

## AN ABSTRACT OF THE DISSERTATION OF

Mark A. Morris for the degree of Doctor of Philosophy in Entomology presented on January 20, 1998. Title: Biological Control of *Tetranychus urticae* (Koch) on Peppermint by *Neoseiulus fallacis* (Garman): Density Relationships, Overwintering, Habitat Manipulation and Pesticide Effects.

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Several aspects affecting population trends and overwintering of *Neoseiulus fallacis* (Garman) on peppermint were examined. *Neoseiulus fallacis* was the most abundant phytoseiid predator mite found in peppermint surveys throughout the western U.S. Results of pesticide exclusion and cage studies showed that *N. fallacis* controlled *Tetranychus urticae* (Koch) on peppermint in central Oregon.

*N. fallacis* overwintered in the field mostly in dead peppermint leaves and debris. Augmenting plots with dead leaves increased overwintering survival of *N. fallacis* while the removal of dead leaves decreased overwintering success. Fall applied carbofuran nearly eliminated *N. fallacis*, leading to outbreaks of *T. urticae* the following spring.

Fall flaming peppermint fields in central Oregon decreased densities of *N. fallacis*. By spring, more spider mites were found in flamed fields compared with unflamed fields. More *N. fallacis* motiles and eggs were found after harvest on prostrate peppermint plants compared to erect peppermint plants. There were no differences detected in the densities of spider mites on prostrate compared to erect plants. The net effect of this temporal-spatial asynchrony may be to stabilize the predator-prey interaction. Because predator mites dispersed 7.5 m from unflamed peppermint plots to surrounding flamed areas, providing unflamed refuges for predator mites may reduce the negative impact of fall flaming on spider mite control.

Populations of *T. urticae* collected from western Oregon, central Oregon and Montana were found to be dicofol resistant. Resistance to dicofol in *T. urticae* and

disruption of *N. fallacis* by dicofol may have contributed to increased severity of *T. urticae* in peppermint. Topical applications of acephate, chlorpyrifos, and oxamyl resulted in 100% mortality to *N. fallacis* in bean leaf disk bioassays. When applied to mint foliage in cages, acephate, chlorpyrifos, and oxamyl resulted in 43%, 81%, and 50% mortality to *N. fallacis*, respectively. Application of 2.5 cm of water to cages 30 minutes after pesticides were applied reduced mortality to *N. fallacis* by 25%. These results suggest that predator avoidance, spray coverage, or other factors may reduce the negative impact of certain pesticides on *N. fallacis*.

Biological Control of *Tetranychus urticae* (Koch) on Peppermint by *Neoseiulus fallacis*  
(Garman): Density Relationships, Overwintering, Habitat  
Manipulation and Pesticide Effects

by

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# **Biological Control of *Tetranychus urticae* (Koch) on Peppermint by *Neoseiulus fallacis* (Garmen): Density Relationships, Overwintering, Habitat Manipulation and Pesticide Effects**

## **INTRODUCTION**

Spider mites are important agricultural pests throughout the world (Hoy 1982, Helle and Sabelis 1985). Severe injury may result from spider mite activity on many horticultural crops (Sances et al. 1979, Welter et al. 1984, Raworth 1986, Welter et al. 1989) and field crops (Helle and Sabelis 1985, Berry et al. 1990 and 1991). Aspects of spider mite biology can render their management difficult. Spider mites can rapidly colonize uninfested agricultural habitats, and once established, disperse quickly within such habitats (Fleschner et al. 1956, Brandenburg and Kennedy 1982, Boykin and Campbell 1984, Flexner et al. 1991). Because of their high reproductive potential and short generation time, spider mites can rapidly increase to damaging levels on susceptible crops, and may become resistant to commonly used pesticides (Cranham and Helle 1985, Glass 1986, Roush and Tabashnik 1990).

Prior to the late 1970s, spider mites were not a serious threat to peppermint production (Morrison and Koontz 1967, Anonymous 1968, Berry 1970, Berry 1977). Although spider mites occasionally reached damaging levels on peppermint, outbreaks were limited and occurred only about every 3 to 4 years. During the 1970s, spider mite control in peppermint focused on the registration of miticides. By 1979, several miticides were available for spider mite control in peppermint, e.g. Kelthane (dicofol), Tedion (tetradifon), Omite (propargite), and Metasystox-R (oxydematon-methyl) (Berry 1979). All miticides were considered effective at this time with the exception of Metasystox-R which provided only limited suppression (Simko 1980, Wyman and Rice-Mahr 1992). In the mid-1960s, dicofol exhibited inconsistent spider mite control and resistance was suspected. Results of laboratory resistance bioassays proved negative, however (Berry 1970).

By the early 1980s, spider mites were becoming a more severe problem in peppermint. Mint that was grown in warm, dry climates showed higher incidence of spider mite injury than mint growing in cooler, more humid climates (Hollingsworth 1980, Berry 1982). Over 90% of the peppermint acres in central Oregon were treated for spider mites in 1981, and 21% of these acres were treated twice. This was a 15% increase over the previous year (Calkin and Fisher 1982). In western Oregon, where temperatures are cooler and humidity is higher, less than 10% of the peppermint acres were treated for spider mites. The cause of increased spider mite pressure during this time was not known, although disruption of natural enemies by pesticides or agricultural practices was suspected (Hollingsworth 1980, Hollingsworth and Berry 1983).

The direction of spider mite research on peppermint changed in the late 1970s from a single focus on pesticides to a more integrated approach (Hollingsworth 1980, Berry and Fisher 1993). A sampling plan was developed by Hollingsworth and Berry (1982) to better assess spider mite densities in peppermint fields. Peppermint agricultural practices and secondary plant compounds also were evaluated for their effect on spider mite biology and population trends. In one study, spider mite outbreaks in the spring were delayed by one month when peppermint fields were plowed the previous fall, and lower spider mite levels were observed two weeks following fall propane flaming (Hollingsworth and Berry 1983). Peppermint plants under water stress showed higher spider mite levels than did plants receiving adequate irrigation (Hollingsworth and Berry 1983). Spider mites laid more eggs, developed faster, and dispersed less often on peppermint leaves with lower levels of phenolic compounds compared with leaves having higher phenolic levels (Larson and Berry 1984). The level of monoterpenes in peppermint leaves, however, did not affect spider mite feeding or biology, perhaps because spider mites avoided feeding on the oil glands where monoterpenes are sequestered (Larson and Berry 1984).

To better understand the effect of spider mite injury to peppermint, damage to peppermint leaves was estimated at different mite densities and feeding intervals (Hollingsworth 1980, DeAngelis 1981). Peppermint leaves infested with spider mites showed increased nocturnal transpiration rates and increased daytime water deficits (DeAngelis et al. 1982), decreased leaf weight (DeAngelis et al. 1983a), reduced

photosynthesis (DeAngelis et al. 1983b), and reduced oil quality (DeAngelis et al. 1983c). Nighttime water loss and daytime water stress, resulting from damage to epidermal cells and cuticle, were thought to be the most significant type of spider mite injury to peppermint (DeAngelis et al. 1983c). When allowed to feed for more than 10 days, population levels of 20 spider mites per leaf usually resulted in complete leaf loss (DeAngelis 1983c). In contrast, field studies conducted by Hollingsworth (1980) in central Oregon during the month of July showed no significant decrease in peppermint oil yields, even at a density of 56 spider mites per leaf. This lack of detectable injury may have been related to feeding duration, crop vigor, or high variability in feeding response at the study site. Based on the results of Hollingsworth (1980) and DeAngelis (1981), an economic injury level of 10 spider mites per leaf and an economic threshold of 5 spider mites per leaf were established.

Of concern to the U.S. mint industry, the severity of spider mite infestations on peppermint continued to increase in the 1990s despite the advances made in integrated pest management during the 1980s. More pesticides were applied to peppermint in the western U.S. for spider mite control than for any other arthropod pest. According to 1991 mint grower surveys conducted by the U.S. mint industry, 100% of the peppermint fields in central Oregon were treated for spider mites, 70% in western Oregon, 79% in Idaho, 66% in Washington state, and 63% in Montana (Morris and Lundy 1995). Increased miticide use has placed an economic burden on peppermint producers in the western U.S. Not only have mint production costs increased directly as a result of additional miticide use, but may also have increased indirectly through pesticide resistance. Pesticide resistance is an increasing problem to agriculture worldwide (Cranham and Helle 1985, Glass 1986, Croft 1990). By reducing the number of miticide applications or the actual rate of active ingredient applied, selection for resistance in spider mite populations may be delayed (Roush and Tabashnik 1990, Denholm and Rowland 1992, Flexner et al. 1995).

Pesticide regulatory issues are another concern to the U.S. mint industry. The 1988 amendments to FIFRA (Federal Insecticide Fungicide and Rodenticide Act) have made it more difficult for agricultural commodities to obtain new pesticide registrations

and to keep those pesticides that are currently registered. This is especially true for minor use crops such as mint. Also, the high cost of pesticide research and development has reduced the number of new pesticides available for registration, including selective miticides (Glass 1986, Croft 1990). For these reasons, the feasibility of implementing biological control of spider mites on mint may be worth re-evaluating. The potential for biological control of spider mites on peppermint was first explored in the early 1980s, although this strategy did not seem practical at the time. Of the 18 spider mite predators identified from Oregon peppermint fields in earlier studies, none was present in sufficient numbers to effectively control spider mites (Hollingsworth 1980, Hollingsworth and Berry 1983). The authors suggested that agricultural practices may have reduced the effectiveness of spider mite natural enemies.

This study had four goals: (1) to identify native phytoseiids from peppermint fields in the western U.S. and determine the effectiveness of *N. fallacis*, the most abundant species found in preliminary surveys, (2) to investigate overwintering habitats and population trends of *N. fallacis* in the arid region of central Oregon as well as the effect of certain agricultural practices on its overwintering success, (3) to determine the effect of fall propane flaming on populations of *N. fallacis* and *T. urticae* on peppermint in central Oregon and how both species dispersed within and among peppermint plants following harvest, and (4) to evaluate the use of laboratory and/or semi-field bioassays in determining pesticide resistance among field populations of *T. urticae* and susceptibility of *N. fallacis* to pesticides used in peppermint.

