

## Effects of acaricides, pyrethroids and predator distributions on populations of *Tetranychus urticae* in apple orchards

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**Abstract** We sampled mites in three apple orchards in Nova Scotia, Canada, that had been inoculated with pyrethroid-resistant *Typhlodromus pyri* and had a history of *Tetranychus urticae* outbreaks. The objective of this study was to monitor populations of *T. urticae* and phytoseiid predators on the ground and in trees and to track dispersal between the two habitats. Pesticides were the chief cause of differences in mite dynamics between orchards. In two orchards, application of favourably selective acaricides (abamectin, clofentezine) in 2002, coupled with predation by *T. pyri* in trees and *Neoseiulus fallacis* in ground cover, decreased high *T. urticae* counts and suppressed *Panonychus ulmi*. By 2003 phytoseiids kept the tetranychids at low levels. In a third orchard, application of pyrethroids (cypermethrin, lambda-cyhalothrin), plus an unfavourably selective acaricide (pyridaben) in 2003, suppressed phytoseiids, allowing exponential increases of *T. urticae* in the ground cover and in tree canopies. By 2004 however, increasing numbers of *T. pyri* and application of clofentezine strongly reduced densities of *T. urticae* in tree canopies despite high numbers crawling up from the ground cover. Another influence on *T. urticae* dynamics was the distribution of the phytoseiids, *T. pyri* and *N. fallacis*. When harsh pesticides were avoided, *T. pyri* were numerous in tree canopies. Conversely, only a few *N. fallacis* were found there, even when they were present in the ground cover and on tree trunks. Low numbers were sometimes due to pyrethroid applications or to scarcity of prey. Another factor was

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likely the abundance of *T. pyri*, which not only competes with *N. fallacis*, but also feeds on its larvae and nymphs. The scarcity of a specialist predator of spider mites in trees means that control of *T. urticae* largely depends on *T. pyri*, a generalist predator that is not particularly effective in regulating *T. urticae*.

**Keywords** *Tetranychus urticae* outbreaks · *Typhlodromus pyri* · *Neoseiulus fallacis* · Pesticide effects on biological control · Generalist and specialist phytoseiids · Competition and intra-guild predation

## Introduction

The European red mite *Panonychus ulmi* (Koch) was the only serious, widespread mite pest in apple orchards in Nova Scotia, Canada until the 1990's (Hardman et al. 1991). Severe outbreaks, attributed to suppression of the phytoseiid mite, *Typhlodromus pyri* Scheuten, followed application of pyrethroids to control winter moth *Operophtera brumata* (L.) or fruit-stinging mirids such as the tarnished plant bug *Lygus lineolaris* (Palisot de Beauvois) (Hardman and Gaul 1990; Hardman and Rogers 1998). To remedy this situation, an organophosphate/ pyrethroid resistant strain of *T. pyri* was imported from New Zealand (Hardman et al. 1997). Following successful trials in research orchards (Hardman et al. 1997, 2000), releases of *T. pyri* in commercial orchards via summer-pruned shoots began in 1993 (Hardman and Rogers 1998). By the late 1990's, pyrethroid-resistant *T. pyri* were widely distributed in orchards in the Maritime Provinces of Canada, often with effective biological control occurring within 1–3 year of predator release (Hardman 1999).

The two-spotted spider mite, *Tetranychus urticae* Koch, previously of minor importance, became a serious pest in the late 1990's during a series of warm, dry summers (Hardman 1999). In some orchards, densities of *T. urticae* exceeded the economic threshold—even where *T. pyri* occurred and acaricides were applied (Hardman 1999). Because *T. pyri* is a type 3 generalist predator (McMurtry and Croft 1997) with low to moderate rates of feeding and reproduction (Sabelis 1985), it has a limited ability to control spider mites within a single season (Nyrop et al. 1998) and sometimes fails to regulate *T. urticae* in orchards (Croft and MacRae 1992).

To explore the causes of *T. urticae* outbreaks, Hardman et al. (2005, 2006) conducted a 2-year study in 12–15 commercial apple orchards. Their major findings were: (1) *T. urticae* densities in tree canopies were correlated with numbers of *T. urticae* crawling up tree trunks; (2) *T. pyri* suppressed *T. urticae* population growth in trees; (3) mid-summer heat and drought promoted *T. urticae* immigration into trees and population growth in the tree canopy; (4) the only canopy pesticides associated with higher rates of *T. urticae* immigration and population growth, were the ethylene bis-dithiocarbamate (EBDC) fungicides, which suppressed phytoseiids; and (5) while application of herbicides toxic to *T. urticae* and to their host plants reduced immigration in several orchards, they did not reduce densities of *T. urticae* in the tree canopy.

The objective of the present study, a follow up to that of Hardman et al. (2005), was to obtain a more detailed understanding of the causes of *T. urticae* outbreaks in Nova Scotian orchards. We sampled tetranychids (*T. urticae* and *P. ulmi*) and phytoseiids (*T. pyri*, *N. fallacis* and several minor species) in 2002–2004 in three orchards treated with differing regimes of pyrethroids, acaricides and fungicides. We monitored mites in the ground cover, on tree trunks and in the inner and outer tree canopy to examine mite dynamics within habitats and exchanges between habitats. By examining changes in mite dynamics after

pesticide applications, and spatial and temporal associations between predators and prey in each habitat, we sought to further clarify the role of pesticides and biotic factors in inducing *T. urticae* outbreaks.

## Materials and methods

### *Study sites and sampling zones*

The study was carried out in the Annapolis Valley of Nova Scotia, Canada, in three orchard blocks which had histories of outbreaks of *T. urticae* and which had been inoculated two years (block 3) or five years previously (blocks 1 and 2) with descendants of a pyrethroid resistant strain of *T. pyri* originating from an orchard near Nelson, New Zealand (Hardman et al. 1997). Blocks are portions of apple orchards having the same mix of cultivars, the same cultural practices, and the same pesticide applications. Block 1, measuring 1.4 ha, was near Medford (N 45°10'47.8'', W 064°22'02.1''), tree rows ran north-south, tree spacing was 4.0 × 5.5 m, tree heights varied from 2.5 to 3.5 m, and the major cultivars were Red Delicious and Empire. Block 2 (8.0 ha) was near Upper Canard (N 45°08'07.2'', W 064°27'48.9''), tree rows ran east-west, tree spacing was 4.5 × 7.0 m, tree heights varied from 3.5 to 4.0 m and the major cultivars were Gloster, McIntosh and Ida Red. Block 3 (2.06 ha) was near Kingston (N 44°59'21.6'', W 064°59'49.1''), tree rows ran north-south at a spacing of 3.7 × 5.5 m, tree heights varied from 3.5 to 4.5 m and the major cultivars were McIntosh, Idared, Spartan and Red Delicious. All mite samples taken in each orchard block, whether from ground cover or trees, came from a 10 row-wide sampling zone of trees in the interior of each block.

