453.

WALKER, E. (1860). Characters of undescribed Neuroptera in the collection of W.W.Sawnders, Esq. *Roy. ent. Soc. Trans., Lond.* 5: 186.

WALTERS, P.J. and DOMINIAK, B. (1978). Field studies of lucerne aphid populations and their interactions with natural enemies in Hunter River lucerne. *Proc. Lucerne aphid Workshop, Tamworth, N.S.W. 1978.* pp. 47-49.

WARD, K.M. (1934). The green peach aphid (*Myzus persicae* Sulzer) in relation to the peach in Victoria and the measures investigated for its control. *J. Dept. Agr. Vic.* 32: 97-105, 134-145 and 258-268.

WATERS, W.E. (1959). A quantitative measure of aggregation in insects. *J. econ. Entomol.* 52: 1180-1184.

WAY, M.J. (1977). Integrated control - practical realities. *Outlook on agric.* 9: 127-135.

WEBB, R.E., LARSON, R.H. and WALKER, J.C. (1952). Relationship of potato leaf roll virus strains. *Wis. Agr. Exp. Sta. Bull.* 178: 1-40.

WHALON, M.E. and SMILOWITZ, Z. (1979). GPA-CAST, a computer forcasting system for predicting populations and implementing control of the green peach aphid on potatoes. *Environ. Entomol.* 8: 908-913.

WHITEHEAD, T., CURRIE, J.F. and DAVIES, W.M. (1932). Virus diseases in relation to commercial seed production - with a study of the aphid population of selected centers. *Ann. appl. Biol.* 19: 529-549.

WILLIAMS, F.X. (1927). The brown Australian lacewing *(Micromus vinaceus)*. *Hawaiian Planter's Rec.* 31: 246-249.

WILLIAMSON, M. (1972). The analysis of biological populations. Edward Arnold, London.

WILSON, F.W. (1960). A review of the biological control of insects and weeds in Australia and Australian New Guinea. *Common. Inst. Bio. Cont. Tech. Commun.* No. 1.

WISE, K.A.J. (1963). A list of the Neuroptera of New Zealand. *Pacific Insects.* 5: 53-58.

WISE, K.A.J. (1973). New records in the New Zealand Neuroptera : Hemerobiidae. *N.Z. Ent.* 5: 181-185.

WITHYCOMBE, C.L. (1922). The life history of *Hemerobius stigma* *Entomologist* 55: 97-99.

WITHYCOMBE, C.L. (1923). A new British Hemerobiid (Order Neuroptera). *Entomologist* 56: 202-204.

WOODFORD, J.A.T. (1973a). The climate within a large aphid-proof field cage. *Ent. exp. & appl.* 16: 313-321.

WOODFORD, J.A.T. (1973b). The flight activity and movement of *Myzus persicae* and *Brevicoryne brassicae* 10: 803. *J. appl. Ecol.*

WOODFORD, J.A.T., SHAW, M.N., McKINLEY, R.G. and FOSTER, G.N. (1977). The potato aphid spray warning scheme in Scotland, 1975-1977. *Proc. 1977 Brit. Crop Protect. Conf. - Pests and Diseases.* pp. 247-254.

WRATTEN, S.D. (1973). The effectiveness of the coccinellid, *Adalia bipunctata* (L.) as a predator of the lime aphid, *Eucallipterus tiliae* L. *J. Anim. Ecol.* 42: 785-802.

YATES, F. and FINNEY, D.J. (1942). Statistical problems in field sampling for wireworms. *Ann. appl. Biol.* 29: 156-157.

ZIMMERMAN, E.C. (1957). Insects of Hawaii. 6. University Hawaii Press, Honolulu. 209 pp.