Phytoseiid surveys of peppermint fields in the western U.S. were needed to identify promising candidates for use in spider mite management programs. If an effective native phytoseiid could be identified, possible negative outcomes of releasing non-indigenous species could be avoided. There is an ongoing debate in the literature concerning the risk of releasing exotic natural enemies for biological control (Ehler and Hall 1982, Howarth 1991, Lockwood 1993). Choosing which method or methods to use in evaluating *N. fallacis* for spider mite control was another issue. Most methods used to date have some constraints. Pesticides used in predator exclusion studies may alter the biology of plants, pests and predators (Luck et al. 1988, Berry et al. 1990) whereas a limitation of cage

exclusion studies is that the environment within the cage may differ appreciably from that in the field (Luck et al. 1988). For these reasons, both pesticide exclusion and cage exclusion were used to gain a better understanding of how each related to actual field observations while recognizing the limitations of both methods.

The study on *N. fallacis* overwintering was included because diapausing females were observed on peppermint leaves in central Oregon during the winter of 1989 and 1990. Although *N. fallacis* requires high humidity to survive (Boyne and Hain 1983, Croft et al. 1993), these observations suggested that overwintering survival in peppermint fields is possible in arid growing regions. Because refuges for *N. fallacis* may not exist in central Oregon outside of irrigated cropping systems, disruption of *N. fallacis* in such limited habitats may be detrimental to long-term biological control. To better manage this species for control of spider mites, studies were required to understand overwintering behavior and the effect of agricultural practices on overwintering *N. fallacis*.

The effect of fall flaming on *N. fallacis* and spider mites was studied because higher spider mite populations and lower predator mite levels were observed in fall-flamed peppermint fields. Understanding how fall flaming affects predators may allow for better survival of *N. fallacis*. I also observed that spider mites remained below damaging levels for up to three years in several unflamed peppermint fields in central Oregon. Because *N. fallacis* was usually associated with temporary mite outbreaks in these fields, it appeared that this species may be contributing to long-term regulation of spider mites. Gaining a better understanding of where *N. fallacis* and *T. urticae* occur on flamed versus unflamed peppermint plants may lead to better ways of managing spider mites. Long-term biological control of spider mites by predator mites may be improved by increasing the structural complexity of the agroecosystem (Huffaker 1958, Huffaker et al. 1963). Aspects of meta-population dynamics may also increase the stability of predator-prey interactions. For example, asynchronous colonization of spider mites and predator mites or other factors resulting in predator free spaces may enhance regulation of pests by natural enemies (Nachman 1988).

The impact of pesticides on *T. urticae* and *N. fallacis* was studied because some peppermint fields treated with certain pesticides appeared to have more spider mites and

fewer *N. fallacis* than did other fields that were not treated. Resistance to dicofol in spider mites, disruption of predators by non-selective pesticides, or a combination of both may help explain the increased spider mite severity on peppermint. Resistance to dicofol in spider mites is a common problem worldwide (Saito et al. 1983, Dennehy et al. 1988, Roush and Tabashnik 1990). Although spider mite resistance to dicofol in mint was not found in an earlier study (Berry 1970), the resistance issue is worth re-examining because it has been over 20 years since tests were conducted.

Because disruption of predator mites with pesticides often results in higher spider mite levels (Helle and Sabelis 1985, Croft 1990), pesticides registered for use on mint or pesticides in the registration process should be tested for their effect on *N. fallacis*. Testing new pesticides on natural enemies is often part of the pesticide registration process in many European countries (Jepson 1993, Stark et al. 1995). The difficulty has been trying to decide which testing method or methods to use. Although traditional laboratory bioassays such as slide dips and leaf dips may determine that a pesticide presents no adverse effects, they may over-estimate the toxicity of some pesticides. Under field conditions, the actual risk posed by pesticides in the field to natural enemies may depend on agricultural practices and biological attributes of the natural enemy (Croft 1990, Jepson and Thacker 1990, Jepson 1993, Wiles and Jepson 1995, Stark et al. 1995). For this study, I evaluated a laboratory bioassay and a semi-field bioassay. A laboratory bioassay may be best to determine physiological selectivity and provide a conservative estimate of risk while a semi-field bioassay may be best to determine ecological selectivity.

## Phytoseiid Mites (Parasitiformes: Phytoseiidae) on Peppermint in the Western U.S. and the Effectiveness of *Neoseiulus fallacis* to Control *Tetranychus urticae*

### INTRODUCTION

Predaceous mites are important natural enemies of many arthropod pests (Mostafa et al. 1975, Helle and Sabelis 1985). Of the predator mites that prey on spider mites, those in the family Phytoseiidae are among the most effective at keeping these pests at low levels (Hoy 1982, Helle and Sabelis 1985, Croft 1990, McMurtry 1992). Phytoseiids are effective at controlling spider mites on many crops including almonds, apple, citrus, hops, and strawberry (McMurtry 1969, Croft and McGroarty 1977, Hoy et al. 1979, Hoy 1982, Raworth 1990, Strong and Croft 1993, Coop and Croft 1995).

*Tetranychus urticae* has become an increasingly important pest of peppermint in the western U.S. (DeAngelis et al. 1982, Hollingsworth and Berry 1982, Morris et al. 1996), especially in arid regions such as central Oregon, eastern Washington state, and western Idaho. Because fewer conventional miticides are available to control spider mites (Glass 1986) and because resistance may limit the useful life of those miticides that are available (Cranham and Helle 1985, Croft 1990, Roush and Tabashnik 1990), biological control of spider mites on peppermint may be a desirable alternative.

Several predator mite species in the family Phytoseiidae are associated with spider mites on peppermint in Oregon, although none have been shown to control spider mites. In western Oregon, *Galendromus occidentalis* (Nesbitt), *Amblyseius andersoni* (Chant), and *Amblyseius brevispinus* (Kennett) were identified by Hadam et al. (1986) and Hollingsworth (1980). In central Oregon, *Neoseiulus fallacis* (Garman) was the only phytoseiid species found on peppermint (Hollingsworth and Berry 1983). Hollingsworth and Berry (1983) suggested that certain agricultural practices may be too disruptive for biological control to occur.

Preliminary sampling data obtained during 1989 and 1990 showed that *N. fallacis* was more widely distributed on peppermint in the western U.S. than was previously reported (Morris, personal observation). Moreover, *N. fallacis* was detected at high levels in arid regions of the western U.S. (Morris et al. 1996). Although *N. fallacis* is adversely affected by low humidities and high temperatures (Kramer and Hain 1989, Mangini and Hain 1991, Croft et al. 1993), it may survive on peppermint in arid regions because frequent irrigation provides a suitable microenvironment (Morris et al. 1996). *N. fallacis* also possesses many biological attributes which make it a good candidate for biological control of spider mites, e.g. high fecundity, short development time, high prey consumption, and good dispersal ability (Smith and Newsom 1970a and 1970b, Croft 1975, Santos 1975, Ball 1980, Raworth 1990, Coop and Croft 1995).

Proving the effectiveness of natural enemies to control pests is difficult because experimental methods used to exclude predators in control treatments may alter predator-prey interactions (Luck et al. 1988). For example, exclusion cages can alter the microenvironment and possibly affect the biological control system under study (Sparks et al. 1966, Hand and Keaster 1967). Alternatively, pesticides used to exclude natural enemies from field plots may change the pest's physiology, e.g. increased fecundity or altered sex-ratio (Luck et al. 1988, Gerson and Cohen 1989). Certain pesticides may also affect pest behavior, e.g. through changes in spatial patterns and dispersal (Gerson and Cohen 1989, Berry et al. 1990). Despite these difficulties, estimating the effectiveness of a natural enemy is important for designing pest management programs.

My objectives for this study were to: (1) conduct a survey of phytoseiid species on peppermint in the western U.S. and (2) evaluate the effectiveness of *N. fallacis*, the most abundant phytoseiid species detected in preliminary peppermint surveys.

## MATERIALS AND METHODS

### Phytoseiid survey

To determine which phytoseiid species were present in peppermint in the western U.S., fields were sampled for phytoseiid predators from 1991 through 1995. Only peppermint fields having populations of both spider mites and predator mites were selected for the survey. These conditions were met in over 90% of the peppermint fields that were examined. Phytoseiid predator mites were collected from 30 peppermint fields in each of western Oregon, central Oregon and eastern Washington. Twenty peppermint fields were sampled in northwest Montana, 15 fields in eastern Oregon (near LaGrande), 12 fields in western Idaho, and 6 fields in northern California. Samples were collected from April through September using the method developed by Hollingsworth and Berry (1982). Using a zigzag pattern to cover the field, samples were collected at 30.5 meter intervals. At each sample site, 10 peppermint plants were collected at random and examined for spider mites and predator mites with 16 power magnification. A minimum of 25 sample sites was visited in each field. Plants observed to have predator mites were collected and placed in brown paper bags, paper bags were placed into plastic garbage bags, and the garbage bags were placed into coolers provisioned with ice packs. In the laboratory, specimens were removed from peppermint leaves with a camel hair brush premoistened with 70% ethanol. Specimens were stored in 70% ethanol until they could be cleared in Hoyer's solution, mounted on microscope slides and identified to species.

### Predator mite exclusion

Three experiments were conducted to evaluate the effectiveness of *N. fallacis* to control spider mites on peppermint in central Oregon. *N. fallacis* was selected for evaluation because this species was the most abundant phytoseiid detected in preliminary

**Table 1.** Peppermint fields in central Oregon used in experimental studies (1991-1993).

<u>Location</u>	<u>Variety</u>	<u>Age (yr.)</u>	<u>Field size (ha)</u>	<u>Growth stage (cm)</u> <sup>1/</sup>	<u>Experiments</u>
Lower Bridge	Murray Mitcham	3	16-20	5-10	1
Lower Bridge	Murray Mitcham	3	32-40	2-18	2
Culver	Todd's Mitcham	4	12-15	20-30	3

<sup>1/</sup> Plant height when experiment was initiated

surveys of peppermint in the western U.S. (Morris, unpublished). By evaluating the most dominant species first, I hoped to avoid any detrimental effects that might arise from introducing exotic phytoseiid species. Although introducing multiple phytoseiid species may enhance the long term regulation of spider mites in some agroecosystems (Yao and Chant 1989, Clements and Harmsen 1992, Croft and MacRae 1992, Croft et al. 1992), potential negative effects are also possible, e.g. through competitive exclusion (Ehler and Hall 1982, McMurtry et al. 1984, Howarth 1991).

Information on study sites is summarized in Table 1. All fields were located in a 50 km<sup>2</sup> area in central Oregon. Sprays were made with a CO<sub>2</sub> backpack sprayer. A four nozzle boom was used for experiments 1 and 2 and a single nozzle boom was used for experiment 3. All pesticides were applied in 289 liters of water per hectare. Mite counts were analyzed using Analysis of Variance (ANOVA), and treatment means were compared using Fisher's Protected LSD test at the p=0.05 level (Peterson 1985). Because pesticides used to exclude predators could alter the physiology of the pest (Luck et al. 1988, Gerson and Cohen 1989, Berry et al. 1990), I included a cage exclusion experiment to determine if results obtained by this method differed from those found in the pesticide exclusion experiments.