### *Sampling mites in ground cover vegetation*

In each orchard block, quadrats were selected by throwing a 20 × 20 cm metal wire frame at a single haphazardly chosen location in six adjacent laneways. Plant species were not noted, although the mix of vegetation was probably similar to that recorded by Hardman et al. (2005) in a survey in 12–15 orchards in 2000–2001: the four broad-leaved plants (*Taraxacum officinale* Weber, *Trifolium repens* L., *Plantago major* L. and *Hieracium* spp.), which predominated in laneways (49–66% of total cover), hosted all stages of *T. urticae*, whereas the cool-season perennial grasses (*Agrostis*, *Festuca*, *Poa* spp., 23–30% of total cover) were not favourable hosts for *T. urticae* (see also Meagher and Meyer 1990; Alston 1994). Laneway vegetation from each quadrat was clipped to ground level and placed in 22 cm tall × 10 cm diameter paper cylinders in the laboratory. Cylinders, previously found efficient at extracting *T. urticae* from vegetation, had a paper bottom and were held upright. The upper 4 cm of the inner surface of the cylinder was lined with Tangletrap® to capture upward crawling mites. Cylinders were held in the laboratory at 8–9 h L, 22 ± 1°C, and 50–70% RH. One week later, *T. urticae* and phytoseiids caught in Tangletrap® were counted under a binocular microscope. Phytoseiids were removed from the Tangletrap® by a fine-tipped paint brush after a droplet of commercial organic solvent, Varsol®, was used to free the mite. Specimens were mounted on microscope slides in BioQuip PVA® mounting media (BioQuip Products Inc., Rancho Dominguez, CA, USA) for later examination under a compound microscope. Species from all habitats (ground cover, sticky bands and tree canopies) were identified using the keys of Chant and Hansell (1971) and Chant et al. (1974). Samples in 2002 were taken at approximately 2-week intervals from 2 May to 5 November,

whereas those in 2003 were taken at 1–2-week intervals from 1 May to 31 October with 1–3-days variation in dates among the three orchard blocks. In 2004 samples, all from orchard block 3, were taken at 2-week intervals from 26 April to 12 August. Mites were also counted on single samples of 100 mature leaves of dandelions, *Taraxacum officinale* Weber, per orchard, where 20 leaves were taken from each of five randomly chosen laneways. Dandelions were chosen because they are widely distributed in commercial orchards and are favourable hosts for *T. urticae* (Hardman et al. 2005). In 2002, dandelion leaves were sampled at 2-week intervals from 23 July to 22 October. In 2003, leaves were taken at 1–2 week intervals from 14 May to 26 August.

### *Sampling mites on tree trunks*

Motile *T. urticae* and phytoseiids crawling up or down tree trunks were captured on 5 cm wide bands of masking tape coated with Tangletrap®. First, 6 cm wide duct tape was wrapped around the tree trunks at a height of 50 cm and sealed with silicone sealant to provide a smooth surface and to close off fissures which could allow escapes. Then the sticky band was applied over the duct tape. Bands were affixed to a single haphazardly chosen tree from each of 10 adjacent rows in each orchard block. In 2002, sticky bands were installed 18 April and were replaced at approximately 2-week intervals until 5 November. In 2003, bands were installed 1 May and were replaced at 1–2 week intervals until 31 October with 1–3 day variations in dates among the three orchard blocks. In 2004 bands were installed 24 April and were replaced at 2-week intervals until 26 October. Bands being transferred to and from orchards were temporarily covered with plastic food wrap to prevent them sticking to other objects. On removal dates, bands were brought indoors where mites were counted under a binocular microscope at a magnification of 10–20×. Separate records were kept for mites caught on the bottom margin of bands (those crawling up the tree) and those caught along the top margin (those crawling downward). Because mites were never seen further in than a few millimeters from either edge of the bands, there was no overlap between upward and downward crawling individuals.

On each sampling date, up to 20 phytoseiids per band were removed and placed in BioQuip® PVA mounting medium on glass microscope slides for later identification under a compound microscope. To do this, it was first necessary to cut out a small piece of plastic food wrap covering the portion of the sticky band housing each mite. Then a drop or two of Varsol® was placed on the band to wash away Tangletrap® embedding the mite. Next the mite was transferred by a single-hair paintbrush to a glass slide and washed again in Varsol® to remove any remaining Tangletrap so that the mounting medium could penetrate and clear the mite for identification.

### *Sampling mites in tree canopies*

The basic sampling unit was a single set of 50 middle-aged leaves taken from the six trees surrounding each laneway quadrat. In 2002, leaves were taken at shoulder height from the distal half of scaffold limbs (outer canopy). In 2003, leaves were also taken from the basal half of limbs (inner canopy). Because there were six laneway quadrats in each block, there were also six outer canopy and six inner canopy samples taken on each sampling date. Sampling dates in all years were synchronized with those for laneway quadrats and for sticky bands, except that leaf sampling did not start until leaf expansion in early to mid-June. Samples were stored at most 2 days at 2°C, after which leaves were each passed twice through a mite-brushing machine (Henderson and McBurnie 1943) before mites were

identified and counted on the collecting plate under a binocular microscope. (Mite brushing machines use a small electric motor to rotate firmly mounted, parallel (10 cm long by 3 cm diameter) cylindrical brushes. When firmly held apple leaves are slid down between the rotating brushes, mites are swept downwards onto a circular glass plate which is coated by a thin layer of liquid soap and lanolin to catch the mites). Counts of phytoseiids were based on numbers on half of the glass collecting plate. Plate counts of phytoseiid motile stages were multiplied by a scaling factor of 2.58 because plate counts represent an average of 39 % of the *T. pyri* actually found on leaves and the same extraction efficiency was assumed for *N. fallacis* (Hardman et al. 1997). Phytoseiids were mounted on slides and identified as described above for mites taken from laneway quadrats and sticky bands. In 2002 and 2003, counts for other, often more numerous, phytophagous mites were from 1/16th of the plate. In 2004, counts were from 1/4 of the plate to increase accuracy and to reduce the likelihood of false zeros. Densities of *T. pyri*, *N. fallacis*, *P. ulmi*, and *T. urticae* are listed as the number of motile mites per leaf.

### Statistical analysis

Repeated measures analysis of variance was used to test differences in time series of mite counts in the inner and outer tree canopy. Mite counts were given the  $\log_{10}(x + 0.01)$  transformation before analysis using the SAS GLM procedure (SAS Institute 1994).

### Pesticide applications

Growers' spray decisions were based on advice from a weekly newsletter and from a private pest monitoring company. Growers used airblast sprayers set to a volume of  $600 \text{ l ha}^{-1}$  to apply tree canopy pesticides to manage mites, insect pests, and diseases, primarily apple scab *Venturia inaequalis* (Cke.) Wint. Tree canopy pesticides with common names, trade names and formulations are listed in Table 1. Growers managed vegetation in laneways by periodic mowing. Tree row vegetation was managed by applying glyphosate (Roundup 356 SN, Monsanto Canada Inc.) in late May with one or two additional applications in June and July, as needed. In some cases, the first application was tank mixed with 2,4-D amine (Estamine 600 EC, Interprovincial Cooperative Ltd.) to improve control of dandelions.

## Results

### Pesticide applications

All of the acaricides listed in Table 1 are rated as harmless (<25% population reduction in orchard trials) to *N. fallacis* (Lasnier et al. 2004 and references therein). With *T. pyri*, all acaricides except pyridaben, which is moderately harmful (50–75% reduction), are rated as harmless, or at least favourably selective, because they are less toxic to *T. pyri* than to tetranychids (Hardman et al. 2003). All insecticides are harmless or only slightly harmful to pyrethroid-resistant *T. pyri* (Hardman et al. 2006), whereas pyrethroids and carbaryl are toxic to some strains of *N. fallacis* but not to others (Lasnier et al. 2004; Bostanian et al. 1985). All of the fungicides are rated harmless or slightly harmful to *N. fallacis* (Bostanian et al. 1998), whereas the EBDC's, metiram and zineb, are moderately harmful to *T. pyri* (Hardman et al. 2006).

