# Biological Control of Damson-hop Aphid on Plum

**Project SF 30**

**HDC Final Report (March 1997)**

HORTICULTURE RESEARCH INTERNATIONAL

EAST MALLING

# Biological Control of Damson-hop Aphid on Plum

**Project SF 30**

**HDC Final Report (March 1997)**

**Previous reports:** First year report (April 1995)
Second year report (January 1996)

**Project Leader:** Dr C A M Campbell
Horticulture Research International East Malling
East Malling
West Malling
Kent
ME19 6BJ

**Key worker:** Mr Chris Hartfield - principal researcher and report author

**Project location:** Kent and Herefordshire

**Project coordinator:** Mr William Jackson

**Date project commenced:** November 1993
**Date of completion:** November 1996

Keywords: **Plum, biological control, damson-hop aphid, leaf-curling plum aphid, mealy plum aphid, natural enemies, Integrated Pest Management, pirimicarb.**

# Contents

HORTICULTURE RESEARCH INTERNATIONAL

EAST MALLING

# Biological Control of Damson-hop Aphid on Plum

**Project SF 30**

**HDC Final Report (March 1997)**

**Previous reports:** First year report (April 1995)
Second year report (January 1996)

**Project Leader:** Dr C A M Campbell
Horticulture Research International East Malling
East Malling
West Malling
Kent
ME19 6BJ

**Key worker:** Mr Chris Hartfield - principal researcher and report author

**Project location:** Kent and Herefordshire

**Project coordinator:** Mr William Jackson

**Date project commenced:** November 1993
**Date of completion:** November 1996

**Keywords:** **Plum, biological control, damson-hop aphid, leaf-curling plum aphid, mealy plum aphid, natural enemies, Integrated Pest Management, pirimicarb.**

# 1.0 PRACTICAL SECTION FOR GROWERS

## 1.1 BACKGROUND AND OBJECTIVE

The damson-hop aphid is the most important pest in UK plum orchards. Two other potentially damaging aphid species occur, the leaf-curling plum aphid and the mealy plum aphid. However, both can be controlled adequately with available non-selective spring-applied insecticide sprays. The damson-hop aphid is a pest of hop throughout the summer and of plum during the spring; consequently, it is subjected to multiple applications of a similar range of insecticides throughout the year. As a result it has successively developed resistance to all the insecticide groups currently registered for use on plum. The only effective chemical control for the damson-hop aphid available to plum growers is tar oil. Although tar oil can provide good control of damson-hop aphid (Umpleby, 1996), it is non-selective and highly toxic to all natural enemies of the aphid overwintering within plum orchards. In addition, tar oil fails to give adequate control of leaf-curling plum aphid (Umpleby, 1996). The absence of an effective insecticide to control damson-hop aphid in spring makes it the key concern for plum growers.

In fruit-tree orchards elsewhere in Europe and in the USA, local natural enemy populations are the major form of biological control available for pest management. The additional availability of synthetic sex pheromone of the damson-hop aphid has provided new opportunities for manipulating pest aphid behaviour which are compatible with other forms of biological control.

The objective of this project was to assess the possibility of achieving biological control of damson-hop aphid on plum by exploiting naturally-occurring enemies of the aphid in combination with novel control strategies.

## 1.2 SUMMARY OF RESULTS

Aphid populations on plum were monitored in experimental and commercial orchards over a three year period from 1994-96. The commonly occurring leaf-curling plum aphid was the first species observed in leaf samples during early spring. In late April, populations of leaf-curling plum aphid built-up rapidly and caused severe damage to infested plum trees in unsprayed orchards. Insecticide-resistant damson-hop aphid also occurred commonly in the orchards studied, where

populations built-up slowly from mid-May and peaked in June. In addition to causing direct feeding damage, infestations of damson-hop aphid contaminated developing fruit as a result of sooty mould development on honeydew. The mealy plum aphid occurred in low numbers, and not in every season. Its distribution in orchards was patchy and localised.

In experimental orchards, where broad-spectrum pesticides were not used, exclusion cage studies demonstrated the large impact of natural enemies, particularly crawling insects and spiders, on damson-hop aphid populations. At the same time, the range and relative abundance of aphid natural enemies were monitored in experimental and commercial plum orchards using coloured sticky traps and beat sampling techniques. More than 50 species of aphid predators, from over 10 arthropod families, were identified. The commonest aphid-specific predators included anthocorid bugs, ladybird beetles, mirid bugs, hoverflies, green lacewings and brown lacewings. The majority of aphid-specific predators only became abundant after populations of leaf-curling plum aphid had peaked. However, aphid species that occurred later in the season, such as the damson-hop aphid, coincided with these peak populations of predators and were subjected to heavy predation. The lack of synchrony between aphid populations and natural enemies early in the season required the use of an insecticide to control leaf-curling plum aphid. The insecticide pirimicarb (Aphox) was chosen for this task because it is a selective aphicide which is safe to honeybees and to most other beneficial insects, such as aphid predators and parasites. This study has demonstrated that leaf-curling plum aphid can be controlled effectively by a single, accurately timed application of 'predator-friendly' pirimicarb. The rationalised use of this selective aphicide had no detectable effects on the most abundant natural enemies present in the orchard. These intact predator populations can then prevent the build-up of insecticide-resistant damson-hop aphid populations later in the season. In addition, pirimicarb gave good control of the mealy plum aphid when it occurred in experimental plum orchards.

Predator release studies established that the numbers of common green lacewing larvae required to reduce damson-hop aphid populations significantly were too high for mass release of this predator to be considered as a control option in commercial orchards.

Non-specific (or polyphagous) aphid predators, such as earwigs and spiders, were also abundant in the orchards. These predators were potentially important because they were often relatively abundant in the orchard during periods of the year when the specific aphid predators were scarce. However, because earwigs and spiders often eat other aphid predators, their usefulness within the natural enemy complex is questionable. Plum aphids were also host to a range of parasitoid wasps and fungal pathogens, but these appeared to be of limited importance in the regulation of aphid numbers on plum. The peak of fungal infection usually occurred well after populations of leaf-curling plum aphid and damson-hop aphid had peaked, while the effectiveness of the parasitoid wasps as control agents was hampered as they themselves were attacked by a range of abundant parasitic wasps (hyper-parasitoids).

A novel biocontrol strategy was developed incorporating damson-hop aphid sex pheromone into 'live' traps designed to inoculate attracted male aphids with a fungal pathogen, which would then be transmitted by the inoculated males to females during mating. Field experiments demonstrated the attractiveness of the sex pheromone to male damson-hop aphids within plum orchards, and transmission of the fungal pathogen between individual aphids under autumnal field conditions.

Comprehensive monitoring studies demonstrated the potential of the presence-absence method of sampling plum aphids, particularly damson-hop aphid. This method, already developed for integrated pest management (IPM) programs in walnut, hop and wheat crops is the simplest and least time-consuming method for pest population assessment by growers.

These studies have demonstrated the wide range of predators and other natural enemies available as biological control agents against damson-hop aphid. In orchards, natural enemy populations like this are often the major form of biological control available for IPM. The results of this research show that natural enemies have the potential to regulate damson-hop aphid populations in plum orchards. In order for the full potential of these natural enemies to be exploited, orchard management practices, primarily concerning the prophylactic use of non-selective insecticides, will need to be modified. The availability of the selective aphicide pirimicarb to plum growers, achieved by the HDC as a direct result of this research, has improved this situation and has provided opportunities for exploiting biological control strategies within plum orchards.

## 1.3 ACTION POINTS FOR GROWERS

- Tar oil winter washes destroy natural enemies of aphids overwintering in plum orchards, give little control of leaf-curling plum aphid, and do not guarantee control of damson-hop aphid. Tar oil should only be used when justified.
- In order to conserve natural enemy populations, non-selective insecticide sprays should not be used to control leaf-curling plum aphid and mealy plum aphid in spring.
- The selective 'predator-friendly' aphicide pirimicarb gives excellent control of leaf-curling plum aphid and mealy plum aphid, and leaves natural enemy populations intact. For optimum control, pirimicarb should be applied before white bud under calm conditions.
- If conserved, aphid natural enemies are capable of preventing damson-hop aphid populations from building up to economically unacceptable levels.

## 1.4 PRACTICAL BENEFITS

This study has clearly identified the value of pirimicarb within an integrated approach to plum aphid control. As a result the HDC have obtained off-label approval for growers to use pirimicarb (Aphox) for the control of leaf-curling plum aphid and mealy plum aphid on plum. The study has also identified the need to conserve aphid natural enemies within plum orchards, primarily by limiting the use of non-selective insecticides, as these natural enemies are capable of controlling insecticide-resistant populations of damson-hop aphid. Furthermore, the study has demonstrated the potential of presence-absence sampling as a reliable and efficient method for damson-hop aphid population assessment by growers. If new pesticides are approved for damson-hop aphid control on plum, aphid monitoring within orchards will be essential to any resistance management strategy in order to ensure that sprays are applied only when necessary.

The work has provided the HDC with the information needed to support the development of an IPM programme for plum aphid control.

# 2.0 SCIENCE SECTION

## 2.1 INTRODUCTION

Aphids are the most important pests of plum (*Prunus domestica*) in the UK where three potentially damaging species overwinter on a range of wild and cultivated *Prunus* species: the leaf-curling plum aphid, *Brachycaudus helichrysi*; the mealy plum aphid, *Hyalopterus pruni*; and the damson-hop aphid, *Phorodon humuli*. The three species debilitate plum trees through the removal of assimilates, decrease photosynthetic ability and contaminate fruit as a result of sooty mould (*Cladosporium* spp.) development on honeydew. The three aphid species are known vectors of plum pox virus (PPV, commonly known as 'Sharka'), a serious viral disease of plums, damsons, peaches and ornamental *Prunus*. However, leaf-curling plum aphid is considered the most important vector of PPV in the UK (Gratwick, 1992).

Of the three aphid pests, the commonly-occurring leaf-curling plum aphid causes the most severe damage (Alford, 1984), its phytotoxic saliva inducing permanent distortion of the leaves and new growth and eventual defoliation of those areas colonised by the aphid. The leaf-curling plum aphid is the first of the three species to hatch from overwintering eggs and subsequent population build-up in the spring can be rapid, often causing significant damage to plum trees before detection and implementation of chemical control measures. The mealy plum aphid only occasionally causes serious problems for growers as its distribution within plum orchards tends to be patchy and localised. The damson-hop aphid is unique among pest aphid species in the UK in having crop plants as primary and secondary hosts; thus it is subjected to a similar range of insecticides throughout the spring on plum, and the summer on hop. This has led to an intense selection pressure, and subsequent resistance to all insecticide groups currently registered for use on plum. The absence of an effective insecticide for damson-hop aphid makes it the greatest concern for growers.

The concern over damson-hop aphid resistance to spring-applied insecticides has prompted a move back towards the traditional use of tar oils as dormant sprays acting against the overwintering eggs of plum aphids. Tar oils are accredited with toxicity against insecticide-resistant damson-hop aphid (Gratwick, 1992). A recent survey of plum orchards in the three

major plum growing areas of the UK (East Anglia, Kent and the West Midlands) concluded that tar oil was the only effective chemical control for damson-hop aphid available to plum growers (Umpleby, 1996). However, the same survey showed that, in Kent orchards, even high volume tar oil applications failed to give complete control of damson-hop aphid. Furthermore, tar oils are ineffective in controlling populations of leaf-curling plum aphid (Umpelby, 1996). Conversely, tar oil winter washes are highly toxic to all natural enemies overwintering within plum orchards.

In spring, adequate control of leaf-curling plum aphid and mealy plum aphid can be achieved through the use of currently-available non-selective insecticides. However, the prophylactic use of these insecticides can destroy natural enemies, allowing populations of insecticide-resistant damson-hop aphid to increase uninhibited.

To relieve the selection pressure for resistance, and minimise detrimental side-effects of pesticides on natural enemy populations, an integrated approach must be developed for aphid management in UK plum orchards. Such an approach should employ a range of alternative biological control strategies. The manipulation of pest and natural enemy complexes offers a possible solution.

To manage a pest species properly, its population dynamics must be understood, and this can only be achieved through comprehensive monitoring studies in the field. Such studies reveal when aphids are abundant and also give clues as to how they may be managed. Concurrent monitoring of natural enemy populations can reveal which control agents are important in the system, when they act and when their manipulation may or may not be beneficial in controlling the aphid pest species. In addition, the frequent assessment of a number of sampling techniques will compare their relative efficiency and convenience, evaluating their usefulness as potential field monitoring tools for future monitoring programmes within plum orchards.

With plum aphids there is the opportunity to investigate two complementary biological control strategies. The first involves manipulation of the aphids' natural enemies. Indigenous natural enemies are often the major form of biological control available for IPM in orchards (Luck *et al.*, 1988). In unsprayed apple orchards, aphids often have no economic importance because they are limited by predators (Niemczyk, 1966). In experimental orchards where non-selective insecticides

are not used, many foliage-feeding pests can be controlled by naturally-occurring enemies (Solomon, 1992; Lawson *et al.*, 1994). However, in order for the full potential of natural enemies to be exploited, orchard management practices, primarily concerning the use of non-selective insecticides, must be modified to encourage biological control (e.g. Easterbrook *et al.*, 1985; Solomon & Fitzgerald, 1990).

This study investigated the effectiveness of aphid natural enemies already present in plum orchards, and the feasibility of augmenting these enemies through the field-release of a commercially-available aphid predator, the larvae of the common green lacewing (*Chrysoperla carnea*). The second biological control strategy investigated involved the direct manipulation of damson-hop aphid behaviour through the use of its sex pheromone. The sex pheromone of the damson-hop aphid was identified following a collaborative study involving HRI East Malling and IACR-Rothamsted (Campbell *et al.*, 1990). Its synthetic production in the laboratory has enabled the integration of the pheromone into field experiments. Studies assessed whether the sex pheromone could be used to attract damson-hop aphid autumn migrants and males into traps designed specifically as delivery systems for a transmissible entomopathogenic fungus, with the aim of initiating a fungal epidemic among the sexual aphid generations on plum during autumn.

## 2.2 MATERIALS AND METHODS

### 2.2.1 Orchard sites

Plum aphids and their natural enemies were monitored between mid-November 1993 and September 1996 at four orchard sites;

(i) Two unsprayed non-commercial plum orchards (cvs. Edwards and Marjorie's Seedling) at Fairbourne Manor Farm, Harrietsham, Kent (hereafter referred to as E-H and MS-H respectively).

(ii) The main experimental orchard: Wiseman at HRI-East Malling (hereafter referred to as WM-EM). It contained 14 rows of 21 plum trees, mainly cv. Victoria, interspersed with 54 pollinator trees of cv. Czar. Both cvs. were grafted on Pixy rootstocks. The trees were planted in December 1980, and averaged *c.* 4 m in height with a head width of *c.* 3 m. The orchard was surrounded by a 3 m wide grass verge, bounded on three sides by cereal fields, and on the southerly side by an alder windbreak (*Alnus glutinosa*). The prevailing wind was from the south-west. No chemical pesticide treatments had been applied since July 1992, and no non-selective insecticides or tar oil winter washes were applied during the course of these experiments.

(iii) Ditton Rough orchard at HRI-East Malling (hereafter referred to as DR-EM). It was a mixed cultivar commercial orchard, but studies were limited to the three rows (40 trees per row) of cv. Victoria. The orchard was surrounded by a 3 m wide grass verge, bounded on three sides by cereal fields, and on the easterly side by a 1.8 ha plantation of dwarf hops, planted in spring 1996. DR-EM was under standard orchard management. In 1996 a single tar oil treatment and three applications of chlorpyrifos, applied at standard field rates, were used for aphid control.

(iv) A 4.5 ha commercial plum orchard (cv. Victoria) at Man of Ross Ltd. (Wilson Farm) Glewstone, Herefordshire (hereafter referred to as MR-HF). It was surrounded by a 3m wide grass verge, bounded on one side by more plum orchards, on the north-westerly side by a birch windbreak, and on the south-westerly side by a wide grass and shrub field margin. The prevailing wind at this locality was from the west. The orchard was under integrated crop management.

### 2.2.2 Experimental applications of insecticide

In 1995 and 1996, WM-EM was divided up into 12 plots, each containing 16 trees, with a row of guard trees between each plot. On 6 randomly-selected plots pirimicarb (Aphox 50% w/w, Zeneca) was applied at 0.14 g a.i.$l^{-1}$ (equivalent to 280 g a.i.$ha^{-1}$, or 560 g product in 200 litres water per hectare) on 31 March 1995, and on 25 April 1996, using a hand-lance attached to a Berthoud 600 sprayer. In both years the remaining 6 plots were left unsprayed as untreated controls. Pirimicarb was used as part of an experimental management strategy for plum aphid control (see section 2.2.7). The results of this study, with respect to the direct effects of pirimicarb application on plum aphid population levels, are presented and discussed in section 2.3.5. Natural enemy populations were monitored throughout WM-EM, within untreated and pirimicarb-sprayed plots.

### 2.2.3 Statistical treatment of data

Counts of insects were transformed [$y = \text{Log}_{10}(x + 1)$, where x = untransformed counts] to stabilize variances, prior to analysis by ANOVA. The Least Significant Difference (LSD) test was used for separation of means at $p<0.05$, when the F statistic for the treatment effect was significant at $p<0.05$.

### 2.2.4 Field monitoring of plum aphids and their potential natural enemies

#### 2.2.4.1 Monitoring of plum aphids

Surveys to provide data on the development of plum aphid populations were conducted in WM-EM from mid-November 1993 to September 1996, in the two unsprayed non-commercial orchards at Fairbourne Manor Farm, E-H and MS-H, during winter 1993-94 and in DR-EM during 1996. Overwintering aphid eggs were monitored by taking separate samples of 100 shoots at weekly intervals during the plum bud developmental stages from dormancy to white bud. When sufficient leaf material was available, weekly samples of 100 leaves were used to monitor spring and autumn plum aphid populations.

#### 2.2.4.2 Monitoring of aphid predators

Predators were monitored at weekly intervals using beat-sampling and sticky traps within the plum orchard and adjacent windbreaks. Three colours of sticky trap (blue, white and yellow) and

clear traps (1996 only) were used. This sampling programme was implemented systematically from early-April to early-November. Beat sampling was continued throughout the winter at less frequent intervals. To complement these studies, predator refugia were used to monitor beneficial species which overwintered within the plum orchard. These refugia were made from 2 l plastic drinks bottles, with the bottom removed and packed with corrugated cardboard. The eggs, larvae and adults of predators were also recorded when found in leaf and shoot samples. Table 1 summarises when and where the various techniques were used to monitor plum aphid predators.