### ***Experiment 1: pesticide exclusion***

Experimental plots were established in April 1992. Plot size was 549 m<sup>2</sup> (9 m x 61 m). Plots were arranged in a randomized complete block design with 3 replicates per

treatment. Treatments were: (1) esfenvalerate applied at 0.02 kg ai per ha to exclude predator mites and (2) a water only control. The entire field had been treated with esfenvalerate the previous season, reducing the levels of native *N. fallacis* by more than 98%. At the start of this study, *T. urticae* was above economically damaging levels (at least 5 spider mites per leaf). Esfenvalerate was first applied on May 12 to exclude *N. fallacis* and again on June 12 and July 5. To reduce economically damaging levels of *T. urticae*, the grower treated the entire field with propargite (2.2 kg ai per ha) on May 25, June 22 and July 17. Sampling began on May 10 and continued through July 15. Twenty plants were collected randomly from each plot on each sample date, and the number of *T. urticae* and *N. fallacis* motile life stages were counted on each of 6 leaves per plant (2 each from the top, middle and bottom of the plant).

#### ***Experiment 2: pesticide exclusion***

Experimental plots were established in April 1993. Plot size was 550 m<sup>2</sup> (9 m x 61 m). Plots were arranged in a randomized complete block design with 5 replications per treatment. Treatments were: (1) esfenvalerate applied at 0.02 kg ai per ha to exclude predator mites and (2) a water only control. At the time this experiment was initiated, *N. fallacis* was providing acceptable control of *T. urticae* in the study area. Esfenvalerate was first applied on April 13 and again on May 11, June 16 and July 15. Propargite was not applied to the plot area during this study. Sampling began on April 13 and continued through July 29. Sampling methods were the same as for experiment 1.

#### ***Experiment 3: cage exclusion***

This experiment was designed to test the effectiveness of *N. fallacis* using a method other than pesticide exclusion. A second factor was included in this experiment to determine how predator mite effectiveness varied when plots were treated with either propargite or propargite in combination with elemental sulfur. Experimental cages were established in June 1993 in a peppermint field with high levels of *T. urticae* and few *N.*

*fallacis*. Cages (38 cm diameter by 51 cm high cylinders made of 1.3 cm PVC pipe) were placed over the plants. Two rectangles (10 cm by 20 cm) were cut into each cylinder for ventilation. A fine mesh screen was placed over the openings to reduce immigration or emigration of predator mites. In addition, a ring of Tanglefoot adhesive was placed on the inner surface of each cylinder, 5 cm from the top, to prevent escape of mites. A factorial set of treatments was arranged in a completely randomized design with 6 replications per treatment. The first factor had two levels of *N. fallacis*: (1) none detected in the cages and (2) at least 30 *N. fallacis* added per cage. Predator mites, collected from the field where the experiment was conducted, were added to each cage on June 8. The second factor was 3 levels of acaricide treatment: (1) a water only control, (2) propargite applied at 2.2 kg ai per ha and (3) propargite applied at 2.2 kg ai per ha in combination with sulfur (Thiolux 80DF) at 3.3 kg ai per ha. Acaricides were applied on June 14. Experimental units were sampled by collecting 20 plants per sample date and counting the number of *T. urticae* and *N. fallacis* motiles on 6 leaves per plant (two each from the top, middle and bottom of the plant).

## RESULTS AND DISCUSSION

### Phytoseiid survey

Over 90% of the peppermint fields sampled in the western U.S. had spider mites and phytoseiids at some time during the season. Of the phytoseiids collected, 99% were *N. fallacis* (Table 2). This species was by far the most abundant species in each growing region sampled, including western Oregon, central Washington state, western Idaho, and in Montana where it had not been previously detected (Hollingsworth 1980, Hadam et al. 1986). In contrast to the observations of Hollingsworth (1980), *N. fallacis* frequently appeared to be controlling spider mites. Perhaps, mint growers in Oregon had subsequently modified their agricultural practices in ways that enhanced the survival of *N.*

**Table 2.** Abundance of phytoseiid species collected from peppermint fields in the western U.S.

	Peppermint growing regions surveyed <sup>1</sup>						
	CO	WO	LaG	CW	ID	MT	NC
<b>Annual rainfall (cm) <sup>2</sup></b>	31.0	100.8	39.6	20.3	29.2	44.2	36.3
<b>No. fields sampled</b>	30	30	15	30	12	20	6
<b>No. phytoseiids collected</b>							
<i>Neoseiulus fallacis</i>	211	165	87	226	78	146	45
<i>Neoseiulus spp.</i>	1	0	0	0	0	0	0
<i>Galendromus occidentalis</i>	0	0	0	6	0	0	0
<i>Typhlodromus pyri</i>	0	3	0	1	0	0	0
<i>Amblyseius andersoni</i>	0	1	0	0	0	0	1

<sup>1</sup> CO=central Oregon, WO=western Oregon, LaG=LaGrande Oregon, CW=central Washington, ID=Idaho, MT=Montana, NC=Northern California

<sup>2</sup> Based on 30 year averages (1960-1990)

*fallacis*. Another explanation is that *N. fallacis* may have adapted to some of the more conventional peppermint agricultural practices. For example, the development of pesticide resistance in this species and many other phytoseiids is well documented (Croft and Hoying 1975, Hoy 1982, Helle and Sabelis 1985, Croft 1990).

Other phytoseiid species also were found on peppermint in the western U.S., although at levels much lower than for *N. fallacis* (Table 2). *Galendromus occidentalis* was found only in Washington state, and then only in close proximity to apple orchards and hop yards. The occurrence of this species in peppermint was probably the result of immigration from apples and hops where *G. occidentalis* is known to commonly occur (Croft and Hoyt 1983, Strong and Croft 1993). *Typhlodromus pyri* (Scheuten) was detected at low levels in western Oregon and Washington state near wild blackberries and apple orchards, respectively. A single specimen of *Amblyseius andersoni* was found in one peppermint field in western Oregon near wild blackberries and in one peppermint field

in northern California near a field margin. This species is known to occur widely on berry crops in western Oregon (Hadam et al. 1986) and the few found on mint were probably incidental immigrants. The only other phytoseiid collected was an unknown species in the genus *Neoseiulus* found in one peppermint field in central Oregon (Table 2).

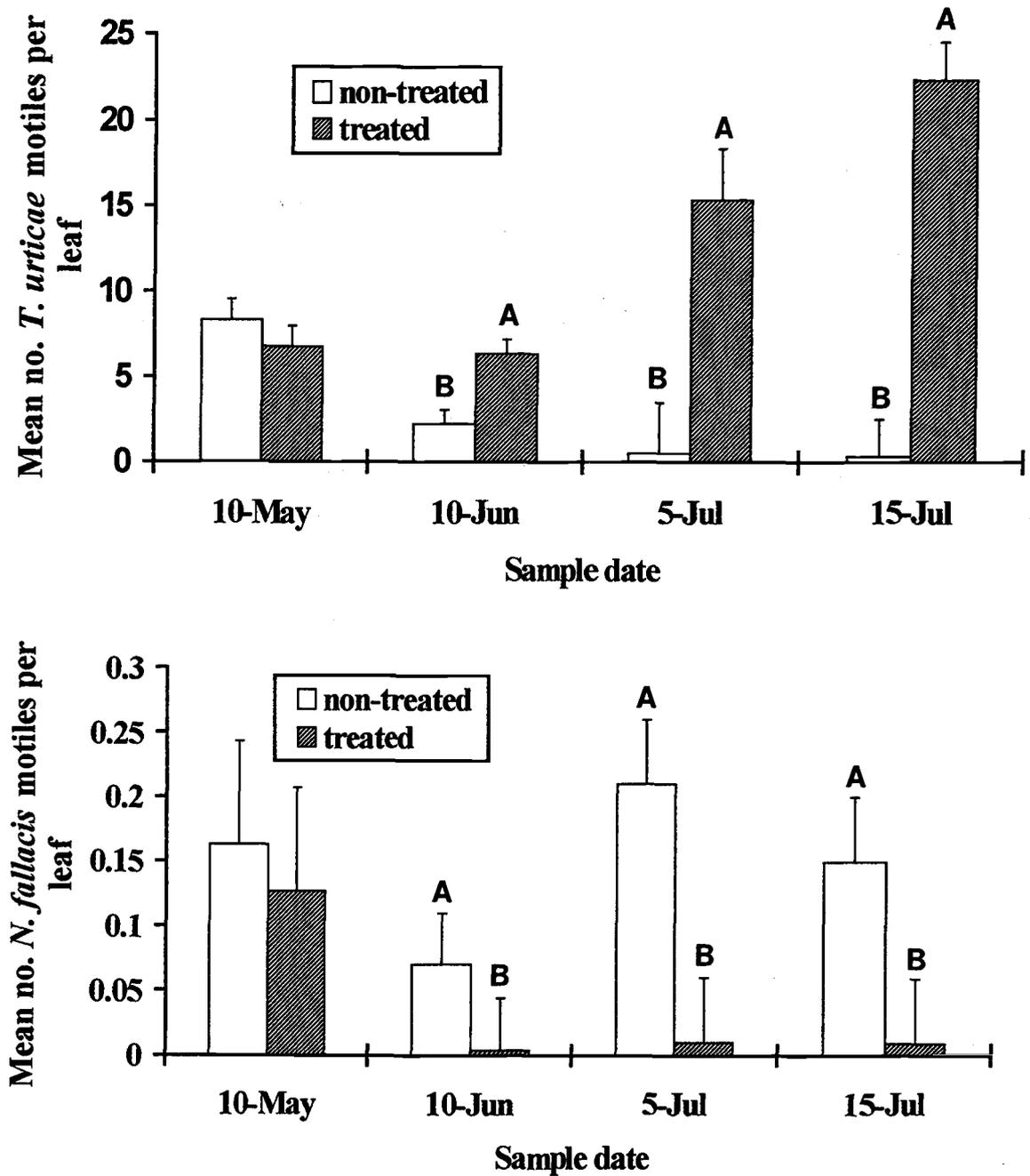
A tydeid mite (*Orthotydeus* spp.) was detected in 27% of the peppermint samples taken throughout the western U.S. Although the ecological role of *Orthotydeus* in peppermint fields is unknown, some species of tydeids may serve as alternate food sources for phytoseiids when their primary food supply is low (Flaherty and Hoy 1971, Hoy et al. 1979, Calis et al. 1988).