**Table 1** Number of applications of pesticides in each orchard block in each year

Pesticides applied	Block 1		Block 2		Block 3		
	2002	2003	2002	2003	2002	2003	2004
<i>Acaricides</i>							
Petroleum oil (Superior 70 oil) <sup>a</sup>	0	0	1	0	1	0	0
Abamectin (Agri-Mek 1.9 EC) + petroleum oil	1	0	0	0	0	0	0
Clofentazine (Apollo 500 SC)	0	0	1	0	0	0	1
Pyridaben (Pyramite 75 WP)	1	0	0	0	1	1	0
<i>Pyrethroid insecticides</i>							
<i>Bacillus thuringiensis</i> (Dipel) + cypermethrin <sup>b</sup> (Ripcord 400 EC)	0	0	0	0	0	1	0
Lambda-cyhalothrin (Matador 120 EC)	0	0	0	0	0	1	2
<i>Other insecticides</i>							
Azinphos-methyl (Guthion 50 WP)	3	2	1	2	0	0	0
Acetimidrid (Assail 70 WP)	0	0	0	1	0	0	1
Carbaryl (Sevin XLR)	1	1	0	1	1	0	1
Malathion (Malathion 500 EC)	0	1	0	0	0	1	0
Phosalone (Zolone Flo)	0	0	0	0	1	1	2
Phosmet (Imidan 50 WP)	0	0	0	0	1	0	1
Pirimicarb (Pirimor 50 DF)	1	1	1	1	0	0	0
<i>EBDC fungicides<sup>c</sup></i>							
Metiram prebloom (Polyram 80 DF)	0	0	2	4	5	4	4
Zineb prebloom (Zineb 80 WP)	1	0	0	0	0	0	0
Metiram postbloom (Polyram 80 DF)	2	0	0	0	0	0	2
<i>Other fungicides</i>							
Captan (Maestro 80 DF)	6	10	11	9	5	11	8
Flusilazole (Nustar 20 DF)	2	0	3	1	0	0	0
Kresoxim-methyl (Sovran 50 WG)	0	0	0	0	1	0	0
Myclobutanil (Nova 40 W)	0	2	0	1	0	0	0

<sup>a</sup> Trade names are given in parentheses

<sup>b</sup> Commercial preparation of *Bacillus thuringiensis* var. *kurstaki* plus 10% of the recommended orchard rate of cypermethrin

<sup>c</sup> Ethylene bis-dithiocarbamate fungicides, which are toxic to phytoseiids

### Mite totals in ground cover vegetation

Seasonal totals for *T. urticae* extracted from laneways were much higher than those for *N. fallacis* in all three orchard blocks in 2002 and 2003 (Table 2). While counts of *T. urticae* decreased from 2002 to 2003 in blocks 1 and 2, they increased in block 3. Because of their low numbers, counts of *N. fallacis* in laneways are not shown in Fig. 1–7. The huge imbalance between *T. urticae* and phytoseiid counts seen in laneway quadrats did not occur with mite counts on dandelion leaves. In most cases counts of phytoseiids, whether *N. fallacis* or *T. pyri*, were comparable to those of *T. urticae* (Table 2).

### Population dynamics in orchard block 1

In 2002, there were two acaricide applications: abamectin (14.3 g ai. ha<sup>-1</sup>) on 22 June and pyridaben (225 g ai. ha<sup>-1</sup>) on 20 August (Fig. 1). Counts of *T. urticae* in laneways and on sticky bands decreased 10 to 100-fold from May to July and remained relatively low for the rest of the season (Fig. 1a,b). From May through late August, upward crawling *T. urticae*

**Table 2** Seasonal totals for mites extracted from laneway quadrats or found on dandelion leaves in three orchard blocks in 2002–2003

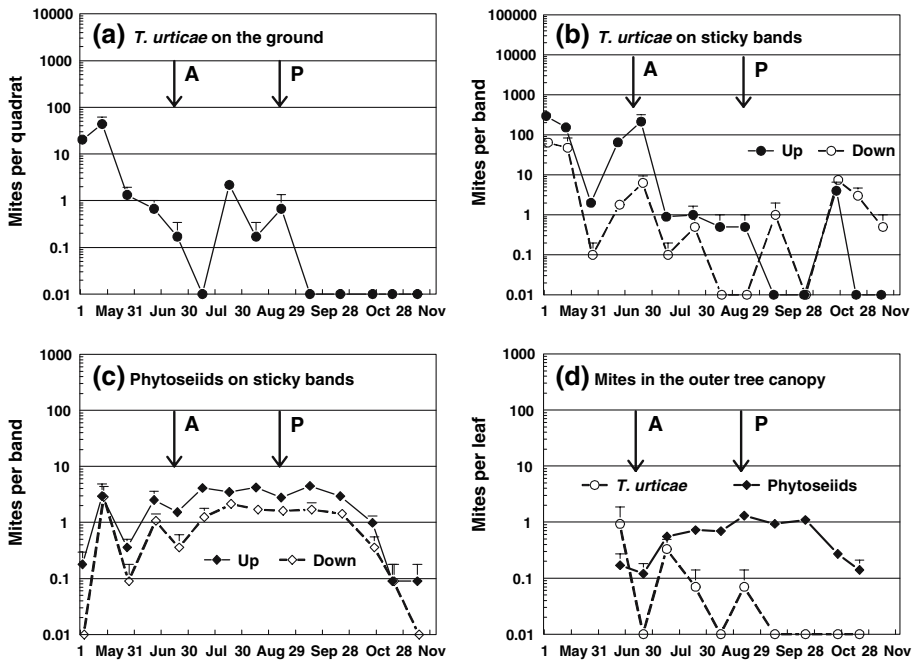
Mite species	Block 1		Block 2		Block 3	
	2002	2003	2002	2003	2002	2003
Laneway quadrats						
<i>Tetranychus urticae</i>	355	14	393	23	326	569
<i>Neoseiulus fallacis</i>	2	0	0	0	8	2
Dandelion leaves						
<i>Tetranychus urticae</i>	1	3	1	5	2	19
<i>Panonychus ulmi</i>	0	0	0	1	0	0
<i>Neoseiulus fallacis</i>	2	0	0	0	0	0
<i>Typhlodromus pyri</i>	2	2	1	0	5	0

outnumbered downward crawlers on sticky bands, but from September onwards downward crawlers predominated (Fig. 1b). *Neoseiulus fallacis* was the most common phytoseiid on sticky bands followed by *T. pyri* and *Neoseiulus iroquois* (Chant and Hansell) (Table 3). Phytoseiid captures on sticky bands, unlike those of *T. urticae*, did not appear to be affected by abamectin or pyridaben (Fig. 1c). Upward crawling phytoseiids equalled or outnumbered downward crawlers all season. Mean densities of *T. urticae* in the tree canopy gradually decreased from 1 per leaf to zero (Fig. 1d). Densities of *P. ulmi* were lower still (0.07 mites per leaf on one date). The phytoseiids, 97% of which were *T. pyri* (Table 4), usually outnumbered the phytophagous mites and did not appear to be suppressed by the two acaricide applications (Fig. 1d).

No acaricides were applied in 2003. Despite this, *T. urticae* counts in laneways (all means <1) and on sticky bands (all means <30) were low all season (Fig. 2a, b). No *N. fallacis* were detected on sticky bands. Overall, the phytoseiids on sticky bands, which included *T. pyri*, *N. iroquois* and *Amblyseius pusillus* (Kennett) (Table 3), were less numerous than the previous year (Fig. 1c, 2c). Phytoseiids in the outer canopy, all of which were *T. pyri* (Table 4), were more numerous than the previous year (Fig. 1d, 2f). Nearly all of the phytoseiids in the inner canopy, except for a few *N. iroquois*, were *T. pyri*. As in 2002, densities of phytoseiids in the tree canopy were usually higher than densities of *T. urticae* and *P. ulmi* (Fig. 2d–f). Although densities of *T. urticae* and *T. pyri* were often higher on inner canopy leaves than on outer canopy leaves (Fig. 2d, f), repeated measures ANOVA indicated no significant effect of canopy habitat (i.e., inner versus outer canopy) on densities of *T. urticae* ( $F = 1.60$ ;  $df = 1, 10$ ;  $P = 0.235$ ) nor on *T. pyri* ( $F = 4.30$ ;  $df = 1, 10$ ;  $P = 0.065$ ). Low densities of *P. ulmi* were only detected twice on outer canopy leaves, where they were more numerous, and once on inner canopy leaves (Fig. 4e). Nonetheless, repeated measures ANOVA indicated a higher density of *P. ulmi* in the outer canopy ( $F = 4.98$ ;  $df = 1, 10$ ;  $P = 0.0498$ ).