TABLE 1. SUMMARY OF THE TECHNIQUES USED TO MONITOR PLUM APHID PREDATORS.

| Season/Location | | Shoot or leaf samples | Beat sampling | Sticky traps | Refugia[1] |
|---|---|---|---|---|---|
| **November 1993-94** | | | | | |
| | E-H | ✓ | | | |
| | MS-H | ✓ | | | |
| | WM-EM | ✓ | ✓ | ✓ | ✓ |
| **1995** | WM-EM | ✓ | ✓ | ✓ | ✓ |
| | WM-EM windbreak | | ✓ | | |
| **1996** | WM-EM | ✓ | ✓ | ✓ | |
| | WM-EM windbreak | | ✓ | | |
| | DR-EM | ✓ | ✓ | | |
| | MR-H | | | ✓ | |
| | MR-H windbreak | | | ✓ | |

[1] Refugia placed in the orchard in autumn and collected early in the following spring.

2.2.4.3 Monitoring of plum aphid parasitoids

In 1994 muslin bands (*c.* 25 x 60 cm) were tied around the base of numerous aphid-infested branches within WM-EM in order to provide potential refuge sites for parasitized aphids. The

species and approximate size of the aphid colonies were noted. In 1995 this study was repeated but, in addition to the muslin bands, a plastic disc coated with Oecotak (a sticky 'glue' for trapping insects) was placed around the branch below the muslin band to trap all aphids which reached it. The muslin bands and Oecotak discs were replaced weekly, and their contents recorded.

2.2.4.4 Monitoring levels of fungal pathogens infecting plum aphid populations

Dead mycosed plum aphids were counted in weekly leaf samples; the aphids were identified to species where possible but the disease organisms were not.

### 2.2.5 Assessing the impact of natural enemies on damson-hop aphid populations in the laboratory and field

2.2.5.1 Exclusion cage experiments

The impact of predators on spring populations of damson-hop aphid was determined using exclusion cages. Exclusion experiments were conducted in WM-EM during each of the three years of the study. The cages were white polyester net bags (60 cm x 100 cm, with mesh holes *c.* 0.1 $mm^2$) slipped over a branch and supported internally by two wire hoops (diameter *c.* 50 cm) which had been cross-braced onto the branch *c.* 50 cm apart. The experimental design consisted of six blocks (where a single tree constituted a "block"), each containing the following six treatments:

(1) uncaged, predators allowed access

(2) closed-caged, net bag tied close and predators removed

(3) open-caged, net bag pegged open, predators allowed access

(4) bird exclusion cage, 1 $m^2$ sections of Netlon polythene mesh (mesh size 15 mm) folded over the treatment branch and sealed at both ends with string

(5) bird and crawling predator exclusion, as for (4), but with the addition of two bands of Oecotak placed around the base of the treatment branch

(6) environmental control, where attempts were made to mimic the properties of the net bags with respect to light and wind interception; all predators allowed access.

All treatment branches were inoculated with five damson-hop aphid nymphs prior to the commencement of the experiment. In 1994 weekly samples of five leaves were removed from

within each treatment to monitor aphid numbers. In 1995 and 1996 visual counts of aphids on 10 leaves per treatment were made *in situ* on a weekly basis. In both these years an 'open-removed' treatment, which was essentially the same as (1) except that all predators were systematically removed from within the treatment branch at regular intervals, was also used. In 1994 the rapid early build-up of leaf-curling plum aphid caused damage and defoliation within many exclusion experiment treatments. Consequently, in 1995 and 1996, the experimental trees were located within the 6 pirimicarb-sprayed plots in an attempt to reduce the disruptive knock-on effects of leaf-curling plum aphid infestation.

In winter 1995, exclusion cage studies were also used to investigate the factors affecting the survival of overwintering eggs of the damson-hop aphid. In the autumn, blackthorn (*Prunus spinosa*) trees (*c.* 0.5 m high) infested with damson-hop aphid eggs were kept in the field and exposed to four different treatments:

(1) Uncaged, exposed to rain, birds and arthropod predators

(2) Rain 'exclusion', birds and arthropod predators allowed access, but sheltered from direct rain impact by a 'roof' of the same material used for treatment (4) below

(3) Bird exclusion, a mesh enclosure constructed from 1 $m^2$ sections of green Netlon polythene mesh to exclude birds, but allow access to rain and arthropod predators

(4) Total exclusion, a nylon mesh cage excluding birds and arthropod predators, and protecting trees from direct impact by rain. In addition, two bands of Oecotak were spread around the base of each tree in the cage to trap any crawling predators that may have gained access to the cage.

Before the 6 replicates of each treatment were set up within the plum orchard, the eggs on each tree were counted and classified as being either mature (black and shiny), immature/infertile (green) or collapsed (due to predation, or possibly intrinsic reasons). Each treatment had over 800 damson-hop aphid eggs. In late February 1996, the eggs were counted and classified again to determine the levels and causes of overwintering egg mortality.

2.2.5.2 Predator voracity studies

When key predators had been identified, as a result of monitoring studies, controlled environment studies were used to assess their voracity. The feeding studies were conducted initially on the

predacious larvae of various ladybird beetle species. Field-collected adults were fed on pea aphids maintained within Petri-dishes. When eggs had been laid, the adults were removed and the eggs incubated. Feeding studies began with newly-hatched first instar ladybird beetle larvae. The larvae were placed in clean 0.2 ml plastic micro-tubes (caps pierced to allow air transfer) with an excess of damson-hop aphids (all stages). The tubes were maintained under controlled conditions: 20°C, 16:8 L:D light regime. The weights of the predatory larva and aphid prey consumed were measured every 24 h until the larva pupated.

### 2.2.6 Manipulation of aphid predators to decrease numbers of damson-hop aphid under semi-field conditions

The effects of releasing predatory larvae of the common green lacewing (*Chrysoperla carnea*, a species commercially available) on damson-hop aphid populations were investigated in three experiments. In experiment I, repeated in 1994 and 1995, lacewing larvae were released onto single plum branches, which had been inoculated previously with damson-hop aphid, and enclosed in inclusion cages. In experiment II, conducted in 1994, lacewing larvae were released onto uncaged whole trees. In experiment III, conducted in 1995, lacewing larvae were released onto uncaged whole blackthorn trees (planted in pots) which had been inoculated previously with damson-hop aphid. In the latter experiment the predatory effectiveness of larval lacewings was compared with that of 10-spot ladybird beetle (*Adalia 10-punctata*) larvae.

EXPERIMENT I

Total exclusion cages (see section 2.2.4.1) were used to enclose each treatment branch. All treatments were inoculated with damson-hop aphid nymphs two weeks prior to release of the predators (as in section 2.2.4.1). The experiment used a randomised complete block design, with 6 blocks (where a single tree constitutes a "block"), each containing the four treatments:

| **1994** | **1995** |
|---|---|
| (1) Nil larvae (control) | (1) Nil larvae (control) |
| (2) 2 lacewing larvae | (2) 8 lacewing larvae |
| (3) 4 lacewing larvae | (3) 16 lacewing larvae |
| (4) 8 lacewing larvae | (4) 32 lacewing larvae |

As with the exclusion cage study, in 1995 all experimental trees were selected from within the

pirimicarb-sprayed plots in order to remove the disruptive effects of leaf-curling plum aphid. At weekly intervals, aphid counts on 5 leaves (1994) or 10 leaves (1995), selected without bias from within each treatment, were used to monitor numbers of damson-hop aphid. Adult lacewings were collected as they emerged from the cages.

EXPERIMENT II

A randomised complete block design was used, with two blocks, each of four trees. The following four treatments were allocated at random to four trees in each block:

(1) Nil larvae (control)
(2) 10 lacewing larvae
(3) 20 lacewing larvae
(4) 40 lacewing larvae

Treated trees were well separated by untreated guard trees. The lacewing larvae were released at the main junction between the branches and trunk, dispersing from there to the rest of the tree. The trees were not inoculated artificially with aphids. At weekly intervals a sample of five leaves, selected without bias, was removed from each tree at three different levels: below 1.5 m, between 1.5 m and 2.25 m, and above 2.25 m. All aphids in samples were identified.

EXPERIMENT III

Common green lacewing larvae and 10-spot ladybird beetle larvae were released onto separate potted blackthorn trees (*c.* 0.5m high). All trees were inoculated with five damson-hop aphid nymphs, two weeks before the predators were released in order to establish that aphid populations were present. The five treatments, each applied to a separate tree, were as follows:

(1) Nil larvae (control)
(2) 3 lacewing larvae
(3) 3 ladybird larvae
(4) 6 lacewing larvae
(5) 6 ladybird larvae

Four replicates of each treatment were allocated at random among 20 experimental trees. At weekly intervals visual counts of damson-hop aphid on 10 leaves, chosen without bias from within each replicate, were made *in situ*.

### 2.2.7 Novel approaches to damson-hop aphid control in plum orchards

#### 2.2.7.1 *Verticillium lecanii* as a microbial insecticide of damson-hop aphid in the laboratory and under orchard conditions

*Verticillium lecanii* is an effective aphid pathogen, and is marketed as a commercial microbial aphicide (Vertalec, Koppert Ltd.) for use within controlled environments such as glasshouses. In this study the specificity of *V. lecanii* for damson-hop aphid, and the spread of infection between sexual morphs, was investigated under controlled conditions in the laboratory and within field cages during autumn. Aphids were "walked" on sporulating plates of *V. lecanii* for 5 minutes to inoculate them with the fungus. Control aphids were walked on blank agar plates. The experiment was repeated in 1994 and 1995.

LABORATORY STUDY

The pathogenicity of *V. lecanii* was assayed in the laboratory using "walked" and "non-walked" damson-hop aphid migrants. Gynoparae were caged individually onto *Prunus* leaves, maintained within small perspex boxes. Larviposition and disease development were monitored.

FIELD TRIAL

The experimental design consisted of four (in 1994) or 6 blocks (in 1995) of a complete factorial design with two treatments (gynoparae and males) at two levels (inoculated and control). Thus, any one block contained the following four treatment combinations:

(1) 10 control gynoparae + 10 control males
(2) 10 control gynoparae + 10 inoculated males
(3) 10 inoculated gynoparae + 10 control males
(4) 10 inoculated gynoparae + 10 inoculated males

Each of the four treatment combinations was allocated randomly to a Pixy rootstock (*c.* 0.8 m high). The trees were cleared of all aphids and potential predators and then caged with a net exclusion bag. In 1994 and 1995 the gynoparae were introduced into the cages on 28 September and 10 November respectively and the males on 1 November and 1 December respectively. The release of the males was determined by the maturity of ovipara and their availability.

2.2.7.2 Influence of synthetic semiochemicals on insects within plum orchards

The potential of a novel strategy for damson-hop aphid control, using 'live' traps baited with sex pheromone and incorporating a fungal pathogen, was investigated. Male damson-hop aphids are attracted into the trap by the pheromone, where they pick up spores of an entomopathogenic fungus. Males then leave the trap, after becoming habituated to the pheromone, and disseminate the fungus among the sexual female aphids in the orchard. The following studies were carried out to assess the aphid-catching efficiency of two 'live' trap designs. The first, the louvred-trap (Figure 1), was designed to attract aphids using a combination of visual and olfactory cues to attract aphids into the internal arena of the 'live' trap where an inoculum of fungal pathogen was placed. The second trap type was the 'Waspy' (Figure 2), a commercially-available yellow trap designed to catch wasps and modified into a 'live' trap for aphids. The aphid-catching efficiency of both trap types was tested against that of standard yellow water traps. Trials were conducted in the autumns of 1994 and 1995.

1994 TRIAL

A quasi-complete 8 x 8 randomised block (Latin square) design, with periodic re-randomisation within the block, was used to compare the attractiveness of sex-pheromone-releasing and control, yellow louvred and yellow water traps within plum orchards. Pheromone-releasing traps incorporated vials containing damson-hop aphid sex pheromone. Three pheromone-releasing and three control louvred traps, plus one pheromone-releasing and one control water trap were used. A thin coat of Oecotak was spread on the Petri-dish housing the vial containing the pheromone, or control vial, within the louvred trap to capture any attracted aphids. The positions of the traps were re-randomised daily, irrespective of catch numbers. All aphids caught were identified to species and sexed. The study was carried out from 27 October to 1 December.

FIGURE 1. LOUVRED 'LIVE' TRAP, RELEASING APHID SEX PHEROMONE: (a) TRAP BASE CONTAINING DAMP FELT MAT, (b) CROSS-BRACE SUPPORTING (c) THE YELLOW LOUVRES EXTERNALLY, AND INTERNALLY (d) THE PETRI-DISH WHICH CONTAINS EITHER (i) OECOTAK COATING FOR MONITORING TRAP EFFECTIVENESS, OR (ii) FUNGAL INOCULUM. (e) 08-CPV CHROMOCOL CONTAINING PHEROMONE AND (f) BLACK PAINTED TRAP LID.

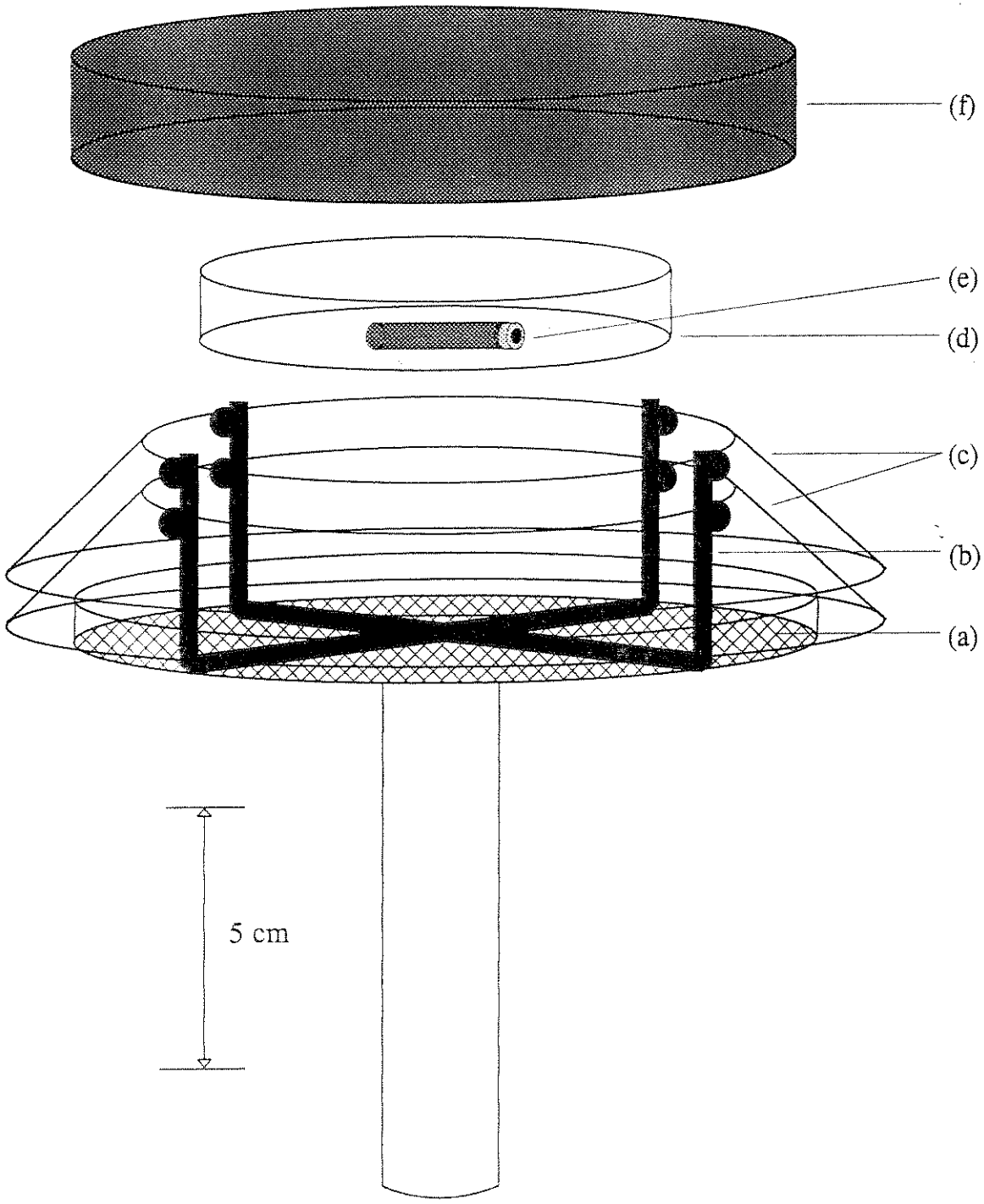
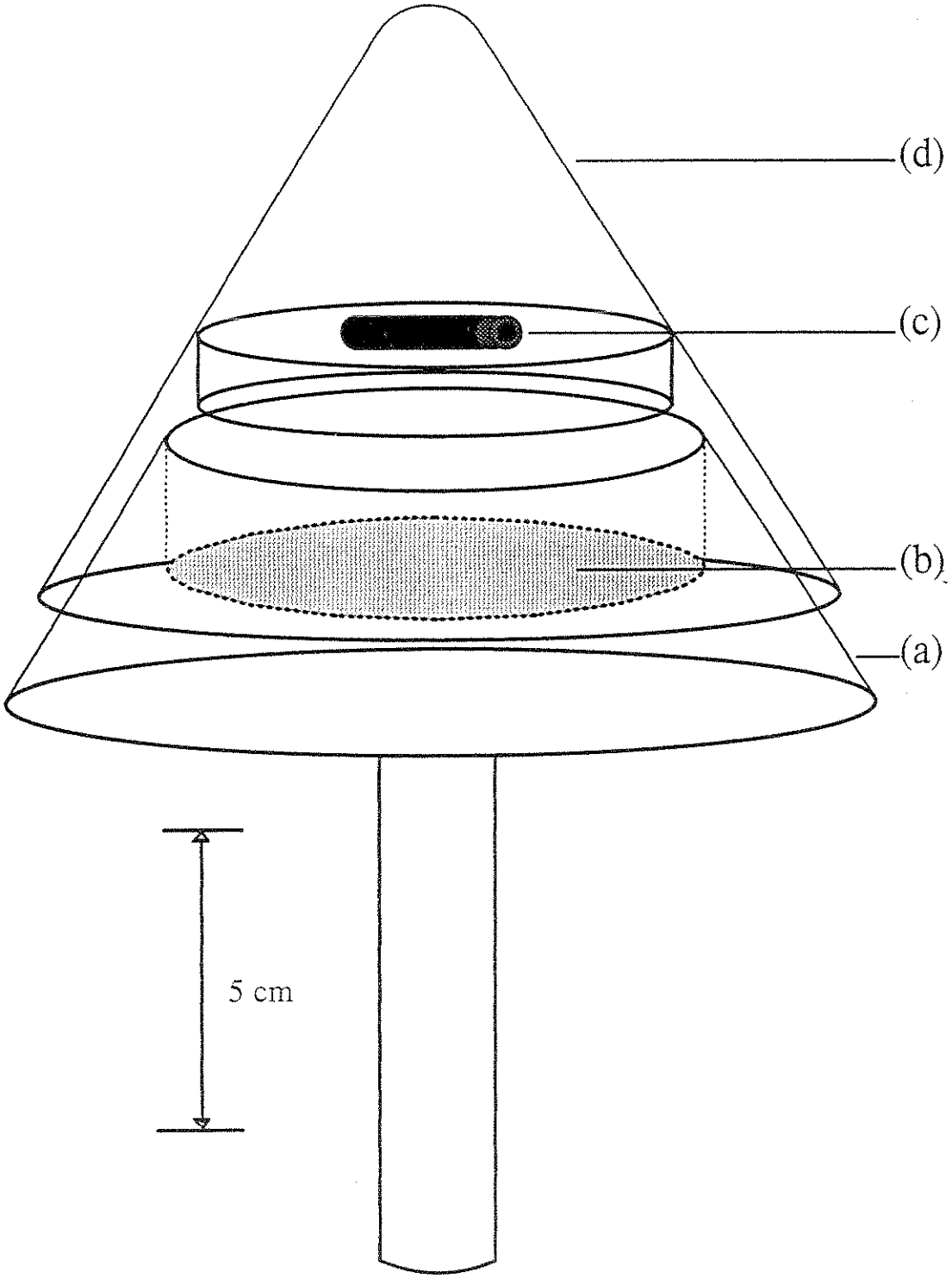


FIGURE 2. 'WASPY' TRAP, RELEASING APHID SEX PHEROMONE: (a) YELLOW TRAP BASE WHICH IS RECESSED, AND CAN HOLD A PETRI-DISH (b) CONTAINING EITHER (i) OECOTAK FOR MONITORING TRAP EFFECTIVENESS, OR (ii) FUNGAL INOCULUM. (c) 08-CPV CHROMOCOL CONTAINING APHID SEX PHEROMONE, ATTACHED TO A PETRI-DISH WEDGED INTO (d) THE FROSTED TOP, WHICH CLIPS INTO THE BASE AND IS RAISED TO CREATE A GAP THROUGH WHICH APHIDS ENTER THE TRAP.