## **Predator mite exclusion**

### ***Experiment 1: pesticide exclusion***

In plots treated with esfenvalerate, *T. urticae* motiles increased from 6.77 per leaf on May 10 to 22.34 per leaf on July 15 (Figure 1). Higher levels of *T. urticae* were found in plots where *N. fallacis* was excluded with esfenvalerate on June 10 ( $F=11.74$ ;  $df=1,2$ ;  $P=0.05$ ), July 5 ( $F=8.03$ ;  $df=1,2$ ;  $P=0.07$ ), and July 15 ( $F=51.58$ ;  $df=1,2$ ;  $P=0.02$ ).

Spider mites remained above the economic threshold of 5.0 mites per leaf in treated plots despite three separate applications of propargite. Resistance evolution to propargite in *T. urticae* is well documented (Keena and Granett 1985, Grafton-Cardwell et al. 1987, Keena and Granett 1990), and undoubtedly was a factor involved in the lack of control when sufficient predators were not present to provide adequate biological control. In untreated plots, *T. urticae* motiles decreased from 8.29 per leaf on May 10 to 0.34 per leaf on July 15. These data suggest that spider mites in the control plots were maintained below the treatment threshold (5.0 spider mites per leaf) by the combined action of *N. fallacis* and propargite. Moreover, after July 5, the ratio of predator mites to



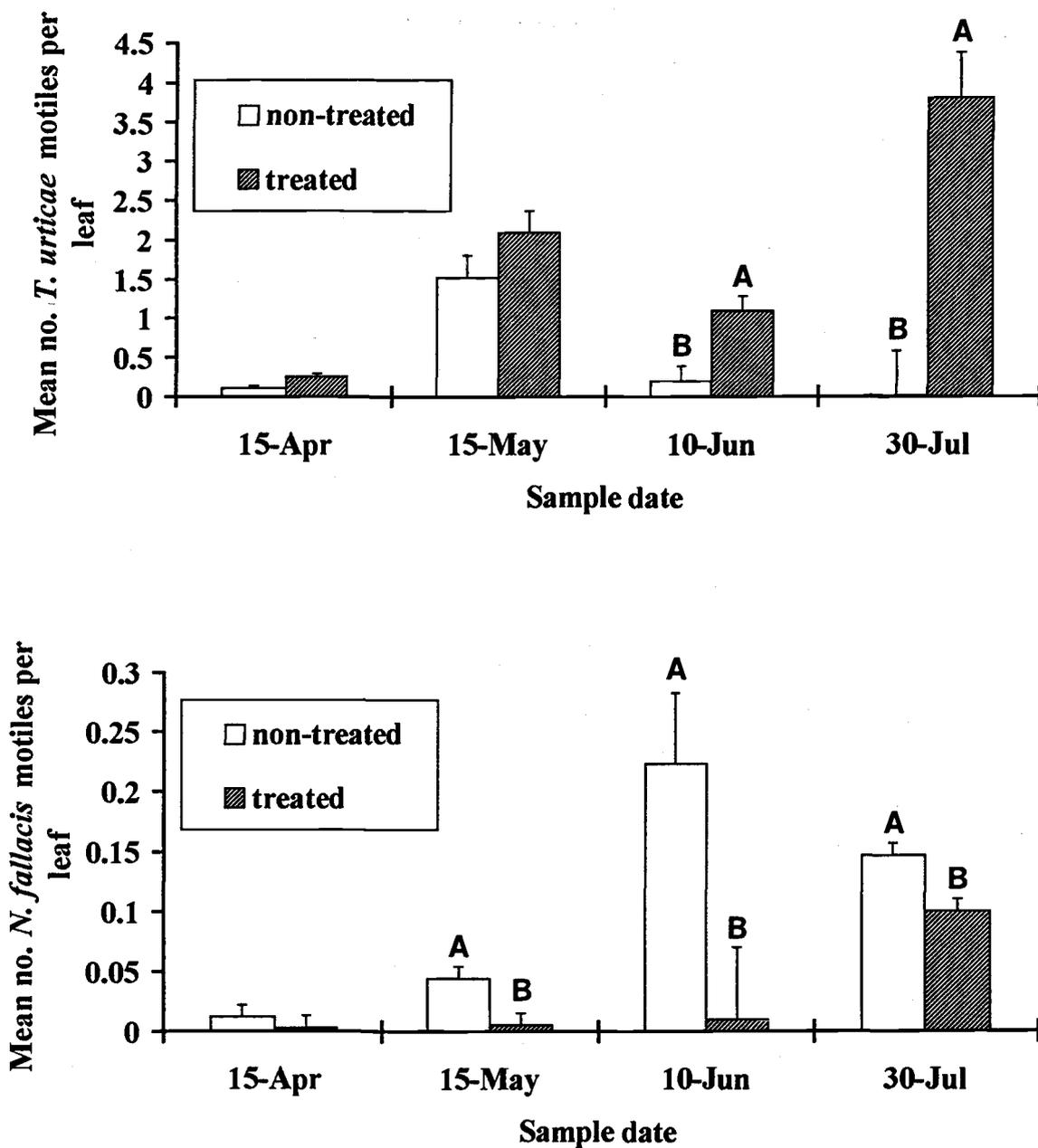
**Figure 1.** Mean number of *T. urticae* and *N. fallacis* motiles per leaf in plots with natural levels of predator mites and plots where predators were excluded with esfenvalerate (central Oregon 1992). Means were compared with Fisher's Protected LSD (Peterson 1985).

spider mites where esfenvalerate was not applied, was within the 1:10 ratio that has been observed to be necessary to control spider mites on other crops (Croft 1975, Croft and McGroarty 1977, Wilson et al. 1984).

Fewer *N. fallacis* motiles were observed in plots treated with esfenvalerate on June 10 ( $F=12.43$ ;  $df=1,2$ ;  $P=0.07$ ) and July 5 ( $F=8.03$ ;  $df=1,2$ ;  $P=0.10$ ), compared with untreated plots (Figure 1). Although esfenvalerate reduced *N. fallacis* in the treated plots by over 90%, it did not exclude them entirely. Because predator mite levels would increase after applying esfenvalerate, three applications spaced about one month apart were required to maintain predator mites at low levels in the treated plots. Also, predator mites from adjacent untreated plots readily dispersed into the treated plots. *N. fallacis* can effectively colonize plants by dispersing on wind currents, especially over short distances (Johnson and Croft 1975, Coop and Croft 1995). When predator mites were observed in the treated plots, they were found colonizing newly formed leaves. Peppermint plants continuously produce new leaves from the plant apex while older leaves at the base of the plant are continuously lost due to senescence. Newly formed leaves are free of esfenvalerate residues and this may allow *N. fallacis* to colonize these leaves first.

### ***Experiment 2: pesticide exclusion***

When this experiment was initiated, spider mites were below the economic threshold and appeared to be under biological control by *N. fallacis*. In plots treated with esfenvalerate, *T. urticae* levels increased from 0.26 mites per leaf on April 15 to 3.80 mites per leaf on July 30 (Figure 2). Higher levels of *T. urticae* were found in treated plots on all sample dates (May 15 ( $F=26.37$ ;  $df=1,4$ ;  $P=0.01$ ), June 10 ( $F=38.21$ ;  $df=1,4$ ;  $P=0.03$ ) and July 30 ( $F=21.26$ ;  $df=1,4$ ;  $P=0.07$ )). In untreated plots, spider mite levels remained below 1.6 mites per leaf throughout the course of this study. As was the case in experiment 1, fewer predator mite motiles were found in plots treated with esfenvalerate compared to untreated plots on May 15 ( $F=19.30$ ;  $P<0.01$ ;  $df=1,4$ ), June 10 ( $F=7.67$ ;  $P=0.05$ ;  $df=1,2$ ) and July 30 ( $F=6.52$ ;  $P=0.06$ ;  $df=1,4$ ) (Figure 2). After June 10, predator mites in the treated plots increased to near levels in the untreated plots because of



**Figure 2.** Mean numbers of *T. urticae* and *N. fallacis* motiles per leaf in plots with natural levels of predator mites and plots where predators were excluded with esfenvalerate (Lower Bridge, Oregon 1993). Means were compared with Fisher's Protected LSD (Peterson 1985).

dispersal from untreated plots, making predator mite exclusion more difficult than for experiment 1.

### ***Experiment 3: cage exclusion***

On June 30, the number of *T. urticae* per leaf detected in the cages depended on the pesticide applied and initial level of predator mites ( $F=9.55$ ;  $df=2,30$ ;  $P<0.01$ ). The highest population of *T. urticae* was found in those cages receiving neither predator mites nor pesticides (Table 3). There were no significant differences in the numbers of *T. urticae* per leaf among the plots receiving predator mites only, pesticides only, or both. On July 14, the number of *T. urticae* depended on the pesticide and predator mite treatment ( $F=14.87$ ;  $df=2,30$ ;  $P<0.01$ ). There were significantly more *T. urticae* per leaf in the control (18.56 per leaf) compared to the other treatments (Table 3). In the absence of predators, propargite applied alone or in combination with sulfur significantly reduced *T. urticae* levels compared with the control. Sulfur improved the efficacy of propargite for spider mite control on this sample date (5.14 *T. urticae* per leaf compared to 10.26 per leaf). All treatments receiving a predator mite inoculation showed significantly lower spider mite numbers than treatments not receiving predators, with the exception of the propargite plus predator mite treatment which did not differ significantly from the propargite plus sulfur treatment (Table 3).

On July 21, a significant interaction among pesticide and predator levels occurred ( $F=6.68$ ;  $df=2,30$ ;  $P<0.01$ ) (Table 3). In the absence of predators, cages treated with propargite or propargite plus sulfur, exhibited significantly lower spider mite densities than the control treatment. Sulfur did not significantly improve the effectiveness of propargite for spider mite control on this sample date (Table 3). All treatments receiving predator mites showed significantly fewer spider mites than did treatments without predators, and no significant differences in spider mite numbers were detected among the treatments receiving predators.

Although the pesticide only treatments were effective in reducing spider mite numbers, spider mites remained near or above the economic threshold of 5.0 spider mites

**Table 3.** The effect of predator mites, propargite, and propargite + sulfur on *T. urticae* motiles (Culver, Oregon 1993).

Sample date	Mean no. <i>T. urticae</i> motiles per leaf <sup>3/</sup>					
	predator mites absent			Predator mites present		
	No miticide	Comite	Comite + S <sup>2/</sup>	No miticide	Comite	Comite + S
June 14 <sup>1/</sup>	32.70 SE=4.90	20.51	18.10	32.72	32.29	16.37
June 18	14.57 SE=2.78	8.58	9.58	13.24	11.79	11.78
June 30	21.3 a SE=1.80	3.05 b	3.58 b	6.19 b	1.11 b	2.55 b
July 14	18.56 a SE=1.25	10.26 b	5.14 c	1.25 d	2.11 cd	1.20 d
July 21	10.52 a SE=0.94	4.10 b	5.56 b	0.34 c	0.53 c	0.71 c

<sup>1/</sup> Pre-application evaluation. Plots were inoculated with predators on June 8, 1993. Pesticides were applied on June 14, 1993.