#### Population dynamics in orchard block 2

In 2002, the acaricide clofentezine (150 g ai. ha<sup>-1</sup>) was applied in late June. As in block 1 in 2002, *T. urticae* in laneways were already decreasing before the acaricide application (Fig. 3a). Counts on sticky bands decreased at least two orders of magnitude after application (Fig. 3b). As in block 1, upward crawlers outnumbered downward crawlers. Low numbers of phytoseiids, mostly *T. pyri* and *N. fallacis* (Table 3), were caught on sticky bands through the season (Fig. 3c). Low densities of *T. urticae* and *P. ulmi* were present in the tree canopy in



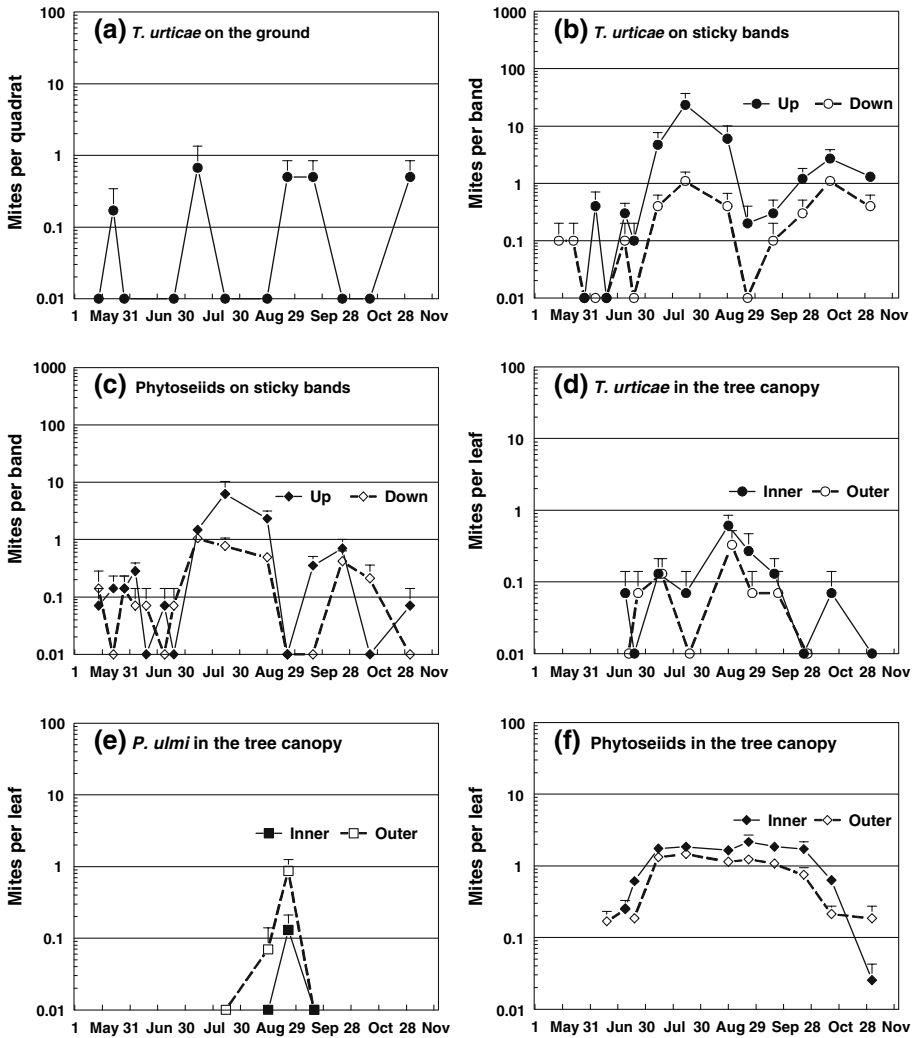
**Fig. 1** Orchard block 1, 2002: mean ( $\pm$ SE) counts of *T. urticae* in laneway quadrats (a), upward and downward crawling *T. urticae* (b) and phytoseiids (c) caught on sticky bands, and number of *T. urticae* and phytoseiids per leaf in the outer canopy of apple trees (d). Arrows indicate dates of application of the acaricides, abamectin (A) and pyridaben (P). In some cases error bars are hidden by the symbols for means

June and July (Fig. 3d). Phytoseiids, 96% of which were *T. pyri* (Table 4), were several times more numerous than the phytophagous mites (Fig. 3d). Clofentezine had no immediate effect on phytoseiid density but a steady decline eventually began in early August.

No acaricides were applied in 2003. Nonetheless, mean counts of *T. urticae* were always low in laneways ( $\leq 1$ ) and on sticky bands ( $\leq 10$ ) (Fig. 4a, b). Upward crawlers on sticky bands were nearly always more numerous than downward crawlers. Only a few phytoseiids, including *T. pyri*, *N. iroquois* and *Typhlodromus caudiglans* (Schuster) (Table 3), were detected crawling up or down tree trunks on most sampling intervals (Fig. 4c). Densities of *T. urticae* in the tree canopy were always  $\leq 2$  per leaf (Fig. 4d) whereas densities of *P. ulmi* were still lower ( $\leq 0.3$  per leaf, Fig. 4e). Densities of *T. urticae* in the inner canopy (Fig. 4d) were significantly higher than those in the outer canopy ( $F = 7.67$ ;  $df = 1, 10$ ;  $P = 0.0198$ ) whereas densities of *P. ulmi* were more often higher in the outer canopy (Fig. 4e), although the difference was not significant ( $F = 0.26$ ;  $df = 1, 10$ ;  $P = 0.6207$ ). All phytoseiids in the tree canopy were *T. pyri* (Table 4). Densities in the inner canopy (Fig. 4f) were higher than those in the outer canopy ( $F = 45.05$ ;  $df = 1, 10$ ;  $P < 0.0001$ ). *Typhlodromus pyri* densities in either habitat were often comparable to, or greater than, the corresponding densities of *T. urticae* and *P. ulmi* and showed an upward trend through most of the season (Fig. 4f).

### Population dynamics in orchard block 3

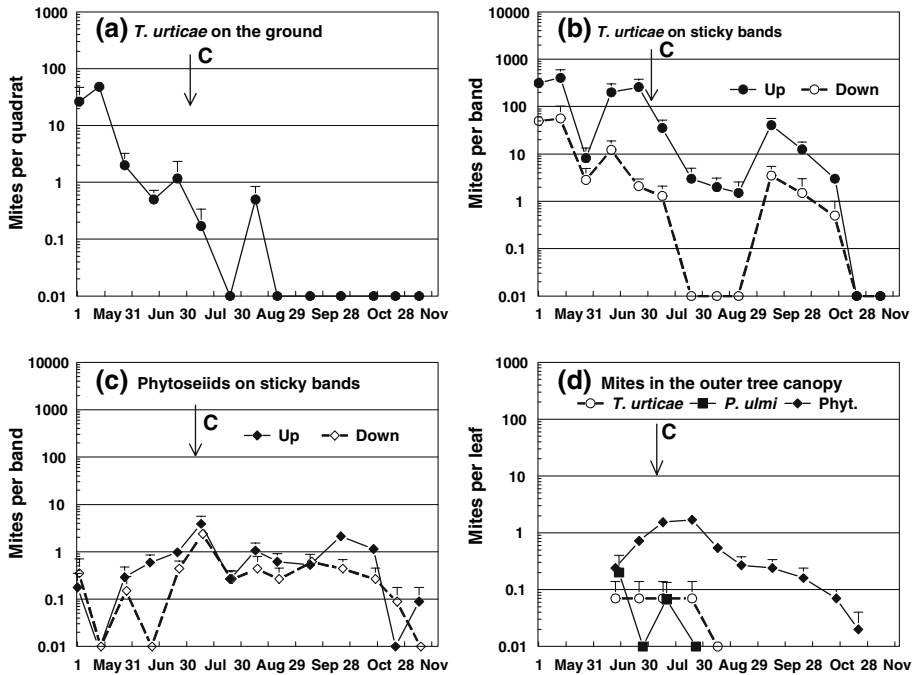
In 2002, there was a late August application of the acaricide pyridaben ( $225 \text{ g ai. ha}^{-1}$ ). Shortly after application, counts of *T. urticae* decreased 2–3 orders of magnitude in laneways