1995 TRIAL

In order to compare the aphid-catching efficiency of yellow louvred traps and yellow 'Waspy' traps, four treatments were applied to each trap-type:

(1) Pheromone only

(2) Pheromone + Oecotak

(3) Pheromone + fungal inoculum

(4) Blank + Oecotak

In addition, one pheromone-releasing and one control yellow water trap were used as test standards. All pheromone-releasing traps incorporated vials containing the damson-hop aphid sex pheromone. Quasi-complete 10 x 10 randomised block (Latin square) designs, with periodic re-randomisation within the blocks, were used. Traps were re-randomised and aphids identified as in 1994. The study was carried out from 29 September to 20 November.

### 2.2.8 Assessing the value of a selective aphicide to an IPM programme for plum aphid control

In 1995 and 1996, aphid population levels and natural enemy abundance in the untreated control plots and the pirimicarb-sprayed plots (see section 2.2.1 for timing, dose and method of spray application) were compared in order to assess the effects of the aphicide, and to determine its value to an IPM approach for plum aphid control. In addition, selected trees within pirimicarb-sprayed plots were utilised in targeted studies (e.g. exclusion cage studies, predator release studies) on damson-hop aphid.

## 2.3 RESULTS AND DISCUSSION

### 2.3.1 Plum aphids and their natural enemies

#### 2.3.1.1 Plum aphid populations

OVERWINTERING POPULATIONS

Examination of shoot samples showed that, although the presence of aphid eggs was detected on the majority of sampling dates during both winters, the numbers of eggs of any one type only once exceeded 20 per 1000 buds (Table 2). In 1993-94, mealy plum aphid eggs were more abundant in orchards E-H and MS-H, than in WM-EM. Conversely, eggs of the damson-hop aphid/leaf-curling plum aphid-type were less abundant in E-H or MS-H than in WM-EM during winter 1993-94. In 1996, mealy plum aphids were found in WM-EM on one sample date only.

Although the majority of plum aphid eggs were deposited in bud axils, their distribution along the shoot showed significant differences between the aphid species ($p<0.001$). Eggs of mealy plum aphid were the most uniformly distributed along the entire length of the shoot, whereas

TABLE 2. SUMMARY OF DATA FOR PRESENCE OF OVERWINTERING EGGS OF MEALY PLUM APHID (**MP**), THE DAMSON-HOP APHID/LEAF-CURLING PLUM APHID-TYPE (**DL**), AND THE COMMON PREDATORY MIRID, *Malacocoris chlorizans* (**MC**), IN SHOOT SAMPLES.

| Orchard | Sampling period | Total no. of samples | Average no. buds/ shoot | No. eggs/1000 buds/sampling date | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | Max. | | | Min. | | |
| | | | | MP | DL | MC | MP | DL | MC |
| **E-H** | 10.12.93-20.04.94 | 10 | 15 | 27 | 3 | 5 | 2 | 0 | 0 |
| **MS-H** | 10.12.93-20.04.94 | 10 | 18 | 9 | 1 | 8 | 1 | 0 | 0 |
| **WM-EM** | 01.12.93-20.04.94 | 10 | 14 | 6 | 7 | 1 | 0 | 0 | 0 |
| **WM-EM** | 18.01.96-02.05.96 | 14 | 9 | 2 | 20 | 7 | 0 | 1 | 0 |

those of the damson-hop aphid/leaf-curling plum aphid tended to be clustered around buds sited towards the proximal end of the shoot. Oviparae are larviposited on the leaf surface, so their initial distribution is probably related to the availability of suitable leaf material. Once oviparae are reproductive, they need only move a short distance to the nearest suitable bud to lay eggs. The majority of mealy-plum aphid oviposition occurs from mid-August to September, much earlier than other plum aphids, when leaf material suitable for the development of oviparae is available along the entire length of the shoot. Oviparae of damson-hop aphid and leaf-curling plum aphid lay eggs much later, during October, when the possibility of progressive leaf senescence from the branch tip downwards could explain the restriction of eggs of these species to the proximal buds. In UK plum orchards, the increasingly common occurrence of rust fungus (*Tranzschelia discolor*) (Umpleby, 1996), which can cause premature defoliation, may limit further the availability of suitable leaf material, and in turn influence the distribution of aphid-oviposition sites on shoots.

The distribution of overwintering eggs deposited on shoots by the predatory mirid *Malacocoris chlorizans* is discussed in section 2.3.1.2.

SPRING POPULATIONS

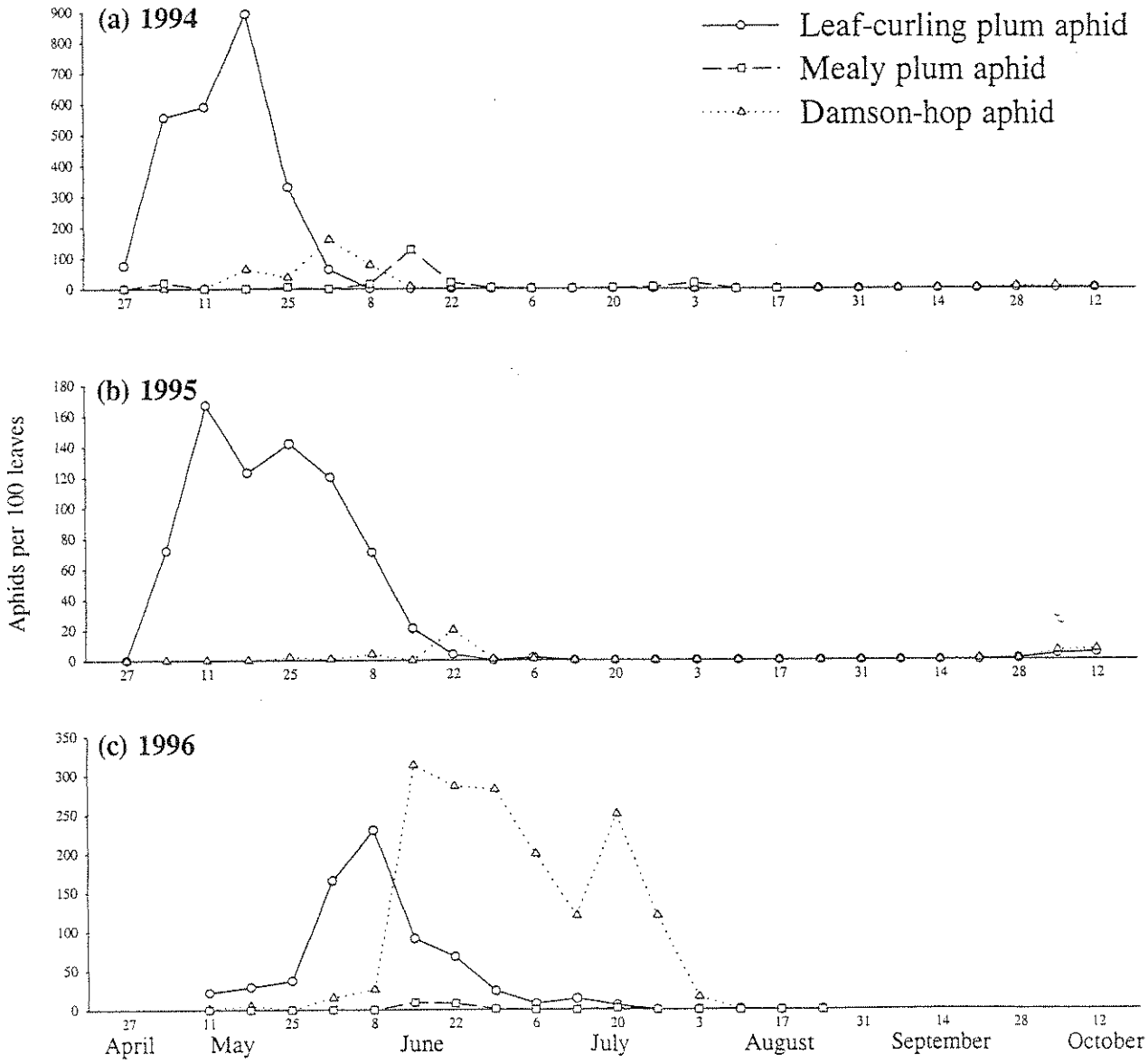
Hatch of damson-hop aphid/leaf-curling plum aphid eggs was observed from mid-January to mid-February (Table 3). Previous studies have shown that the eggs of the leaf-curling plum aphid hatch shortly after oviposition, and hatching is completed by early January. With no direct observations of leaf-curling plum aphid egg-hatch it was necessary to extrapolate back from the earliest observations of fundatrices. In 1995 and 1996, the first leaf-curling plum aphid fundatrices were observed at the beginning of February. In 1996, these observations included an adult fundatrix. In a similar study, the developmental period for leaf-curling plum aphid fundatrices in the field was estimated at 6-8 weeks. Thus we can speculate that the earliest egg hatch of leaf-curling plum aphid during these studies would have occurred in early- to mid-December. In spring, populations of leaf-curling plum aphid built up rapidly, commonly peaking in abundance during mid-May (1994 and 1995) (Figure 3).

TABLE 3. EARLIEST AND LATEST SEASONAL OCCURRENCE OF OVERWINTERED EGGS AND SPRING GENERATIONS OF PLUM APHIDS AT ORCHARD SITES AND IN ROTHAMSTED INSECT SURVEY (RIS) SUCTION TRAPS.

| **Form**/Sampling method | **Occurrence** | **Site** | **Aphid species/Date** | | |
|---|---|---|---|---|---|
| | | | **Leaf-curling plum aphid** | **Damson-hop aphid** | **Mealy plum aphid** |
| **Intact eggs** Shoot samples | Earliest | ED-H | 10/12/93 | | 10/12/93 |
| | | MS-H | 6/ 1/94 | | 10/12/93 |
| | | WM-EM | 25/11/93 | | |
| | | WM-EM | 26/10/94 | | 13/ 1/94 |
| | | WM-EM | 18/ 1/96 | | 15/ 2/96 |
| | Latest | ED-H | 3/ 2/94 | | 28/ 3/94 |
| | | MS-H | 17/ 2/94 | | 17/ 3/94 |
| | | WM-EM | 13/ 1/94 | | 23/ 3/94 |
| | | WM-EM | 14/ 3/96 | | 15/ 2/96 |
| **Hatched eggs**[*1] Shoot samples | Earliest | ED-H | 3/ 2/94 | | |
| | | MS-H | | | 6/ 1/94 |
| | | WM-EM | 13/ 1/94 | | 10/ 2/94 |
| | | WM-EM | 2/ 2/95 | | 2/ 2/94 |
| | | WM-EM | 8/ 2/96 | | |
| **Fundatrices** Shoot samples (Leaf samples) | Earliest | WM-EM | 18/ 4/94 | 24/ 1/94 | |
| | | WM-EM | 2/ 2/95 | | 8/ 4/94 |
| | | WM-EM | 1/ 2 96 | 1/ 2/96 | |
| | Latest | WM-EM | 18/ 4/94 | 24/ 1/94 | |
| | | WM-EM | (11/ 5/96) | 4/ 4/96 | ( 4/ 5/94) |
| **Apterous fundatrigeniae** Leaf samples (Shoot samples) | Earliest | WM-EM | 18/ 4/94 | 27/ 4/94 | 27/ 4/94 |
| | | WM-EM | 27/ 4/95 | 25/ 5/95 | 13/ 6/96 |
| | | WM-EM | (25/ 4/96) | (25/ 4/96) | |
| | Latest | WM-EM | 1/ 6/94 | 15/ 6/94 | 3/ 8/94 |
| | | WM-EM | 6/ 7/95 | 6/ 7/95 | 17/ 7/96 |
| | | WM-EM | 8/ 8/96 | 1/ 8/96 | |
| **Alatoid IV instar fundatrigeniae** Leaf samples | Earliest | WM-EM | 4/ 5/94 | 18/ 5/94 | |
| | | WM-EM | 4/ 5/95 | 1/ 6/95 | 15/ 6/94 |
| | | WM-EM | 30/ 5/96 | 6/ 6/96 | |
| | Latest | WM-EM | 1/ 6/94 | 22/ 6/94 | |
| | | WM-EM | 6/ 7/95 | 29/ 6/95 | 10/ 8/94 |
| | | WM-EM | 18/ 7/96 | 1/ 8/96 | |
| **Alate fundatrigeniae** Leaf samples | Earliest | WM-EM | 11/ 5/94 | 22/ 6/94 | |
| | | WM-EM | 25/ 5/95 | 22/ 6/95 | 3/ 8/94 |
| | | WM-EM | 6/ 6/96 | 13/ 6/96 | |
| | Latest | WM-EM | 1/ 6/94 | 22/ 6/94 | |
| | | WM-EM | 8/ 6/95 | 22/ 6/95 | 3/ 8/94 |
| | | WM-EM | 6/ 6/96 | 18/ 7/96 | |
| RIS | Earliest | Wye | 15/ 5/94 | 15/ 5/94 | 5/ 6/94 |
| | | Wye | 7/ 5/95 | 14/ 5/95 | 11/ 6/95 |
| | | Wye | 2/ 6/96 | 2/ 6/96 | 9/ 6/96 |
| | Latest | Wye | | 17/ 7/94 | |
| | | Wye | 17/ 7/94 | 16/ 7/95 | |
| | | Wye | 30/ 7/95 | 11/ 8/96 | |

*[1] No 'latest' occurrence for eclosion because hatched eggs persisted and accumulated.

FIGURE 3. PHENOLOGY OF PLUM APHIDS IN UNTREATED WM-EM PLOTS.



The earliest newly-hatched fundatrices of damson-hop aphid were observed between late January and early February (Table 3), while plum buds were still dormant. This observation questions the accuracy of forecasting studies which use bud-burst of the overwintering host as the phenological indicator for timing the first egg hatch of this species. Typically, damson-hop aphid populations built-up slowly from mid-May and peaked during June (1994 and 1995) (Figure 3). Spring populations of mealy plum aphid only occurred in the sampled orchards during 1994 and 1996. The presence of mealy plum aphid in samples was erratic and overall numbers were low compared to those of damson-hop aphid and leaf-curling plum aphid.

The development of aphid populations on plum followed the same pattern in each year, where leaf-curling plum aphid, having hatched first, built up into larger numbers earlier than either damson-hop aphid or mealy plum aphid. This pattern of development was also found in previous studies (Ward, 1969). The major population decline for plum aphids tended to correspond well with the period of spring migration, as recorded in Rothamsted Insect Survey (RIS) suction trap data for the period 1994-1996 (data kindly supplied by Dr R. Harrington, IACR-Rothamsted). However, in 1996 bud-burst at WM-EM was delayed by nearly four weeks compared to development in 1994. Although egg hatch was not delayed apparently, subsequent aphid population development was retarded (Figure 3). Consequently, low numbers of damson-hop aphid and leaf-curling plum aphid spring migrants were found in RIS suction trap catches at Wye and Writtle during 1996 compared to the previous two years. It is likely that the period of high minimum temperatures during January 1996 was sufficient to stimulate aphid egg hatch and favour the development of the resulting fundatrices. However, the unusually cold weather in February and March delayed bud-burst and the subsequent development of the fundatrigenous generations.

One apparent consequence of the relatively small spring migration of damson-hop aphid in 1996 was an exceptionally good year for commercial hop production, with respect to the low levels of aphid infestation. However, the numbers of damson-hop aphid in the experimental plum orchard WM-EM were higher in the spring of 1996 than in the previous two years (Figure 3). During the autumn of 1995, large numbers of damson-hop aphid gynoparae and males were released into an inclusion cage set up within WM-EM as part of an aphid-egg mortality study (see section

2.2.5.1). The high numbers of damson-hop aphid in WM-EM during 1996 may have indicated that the inclusion cage was not completely 'aphid-proof', possibly allowing some gynoparae and males to escape and artificially increase the natural levels of overwintering aphid eggs on surrounding trees in the orchard.

PRESENCE-ABSENCE SAMPLING FOR PREDICTING DENSITY OF APHIDS ON PLUM IN THE SPRING

Figure 4 shows that, in a plum orchard, the percentage of aphid-infested leaves in a sample was closely related to the numbers of aphids on those leaves. This relationship was similar over a range of densities during 1996. Such consistent correlations can justify the use of presence-absence samples to estimate pest population sizes and develop economic-threshold levels for those pests. The presence-absence method of sampling aphids, already developed for integrated pest management programs in walnut, hop and wheat crops, is the simplest and least time-consuming method for pest population assessment by growers. Further experiments will need to be undertaken in a range of plum orchards across a number of seasons in order to validate these relationships, as this study was limited to a single orchard in 1996. However, this study has identified the potential value of presence-absence sampling as a basic integral part of future IPM programmes for plum aphid control. In the event of new pesticides being approved for damson-hop aphid control on plum, such presence-absence sampling plans will be essential to any resistance management strategy.

AUTUMN POPULATIONS

Autumn populations of damson-hop aphid and leaf-curling plum aphid were first observed in WM-EM leaf samples during the second half of September (Table 4). The timing of autumn migration was in agreement with suction trap catches at Wye (Table 4). Mealy plum aphid autumn migrants were not observed in either 1994 or 1995 (Figure 3).