<sup>2/</sup> Comite + S = propargite (2.2 kg ai per ha) + sulfur (3.3 kg ai per ha)

<sup>3/</sup> Means within rows were compared with Fisher's Protected LSD (Peterson 1985). Means within rows with same letter were not significantly different.

per leaf in treatments not receiving predator mites (Table 3). Predator mites appeared to complement propargite by reducing spider mite populations more than propargite alone. Another way predator mites complement propargite is to maintain spider mites below damaging levels even in the presence of low levels of propargite resistance in the spider mite population. By prolonging the useful life of propargite, predator mites also benefit themselves because propargite is presently the only selective miticide registered for use on mint.

There were significantly more *N. fallacis* in cages receiving predator mites compared to cages that did not receive predator mites on all sample dates (June 18 (F=13.90; df=1,30; P<0.01), June 30 (F=29.07; df=1,30; P<0.01), July 14 (F=13.76; df=1,30; P<0.01) and July 21 (F=25.49; df=1,30; P<0.01)) (Table 4). None of the pesticide applications affected the number of predator mites observed in this experiment. These results suggest that neither propargite nor propargite in combination with sulfur were disruptive to *N. fallacis* in this study. The cages used in this experiment were

**Table 4.** Levels of *N. fallacis* in the six treatments of the cage exclusion study (Culver, Oregon 1993).

Sample date	Mean no. <i>N. fallacis</i> per leaf <sup>3/</sup>					
	No predator mites present			Predator mites present		
	No miticide	Comite	<sup>2/</sup> Comite + S	No miticide	Comite	Comite + S
June 18 <sup>1/</sup>	0.000 a SE=0.019	0.000 a	0.000 a	0.082 b	0.132 b	0.095 b
June 30	0.000 a SE=0.039	0.000 a	0.000 a	0.353 b	0.256 b	0.287 b
July 14	0.000 a SE=0.021	0.000 a	0.004 a	0.196 b	0.045 b	0.086 b
July 21	0.007 a SE=0.012	0.005 a	0.005 a	0.057 b	0.095 b	0.112 b

<sup>1/</sup> Pre-application evaluation. Plots were inoculated with predators on June 8, 1993. Pesticides were applied on June 14, 1993.

<sup>2/</sup> Comite + S = Comite (2.2 kg ai per acre) + sulfur (3.3 kg ai per acre)

<sup>3/</sup> Means within rows were compared with Fisher's Protected LSD (Peterson 1985). Means within rows with same letter were not significantly different.

effective in confining predator mites and preventing significant dispersal of predator mites from untreated to treated cages. Although *N. fallacis* was observed in cages where predators were not released, their level remained low for the duration of this study.

## CONCLUSIONS

*N. fallacis* was the most abundant phytoseiid species found on peppermint in the western U.S. and often was present at levels that appeared to control spider mites. Peppermint is a suitable crop for maintaining *N. fallacis* as part of a spider mite management program because: (1) frequent irrigation results in lush foliage and high humidities which *N. fallacis* prefers (Croft et al. 1993), (2) mint is a perennial crop which allows time for *N. fallacis* to colonize and establish itself and (3) cosmetic tolerance is not an issue in peppermint grown for oil; therefore, higher spider mite levels may be tolerated

before management is necessary. Moreover, these data suggest that *N. fallacis* can be effective in controlling spider mites on peppermint in central Oregon. Spider mites were reduced below damaging levels in the presence of *N. fallacis* in both pesticide and cage exclusion experiments, and they reached damaging levels when *N. fallacis* was excluded by both methods. In the pesticide exclusion experiments it was difficult to maintain low levels of *N. fallacis* in treated plots because of dispersal from adjacent untreated plots.

Ways to enhance biological control of spider mites with *N. fallacis* are suggested by these data. Allowing refugia for *N. fallacis* against disruptive agricultural practices may enhance biological control of spider mites in peppermint. When *N. fallacis* was disrupted by esfenvalerate in pesticide exclusion studies, recolonization occurred from adjacent untreated plots within 1 to 3 weeks as long as plots were small and adequate numbers of *N. fallacis* were present in adjacent plots. Treatment of large, continuous peppermint acreage may not allow for such rapid re-establishment. Managing disruptive agricultural practices may be especially important in arid growing regions where *N. fallacis* may be unable to survive outside irrigated agroecosystems. Based on these results, registration of pesticides that are disruptive to *N. fallacis* should be discouraged unless no other practical alternatives are available.

If peppermint agricultural practices were changed in the future toward a less disruptive management system (e.g. a reduction in pesticide use), a species shift in predator mites favoring other more generalist phytoseiid species may occur. Such species displacements have been seen on other perennial crops when less disruptive practices have been employed (McMurtry 1992, Croft and MacRae 1992, McMurtry and Croft 1997). Although other phytoseiid species were occasionally found on peppermint, their levels were low and often closely associated with preferred plant species that were growing adjacent to peppermint. Possibly, more generalist species would increase in abundance if pesticide use was reduced or management practices were altered to increase long-term stability in the mint system.

## Overwintering and Effect of Fall Habitat Manipulation and Carbofuran on *Neoseiulus fallacis* and *Tetranychus urticae* in Peppermint

### INTRODUCTION

*Neoseiulus fallacis* is distributed across North America where it occurs on many arboreal and low growing crops (Croft and McGroarty 1977, Hadam et al. 1986, Croft et al. 1993). It is a key biological control agent on apples and strawberries in humid areas of the eastern and midwestern USA (Croft 1990). Humidity greatly affects survival of *N. fallacis* and many other phytoseiids (Sabelis 1985, Zhang and Kong 1985, van Dinh et al. 1988, Croft et al. 1993). In a simulation analysis of biological control on corn, Berry et al. (1991) showed that *N. fallacis* was most effective under cool, humid conditions. Their results agreed with many laboratory studies that have documented adverse effects of low humidity and high temperatures on *N. fallacis* (Boyne and Hain 1983, Heintz 1988, Kramer and Hain 1989, Mangini and Hain 1991, Croft et al. 1993).

In western North America, *N. fallacis* is confined to crops that provide high humidity and moderate temperatures. It occurs on strawberries, corn and hops (Hadam et al. 1986, Croft et al. 1993, Strong and Croft 1993, Croft and Croft 1993), but not on deciduous fruit trees (Downing and Moilliet 1974, Hadam et al. 1986). *N. fallacis* occurs even in relatively arid areas on peppermint (*Mentha piperita* L.) if supplemental irrigation is used. *Tetranychus urticae* is a major pest of mint in the Pacific Northwest (DeAngelis et al. 1982, Hollingsworth and Berry 1983) but it can be controlled if *N. fallacis* is present at sufficient levels in early season. Factors governing *N. fallacis* abundance in early season may include: (1) winter mortality from cold or exposure, (2) lack of suitable overwintering habitat, (3) spring or fall mortality due to low humidity or high temperatures, especially in the absence of irrigation or a mint canopy, (4) adverse effects of pesticides or (5) a combination of the above factors.

Some references have been made to the overwintering biology of *N. fallacis* (Croft and McGroarty 1977, Luckmann and Metcalf 1982), but data on overwintering sites or

winter population trends have seldom been reported. During 1991 and 1992, *N. fallacis* were found on lower leaves in peppermint fields throughout the winter, demonstrating that they can overwinter successfully on peppermint foliage in central Oregon. Counts of both mite species did not vary much during winter which suggested that little predation and reproduction occurred and that both *T. urticae* and *N. fallacis* probably were in diapause. The objectives of this study were to (1) identify predator mite overwintering sites, (2) assess whether natural overwintering habitats change seasonally and if predators are affected by these changes, (3) determine whether adding or removing habitat materials affect predator mite survival and (4) evaluate the impact of a fall carbofuran application on *N. fallacis* and *T. urticae*.

## **MATERIALS AND METHODS**

Information on study sites is summarized in Table 5. The study sites were 1.5 to 4.0 year old fields of either Murray or Todd's Mitcham peppermint located within a 50 km<sup>2</sup> area in central Oregon. Carbofuran (Furadan 4F) was applied in 280.5 liters of water per ha at a rate of 2.24 kg ai per ha using a CO<sub>2</sub> backpack sprayer with a single nozzle boom. At the time of pesticide application, mint plants varied in height from 1 to 8 cm. Mite counts were analyzed by Analysis of Variance (ANOVA) and treatment means were compared using Fisher's Protected LSD test at the p=0.05 level (Peterson 1985).

### **Distribution in habitats in fall (DF)**

In October 1993, 25 adult female *N. fallacis* were released into 0.6 m<sup>2</sup> plots to augment native mites. All introduced mites were collected from the same peppermint field where the experiment was located. Plots were arranged in a completely randomized design with seven replicates per treatment. Treatments consisted of four habitat types: (1) live leaves, (2) dead leaves, forming a layer below or intermixed with live leaves, (3)

**Table 5.** Peppermint fields in central Oregon used in experimental studies (1991-1993).

<u>Location</u>	<u>Variety</u>	<u>Age (yrs)</u>	<u>Field size (ha)</u>	<u>Growth stage (cm)</u>	<u>Experiments</u> <sup>1/</sup>
Lower Bridge	Murray Mitcham	2	14	2-6	FC
Culver	Murray Mitcham	2	5	1-7	DF, OW, MH
Culver	Todd's Mitcham	4	14	2-8	OW

<sup>1/</sup>DF=distribution in habitats in fall, MH=manipulation of overwintering habitats, FC=fall applied carbofuran, OW=overwintering distribution

debris, consisting primarily of crumbled dead leaves and stems below the dead leaf layer and (4) hollow stems from the previous season. One month after setting up the plots, habitat types were collected and placed into separate plastic bags. Bags were placed in coolers, taken to the laboratory and processed within 48 hours. The extraction process consisted of placing the samples into Tullgren Berlese funnels for 48 hours under 40 watt lights. Predator mites were collected in 0.46 liter glass jars filled 1/3 full with 70% ethanol and attached to the bottom of the funnels.