**Fig. 2** Orchard block 1, 2003: mean ( $\pm$ SE) counts of *T. urticae* in laneway quadrats (a), upward and downward crawling *T. urticae* (b) and phytoseiids (c) caught on sticky bands, and number of *T. urticae* (d), *P. ulmi* (e) and phytoseiids (f) per leaf in the inner and outer canopy of apple trees

and on sticky bands (Fig. 5a, b). Earlier counts on sticky bands and in laneways had shown an initial increase followed by a plateau and then by a decrease (Fig. 5a, b). As in blocks 1 and 2, the number of upward crawlers caught on sticky bands usually exceeded the number of downward crawlers. Most phytoseiids caught on bands were *T. pyri* and *N. fallacis* with a few *Chelaseiulus tundra* (Chant and Hansell) and *Neoseiulus salish* (Chant and Hansell) (Table 3, Fig. 5c). Counts were often 100-fold lower than those of *T. urticae*. Tree canopy densities of *T. urticae*, *P. ulmi* and phytoseiids, 99% of which were *T. pyri* (Table 4), decreased after the pyridaben application (Fig. 5d). Before application, densities of *T. pyri* were usually higher than those of the tetranychids, which were always <1 per leaf.

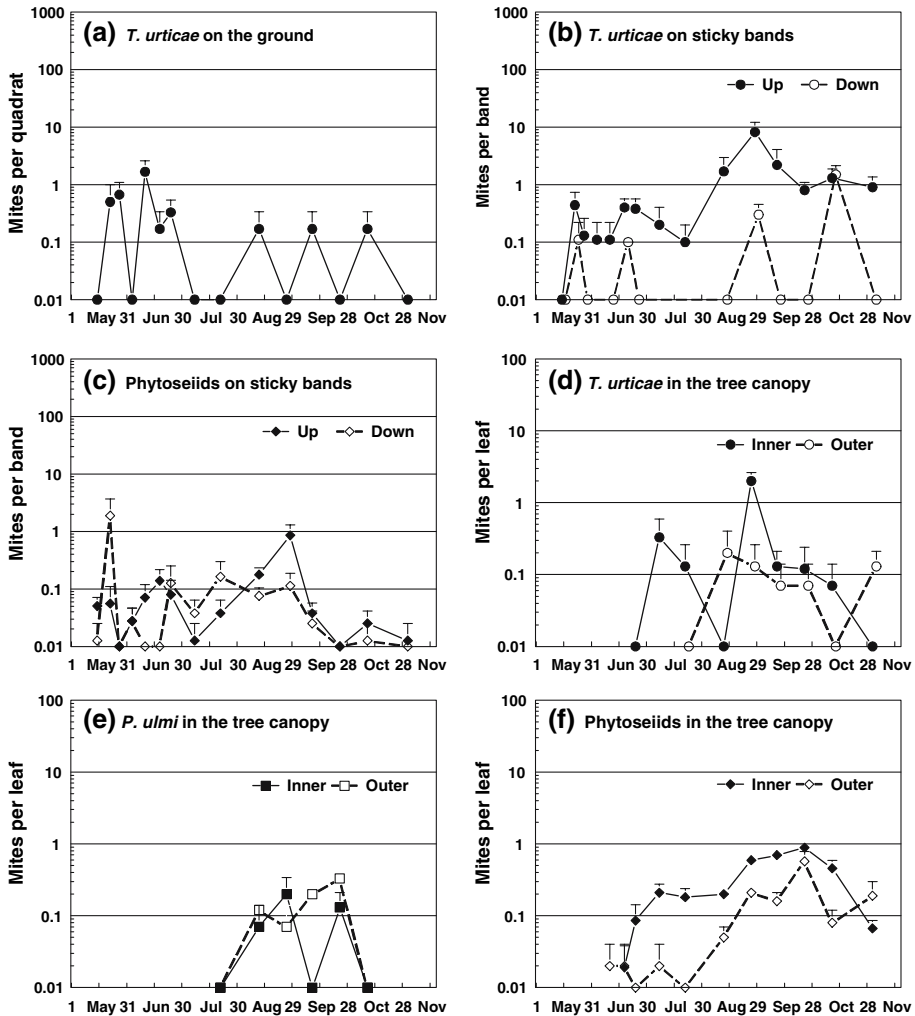
In 2003, the first pyrethroid application was a mixture of Dipel plus dilute cypermethrin (5 g ai. ha<sup>-1</sup>), because the mixture was as efficacious in controlling Lepidoptera as the full



**Fig. 3** Orchard block 2, 2002: mean ( $\pm$ SE) counts of *T. urticae* in laneway quadrats (a), upward and downward crawling *T. urticae* (b) and phytoseiids (c) caught on sticky bands, and number of *T. urticae*, *P. ulmi* and phytoseiids per leaf in the outer canopy of apple trees (d). Arrow indicates date of application of the acaricide, clofentezine

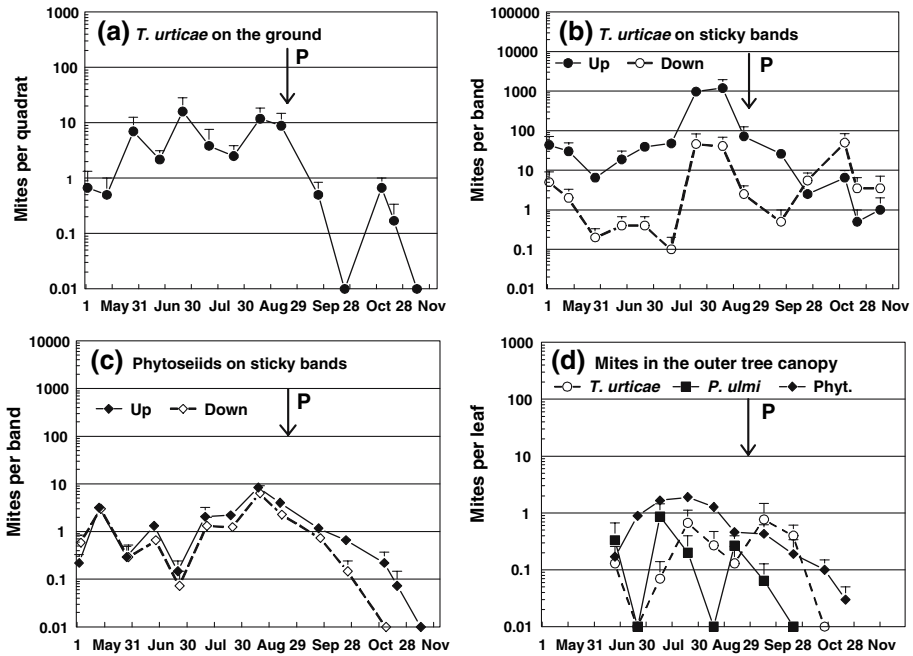
recommended rate of cypermethrin, but less detrimental to phytoseiids (Hardman and Gaul 1990). After this was the full recommended rate of the pyrethroid, lambda-cyhalothrin ( $10 \text{ g ai. ha}^{-1}$ ), in mid-June followed by the acaricide, pyridaben ( $225 \text{ g ai. ha}^{-1}$ ) in late August (Fig. 6). Counts of *T. urticae* in laneways were low in May and June, but by early October they had increased 20-fold (Fig. 6a). A similar increase occurred on sticky bands, first with upward crawling mites, then with downward crawlers (Fig. 6b). The only phytoseiid captured on sticky bands in 2003 was a single *N. fallacis*. The temporal pattern for *T. urticae* in the tree canopy showed the same rise to a plateau seen with mites in laneways and on sticky bands (Fig. 6c). In both the inner and outer canopy, densities increased exponentially from June to early September and then decreased gradually about 2 wk after the pyridaben application (Fig. 6c). Densities were higher in the inner canopy ( $F = 77.87$ ;  $df = 1, 10$ ;  $P < 0.0001$ ) with a mean peak of 90 mites per leaf versus only 20 per leaf in the outer canopy. Densities of *P. ulmi* were 1–2 orders of magnitude lower than those of *T. urticae* (Fig. 6d). Their densities in the inner canopy did not differ from those in the outer canopy ( $F = 0.27$ ;  $df = 1, 10$ ;  $P = 0.6122$ ). Although low densities of phytoseiids, which included both *T. pyri* and *N. fallacis* (Table 4), were detected on most sampling dates in the inner tree canopy, phytoseiids were only detected twice in the outer canopy (Fig. 6e). Phytoseiid densities were higher in the inner canopy than in the outer canopy ( $F = 9.24$ ;  $df = 1, 10$ ;  $P = 0.0125$ ).