FIGURE 4. RELATIONSHIP BETWEEN THE AVERAGE NUMBER OF PLUM APHIDS PER LEAF AND THE PROPORTION OF LEAVES WITH NO APHIDS, FOR DAMON-HOP APHIDS IN SAMPLES FROM UNTREATED (CIRCLES) AND PIRIMICARB-SPRAYED PLOTS (SQUARES), AND LEAF-CURLING PLUM APHID FROM UNTREATED PLOTS (TRIANGLES). THE STRAIGHT LINE IS THE REGRESSION LINE FITTED THROUGH ALL THE POINTS, $\ln(m) = 2.70 + 1.50 \ln(-\ln p)$ ($r^2 = 0.91$, n = 38).

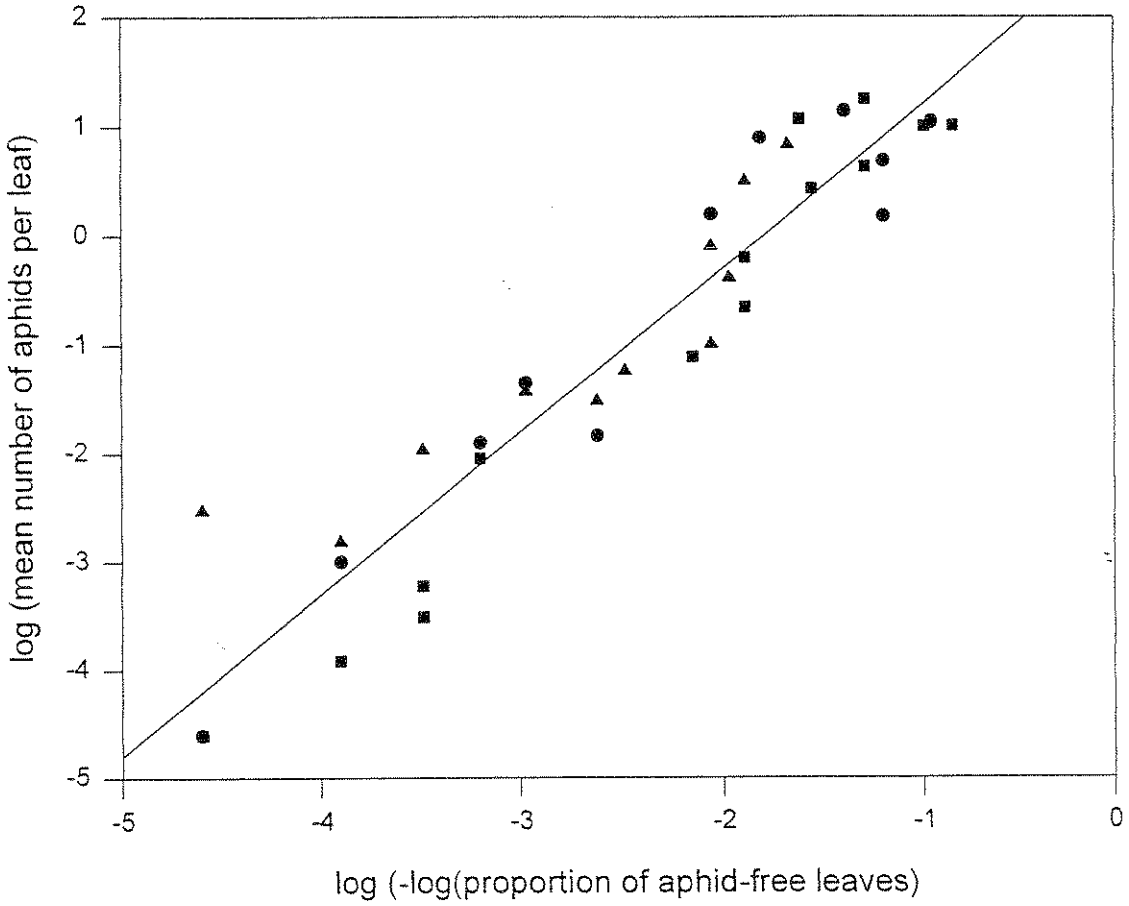


TABLE 4. EARLIEST AND LATEST SEASONAL OCCURRENCE OF GYNOPARAE AND SEXUALES OF THREE PLUM APHID SPECIES IN WM-EM LEAF SAMPLES AND RIS SUCTION TRAPS.

| Form/Sampling method/Site | Occurrence | Aphid species/Date | | |
|---|---|---|---|---|
| | | Leaf-curling plum aphid | Damson-hop aphid | Mealy plum aphid |
| **Gynoparae** | Earliest | 28/ 9/94<br>5/10/95 | 21/ 9/94<br>19/10/95 | |
| Leaf samples | Latest | 12/10/94<br>5/10/95 | 28/ 9/94<br>19/10/95 | |
| RIS Writtle | Earliest | 28/ 8/94<br>10/ 9/95 | 9/10/94<br>29/10/95<br>13/10/96 | |
| | Latest | 20/11/94<br>29/10/95<br>27/10/96 | 9/10/94<br>12/11/95<br>27/10/96 | 6/11/94<br>15/10/95<br>13/10/96 |
| RIS Wye | Earliest | 28/ 8/94<br>3/ 9/95 | 4/ 9/94<br>10/ 9/95<br>25/ 8/96 | |
| | Latest | 20/11/94<br>22/10/95<br>3/11/96 | 30/10/94<br>5/11/95<br>3/11/96 | 18/ 9/94<br>22/10/95<br>29/ 9/96 |
| **Males** | Earliest | 5/10/95 | 5/10/94<br>12/10/95 | |
| Leaf samples | Latest | 5/10/95 | 5/10/94<br>12/10/95 | |
| RIS Writtle | Earliest | 9/ 9/94<br>29/10/95<br>29/ 9/96 | 29/10/95<br>8/ 9/96 | 8/10/95<br>20/10/96 |
| | Latest | 23/10/94<br>29/10/95<br>27/10/96 | 12/11/95<br>15/ 9/96 | 15/10/95<br>27/10/96 |
| RIS Wye | Earliest | 30/ 9/94<br>8/10/95<br>29/ 9/96 | 18/ 9/94<br>24/ 9/95<br>29/ 9/96 | 18/ 9/94<br>24/ 9/95 |
| | Latest | 23/10/94<br>22/10/95<br>13/10/96 | 23/10/94<br>5/11/95<br>3/11/96 | 18/ 9/94<br>22/1 /95 |
| **Oviparae** | Earliest | 28/ 9/94<br>28/ 9/95 | 15/ 9/94<br>21/ 9/95 | |
| Leaf samples | Latest | 12/10/94<br>2/11/95 | 12/10/94<br>2/11/95 | |

2.3.1.2 Monitoring aphid predators

The commonest aphid-specific predators in beat samples were anthocorid bugs (Anthocoridae), green lacewing larvae (Chrysopidae), ladybird beetles (Coccinellidae), mirid bugs (Miridae) and hoverfly larvae (Syrphidae) (Figures 5-7). The most abundant non-specific aphid predators included spiders (Araneae) and the common earwig, *Forficula auricularia* (Dermaptera) (Figures 5-7). Aphid-specific predators caught most frequently on sticky traps included adult ladybird beetles, lacewings and hoverflies (only the larvae of which are predatory) (Figure 8).

AUTUMN POPULATIONS

In all three years, adult anthocorids, ladybird beetles and green lacewing larvae were the aphid-specific predators found most frequently in beating-tray samples from mid-September onwards (Figures 5-7). Various anthocorid species, the 7-spot ladybird (*Coccinella septempunctata*) and 10-spot ladybird (*Adalia decempunctata*) overwintered within WM-EM in low numbers and remained active until mid-November.

Earwigs and spiders were usually the most abundant predators during autumn (Figures 5-7). Previous studies have shown that earwigs and spiders are able to deplete small populations of aphids during autumn. By virtue of their polyphagous habit, indigenous populations of such predators remain high throughout the year (compared to those of aphid-specific predators), switching to alternative food when aphids become scarce in the orchard. As a result, earwigs and spiders are already present in the orchard when plum aphids start to invade or accumulate, representing a potentially useful predatory resource that may impact upon the sexual generations of plum aphids. However, as earwigs occasionally cause unacceptable levels of damage to fruit, and earwigs and spiders will eat other aphid predators, their importance as beneficial arthropods is questionable.

PREDATOR REFUGIA

The predator refugia used in this study contained few overwintering aphid-specific predators, but large numbers of male earwigs and spiders. Adult earwigs mate during autumn in underground nests. Prior to egg-laying the female expels male earwigs from the nest. In refugia 98-100% of earwigs were male, suggesting that, after expulsion from the nest, males remain above ground,

FIGURE 5. CHANGES IN APHID AND PREDATOR POPULATIONS IN WM-EM DURING 1994. (a)-(h): WEEKLY COUNTS OF PREDATORS MADE BY BEAT SAMPLING. (i) CHANGES IN APHID NUMBERS PER 100 LEAVES, DUPLICATED FROM FIGURE 3 FOR PHENOLOGICAL COMPARISON.

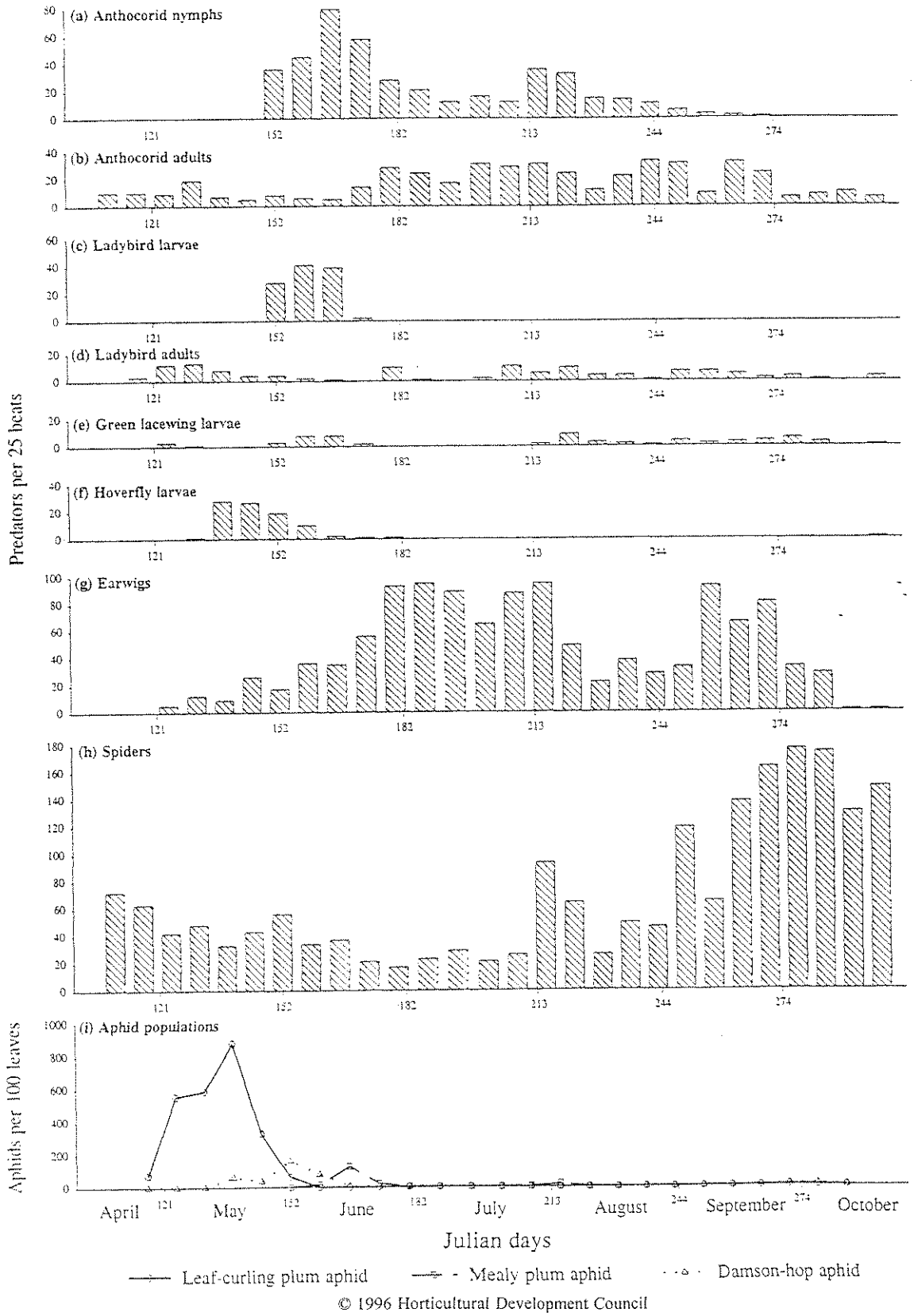


FIGURE 6. CHANGES IN APHID AND PREDATOR POPULATIONS IN WM-EM AND THE ADJACENT ALDER WINDBREAK DURING 1995. (a)-(e) AND (g)-(j): WEEKLY COUNTS OF PREDATORS MADE BY BEAT SAMPLING. (f): CHANGES IN APHID NUMBERS PER 100 LEAVES, DUPLICATED FROM FIGURE 3 FOR PHENOLOGICAL COMPARISON.

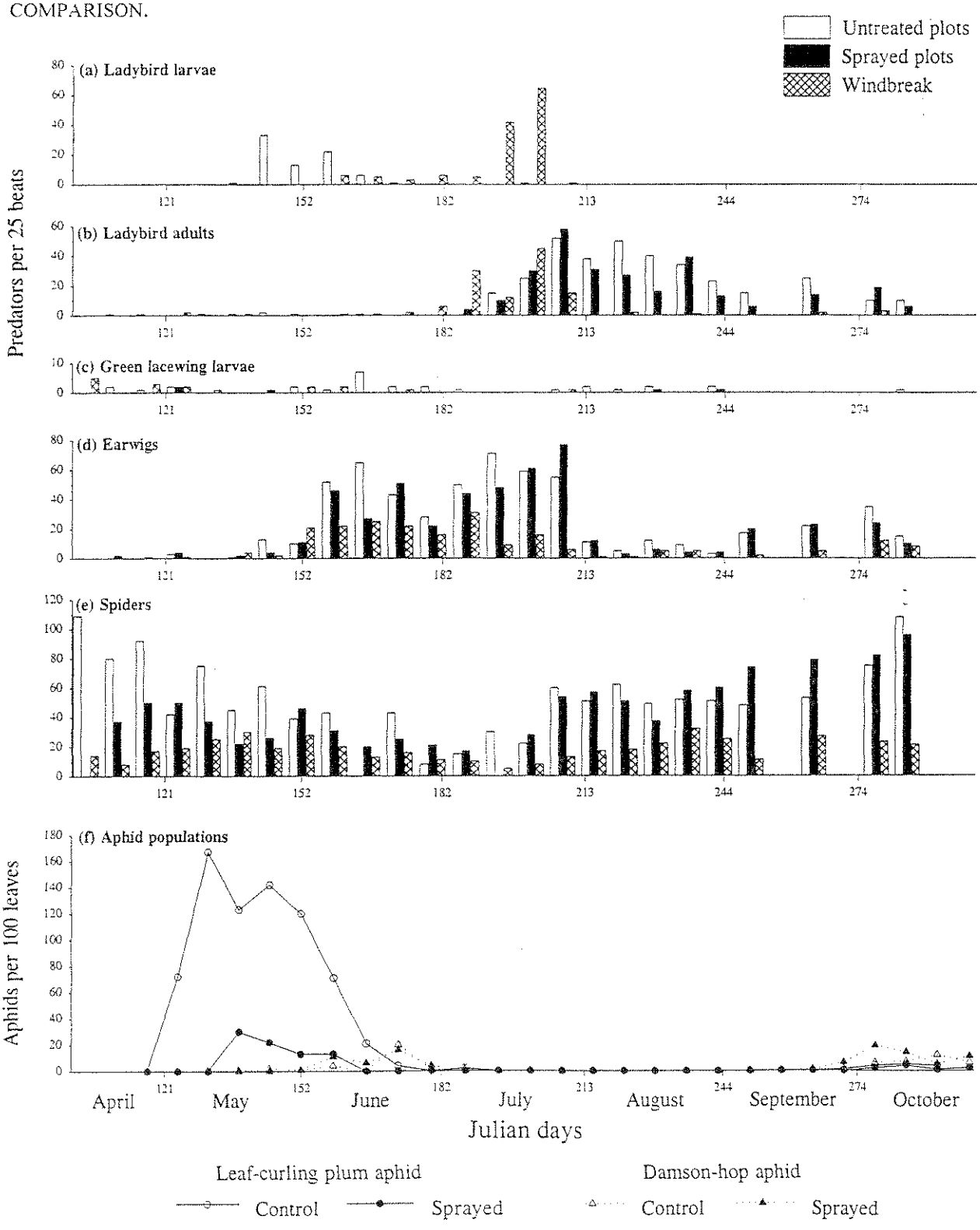


FIGURE 6 CONTINUED.