### **Overwintering Distribution (OW)**

Plant material was collected from each habitat type described above from November 1992 to April 1993. For each plot, the dry weight of the plant material was recorded and *N. fallacis* was extracted using Tullgren Berlese funnels. In this study, the funnels were provisioned with a bouquet of lima bean plants infested with *T. urticae* with the stem ends extending into the collection jar below which was half-filled with water. Predator mites present in the sample were collected on the bean foliage inside the funnels. The extraction process lasted 5-7 days under 40 watt lights. The bean foliage was then examined under 20x magnification for predator mites. This experiment was set up as a randomized complete block design with six blocks (November samples were unreplicated). Blocks were used to compare two fields with different mite densities. Blocks 1-3 were located in a 2 year old field of Murray Mitcham where predator mites had yet to reduce *T.*

*urticae* and were near maximum levels going into winter. Blocks 4-6 were in a 4 year old field of Todd's Mitcham where predator mites had reduced *T. urticae* and their abundance was low. Plots were sampled on November 3, December 30, January 25, February 28 and April 1. In November, plot size was 0.9 m<sup>2</sup>; thereafter, it was 3.1 m<sup>2</sup>.

### **Manipulation of overwintering habitats (MH)**

Manipulation of overwintering habitats took place in the fall of 1993 and consisted of the following treatments: (1) undisturbed plots of mint following harvest, (2) plots with dead leaves removed, (3) plots with the addition of 1.3 cm layer of dead leaves and (4) plots where carbofuran was applied in the fall. A completely randomized design was used with 9 replicates. Test plots were 38 cm diameter by 51 cm high cylinders made from 1.3 cm PVC pipe and placed over the plants. Two windows (20 cm by 10 cm) were cut into each cylinder for ventilation. A fine mesh screen was placed over the openings to reduce immigration or emigration of mites. A ring of Tanglefoot adhesive was placed on the inner surface of each cylinder, 5 cm from the top, to prevent mites from escaping. Plots were established in October and debris was added or removed at this time. Predator mites (30 adult females) were collected from the field where the experiment was conducted and added to native populations in each PVC plot. Carbofuran was applied October 20, 1993 and plots were sampled on April 5, 1994. All predators and spider mites on the foliage in each cage were counted with 20x magnification. In addition, dead leaves, stems and other debris were placed into plastic storage bags and processed the same way as described above for the overwintering distribution study.

### **Fall applied carbofuran (FC)**

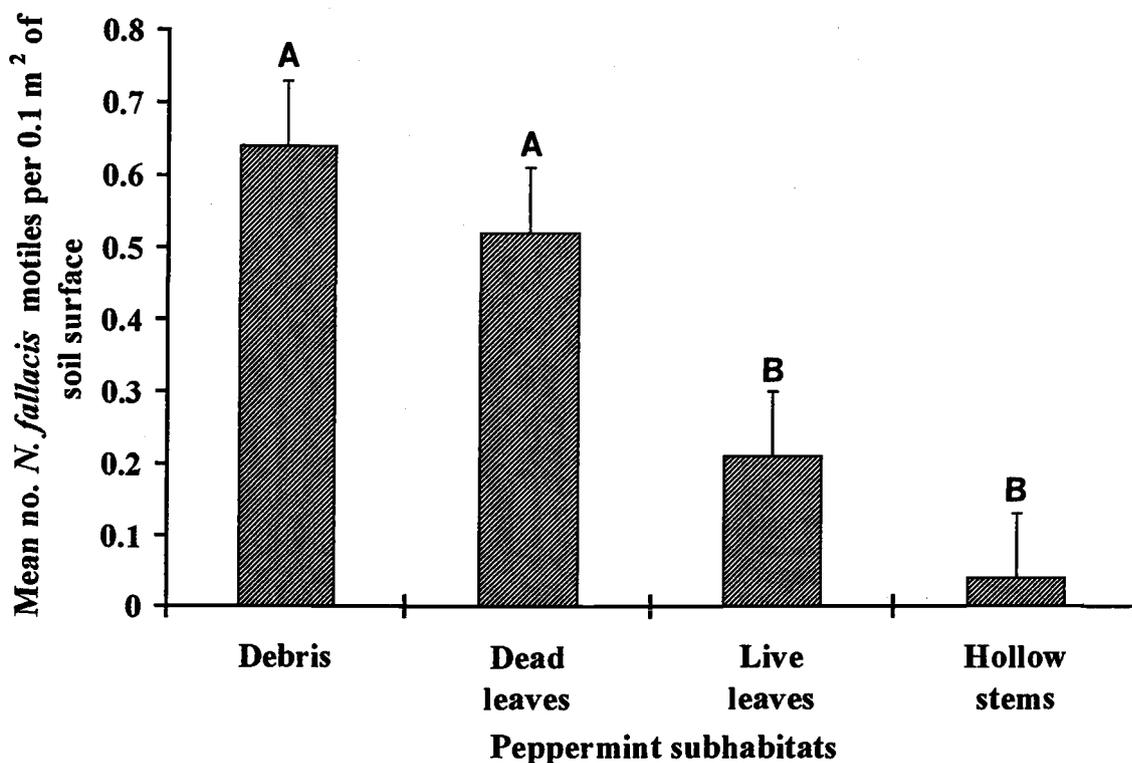
This experiment was conducted in a two year old field with a dense population of *T. urticae* and few *N. fallacis*. Treatments were: (1) *T. urticae* only, (2) *T. urticae* plus 30 *N. fallacis* and (3) *T. urticae* plus 30 *N. fallacis* followed by a carbofuran application. A

completely randomized design was used with 10 replicates per treatment. Plots were 18.9 liter plastic cylinders (buckets with bottoms removed) ringed with Tanglefoot adhesive to prevent mite escape. The plots were established in October 1993. Predator mites were obtained from a laboratory colony maintained at Oregon State University that originated with predator mites collected in central Oregon in 1992. Plots were evaluated on May 5, 1994 by counting mites on the foliage under 20x magnification.

## RESULTS AND DISCUSSION

### Distribution in habitats in fall (DF) and overwintering distribution (OW)

In early November, there were more *N. fallacis* per unit area in debris and dead leaves than on live foliage or in hollow stems ( $F=10.02$ ;  $df=3,24$ ;  $P < 0.05$ ;  $SE=0.09$ ) (Figure 3). A similar trend was observed in the November unreplicated plot (Table 6). On December 30, there were fewer predators per unit area in hollow stems compared with the other habitat types ( $F=3.35$ ;  $df=3,15$ ;  $P < 0.01$ ) (Table 6). On January 25, there were more *N. fallacis* per unit area in debris and dead leaves than on live leaves ( $F=3.08$ ;  $df=3,15$ ;  $P < 0.05$ ) (Table 6). At the end of February, there were more ( $F=5.92$ ;  $df=3,15$ ;  $P < 0.01$ ) *N. fallacis* per unit area in debris (53%) than on live foliage (0%), and by April 1, there were more ( $F=88.87$ ;  $df=3,15$ ;  $P < 0.01$ ) *N. fallacis* per unit area on new foliage (95%) than in other habitat sites. The data showed that while *N. fallacis* will survive on all four strata throughout the winter, it preferred debris and dead leaves which were near the soil surface. These sites may have a more favorable microclimate, e.g. higher humidity and protection from wind and temperature extremes. While differences were not great, there was some indication that hollow stems were preferred over live foliage in January and February. Dead stems typically extend above the foliage but their bases often are protected. Also, the amount of live foliage declines appreciably in winter due to



**Figure 3.** Occurrence of *Neoseiulus fallacis* in peppermint habitats in fall (DF) (Culver, Oregon, November 1993). Error bars represent pooled variance across treatment means.

**Table 6.** Overwintering of *Neoseiulus fallacis* in habitats on peppermint (OW) (Culver, Oregon 1993).

Treatment	Mean no. <i>N. fallacis</i> motiles per 0.01 m <sup>2</sup> of soil surface				
	Sample Date				
	November 3 <sup>1/</sup>	December 30	January 25	February 28	April 1
<b>Peppermint</b>					
Debris	0.11	0.17 a	0.14 a	0.17 a	0.050 b
Dead leaves	0.07	0.16 a	0.15 a	0.01 a b	0.000 b
Live leaves	0.02	0.08 a b	0.02 b	0.00 b	1.050 a
Hollow stems	0.01	0.03 b	0.07 a b	0.03 a b	0.000 b
Standard error		0.04	0.03	0.03	0.055

<sup>1/</sup> Experimental units were not replicated in November. On other sample dates, means in columns were compared with Fisher's Protected LSD (Peterson 1985). Column means with the same letter were not significantly different.

senescence. By April, the majority of *N. fallacis* were feeding on *T. urticae* on newly emerged foliage.

Evaluation of overwintering distribution on a per weight basis for each habitat type showed no differences in numbers of *N. fallacis* per gram of dead leaf versus debris (Table 7). At the end of December ( $F=3.05$ ;  $df=3,15$ ;  $P=0.06$ ) there were fewer predators per gram in hollow stems (8%) than in the other habitats whereas at the end of January ( $F=2.39$ ;  $df=3,15$ ;  $P=0.09$ ) there were fewer predators per gram on live foliage compared to the other habitats. At the end of February, there were no predators detected on live leaves ( $F=2.96$ ;  $df=3,15$ ;  $P=0.05$ ). This may be explained by the absence of foliage in February. By April ( $F=46.29$ ;  $df=3,15$ ;  $P < 0.01$ ) more predators were found per gram of live foliage than in other habitat types.