In 2004, lambda-cyhalothrin ( $10 \text{ g ai. ha}^{-1}$ ) was applied in mid-June and again in late June followed by clofentezine ( $150 \text{ g ai. ha}^{-1}$ ) in early July. Counts of *T. urticae* in laneways increased from May to late July and then decreased (Fig. 7a). There was a different



**Fig. 4** Orchard block 2, 2003: mean ( $\pm$ SE) counts of *T. urticae* in laneway quadrats (a), upward and downward crawling *T. urticae* (b) and phytoseiids (c) caught on sticky bands, and number of *T. urticae* (d), *P. ulmi* (e) and phytoseiids (f) per leaf in the inner and outer canopy of apple trees in orchard block 2 in 2003

temporal pattern for *T. urticae* caught on sticky bands: the May to early June decline was followed by a rise to a late June-early July plateau, and then by a gradual decline after the clofentezine application (Fig. 7b). Counts of upward crawlers were always several-fold higher than those of downward crawlers. Phytoseiids were not detected on sticky bands. Densities of *T. urticae* in the inner canopy started to decrease a few weeks after the clofentezine application (Fig. 7c). In contrast, densities in the outer canopy increased from mid to late July although they remained significantly lower than those in the inner canopy ( $F = 194.86$ ;  $df = 1, 10$ ;  $P < 0.0001$ ). In both habitats, *T. urticae* were always below the economic threshold of 5 motile stages per leaf. Phytoseiids, 78% *T. pyri* and 22% *N. fallacis* (Table 4), were first detected in mid-July in the inner canopy but those in the outer canopy (100% *T. pyri*) were not recorded until the end of the month (Fig. 7e).



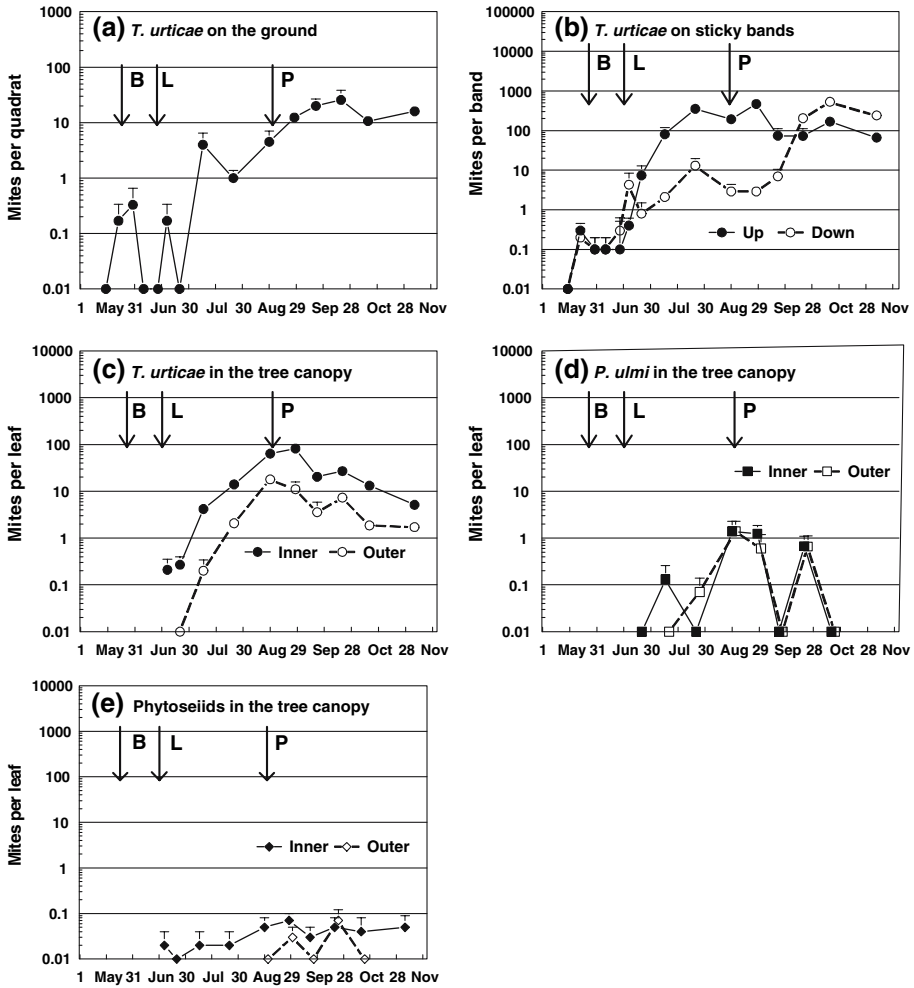
**Fig. 5** Orchard block 3, 2002: mean ( $\pm$ SE) counts of *T. urticae* in laneway quadrats (a), upward and downward crawling *T. urticae* (b) and phytoseiids (c) caught on sticky bands, and number of *T. urticae*, *P. ulmi* and phytoseiids per leaf in the outer canopy of apple trees (d). Arrow indicates date of application of the acaricide, pyridaben

Densities were greater, but not significantly so, in the inner canopy ( $F = 1.97$ ;  $df = 1, 10$ ;  $P = 0.191$ ). Densities in both habitats converged to similar values of 0.5 to 0.7 per leaf by late August. No *P. ulmi* were detected in 2004.

**Discussion**

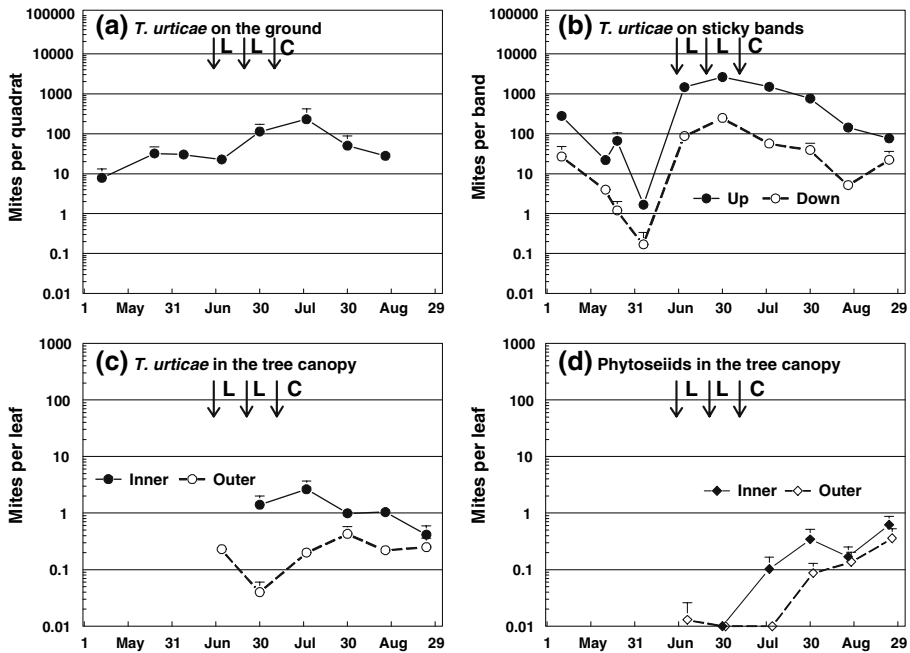
The three orchard blocks examined in this study had contrasting mite dynamics. Blocks 1 and 2 exemplified the restoration of biological control of *T. urticae* by phytoseiids as prey densities decreased in 2002 with the help of acaricides and remained at low levels in 2003 without acaricide application. Conversely, the progression in block 3 was from prey regulation (<5 motile stages of *T. urticae* per leaf) in 2002 to prey outbreak in 2003 with a return to regulation in 2004. Factors which may have induced contrasting *T. urticae* dynamics include weather, pesticide use and predator distributions in the different orchard habitats.