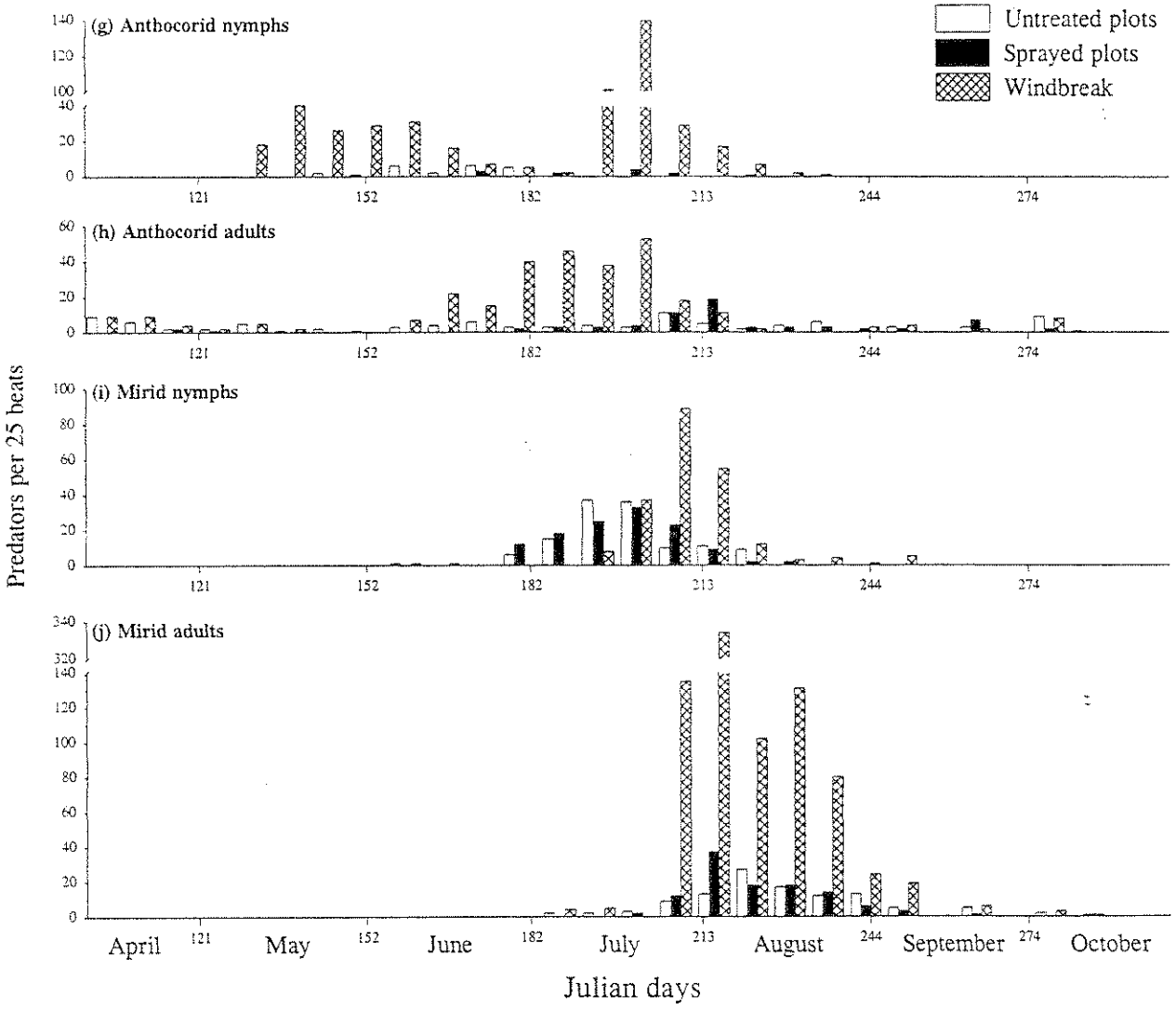


FIGURE 7. CHANGES IN APHID AND PREDATOR POPULATIONS IN WM-EM AND THE ADJACENT ALDER WINDBREAK DURING 1996. (a)-(f) AND (h)-(k): WEEKLY COUNTS OF PREDATORS MADE BY BEAT SAMPLING. (g): CHANGES IN APHID NUMBERS PER 100 LEAVES, DUPLICATED FROM FIGURE 3 FOR PHENOLOGICAL COMPARISON.

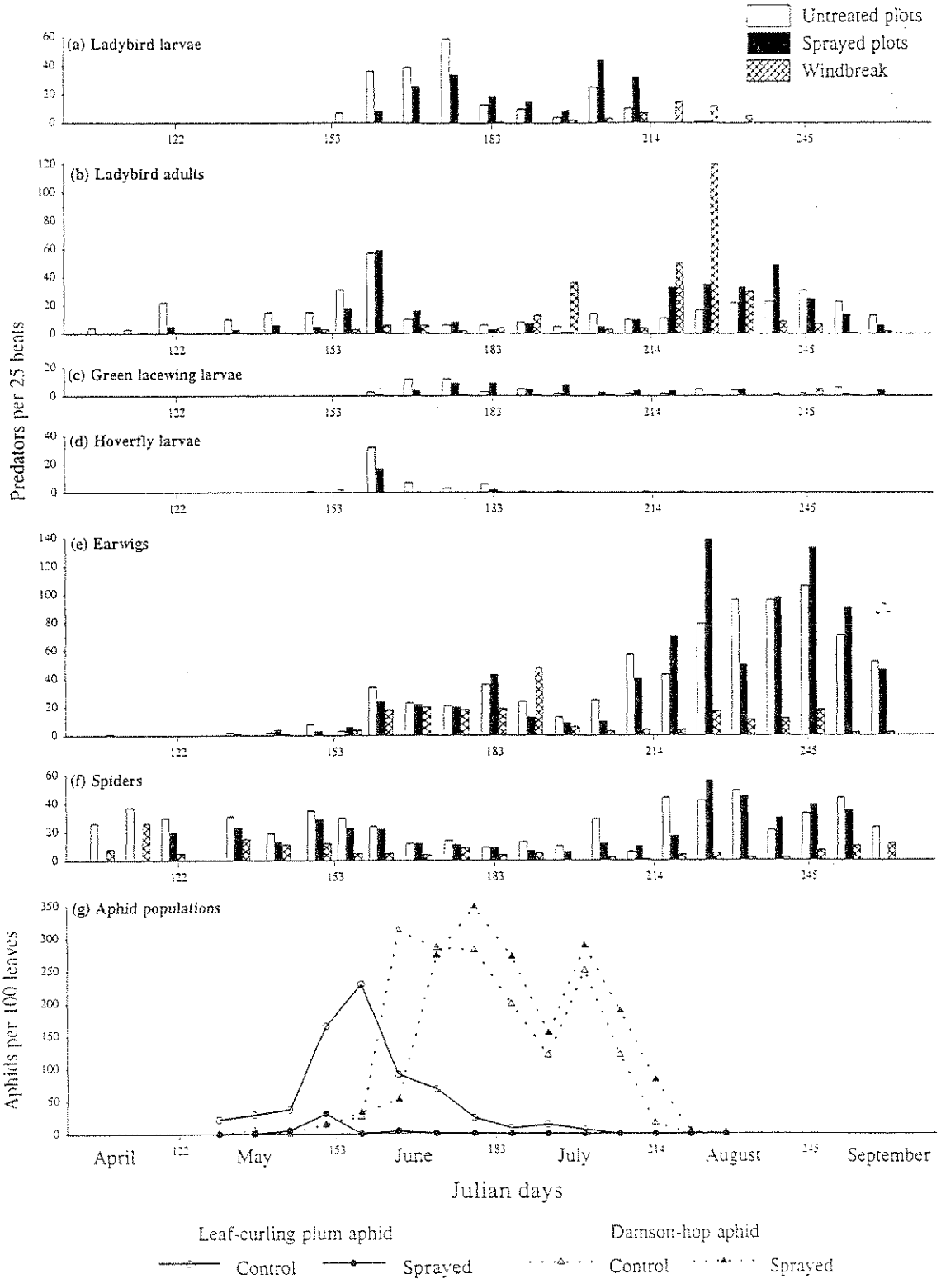


FIGURE 7 CONTINUED.

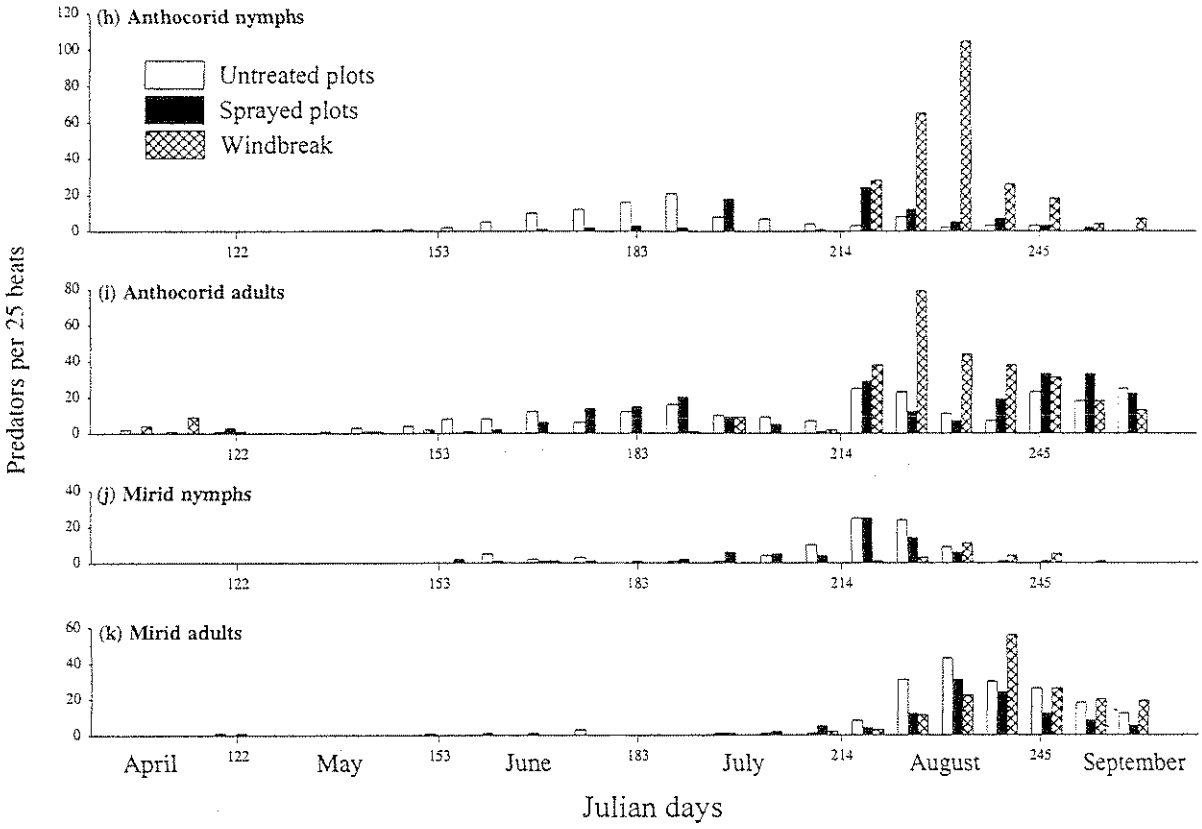


FIGURE 8. CATCHES OF APHID PREDATORS ON COLOURED AND CLEAR (GREY BARS, 1996 ONLY) STICKY TRAPS PLACED IN WM-EM AND MR-HF (1996 ONLY). APHID PREDATORS CAUGHT INCLUDE THE HOVERFLIES *Episyrphus balteatus* (Eb), *Eupeodes corollae* (Ec), *Eupeodes luniger* (El), *Sphaerophoria scripta* (Ss), *Melanostoma mellinum* (Mm) AND *Platycheirus* SPP. (P), THE GREEN LACEWING *Chrysoperla carnea* (Cc), THE ANTHOCORIDS *Anthocoris nemorum* (An) AND *Orius* SPP. (O), THE MIRID *Heteroptera meriopterus* (Hm) AND THE LADYBIRDS *Adalia bipunctata* (2-SPOT, Ab), *Adalia decempunctata* (10-SPOT, Ad), *Coccinella septempunctata* (7-SPOT, Cs) AND *Propylea quatuordecimpunctata* (14-SPOT, Pq).

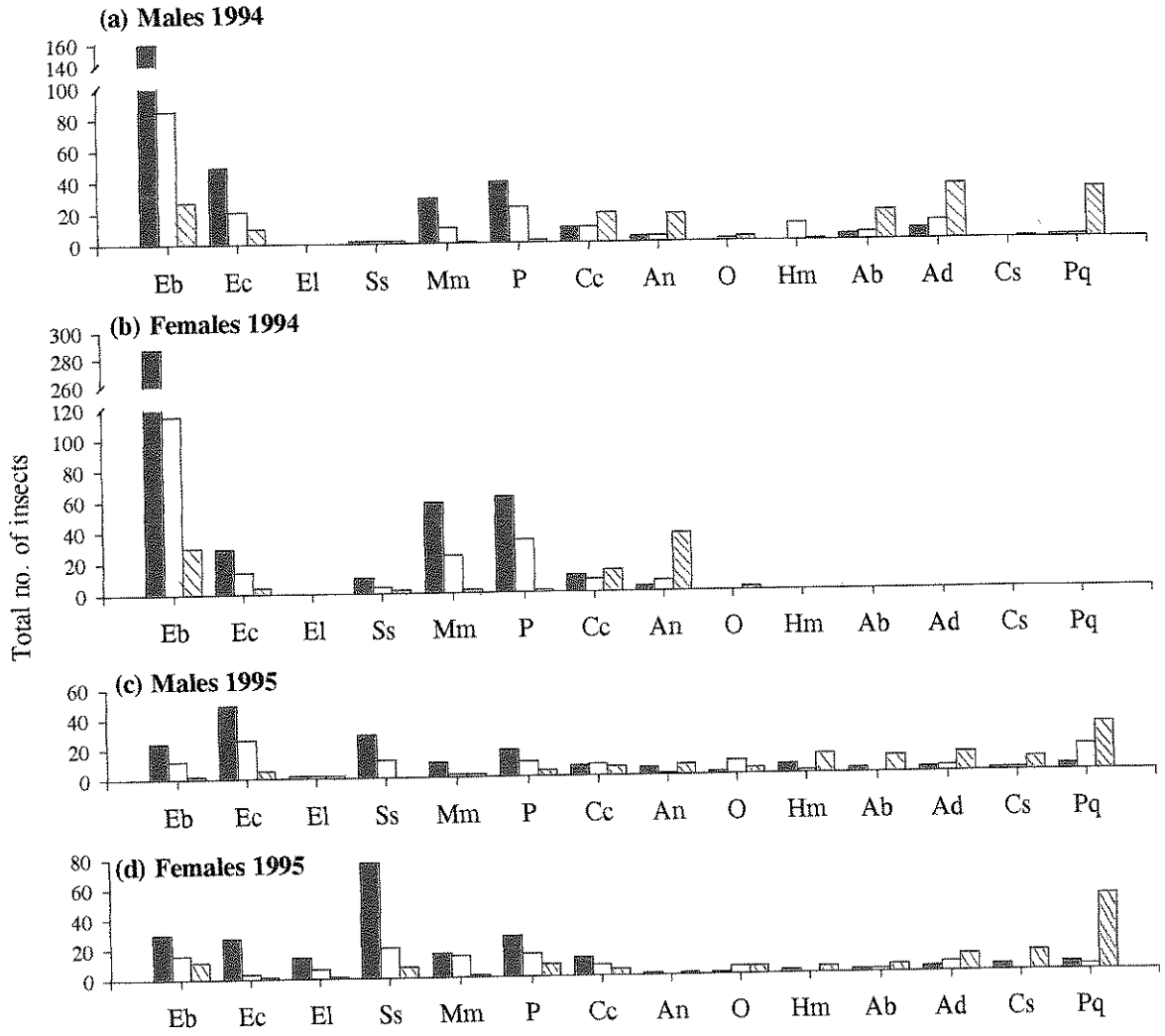
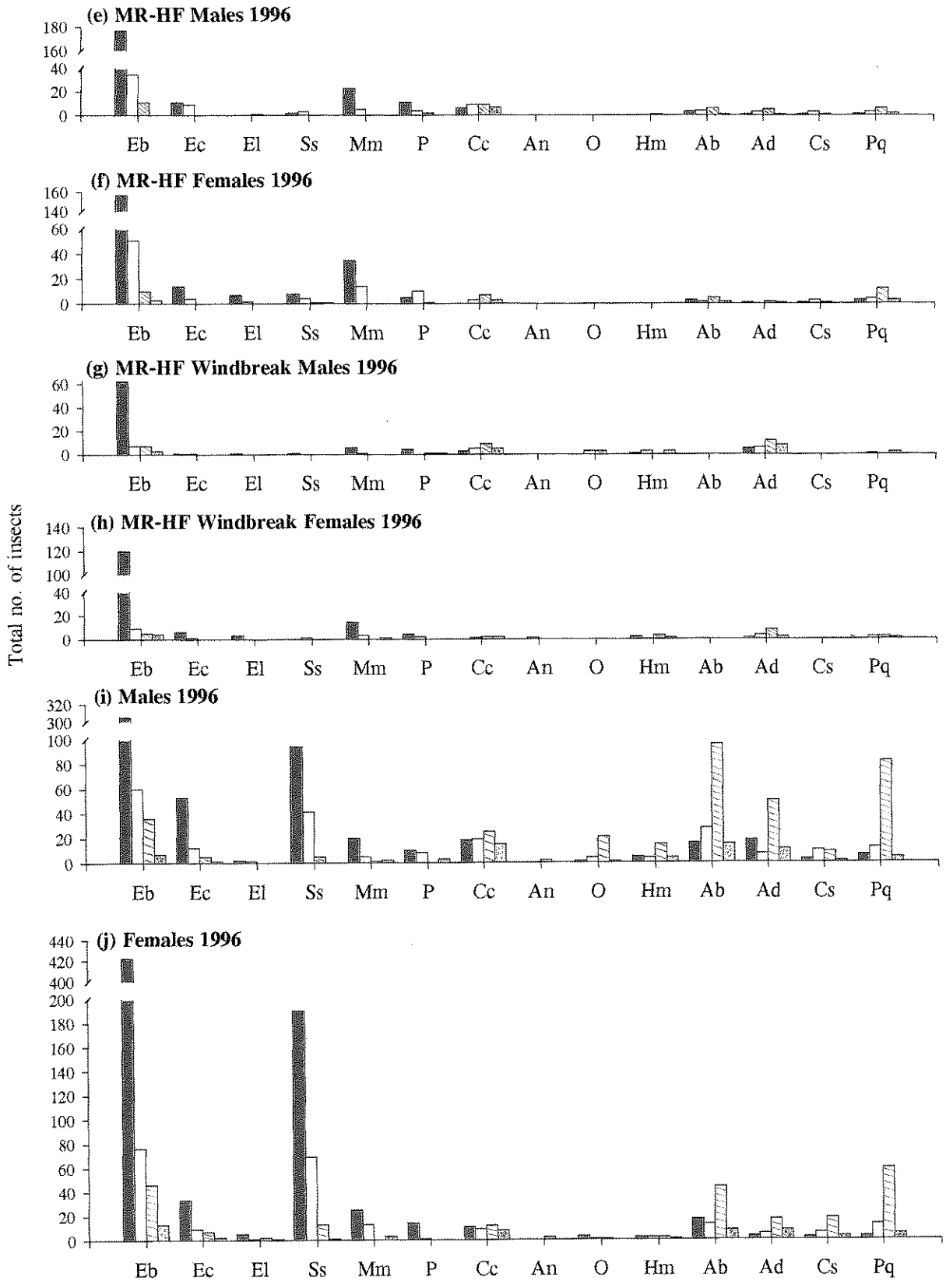


FIGURE 8 CONTINUED.



making use of any available refuge they encounter.

SPRING AND SUMMER POPULATIONS

Spiders were the most abundant predators in orchard and windbreak beat samples during April and early May of each year (Figures 5-7). Conversely, earwigs were rarely found in beat samples during early spring. Of the aphid-specific predators, low numbers of adult ladybird beetles and anthocorids were frequently found in beat samples during April (Figures 5-7).

In each season anthocorid species caught in orchard (WM-EM and DR-EM) and windbreak beat samples were dominated by two taxa: *Anthocoris* spp. (*nemoralis* and *nemorum*) and *Orius* species. Similarly, 81-91% of the adult coccinellids found in each year at each location in beat samples were a combination of four species: the 2-spot ladybird (*Adalia bipunctata*), the 10-spot ladybird, the 7-spot ladybird and the 14-spot ladybird (*Propylea quatuordecimpunctata*).