*N. fallacis* per unit area declined about 45 % between late January and the end of February (Table 6). This loss may be explained by a combination of overwintering mortality and loss of habitat, e.g. dissemination of dead leaves or debris by the wind. In the December and January data, blocking for spider mite population differences improved

**Table 7.** Overwintering of *Neoseiulus fallacis* in habitat types (OW) (Culver, Oregon 1993).

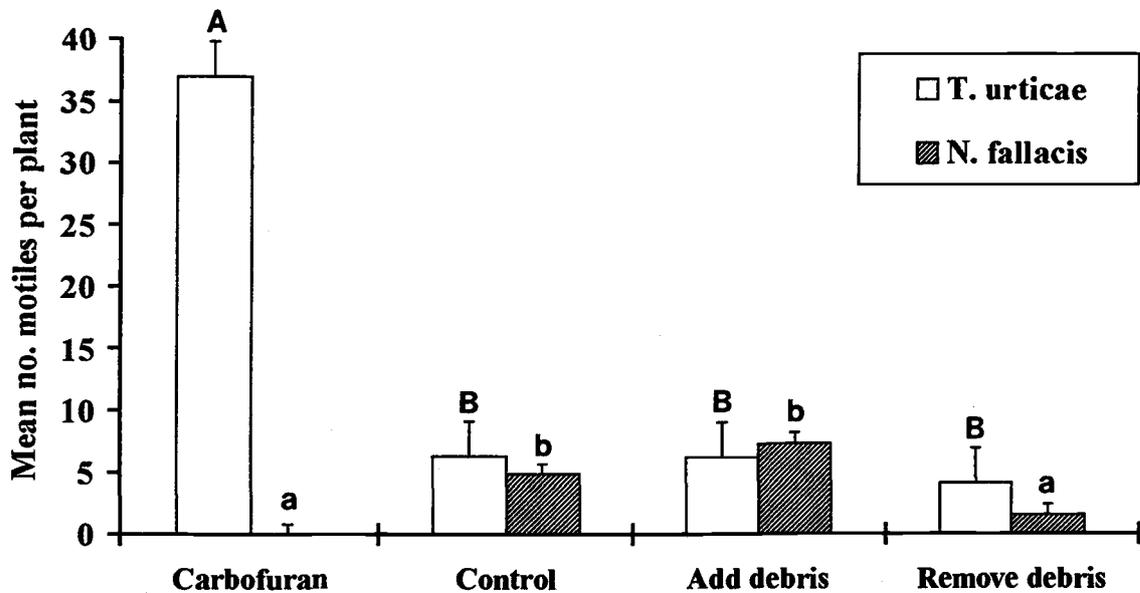
<u>Mean no. <i>N. fallacis</i> motiles per gram of habitat</u>					
	<u>Sample Date</u>				
<u>Treatment</u>	<u>November 3<sup>1/</sup></u>	<u>December 30</u>	<u>January 25</u>	<u>February 28</u>	<u>April 1</u>
<u>Peppermint</u>					
Debris	0.050	0.060 a b	0.110 a	0.250 a	0.003 b
Dead leaves	0.080	0.120 a	0.220 a	0.080 a	0.000 b
Live leaves	0.040	0.060 a b	0.040 b	0.000 b	0.450 a
Hollow stems	0.030	0.020 b	0.140 a	0.120 a	0.000 b
Standard error		0.025	0.046	0.060	0.033

<sup>1/</sup> Experimental units were not replicated in November. On other sample dates means were compared with Fisher's Protected LSD (Peterson 1985). Column means with the same letter were not significantly different.

the precision of analyses in estimating *N. fallacis* densities on both a per unit area and per weight basis. More *N. fallacis* were found in early winter in the 2 year old field which had higher spider mite densities than the 4 year old field. There was some evidence for such a trend in February and April as well. This suggests that more *N. fallacis* overwinter in fields where *T. urticae* had not been reduced to low levels. Fewer *N. fallacis* in the 4 year old field may have been due to starvation or dispersal. Reductions in *N. fallacis* overwintering in orchards have similarly been correlated with these factors (Croft and McGroarty 1977).

### **Manipulation of overwintering habitats (MH) and fall applied carbofuran (FC)**

There were more *T. urticae* in plots treated with carbofuran but there were no differences among the other treatments ( $F=31.38$ ;  $df=3,32$ ;  $P < 0.01$ ;  $SE=2.81$ ) (Figure 4). Fewer *N. fallacis* occurred in plots treated with carbofuran and in plots where debris was removed compared to the other treatments ( $F= 15.43$ ;  $df=3,32$ ;  $P < 0.01$ ;  $SE=0.84$ ) (Figure 4). Carbofuran completely eliminated predators while removal of debris caused a 68% reduction over the control. There were 78% fewer *N. fallacis* when debris was removed than when it was added. Adding debris increased the number of *N. fallacis* per plant over the other treatments (Figure 4). The data indicate that a fall application of carbofuran may contribute to outbreaks of *T. urticae* the next spring. Disruption of predator mites seems to be the primary reason for this effect but some enhanced fecundity on *T. urticae* due to the sublethal effects of carbofuran may also have been involved (Mellors et al. 1984). In a second test designed to determine if carbofuran could increase spider mite fecundity, a fall treatment of carbofuran significantly increased *T. urticae* the following spring (Table 8). There were no *N. fallacis* detected in plots where carbofuran was applied; however, differences were not significant among the treatments (Table 8).



**Figure 4.** Effect of removing or adding peppermint debris and application of carbofuran (2.24 kg ai/ha) on the overwintering survival of *Neoseiulus fallacis* and *Tetranychus urticae* on peppermint (Culver, Oregon 1993). Error bars represent pooled variance across treatment means.

**Table 8.** Population densities of *N. fallacis* and *T. urticae* on peppermint foliage after adding predators, not adding predators and adding predators and applying a single application of carbofuran (Lower Bridge, Oregon 1994).

Treatment	Mean no. <i>T. urticae</i> motiles/plant <sup>1/</sup>	Mean no. <i>N. fallacis</i> motiles/plant <sup>1/</sup>
Predators + Carbofuran	1.310 a	0.000 a
Predators added	0.067 b	0.023 a
No predators added	0.032 b	0.005 a
Standard error	0.310	0.006

<sup>1/</sup> Means were compared with Fisher's Protected LSD (Peterson 1985). Means with the same letter are not significantly different.

## CONCLUSIONS

If cultural conditions are amenable, natural populations of *N. fallacis* may overwinter and provide effective biological control of spider mites on peppermint even in arid areas of Oregon and similar areas in western North America. Manipulation of crop residues, irrigation and pesticides may be critically important for survival of *N. fallacis* under these circumstances. From an economic standpoint, conserving natural populations of this mite may be more cost effective than continuous inundative releases. Furthermore, conserving natural populations may help maintain genetic traits that allow survival in such environmentally inhospitable areas (Roush and McKenzie 1987).

The ability of *N. fallacis* to overwinter successfully in peppermint was encouraging, especially when high levels of predator mites were found in young fields. Unless heavily flamed or tilled, fields accumulate debris as they age which provides overwintering habitat for *N. fallacis*. Young fields have limited amounts of dead leaves or debris. *N. fallacis* also appears to tolerate extremely dry winters in peppermint fields. The winter of 1994 was cold and dry without an insulating snow pack, yet *N. fallacis* successfully overwintered. Irrigation may also play a role in overwintering success. Low survival of *N. fallacis* may occur when fields are not irrigated intensively after harvest. In all studies, irrigation was applied through October.

Methods to enhance survival of *N. fallacis* are suggested from these data. Tillage and burning of debris is probably detrimental to survival of *N. fallacis*. Mint fields can be disked every second or third year to control weeds and thicken stands. In addition, peppermint is often propane-flamed each year to manage rust and verticillium wilt. Although these practices may be beneficial for disease management, it may be detrimental to the biological control of spider mites. Keeping a supply of duff and leaf litter appears to be important and allowing at least some of this material to build up and remain in fields may result in added overwintering survival of *N. fallacis*. Our results on mint are similar to those reported by Croft and McGroarty (1977) and Luckmann and Metcalf (1982) who recommend vegetation and duff to remain around the base of orchard trees so as to enhance survival of *N. fallacis*.

## Distribution and Dispersal of *Tetranychus urticae* and *Neoseiulus fallacis* in Fall and Influence of Fall Flaming on Biological Control of *T. urticae* in Peppermint in Central Oregon

### INTRODUCTION

Spider mites are important pests of agricultural crops throughout the world (Hoy 1982, Helle and Sabelis 1985), and they are an increasing problem for peppermint in the western U.S. (DeAngelis et al. 1983a, Hollingsworth and Berry 1983, Larson and Berry 1984, Morris et al. 1996). Spider mites are especially severe in arid growing regions such as central Oregon where the majority of peppermint fields are treated each season for this pest (Morris and Lundy 1995). Peppermint injury caused by spider mites may become more severe if available miticides lose their effectiveness through resistance development. Resistance of spider mites to miticides is an increasing problem worldwide (Helle and Sabelis 1985, Glass 1986, Roush and Tabashnik 1990).

Predator mites in the family Phytoseiidae are effective in controlling spider mites on many crops including almonds, apple, citrus, hops, and strawberry (McMurtry 1969, Croft and McGroarty 1977, Hoy et al. 1979, Hoy 1982, Raworth 1990, Strong and Croft 1993, Coop and Croft 1995). On peppermint, the phytoseiid *Neoseiulus fallacis* is effective if its levels are adequate in relation to the prey, *T. urticae*. Factors which contribute to the success of *N. fallacis* include an effective numerical response to increasing spider mite density, a high degree of prey specificity and prey consumption, and good dispersal ability (Smith and Newsom 1970a and 1970b, Croft 1975, Santos 1975, Ball 1980, Raworth 1990, Coop and Croft 1995). Also, with sufficient irrigation, *N. fallacis* survives well and successfully overwinters in peppermint grown in arid regions (Morris et al. 1996). Previous research has shown that *N. fallacis* prefers high humidity and its survival may be greatly limited even under moderate humidity (Kramer and Hain 1989, Mangini and Hain 1991, Croft et al. 1993).

Habitat disruption can influence the effectiveness of phytoseiids in controlling spider mites (van de Vrie et al. 1972, Croft 1975, Croft and McGroarty 1977, Croft and

Hoyt 1983, Strong and Croft 1993). Peppermint fields often are flamed following harvest in both central and western Oregon to reduce levels of the mint pathogen *Verticillium dahliae* (Horner and Dooley 1965, McIntyre and Horner 1973). Fall flaming destroys much of the dead leaves and debris remaining on the soil surface after harvest (McIntyre and Horner 1973) and these are important overwintering habitats for *N. fallacis* (Morris et al. 1996). Fall flaming was also shown to reduce levels of spider mites on peppermint in one study (Hollingsworth and Berry 1983). However, monitoring was not continued throughout the fall and the following spring to determine the impact on predator mites and if there were subsequent outbreaks of spider mites. A better understanding of the effect of fall flaming on predator mites and spider mites may enhance spider mite management on peppermint.

One other aspect of using fall flaming as a cultural practice may be important. Fall propane flaming changes the physical structure of the plant and probably the biotic diversity of peppermint fields. Fall-flamed fields exhibit less variability in plant height than fields that are not flamed. The long-term stability of predator mite/spider mite interactions may be enhanced as the structural complexity of the agroecosystem is enhanced (Huffaker 1958, Huffaker et al. 1963, Gough 1991). For example, regional persistence of biological control may be increased if (1) asynchronous colonization occurs for the predator and its prey, (2) predator-free refuges exist for the prey, or (3) environmental conditions within the habitat stabilize the predator-prey interaction (Nachman 1988). Studying predator mite dispersal and determining the temporal and spatial dynamics of spider mites and predator mites following harvest may allow management practices to be adjusted so that biological control is enhanced.

This study had three objectives: (1) to investigate the effect of fall flaming on spider mite and predator mite levels in the fall and following spring, (2) to determine the location of predator mites on peppermint regrowth following harvest in non-flamed fields, and (3) to determine if predator mites would disperse from unflamed to flamed areas.