Weather was a major factor in an earlier study (Hardman et al. 2005). Greater heat and a mid-summer drought in 2001 caused more *T. urticae* to crawl up tree trunks and promoted their population growth in tree canopies compared with trends in 2000. These increases occurred in spite of greater acaricide use and the continued presence of *T. pyri*. Statistical comparisons between 2001 and 2000 were facilitated because data were available from 11 orchard blocks that were sampled in both years. Conversely, in this study we only counted mites in three orchard blocks, making statistical comparisons between blocks difficult, at best. There were no midsummer droughts as occurred in 2001: monthly rainfall in summer



**Fig. 6** Orchard block 3, 2003: mean ( $\pm$ SE) counts of *T. urticae* in laneway quadrats (a), upward and downward crawling *T. urticae* (b) caught on sticky bands, and number of *T. urticae* (c), *P. ulmi* (d), and phytoseids (e) per leaf in the inner and outer canopy of apple trees. Arrows indicate dates of application of the pyrethroids, *Bacillus thuringiensis* + dilute cypermethrin (B) and lambda-cyhalothrin (L), and of the acaricide, pyridaben (P)

was always >46 mm for 2002 to 2004. Based on data from Herbert (1981), developmental heat units for local *T. urticae* are computed above a threshold of approximately 10°C, with a mean generation time of 168.9 degree-days ( $^{\circ}D_{10}$ ). Heat units and potential *T. urticae* generations were greater in 2003 (917  $^{\circ}D_{10}$ , 5.4 generations) than in 2002 (829  $^{\circ}D_{10}$ , 4.9 generations) or 2004 (827  $^{\circ}D_{10}$ , 4.9 generations). However, there were no consistent positive associations between *T. urticae* population increases and the warmer weather in 2003. Depending on habitat (ground cover, sticky band or canopy), blocks 1 and 2 showed decreases or no change from 2002 to 2003, whereas in block 3 counts in laneways and on sticky bands increased steadily from 2002 to 2004. The only trend in accordance with greater heat in 2003 was with canopy counts in block 3, which increased from 2002 to 2003. Thus the effects of weather were less evident than in the earlier study (Hardman et al.



**Fig. 7** Orchard block 3, 2004: mean ( $\pm$ SE) counts of *T. urticae* in laneway quadrats (a), upward and downward crawling *T. urticae* (b) caught on sticky bands, and number of *T. urticae* (c) and phytoseiids (d) per leaf in the inner and outer canopy of apple trees. Arrows indicate dates of application of the pyrethroid insecticide, lambda-cyhalothrin (L) and the acaricide, clofentezine (C)

2005). In contrast, there were clear associations between *T. urticae* and phytoseiid dynamics and pesticide applications and there was some evidence that predator distributions in the orchard habitats also affected *T. urticae* dynamics.

Effects of canopy pesticides

Hardman et al. (2006) reported that EBDC fungicides suppressed *T. pyri* in tree canopies and promoted *T. urticae* immigration from ground cover vegetation, likely because of suppression of *N. fallacis*. There was some evidence of *T. pyri* suppression in this study. While EBDC use decreased in block 1 from 2002 to 2003, the reverse occurred in block 2 (Table 1). Decreasing use in block 1 was associated with increasing total *T. pyri* in the outer tree canopy, whereas increasing use in block 2 was associated with a sharp decrease in *T. pyri*. However, acaricides and pyrethroids had more pronounced effects and their use contributed greatly to the contrasts in dynamics between blocks 1 and 2 versus block 3.

Abamectin and clofentezine, favourably selective acaricides, are more toxic to tetranychids than to phytoseiids (Grafton-Cardwell and Hoy 1983; Hardman et al. 2003; Yoo and Kim 2000). In 2002, applications of abamectin in block 1 and clofentezine in block 2 were followed by lower counts of *T. urticae* in laneways, on tree trunks and in tree canopies. Less severe reductions in *T. pyri* led to higher predator-prey ratios in tree canopies. Carry-over effects were evident in 2003 when *T. urticae* and *P. ulmi* remained at low densities, whereas *T. pyri* densities were either higher than or similar to those of their prey. Clofentezine application in block 3 in 2004 was followed by lower *T. urticae* counts in laneways, on

**Table 3** Seasonal total counts of phytoseiids found on sticky bands in each orchard block from 2002 to 2004

Mite species	Block 1		Block 2		Block 3	
	2002	2003	2002	2003	2002	2003
<i>Typhlodromus pyri</i>	150	118	104	13	258	0
<i>Neoseiulus fallacis</i>	218	0	58	0	130	1
<i>Neoseiulus iroquois</i>	86	31	0	5	0	0
<i>Typhlodromus caudiglans</i>	0	0	0	3	0	0
<i>Chelaseius tundra</i>	0	0	3	0	15	0
<i>Neoseiulus salish</i>	0	0	5	0	3	0
<i>Amblyseius pusillus</i>	0	5	0	0	0	0
Total on bands	454	154	170	21	406	1
Phytoseiids identified <sup>a</sup>	127	64	67	8	134	1

<sup>a</sup> Number of slide-mounted mites keyed to species. Estimated counts are the total on bands times the percentage that were a given species

**Table 4** Seasonal total counts of phytoseiids in the tree canopy in each orchard block from 2002 to 2004

Species	Block 1		Block 2		Block 3		
	2002	2003	2002	2003	2002	2003	2004
Outer canopy							
<i>Typhlodromus pyri</i>	337	465	306	75	413	3	33
<i>Neoseiulus fallacis</i>	10	0	14	0	4	3	0
Total on leaves	347	465	320	75	417	6	33
Phytoseiids identified <sup>a</sup>	107	121	113	44	116	6	18
Inner canopy							
<i>Typhlodromus pyri</i>	–	719	–	199	–	14	54
<i>Neoseiulus fallacis</i>	–	0	–	0	–	6	15
<i>Neoseiulus iroquois</i>	–	9	–	0	–	0	0
Total on leaves	–	728	–	199	–	20	69
Phytoseiids identified <sup>a</sup>	–	160	–	100	–	14	9

<sup>a</sup> Number of slide-mounted mites keyed to species. Estimated counts are the total on leaves times the percentage that were a given species

sticky bands and in the inner canopy. Ongoing increases in the outer canopy were likely due to outward dispersal from the more dense population in the inner canopy (Meyer 1974; Meagher and Meyer 1990). Equally important, clofentezine application was actually followed by increases in phytoseiids in the inner and outer tree canopy.

In contrast, the acaricide pyridaben is unfavourably selective because it is more toxic to phytoseiids than to tetranychids (Yoo and Kim 2000; Hardman et al. 2003). Moreover, pyridaben causes greater long-term suppression of *P. ulmi* than of *T. urticae* in orchard trials (Franklin et al. 2002; Hardman et al. 2002), likely because adult *P. ulmi* are more susceptible than adult *T. urticae* (Kimura and Kushita 1994). Thus, pyridaben is not only directly toxic to *T. pyri*, but it shifts the tetranychid complex away from a more nutritious prey (*P. ulmi*) to a less favourable one (*T. urticae*) (Genini 1987, Lester 1998) that is less easily regulated by this predator.