Although anthocorids and ladybirds appeared early in the spring, the majority of aphid-specific predators only became abundant after the populations of leaf-curling plum aphid had peaked. Thus, the decline in populations of leaf-curling plum aphid, though hastened by increasing levels of predation, was primarily due to other factors such as intraspecific competition and the dispersal of alates to secondary hosts.

There was a greater synchrony between the build-up of damson-hop aphid populations and that of certain aphid-specific predators, particularly the anthocorid, ladybird and hoverfly larvae. As a result, these mid- to late-season populations of damson-hop aphid were predated heavily.

Sticky trap catches allowed the activity of highly mobile predator groups, e.g. adult ladybirds and hoverflies, to be monitored more effectively. The most abundant ladybird species in beat samples were also found in large numbers on sticky traps hung within plum orchards. Yellow sticky traps were significantly more attractive than either blue or white for the 2-spot ladybird ($p<0.01$), the 10-spot ladybird ($p<0.05$) and 14-spot ladybird ($p<0.001$), and also the anthocorid *A. nemorum* ($p<0.001$) (Figure 8). Adult hoverflies from 23 species with predatory larvae and 8 species with non-predatory larvae were caught on sticky traps. The most numerous adult syrphids with

predatory larvae known to be associated with aphid colonies occur at about the same time of year, from late June to August. Hoverflies are effective aphid predators; they respond rapidly to increases in prey abundance and discriminate between aphid colonies, selecting only the most suitable sites for egg-laying. Colour had a significant impact on sticky-trap catches of adults of the most abundant hoverfly species: *Episyrphus balteatus* ($p<0.05$), *Eupeodes corollae* ($p<0.05$), *Melanostoma mellinum* ($p<0.05$) and *Platycheirus peltatus* ($p<0.05$). Blue was the most attractive colour, followed by white and yellow (Figure 8). Blue and yellow are clearly important visual stimuli used by aphid predators within orchards. Coloured sticky traps are a useful tool for studying the visual ecology of plum aphid predators. With a little further study, it may be possible to incorporate the appropriate visual stimuli into ecologically selective traps for population monitoring and also assess the feasibility of managing orchard margins and ground cover to increase predator abundance, as demonstrated with hoverflies in arable agro-ecosystems. Further work is also needed to establish the strength of visual cues, and whether they interact with other stimuli such as aphid honeydew, aggregation or sex pheromones released by aphid prey, or plant damage volatiles resulting from aphid feeding.

Sticky trap catches also highlighted differences in the sex ratios of certain predators in flight, catching significantly more ♀ than ♂ of the hoverflies *E. balteatus* ($p<0.001$) and *M. mellinum* ($p<0.05$), and more ♂ than ♀ of the predatory mirid *Malacocoris chlorizans* ($p<0.001$).

Lacewings showed no consistent attraction to any particular sticky trap colour. However, the brown lacewing *Hemerobius humulinus* (Hemerobiidae), along with the mirid *M. chlorizans*, showed a significant spatial pattern of occurrence in WM-EM during 1994 ($p<0.05$). A greater proportion of these insects was caught in the south-western corner of the plot. This trend was later reflected in catches of other predatory mirid bugs, including *Heterotoma meriopterus*, *Phytocoris tiliae* and *Plagiognathus arbustorum*, which were caught in larger numbers on the sticky-traps placed closest to the alder windbreak during 1996.

Windbreaks are an integral part of many orchard margins. They not only provide benefits to horticulture, such as shelter from adverse weather, but also benefits to natural enemies. These include the provision of refugia - for protection and overwintering, alternative food and foraging

sites, reproductive habitat, and 'travel corridors'. Nymphal and adult anthocorid and mirid bugs were the most abundant predators within the alder windbreak adjacent to WM-EM (Figures 6 and 7). However, both families of predatory bugs were dominated largely by species which are not considered to be aphid-specific predators. In 1995 and 1996, the majority of anthocorid larvae (89% and 97% respectively) and anthocorid adults (79% and 83% respectively) were *Anthocoris nemoralis* which, within windbreaks, prey largely on psyllids. In the same years, the majority of mirid larvae (89% and 96% respectively) and mirid adults (79% and 84% respectively) were black-kneed capsids, *Blepharidopterus angulatus*, which are recognised as important predators of the fruit tree red spider mite. Numbers of spiders and earwigs were generally lower in the windbreak than in the plum orchard (Figures 6 and 7). Differences in the abundance and occurrence of individual species between the windbreak and the orchard were also evident for aphid-specific predators, most notably the ladybird beetles. Predatory ladybird beetles usually require abundant supplies of prey to stimulate egg-laying. Thus, the delayed appearance of ladybird larvae in the windbreak, compared to the untreated orchard plots, is probably a result of food availability. Once plum aphid populations had begun to decline in the orchard, the stimulus for egg-laying was removed progressively. As plum aphid numbers were declining, many ladybird larvae pupated to adults; consequently the numbers of adults began to increase at this time (Figure 6 and 7). Adult ladybirds represent a mobile foraging population. As aphid prey declined in abundance within the orchard, a proportion of this mobile population moved into the adjacent windbreak to forage for food. The alder aphids and psyllids present in the windbreak provide the necessary egg-laying stimuli for incoming ladybird beetles. Numbers of ladybird beetles, and anthocorid and mirid bugs in windbreak samples declined sharply around mid-August, coinciding with the decline in the numbers of alder aphids.

Plum aphids and their natural enemies do not form a closed system. Predators may spend one or more generations elsewhere, only preying on plum aphids for part of the year. Many of the mid-to-late season predators among the hoverflies, ladybird beetles and mirid bugs may spend at least one generation in other habitats, feeding on different prey before moving into the plum orchard. This is clearly the case for 7-spot ladybird adults, as larvae were always found in relatively small numbers in the orchard compared to the preponderance of adults later in the season. It follows that the degree of biological control of aphids depends to an unknown extent upon the habitats

and prey species surrounding the orchard and that, by manipulating nearby plant species and/or orchard ground cover, one might further improve biocontrol prospects.

2.3.1.3 Monitoring plum aphid parasitoids

The use of muslin bands at sites of damson-hop aphid and plum aphid infestation highlighted distinct differences in the distribution of parasitized aphids on plum trees (Tables 5 and 6). In 1994 and 1995, the majority (99% and 94% respectively) of parasitized damson-hop aphid collected contained *Ephedrus* spp. parasitoids and the majority (98% and 99% respectively) of these were found off the foliage within muslin bands (Tables 5 and 6).

In 1995, the Oecotak-coated plastic discs were used to assess whether the movement of damson-hop aphids parasitized by *Ephedrus*, off the foliage and along the branch to mummification sites within muslin bands, was the result of parasitoid-mediated behavioural modification and not simply a reflection of a general movement of all aphids along the branch. During June, the proportion of parasitized aphids was greater in the muslin bands (57-68%) than on the proximal surfaces of the sticky discs (0-19%) (Table 6), which suggests that parasitized aphids were actively seeking mummification sites within the muslin band. By early July, there was little difference between the two 'capture' sites. Further studies are necessary in order to understand exactly how parasitism modifies aphid behaviour.

In 1994, 93% of the aphid mummies found on plum foliage contained *Praon* spp. parasitoids. The commonest host (97%) for this parasitoid was the mealy plum aphid (Table 5).

Approximately 92% of the damson-hop aphid mummies found on foliage in 1995 contained *Aphidius* spp. parasitoids; this represented 90% of the total *Aphidius*-type mummies collected (Table 6). Damson-hop aphids parasitized by *Aphidius* spp. rarely move off the leaves, clearly showing a strong preference to mummify *in situ*. This is supported further by the complete absence of *Aphidius*-type mummies on the sticky-discs.

In 1995, parasitoids emerged from only 95 of the field-collected mummies. Only 11 of these were primary parasitoids (9 *Ephedrus* spp., 2 *Aphidius matricariae*). In both years the majority of adult

TABLE 5. PLUM APHID PARASITOIDS: A COMPARISON OF APHID MUMMY ABUNDANCE AND MUMMIFICATION SITE IN THE PLUM ORCHARD DURING 1994

| | JUNE | JULY | | | | AUGUST | |
|---|---|---|---|---|---|---|---|
| | 29 | 6 | 13 | 20 | 27 | 3 | 10 |
| **Associated aphid spp.** | **No. muslin bands/week/aphid species** | | | | | | |
| Damson-hop aphid | 14 | 13 | 11 | 8 | 6 | 0 | 0 |
| Mealy plum aphid | 9 | 9 | 5 | 4 | 3 | 5 | 7 |
| | **Average counts/muslin band** | | | | | | |
| **Damson-hop aphid mummies containing *Ephedrus* spp. parasitoids** | | | | | | | |
| ON MUSLIN BAND | 10.0 | 6.5 | 6.3 | 2.5 | 0 | 0 | 0 |
| ON FOLIAGE | 0 | 0 | 0 | 0 | 0.8 | 0 | 0 |
| **Mealy plum aphid mummies containing *Ephedrus* spp. parasitoids - NONE** | | | | | | | |
| **Damson-hop aphid mummies containing *Praon* spp. parasitoids** | | | | | | | |
| ON MUSLIN BAND | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| ON FOLIAGE | 0 | 0 | 0 | 0 | 0.5 | 0 | 0 |
| **Mealy plum aphid mummies containing *Praon* spp. parasitoids** | | | | | | | |
| ON MUSLIN BAND | 0 | 0 | 0 | 0 | 1.3 | 1.4 | 0 |
| ON FOLIAGE | 0 | 0 | 0 | 0.3 | 1.0 | 8.6 | 7.7 |
| **Damson-hop aphid mummies containing *Aphidius* spp. parasitoids - NONE** | | | | | | | |
| **Mealy plum aphid mummies containing *Aphidius* spp. parasitoids** | | | | | | | |
| ON MUSLIN BAND | 0 | 0 | 0.2 | 0.8 | 0 | 0 | 0 |
| ON FOLIAGE | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

*Ephedrus* spp. emerging in the laboratory were *E. persicae*. *Ephedrus persicae* is an important parasitoid of aphids in orchard habitats, particularly leaf-curling aphid species. However, the effectiveness of *E. persicae* within any biocontrol strategy for plum aphids may be limited severely by the common incidence of a number of hyperparasitoids. These wasps, which attack the primary parasitoid larvae in aphid mummies, accounted for more than 88% of the parasitoids emerging in the laboratory in 1995.

TABLE 6. DAMSON-HOP APHID PARASITOIDS: A COMPARISON OF APHID MUMMY ABUNDANCE AND MUMMIFICATION SITE ON PLUM DURING 1995 .

| | JUNE | | JULY | | | | |
|---|---|---|---|---|---|---|---|
| | 19 | 26 | 3 | 10 | 17 | 24 | 31 |
| | **Average counts/muslin band (n = 20)** | | | | | | |
| **Damson-hop aphid** | | | | | | | |
| ON FOLIAGE approx. | 425 | 310 | 213 | 71 | 35 | 1 | 0 |
| ON MUSLIN BAND | 7.2 (56.9)[1] | 10.0 (67.8) | 3.2 (68.3) | 0.8 (26.7) | 0 | 0 | 0 |
| ON STICKY DISC | | | | | | | |
| Proximal surface | - | 4.3 (8.2) | 4.6 (61.5) | 1.0 (75.0) | 0.4 (25.0) | 0 | 0 |
| Distal surface | - | 1.4 (18.5) | 1.1 (47.6) | 0.4 (75.0) | 0.1 (0) | 0 | 0 |
| **Aphid mummies containing *Ephedrus* spp. parasitoids** | | | | | | | |
| ON FOLIAGE | 0 | 0.3 | 0 | 0.2 | 0 | 0 | 0 |
| ON MUSLIN BAND | 27.6 | 30.8 | 15.9 | 5.1 | 0.6 | 0.1 | 0 |
| ON STICKY DISC | | | | | | | |
| Proximal surface | - | 0.4 | 0.4 | 0 | 0 | 0 | 0 |
| Distal surface | - | 1.1 | 0.7 | 0.1 | 0.2 | 0 | 0 |
| **Aphid mummies containing *Aphidius* spp. parasitoids** | | | | | | | |
| ON FOLIAGE | 1.9 | 2.3 | 0.7 | 0.2 | 0 | 0 | 0 |
| ON MUSLIN BAND | 0.4 | 0.2 | 0.1 | 0 | 0 | 0 | 0 |
| ON STICKY DISC | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

[1] % parasitism indicated in parentheses. Parasitism detected by either rearing collected aphids (as in the case of aphids collected from muslin bands) or by dissection (as in the case of aphids collected on sticky discs).

It is clear that the abundance of *Ephedrus*-type mummies is related closely to damson-hop aphid population levels and that, in the absence of muslin bands, parasitized aphids would move off leaf surfaces to mummify in sheltered sites on trees, such as in bark crevices, where they are overlooked easily. The concealed position of many plum aphid mummies has led

undoubtedly to an underestimation of the level of parasitism by *Ephedrus* spp. Using the muslin band technique, developed during 1994, comprehensive assessments of the levels of parasitism in plum aphids can now be made.

#### 2.3.1.4 Significance of fungal pathogens infecting plum aphids

Populations of leaf-curling plum aphid and damson-hop aphid are infected commonly with aphid-pathogenic fungi of the family Entomophthoraceae (Ward, 1969). In 1994 and 1995, populations of both aphid species in WM-EM were infected frequently with fungal pathogens (Figure 9). The pattern of occurrence for entomopathogenic fungal infection was similar in both years, where levels of infection increased during May and reached a peak between late-May and early-June (Figure 9). However, in both years, peak levels of fungal infection occurred only after plum aphid populations had become damaging. The fungal pathogens were associated largely with colonies of leaf-curling plum aphid and, just as the numbers of this aphid species were markedly lower in 1995 than during the previous year, the overall numbers of mycosed aphids were also much reduced (Figure 9). It appears that the importance of entomopathogenic infection as a mortality factor for leaf-curling plum aphid increases as the aphid population size increases. In 1996, the delayed build-up of plum aphid populations would have presented a large number of potential hosts for fungal infection at a time of year more favourable to the development of epizootics. However, in 1996, aphids infected with fungal pathogens were observed rarely in leaf samples.

### 2.3.2 Assessing the significance of natural enemies in plum orchards

In 1994, the rapid early build-up of leaf-curling plum aphid caused damage and defoliation within many treatment cages, hampering interpretation of the results. However, important trends were apparent; the numbers of damson-hop aphid were lowest in treatments where there was greatest access for predators (Table 7). In 1995 and 1996, the use of trees from within pirimicarb-sprayed WM-EM plots as experimental blocks eliminated the disruptive knock-on effects of leaf-curling plum aphid experienced in 1994. Figure 10 shows clearly the impact of natural enemies on damson-hop aphid populations in plum orchards. By week six in both years (2 June and 27 June respectively) aphid numbers were significantly higher within closed-caged (total exclusion) treatments than in any other treatment ($p<0.05$). In 1995 and 1996, treatments which excluded birds and crawling arthropods generally contained significantly more aphids than treatments where

FIGURE 9. CHANGES IN THE LEVEL OF FUNGAL INFECTION WITHIN POPULATIONS OF PLUM APHID IN UNTREATED WM-EM PLOTS, SAMPLED USING WEEKLY LEAF SAMPLES, DURING 1994 AND 1995.

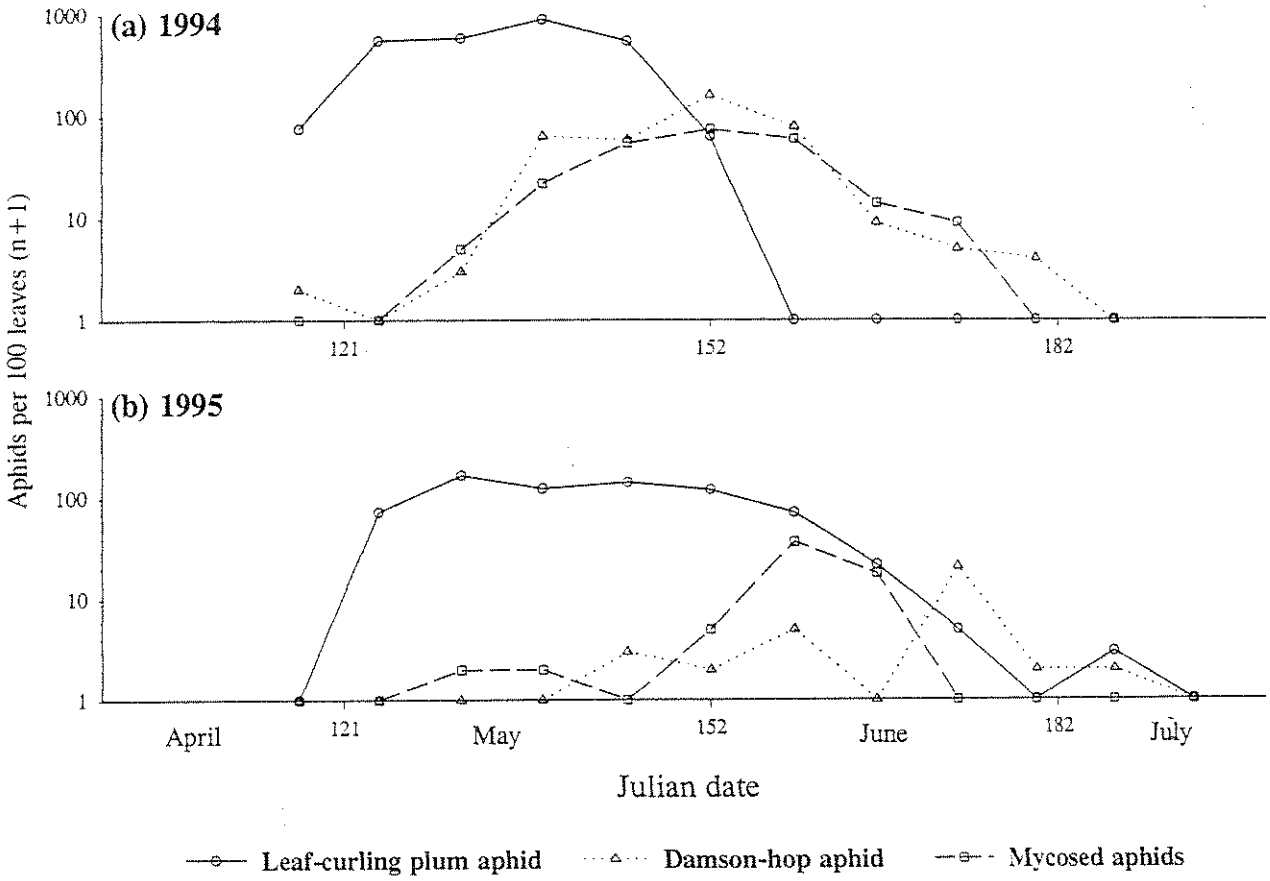


FIGURE 10. THE EFFECT OF VARIOUS LEVELS OF PREDATOR EXCLUSION ON DAMSON-HOP APHID POPULATIONS WITHIN PIRIMICARB-SPRAYED WM-EM PLOTS.