The pyridaben application in block 1 in 2002 was followed by rapid decreases in *T. urticae* in all orchard habitats but surprisingly, in this instance there were no evident adverse effects on *T. pyri* on sticky bands nor in tree canopies. Thus the favourable predator-prey ratio that arose in 2003 was due to the lack of adverse effects on phytoseiids in 2002. A different pattern

occurred in block 3 in 2002: while the application reduced *T. urticae* counts in all habitats, *P. ulmi* densities in the tree canopy decreased more quickly, and *T. pyri* counts on sticky bands and in canopies began a long steady decline. Despite this, the application was followed by low initial counts of *T. urticae* in all habitats in 2003. Pyridaben had less impact in 2003. After application, *T. urticae* counts in laneways or on sticky bands either increased or were slow to decrease. Also densities of *T. urticae* in the tree canopy were slow to decrease below the economic threshold of 5 motile stages per leaf, while phytoseiids remained at very low levels. Moreover, carry-over effects were not favourable: initial laneway and sticky band counts of *T. urticae* were much higher in 2004 than in 2003. However, some of this increase was probably due to the pyrethroid applications in 2003, which had suppressed *T. pyri* and *N. fallacis*, interfering with biological control.

Pyrethroids are well known for their adverse effects on phytoseiids and for inducing outbreaks of tetranychids (Gerson and Cohen 1989), but not when pyrethroid-resistant phytoseiids are present (Hardman et al. 1997, 2000). However, precautions must be taken to prevent the introduced resistant strain from cross-breeding with the indigenous susceptible strain. Hardman et al. (2000) found that application of a pyrethroid in the year of *T. pyri* release (thus eradicating susceptible individuals) ensured continued control of *P. ulmi* in subsequent years, but that outbreaks occurred where pyrethroid application was delayed until the year after release. In this study, the pyrethroid applications in block 3 in 2003 were three years after the release of pyrethroid-resistant *T. pyri*. Applications were soon followed by exponential increases in *T. urticae* in the laneways, on sticky bands and in the tree canopy. Moreover, *T. pyri* densities were low all season. However, by 2004, maximum densities of *T. urticae* in the inner and outer canopy were only 3% of those in 2003, despite two full rate applications of lambda-cyhalothrin. Application of clofentezine in early July and increasing *T. pyri* numbers in tree canopies were the likely causes of this decrease.

Pyrethroids probably had a different effect on *N. fallacis*. Successive increases of *T. urticae* and the scarcity of *N. fallacis* in laneways and on tree trunks from 2002 to 2004 suggest that *N. fallacis* populations were probably pyrethroid-susceptible. The presence of a few *N. fallacis* in trees in 2003 and 2004 was likely due to their high capacity for aerial dispersal, possibly from vegetation outside the orchard (Johnson and Croft 1981).

#### Effects of predator distributions in the orchards

Generalist phytoseiids such as *T. pyri* have difficulty in controlling web-building spider mites such as *T. urticae*, which are highly mobile, and have short generation times coupled with very high reproductive rates (Croft and MacRae 1992). *Typhlodromus pyri* is less mobile than *T. urticae*, and has a much lower rate of population growth (Sabelis 1985). Equally important, *T. pyri* does not aggregate on leaves where tetranychids are located, but is distributed at random in relation to its prey (Nyrop 1988). This means that in early summer, when *T. pyri* and tetranychid densities are low, there will be few encounters between predators and prey, allowing *T. urticae* populations to increase with little hindrance. This is the likely reason why factors such as warm, dry weather, application of pesticides that are only moderately toxic to *T. pyri*, and even modest rates of *T. urticae* immigration from the ground cover may cause a breakdown in biological control.

In contrast to generalists, phytoseiids such as *N. fallacis* and *Metaseiulus occidentalis* (Nesbitt), which are better adapted to feed on web-building tetranychids, readily move between ground cover and trees by crawling or aerial dispersal (Johnson and Croft 1981; Croft and MacRae 1992). Specialists have a narrower diet range, shorter generation times, higher reproductive rates, and will aggregate on leaves where more prey are located

(McMurtry and Croft 1997; Pratt et al. 1999). Many, including *N. fallacis*, are effective natural enemies of *T. urticae* (Westigard et al. 1967; Meyer 1974; Johnson and Croft 1981; Croft and MacRae 1992; Alston 1994).

In this study, the occurrence of *N. fallacis* was sporadic. Very few *N. fallacis* were extracted from laneway quadrats or counted on dandelion leaves. Occasionally higher numbers were counted on sticky bands, but this was because *N. fallacis* crawling up trees could be drawn from areas of several m<sup>2</sup> whereas mites in quadrats were taken from only 0.04 m<sup>2</sup>. The high counts on bands in 2002 were followed by virtually no *N. fallacis* in 2003. Densities of *N. fallacis* in tree canopies were always low, a finding supported by a more extensive survey in 2002–2003 where *T. pyri* heavily outnumbered *N. fallacis* in 11 out of 12 orchard blocks (Hardman and Franklin, unpub. data). A similar pattern was observed in western New York, USA where only four out of the 23 apple orchards surveyed had both *T. pyri* and *N. fallacis* (Nyrop et al. 1994).

Three factors—low prey numbers, application of toxic pesticides, and competition from *T. pyri*—were the most likely causes of the sporadic occurrence of *N. fallacis*. Low counts on tree trunks in blocks 1 and 2 in 2003 were likely due to the scarcity of prey in laneways: few *T. urticae* on the ground often result in few *N. fallacis* in trees (Meyer 1974). Scarcity of prey in tree canopies, evident in every instance except for block 3 in 2003, also contributed to the low numbers of *N. fallacis* always seen in that habitat (Johnson and Croft 1981). A second probable factor was the application of toxic pesticides. Despite high numbers of *T. urticae* in all habitats in block 3 in 2003, counts of *N. fallacis* were low to non-existent. The likely reason was application of pyrethroids, which can cause severe reductions in *N. fallacis* populations in orchards (Bostanian et al. 1985; Li and Harmsen 1992) unless the population is pyrethroid-resistant (Lasnier et al. 2004). In contrast, earlier studies suggest that the organophosphate insecticides (azinphos-methyl, malathion, phosmet, and phosalone), which were applied in all orchard blocks in this study, probably had little impact on *N. fallacis* (Hislop and Prokopy 1981). These assumptions are supported by 24 h laboratory bioassays where the pyrethroids, cypermethrin and lambda-cyhalothrin, caused moderate (>70%) mortality, whereas organophosphates were only slightly toxic (<50% mortality) to local populations of this predator (Franklin JL, unpub. data). Another reason for the scarcity of *N. fallacis* in tree canopies was probably the prevalence of *T. pyri*, which not only competes with *N. fallacis* for prey, but also feeds on the larvae and nymphs of *N. fallacis* (Schausberger 2003). With the exception of block 3 in 2003, *T. pyri*, undoubtedly contributed to the low densities of tetranychid mites seen in all blocks in all years. As already stated, low prey densities are a strong deterrent to colonization of trees by *N. fallacis* (Johnson and Croft 1981). Intra-guild predation was likely also influential. Lester (1998) mentioned this as an important factor when he found that *T. pyri* almost completely eliminated *N. fallacis* within a few weeks, even though the potted apple trees they inhabited were still heavily infested with *P. ulmi*. It is also noteworthy that Croft and MacRae (1992), in their outdoor study with potted apple trees, attributed displacement of the specialist, *G. occidentalis*, by *T. pyri* to intra-guild predation and not just to competition. Whatever the causes of the scarcity of *N. fallacis*, the consequence is a near total dependence on *T. pyri* for biological control of *T. urticae* in apple trees. The low counts of *N. fallacis* and the limitations of *T. pyri* in regulating *T. urticae* are a risk factor predisposing orchards to outbreaks of *T. urticae*.

An interesting aspect of mite distributions in tree canopies was the preference of *T. urticae* and *T. pyri* for the inner canopy. While this tendency was season long in our study, it was temporary for *T. urticae* in the USA (Meyer 1974; Meagher and Meyer 1990) and for *T. pyri* in Europe (Zacharda 1989). Although the effect of this inner canopy bias of *T. urticae* and

*T. pyri* on biological control is not clear, it could be beneficial if it increases overlap of predators and prey on leaves. This aspect of the predator-prey interaction requires further investigation.

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