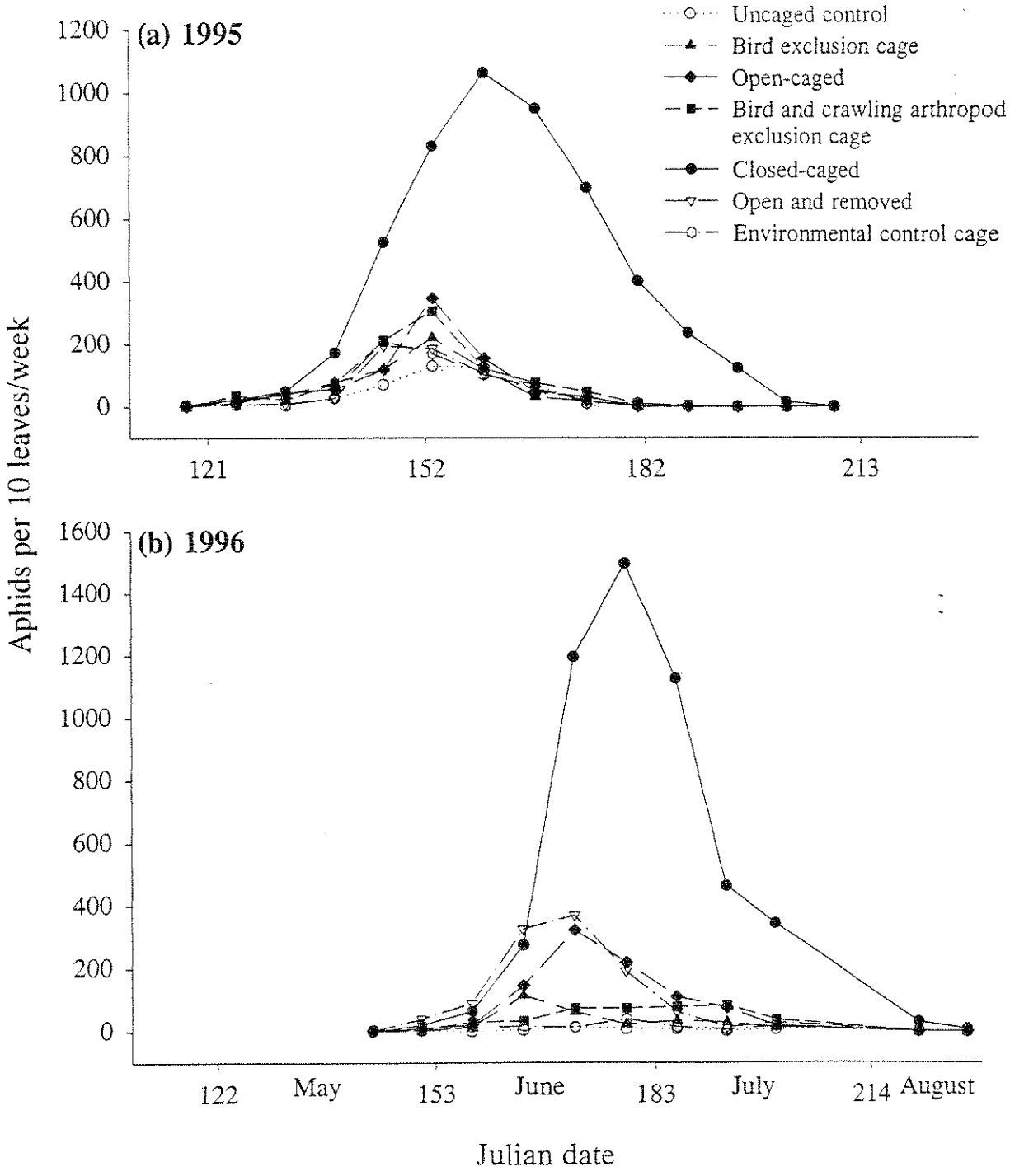


TABLE 7. THE EFFECT OF VARIOUS LEVELS OF PREDATOR EXCLUSION ON DAMSON-HOP APHID POPULATIONS ON PLUM[1].

| TREATMENT | LOG (n+1) MEAN APHID COUNTS[2,3] | | |
|---|---|---|---|
| | **1994** | **1995** | **1996** |
| **Uncaged control** | $2.21^{a}$ | $2.01^{c}$ | $0.90^{e}$ |
| **Closed-caged** | $3.34^{a}$ | $4.95^{a}$ | $4.17^{a}$ |
| **Open-caged** | $2.77^{a}$ | $2.26^{c}$ | $2.59^{b}$ |
| **Bird exclusion cage** | $3.83^{a}$ | $2.16^{c}$ | $1.60^{cd}$ |
| **Bird and crawling arthropod exclusion cage** | $3.94^{a}$ | $2.82^{b}$ | $2.17^{bc}$ |
| **Open and removed** | - | $2.08^{c}$ | $2.68^{b}$ |
| **Environmental control cage** | $1.38^{a}$ | $2.28^{c}$ | $1.48^{de}$ |
| SED (p = 0.05, d.f. = 22, 30, 30) | 1.522 | 0.162 | 0.337 |

[1] Treatment trees within pirimicarb-sprayed WM-EM plots.
[2] Means subtended by the same letter are not significantly different ($p<0.05$), by an LSD test.
[3] Summary of 14, 13 and 13 weekly records in 1994, 1995 and 1996 respectively.

they were allowed access ($p<0.05$) (Table 7). In 1996 this included the open-removed treatment from which aphid predators had been removed systematically. Using these various levels of predator exclusion demonstrates clearly the importance of aphid predators which crawl over branches and foliage to forage for aphid prey. In 1996, aphid numbers for the open-caged treatment were not significantly different from aphid numbers on the uncaged control branches (Table 7), suggesting that any alterations to microclimate caused by the net bags were not sufficient to affect damson-hop aphid development. However, this was not the case in 1996 when aphid numbers in open-caged treatments were significantly greater than those in uncaged control treatments on each sampling date between 6 June and 18 July inclusive ($P<0.05$) (Figure 10).

The exclusion cage study aimed at assessing the factors affecting overwintering survival of damson-hop aphid eggs failed to identify any significant mortality factors. However, the percentage increase in the number of collapsed or damaged damson-hop aphid eggs during the course of the study was lowest within the total exclusion treatment.

Predator voracity studies showed that 2-spot and 10-spot ladybirds consumed more damson-hop aphid than leaf-curling plum aphid during the first two larval instars (Tables 8 and 9). However, the 2-spot ladybird consumed more of both aphid species during its larval development than did the 10-spot ladybird. Two-spot ladybird larvae fed on damson-hop aphid and leaf-curling plum aphid took an average of 13.2 and 10.6 days from egg-hatch to pupation. Ten-spot ladybird larvae fed on damson-hop aphid and leaf-curling plum aphid took an average of 14.4 and 11.1 days to develop similarly when provided with an excess number of aphids. These feeding studies have shown that both ladybird species are particularly effective predators of damson-hop aphid, with each 2-spot and 10-spot ladybird larva capable of consuming an average total of 27 mg and 22 mg of aphids respectively (which equates to *c.* 100 and 82 individual aphids respectively) during their larval development. This has particular relevance as 2-spot and 10-spot ladybirds were abundant in plum orchard beat-samples.

TABLE 8. MEAN WEIGHT (MILLIGRAMS) OF DAMSON-HOP APHID CONSUMED DURING THE LARVAL DEVELOPMENT OF 2-SPOT AND 10-SPOT LADYBIRD BEETLES.

| Ladybird species | *n* | **Mean weight (mg) of aphids[1] consumed during each larval instar ± SE** | | | | |
|---|---|---|---|---|---|---|
| | | **1** | **2** | **3** | **4** | **Total** |
| **2-spot** | 12 | 1.43 ± 0.1 | 2.44 ± 0.2 | 4.32 ± 0.4 | 18.80 ± 1.0 | 26.98 ± 0.8 |
| **10-spot** | 24 | 1.43 ± 0.1 | 2.73 ± 0.1 | 4.09 ± 0.2 | 13.89 ± 0.4 | 22.13 ± 0.5 |

[1] Larvae presented with an excess amount of fresh aphids on a daily basis.

TABLE 9. MEAN WEIGHT (MILLIGRAMS) OF LEAF-CURLING PLUM APHID CONSUMED DURING THE LARVAL DEVELOPMENT OF 2-SPOT AND 10-SPOT LADYBIRD BEETLES.

| Ladybird species | *n* | Mean weight (mg) of aphids[1] consumed during each larval instar ± SE | | | | |
|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | Total |
| **2-spot** | 19 | 0.47 ± 0.1 | 1.41 ± 0.1 | 4.39 ± 0.2 | 17.00 ± 0.5 | 23.26 ± 0.6 |
| **10-spot** | 9 | 0.30 ± 0.1 | 0.85 ± 0.1 | 2.72 ± 0.4 | 12.20 ± 0.8 | 16.07 ± 0.9 |

[1] Larvae presented with an excess amount of fresh aphids on a daily basis.

### 2.3.3 Decreasing numbers of pest aphid species through manipulation of natural enemies

EXPERIMENT I

'On-tree' inclusion cages were used in 1994 and 1995 to investigate the impact of artificial releases of lacewing larvae on damson-hop aphid populations. In 1994, 42% of the experimental branches were defoliated by leaf-curling plum aphid, thus reducing the number of available replicates. The numbers of damson-hop aphid were lowest in treatment cages which received the highest release of lacewing larvae (Table 10), although this was not significant statistically. As with the exclusion cage experiment, the selection of experimental trees from within pirimicarb-sprayed WM-EM plots eliminated the disruptive knock-on effects of leaf-curling plum aphid in 1995. The numbers of damson-hop aphid were significantly reduced in cages where 32 lacewing larvae had been released (Table 10). The high numbers of lacewing larvae that are required in order to reduce damson-hop aphid levels significantly would suggest that mass-release of this predator species is not a commercially viable prospect.

TABLE 10. THE EFFECT OF PREDATOR RELEASE, USING LARVAE OF THE COMMON GREEN LACEWING, ON DAMSON-HOP APHID POPULATIONS WITHIN INCLUSION CAGES[1] ON PLUM TREES .

| 1994 | | 1995 | |
|---|---|---|---|
| No. released larvae/ cage | Log (n+1) mean aphid counts[2] | No. released larvae/ cage | Log (n+1) mean aphid counts[2] |
| **0** | 6.50[a] | **0** | 4.22[a] |
| **2** | 6.06[a] | **8** | 4.05[a] |
| **4** | 5.85[a] | **16** | 4.01[a] |
| **8** | 5.55[a] | **32** | 3.34[b] |
| SED (0.05, 9 d.f.) | 1.629 | SED (0.05, 15 d.f.) | 0.20 |

[1] Summary of 13 and 7 weekly records in 1994 and 1995 respectively.
[2] Means subtended by the same letter are not significantly different ($p<0.05$), by a LSD test.

EXPERIMENT II

Where lacewing larvae were released onto whole plum trees, there was no correlation between the numbers of predators released and the corresponding population densities of either damson-hop aphid or leaf-curling plum aphid. However, for both aphid species, it was apparent that more aphid individuals were found on leaves sampled from the 1.5 - 2.25 m sampling height (Table 11). This difference in spatial distribution of the aphids within the tree was only significant for leaf-curling plum aphid ($p<0.05$), which was present in higher numbers than damson-hop aphid on experimental trees.

TABLE 11. THE DISTRIBUTION OF LEAF-CURLING PLUM APHID AND DAMSON-HOP APHID POPULATIONS ON PLUM TREES[1].

| | LOG (n+1) MEAN APHID COUNTS[2] | |
|---|---|---|
| SAMPLING HEIGHT | **Damson-hop aphid** | **Leaf-curling plum aphid** |
| **< 1.5 m** | 1.44[a] | 2.89[a] |
| **1.5-2.25 m** | 1.47[a] | 4.28[b] |
| **>2.25 m** | 0.95[a] | 3.43[a] |
| SED (0.05, 0.01 and 11 d.f.) | 0.900 | 0.299 |

[1] Summary of 10 weekly records.
[2] Means subtended by the same letter are not significantly different ($p<0.05$), by an LSD test.

EXPERIMENT III

In 1995, predator-release experiments were conducted on potted whole blackthorn trees which had been inoculated with damson-hop aphid. The trees were uncaged throughout the experiment and, as a result, the aphid populations were subject to attack by local natural enemies. These natural enemy populations were augmented by separate releases of the laboratory-reared larvae of the common green lacewing and the 10-spot ladybird. Figure 11 shows the relationship between the numbers of released predatory larvae and the corresponding population densities of damson-hop aphid. Aphid numbers on the control treatments, onto which no predators had been released, were only significantly higher than treatments inoculated with predators during the period 9-16 June ($p<0.05$). Larvae of the common green lacewing appeared to be less effective predators than those of the 10-spot ladybird (Figure 11). Lacewing larvae tend to disperse rapidly from release sites and, as a result, control of the target pest can be less reliable. The larvae of the 10-spot ladybird appeared to disperse from release sites less readily, provided there were sufficient aphid prey available there. Thus, ladybird larvae may prove to be more effective predators than lacewing larvae within the orchard situation. Considering the abundance of naturally-occurring ladybirds within plum orchards (see section 2.3.1.2), ladybird larvae may be better suited than lacewing larvae as predators for use in augmentative releases. However, to date, aphidophagous ladybird larvae (or indeed adults) are not available commercially in the UK.

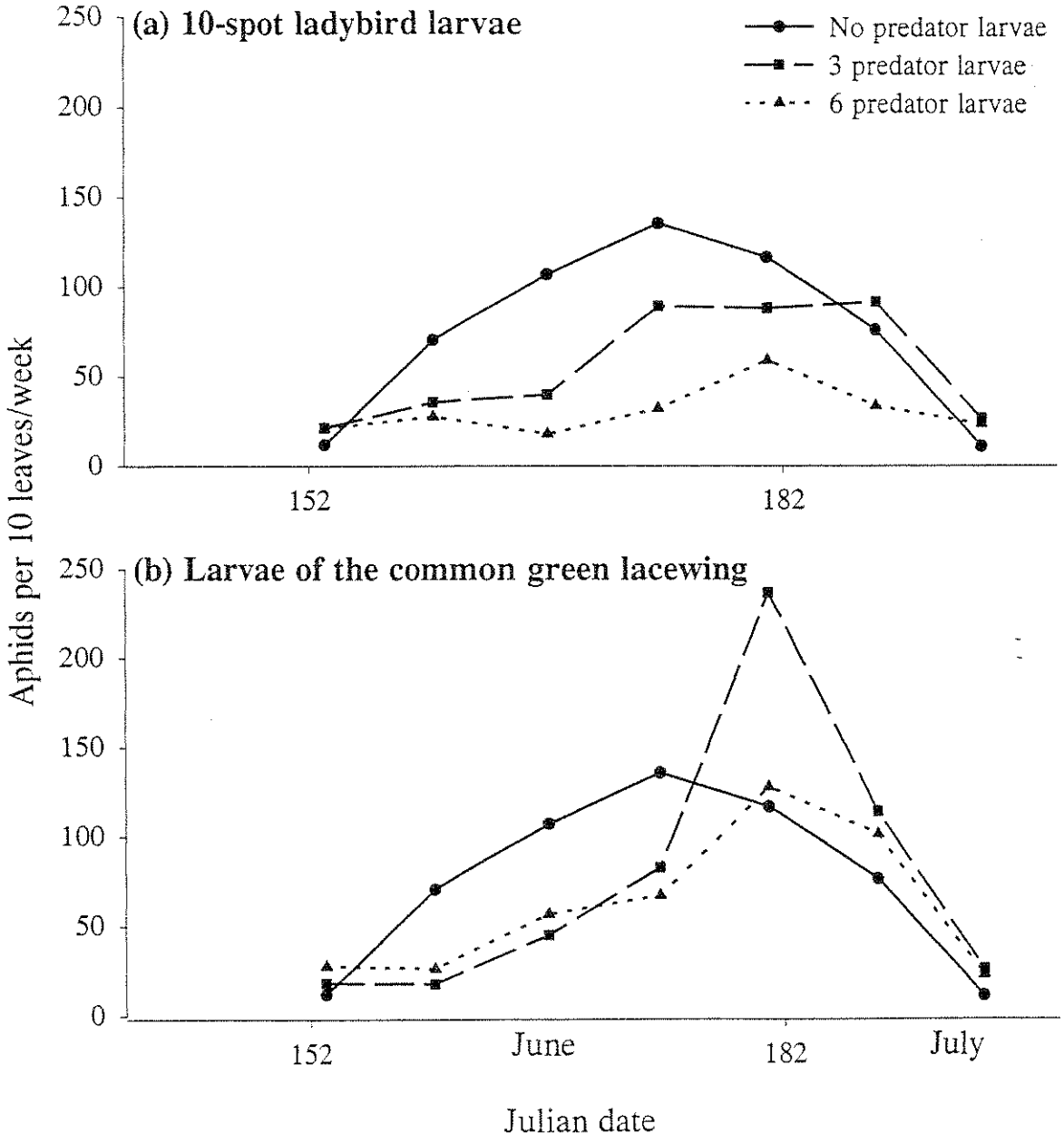
### 2.3.4 Novel approaches to damson-hop aphid control

#### 2.3.4.1 *Verticillium lecanii* as a microbial insecticide of damson-hop aphid in the laboratory and field

LABORATORY STUDY

The aphicidal potential of *V. lecanii* was confirmed; 38% of the damson-hop aphid gynoparae which had been inoculated with the fungus died within 48 hours, and 75% died within 8 days. All aphid deaths were due to mycosis, as evidenced by sporulation on the surface of the cadavers. After 4 days, 6% of the oviparous offspring of the inoculated gynoparae had also died as a result of fungal infection. Infection by *V. lecanii* was not evident in any of the control populations.

FIGURE 11. COMPARING THE EFFECTIVENESS OF LARVAE OF THE 10-SPOT LADYBIRD LARVAE AND LARVAE OF THE COMMON GREEN LACEWING AS PREDATORS OF DAMSON-HOP APHID ON BLACKTHORN TREES.



Damson-hop aphid gynoparae larviposit the majority of oviparae within 48 hours of their final moult. With up to 40% mortality occurring among inoculated gynoparae by way of fungal infection, within the same time period, there is potential for a significant reduction in the numbers of resulting oviparae. The laboratory studies also showed that transmission of *V. lecanii* occurred from damson-hop aphid gynoparae to their oviparous offspring.

FIELD TRIAL

Infection by *V. lecanii* accounted for 92% of deaths among inoculated gynoparae recovered from the field. Production of oviparae by gynoparae inoculated with *V. lecanii* was nearly 50% lower than that by control gynoparae; however, this was not significant statistically. Inoculation of males prior to introduction into the field had no significant effect on either numbers of oviparae, or resulting eggs, but it was not possible to assess whether eggs were contaminated with spores. These field studies have shown that transmission of the entomopathogen *V. lecanii* between aphid morphs is possible under autumnal weather regimes. Indeed, it appeared that aphid mortality due to fungal infection was amplified by additional stresses (e.g. weather) not present under laboratory conditions. It may also be possible that aphid mummies (containing *V. lecanii* spores) remain on the host plant over winter to serve as sources of infection in the following spring. Entomopathogenic fungi such as *V. lecanii* show considerable potential for the control of aphid populations under field conditions and warrant further study as components of integrated control strategies.

### 2.3.4.2 Influence of synthetic semiochemicals on insects within plum orchards

Trials were conducted in 1994 and 1995 to assess the practical efficiency of traps releasing damson-hop aphid sex pheromone within plum orchards.

Damson-hop aphid gynoparae were only caught in traps during early October in 1995 and significantly greater numbers were found in traps releasing sex-pheromone. In 1994, male damson-hop aphids were found exclusively within pheromone-baited traps, providing the first conclusive evidence that the synthetic sex-pheromone is attractive to aphids within an orchard of the aphid's primary host, *Prunus* spp. (Table 12). Furthermore, the strength of the attraction was sufficient to draw male damson-hop aphids into the internal arena of the louvred traps and onto

a dish which, in future trials, could contain a fungal inoculum. In 1995, the occurrence of male damson-hop aphid was divided clearly into two main 'catching-periods' (see Table 12). Catches of males were consistent across the two periods and there was a clear effect of the pheromone (Table 12). Again, the strength of this attraction was sufficient to draw male damson-hop aphids into the internal arenas of the louvred and the 'Waspy' trap, where they came into contact with the fungal inoculum. In 1995, the pheromone-releasing louvred-traps and 'Waspy'-traps were more effective than pheromone-releasing water-traps in attracting males (Table 12). The 'Waspy'-trap was at least as effective as the louvred-trap, if not more so. Considering the commercial availability of the 'Waspy'-trap, it offers an efficient 'live' trap design that may provide a readily available means for disseminating fungal pathogens among the oviparous aphid population and thus provide a novel component for improving the IPM of damson-hop aphid, and potentially other aphid pests, on plum.

TABLE 12. TOTAL NUMBER OF MALE DAMSON-HOP APHIDS CAUGHT IN PHEROMONE-RELEASING [(4a*R*, 7*S*, 7a*S*)-nepetalactol] AND CONTROL, YELLOW PETRI DISH WATER TRAPS, LOUVRED TRAPS AND 'WASPY' TRAPS PLACED WITHIN A PLUM ORCHARD DURING AUTUMN 1994 AND 1995.

| **Yellow trap type**[1] | | **1994** | **1995** | |
|---|---|---|---|---|
| | | **27 Oct. - 1 Dec.** | **2 - 20 Oct.** | **31 Oct. - 20 Nov.** |
| Water trap | B | 0 | 2 | 1 |
| | P | 41 | 19 | 12 |
| Louvred trap | BO | 0 | 0 | 1 |
| | P | - | 0 | 0 |
| | PO | 21 | 18 | 21 |
| | PI | - | 3 | 0 |
| 'Waspy' trap | BO | - | 0 | 0 |
| | P | - | 0 | 0 |
| | PO | - | 34 | 11 |
| | PI | - | 0 | 0 |

[1] Where B = blank, releasing solvent only, P = pheromone-releasing, O = trap with Oecotak to capture attracted aphids, and I = trap with fungal inoculum.

### 2.3.5 The value of a selective aphicide to an IPM programme for plum aphid control

Within European stone-fruit orchards where growers have adopted integrated production techniques, IPM policy depends upon the rationalised use of selective insecticides. The introduction of such IPM techniques in plum, incorporating the use of the selective aphicide pirimicarb (Aphox), can reduce the number of treatments and overall insecticide costs by 40% compared to orchards where conventional pest management is practised (Malavolta *et al.*, 1995).

In the UK, current orchard management practices also carry a higher environmental cost. The prophylactic use of highly toxic tar-oil winter washes and conventional broad-spectrum spring-applied insecticide sprays kill the majority of aphid natural enemies present within plum orchards. It is clear that, for plum aphids, such chemical controls are not compatible with biological control. However, it would be unwise to completely reject the use of insecticides in favour of biological control, despite the clear potential of natural enemies to control aphid populations on plum.

Damaging populations of leaf-curling plum aphids build up too early in the season to be controlled effectively by local natural enemies (see section 2.3.1.2). Therefore, it is necessary to use an insecticide to control this aphid species. Figure 12 shows that a single application of the selective insecticide pirimicarb significantly reduced numbers of leaf-curling plum aphid in sprayed plots compared to untreated plots in 1995 and 1996 ($p<0.001$ in both years). Furthermore, in 1996, there was no significant difference ($p>0.05$) between the numbers of leaf-curling plum aphids in samples from pirimicarb-sprayed WM-EM plots and in samples from DR-EM, an orchard that was under conventional management and had received multiple prophylactically-applied insecticide sprays (including tar-oil). As expected, damson-hop aphid was unaffected by the application of pirimicarb. In 1996, the numbers of damson-hop aphid were unusually high in WM-EM, whereas in most plum orchards they were generally small. This was also reflected by the small spring migration of damson-hop aphid recorded in RIS suction trap samples during 1996. In the autumn of 1995, large numbers of damson-hop aphid gynoparae and males were released into an inclusion cage in WM-EM as part of an egg mortality study (see section 2.2.4.1). It is possible that a proportion of the aphids released into this cage escaped and consequently increased the natural population levels of damson-hop aphid in WM-EM.

FIGURE 12. PLUM APHID PHENOLOGY IN UNTREATED (○) AND PIRIMICARB-SPRAYED (●) WM-EM PLOTS.

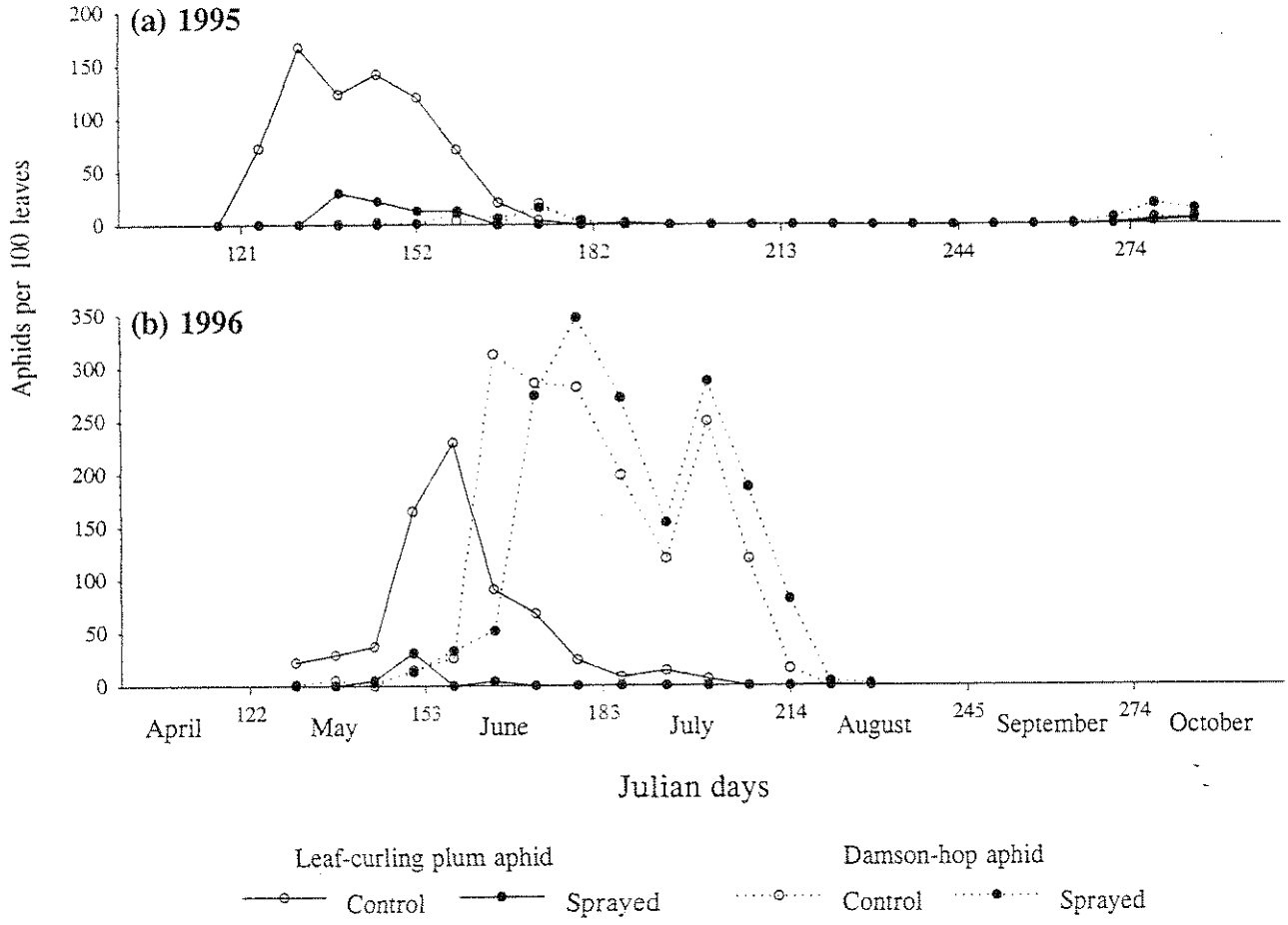


Table 13 shows that, in both years, the numbers of the most abundant polyphagous predators (spiders and earwigs) sampled within the untreated plots and the pirimicarb-sprayed plots were not significantly different. Differences in abundance of predator groups between the untreated and pirimicarb-sprayed plots were evident for some aphid-specific species, such as the ladybirds. In 1995, the catches of ladybirds were dominated by larvae (64%) which were found exclusively within the untreated plots. Predatory ladybird beetles usually require abundant supplies of prey to stimulate egg-laying. Hence, the total absence of ladybird larvae from pirimicarb-sprayed orchard plots reflected the low numbers of aphid prey that were available, i.e. the absence of any ovipositional stimuli for adults. Once adult, these aphid predators became more mobile and consequently were equally abundant in untreated and sprayed orchard plots. In 1996, the numbers of aphid-specific predators such as ladybirds and green lacewings did not differ significantly between untreated and pirimicarb-sprayed plots because the artificially high numbers of damson-

TABLE 13. TOTAL NUMBER OF VARIOUS PREDATORY ARTHROPODS CAUGHT DURING THE PERIOD OF DAMSON-HOP APHID INFESTATION IN 1995 AND 1996, USING BEAT-SAMPLING WITHIN UNTREATED AND PIRIMICARB-SPRAYED PLUM ORCHARD (WM-EM) PLOTS.

| | **1995** (18 May - 6 July) | | **1996** (9 May - 15 August) | |
|---|---|---|---|---|
| Arthropod taxa | Untreated plots | Pirimicarb-sprayed plots | Untreated plots | Pirimicarb-sprayed plots |
| Anthocorid bugs | 50 | 13 | 240 | 177 |
| Cantharid beetles | 4 | 4 | 20 | 16 |
| Earwigs | 333 | 255 | 370 | 404 |
| Green lacewings[1] | 16 | 0 | 46 | 48 |
| Hoverflies[1] | 4 | 1 | 53 | 19 |
| Ladybird beetles | 97 | 6 | 416 | 402 |
| Mirid bugs | 64 | 55 | 122 | 86 |
| Spiders | 359 | 245 | 318 | 250 |
| **TOTAL** | **927** | **579** | **1585** | **1402** |

[1] Larval stages only.

hop aphid provided sufficient ovipositional stimuli.

When applied correctly, pirimicarb has little harmful effect on ladybirds, other aphid predators and beneficials such as bees.

These studies have shown the value of the selective aphicide pirimicarb for the integrated control of plum aphids in the UK. Control of severely damaging leaf-curling plum aphid populations can be achieved with a single, accurately-timed application of pirimicarb. The rationalised use of this selective aphicide had no detectable effects on the most abundant indigenous natural enemies present in the orchard. With these predator populations intact, insecticide-resistant populations of damson-hop aphid that occur later in the season are predated heavily and can thus be prevented from reaching damaging levels.

As a result of this research, the HDC have now obtained full approval for the off-label use of pirimicarb (Aphox) to control leaf-curling plum aphid and mealy plum aphid in plum orchards. The availability of pirimicarb to UK plum growers has enhanced considerably the prospects for the integrated control of aphid pests in this crop.

## 2.4 CONCLUSIONS

- Aphid populations on plum follow a clear pattern during spring, where leaf-curling aphid, having hatched first, rapidly builds up into larger numbers earlier than either damson-hop aphid or mealy plum aphid.

- The lack of synchrony between the build-up of 'early-season' leaf-curling plum aphid populations and the increase in the numbers of beneficial insects means that it is necessary to use an insecticide to control this damaging aphid species.

- The chemical controls available at the start of this study are either of limited use against insecticide-resistant populations of damson-hop aphid (spring-applied sprays) or give inconsistent results (tar-oils). All of these insecticides are non-selective and destroy aphid natural enemies.

- Monitoring studies have identified a diverse range of aphid predators, parasitoids and fungal pathogens in orchards where non-selective pesticides are not used. Furthermore, exclusion cage experiments have demonstrated the large impact of these natural enemies on insecticide-resistant damson-hop aphid populations.

- The insecticide pirimicarb gave excellent control of leaf-curling plum aphid and mealy plum aphid. Because this insecticide is selective it leaves natural enemy populations intact. As a result, the populations of damson-hop aphid occurring later in the season are heavily predated. The availability of this aphicide to plum growers via a SOLA has considerably improved prospects for the integrated control of plum aphids in the UK.

- The use of pheromone-releasing 'live' traps, designed to inoculate aphids with fungal pathogens, shows considerable promise as a novel biological control strategy for damson-hop aphid populations on plum, but further development work is necessary before this approach is available to growers. The availability of this species-specific sex pheromone of damson-hop aphid offers other control opportunities that also warrant further investigation.

## GLOSSARY

**Alate:** having wings

**Alatiform/Alatoid:** a nymph which will eventually moult to an alate adult, identified by the presence of wing buds, which are usually only visible in the 3rd or 4th instar.

**Apterous:** wingless

**Autumn migrants:** in heteroecious aphids, alate parthenogenetic females which migrate between the secondary and primary host (= gynoparae).

**Entomopathogen:** any disease organism growing on or in insects.

**Epizootic:** a rapidly spreading disease affecting a large number of animals throughout a large area.

**Fundatrigeniae:** the progeny of the fundatrix.

**Fundatrix:** parthenogenetic female developing from a fertilized egg.

**Gynopara:** a parthenogenetic female which produces oviparae. In heteroecious aphids, gynoparae move to the primary host in autumn.

**Heteroecious:** having an annual alternation between primary and secondary hosts.

**Morph:** an adult phenotype of a species that is morphologically (and/or reproductively) distinct from another phenotype of that species.

**Mummy:** **1.** empty skin of a parasitized aphid, containing or surmounting the cocoon of a parasitic wasp. **2.** a shrivelled, dry cadaver that results from the effects of fungal infection.

**Mycosis:** any infection or disease caused by a fungus.

**Nymph:** a juvenile form without wings or with incomplete wings in insects with incomplete metamorphosis.

**Ovipara:** the sexual female morph of an aphid which mates with males and lays eggs.

**Parasitoid:** an animal, especially an insect, that is parasitic during the larval stage of its life cycle but becomes free-living when adult and always destroys its host.

**Parthenogenesis:** reproduction by development from unfertilized eggs, producing offspring which are genetically identical to the parent.

**Phenology:** recording and study of periodic events, as of flowering, mating, migration, etc., in relation to climactic and other factors.

**Pheromone:** a substance that is secreted by an organism to the outside and causes a specific reaction in a receiving organism of the same species

**Primary host:** the plant on which the sexual phase of the life cycle and egg laying occurs.

**Proximal:** situated towards the point of attachment of a branch.

**Secondary host:** in heteroecious species, the plant on which only parthenogenetic reproduction takes place.

**Semiochemical:** a chemical involved in the interaction between organisms.

**Spring/Primary migrants:** winged parthenogenetic females migrating from primary to secondary host.

## REFERENCES

**Alford, D.V. (1984)**. *The Colour Atlas of Fruit Pests; their recognition, biology and control.* Wolfe Publishing Ltd., London, 320 pp.

**Campbell, C.A.M., Dawson, G.W., Griffiths, D.C., Pettersson, J., Pickett, J.A., Wadhams, L.J. & Woodcock, C.M. (1990)**. The sex attractant of the damson-hop aphid *Phorodon humuli* (Homoptera, Aphididae). J. chem. Ecol., **16:** 3455-3464.

**Easterbrook, M.A., Solomon, M.G., Cranham, J.E. & Souter, E.F. (1985)**. Trials of an integrated pest management programme based on selective pesticides in English apple orchards. Crop. Prot., **4:** 215-230.

**Gratwick, M. (1992)** Ed. *Crop pests in the UK: Collected edition of MAFF leaflets*. Chapman & Hall, London. pp. 56-59.

**Lawson, D.S., Ressig, W.H., Nyrop, J.P. & Brown, S.K. (1994)**. Management of arthropods on columnar apple trees using exclusionary cages. Crop Prot., **13:** 346-356.

**Luck, R.F., Shepard, B.M. & Kenmore, P.E. (1988)**. Experimental methods for evaluating arthropod natural enemies for integrated pest management. A. rev. Ent., **33:** 367-391.

**Malavolta, C., Ponti, I., Pollini, A., Galassi, T., Cravedi, P., Molinari, F. Brunelli, A., Pasini, F., Missere, D., Scudellari, D. & Pizzi, M. (1995)**. The application of integrated production on stone fruits in Emilia-Romagna (Italy). Bull. SROP, **18 (2):** 55-69.

**Niemczyk, E. (1966)**. Predators of aphids, associated with apple orchards. Ecology Aphidoph. Insects, Proc. Symp. Sept. Oct. 1965 Praha-Liblice; Academia, pp. 275-276.

**Solomon, M.G. (1992)**. Exploitation of predators in UK fruit and hop culture. Phytoparasitica **20:** Suppl., 51S-56S.

**Solomon, M.G. & Fitzgerald, J.D. (1990)**. Fenoxycarb, a selective insecticide for inclusion in integrated pest management systems for pear in the UK. J. Hort. Sci., **65:** 535-539.

**Umpleby, R.A. (1996)**. Plum: chemical control of damson-hop aphid. Final Report on HDC Project SF/25, Horticultural Development Council, Petersfield, 26 pp.

**Ward, L.K. (1969)**. A survey of the arthropod fauna of plum trees at East Malling in 1966. Bull. ent. Res., **58:** 581-599.