## **MATERIALS AND METHODS**

For all experiments, plots were harvested in late summer and designated plots were flamed 3 to 7 days later using a gas propane flamer (4 km per hr at 2 kg per cm<sup>2</sup> pressure). Plant height prior to harvest ranged in size from 30-90 cm. Following harvest, plants in flamed plots ranged in size from 1.5-5.0 cm, and in unflamed plots from 1.5 to 25.0 cm. In flamed and unflamed plots, plant size ranged from 2.5-10.0 cm and 5.0-17.5 cm, respectively, the following spring. In unflamed plots, there were more old stems and plant debris than in flamed plots. These experiments were analyzed using GLM ANOVA. Fisher's Protected LSD at the  $p=0.05$  level was used to separate means (Peterson 1985).

### **Effect of fall flaming**

Experimental units were 20 peppermint fields located in a 50 km<sup>2</sup> area of central Oregon. Fields ranged in size from 8 to 32 hectares and were sampled in late summer just prior to harvest. The 20 fields were selected with the specification that they had an average of at least 0.7 spider mites per leaf and that predator mites were present in sufficient numbers for a prey to predator ratio ranging between 6:1 and 100:1. Following harvest, 10 of the 20 fields were flamed. All fields were sampled again in the fall and the following spring in April and May. The sampling regime used was based on a method developed by Hollingsworth and Berry (1982). The number of sample sites within a field was calculated on the basis of one site every 1.0 hectares up to 12 hectares, and one site every 2 hectares thereafter. Using a zigzag pattern to cover the field, 15 peppermint plants were randomly collected from a 1 m<sup>2</sup> area at each sample site. With the aid of a 16x handlens, 3 leaves from each plant (one from the top, middle and bottom) were selected and the total number of spider mite motiles, predator mite motiles and predator mite eggs were recorded. For this experiment, a completely randomized design (CRD) was used.

### **Location of predator mites on peppermint**

Five 27 m<sup>2</sup> (3m x 9m) plots were left unflamed in a fall-flamed peppermint field in central Oregon. In each plot, three types of plants (10 plants of each type) were sampled during the first week of October 1995. The first type of plant was 15-25 cm tall without leaves on the lower 7.5 cm. The second type of plant was 2.5-7.5 cm tall with at least 3 sets of leaves and the last set within 1.3 cm of the soil surface. The third type of plant was prostrate on the soil surface. For each plant type sampled, the number of spider mite motiles, predator mite motiles and predator mite eggs were counted on three leaves per plant. The experiment was arranged in a randomized complete block design (RCBD).

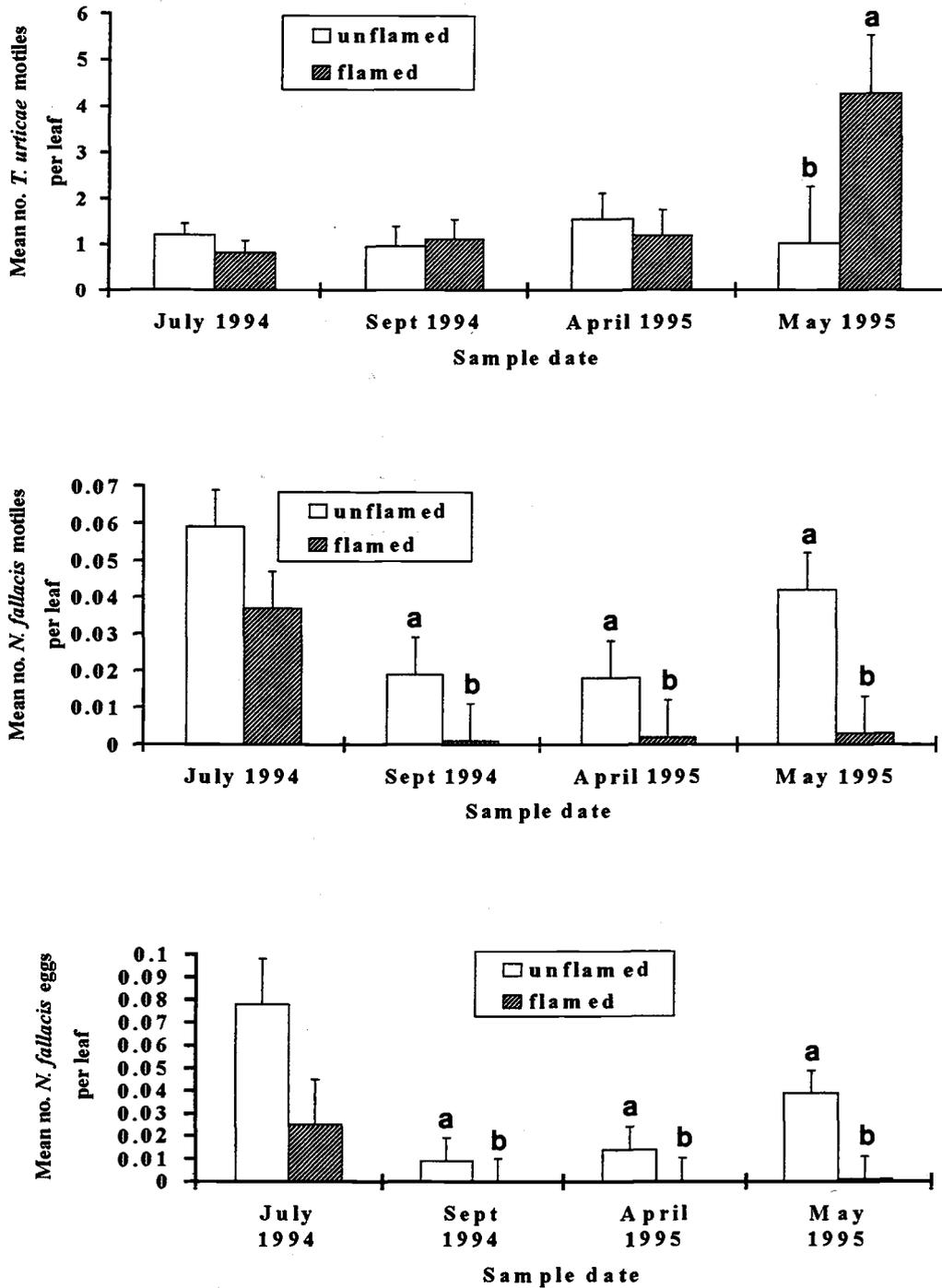
### **Dispersal of predator mites**

Three 27 m<sup>2</sup> (3m x 9m) plots were left unflamed in a fall-flamed peppermint field in central Oregon. The three plots and the flamed area adjacent to each of the plots were sampled on October 13, 1995 and again on November 8, 1995. A final evaluation of the experiment occurred the following spring on April 27, 1996. Sampling consisted of collecting 10 plants from within the plot area, and for each plant, counting the number of spider mite motiles, predator mite motiles and predator mite eggs on six leaves: 2 from the top, 2 from the middle and 2 from the bottom of the plant. Another sample of 10 plants was taken 3 m from the edge of the plots in the flamed area. On the last evaluation date, samples in the flamed areas were taken 7.5 m from the edge of the plots. The experiment was set up as a randomized block design (RBD). Spider mite motiles, predator mite motiles and predator mite eggs were analyzed separately on each evaluation date.

## RESULTS AND DISCUSSION

### Effect of fall flaming

In late July, there were no significant differences between flamed and unflamed fields in the number of spider mite motiles ( $F=1.17$ ;  $df=1,18$ ;  $p=0.29$ ;  $SE=0.25$ ), predator mite motiles ( $F=1.27$ ;  $df=1,18$ ;  $p=0.27$ ;  $SE=0.01$ ), or predator mite eggs ( $F=2.58$ ;  $df=1,18$ ;  $p=0.13$ ;  $SE=0.02$ ) (Figure 5). In early September, after harvest and flaming, there were 98 % fewer predator mite motiles ( $F=7.06$ ;  $df=1,18$ ;  $p=0.02$ ;  $SE=0.005$ ) and no predator mite eggs ( $F=5.34$ ;  $df=1,18$ ;  $p=0.03$ ;  $SE=0.003$ ) on the regrowth in flamed fields compared to fields that were not flamed (Figure 5). During this same evaluation period, there was no significant difference in the number of spider mite motiles between flamed and unflamed fields ( $F=0.33$ ;  $df=1,18$ ;  $p=0.58$ ;  $SE=0.42$ ) (Figure 5). In April of the following year, there was again no significant difference in the number of spider mite motiles in flamed versus unflamed fields ( $F=0.20$ ;  $df=1,18$ ;  $p=0.66$ ;  $SE=0.56$ ); however, 89 % fewer predator mite motiles ( $F=9.99$ ;  $df=1,18$ ;  $p<0.01$ ;  $SE=0.003$ ) and 99% fewer predator mite eggs ( $F=10.90$ ;  $df=1,18$ ;  $p<0.01$ ;  $SE=0.003$ ) were found in flamed fields compared to unflamed fields (Figure 5). In May, there were significantly more spider mite motiles ( $F=3.46$ ;  $df=1,18$ ;  $p=0.08$ ;  $SE=1.24$ ) in flamed fields and over 90 % fewer predator mite motiles ( $F=12.17$ ;  $df=1,18$ ;  $p<0.01$ ;  $SE=0.008$ ) and no predator mite eggs ( $F=8.22$ ;  $df=1,18$ ;  $p=0.01$ ;  $SE=0.01$ ) (Figure 5). The study was terminated in May 1995 by applying Comite (propargite) to those fields where spider mite levels were excessively high. Based on a treatment threshold of 5 spider mites per leaf, 7 of the 10 flamed fields were treated with propargite compared to 2 of the 10 unflamed fields.



**Figure 5.** Mean number of *T. urticae* motiles, *N. fallacis* motiles and *N. fallacis* eggs in flamed and unflamed experimental units (central Oregon 1994-1995). Sample means were compared with Fisher's Protected LSD (Peterson 1985).

### Location of predator mites on peppermint

More predator mite motiles ( $F=5.89$ ;  $df=2,8$ ;  $p<0.01$ ) and predator mite eggs ( $F=4.75$ ;  $df=2,8$ ;  $p=0.01$ ) were detected on prostrate peppermint plants than on either of the erect plant types (Table 9). This may be related to humidity differences between short and tall plants. *N. fallacis* prefers humid conditions which may occur closer to the soil surface (Boyne and Hain 1983, Croft et al. 1993). Although not significant, there was also a trend showing higher levels of predator mites and predator mite eggs on the 2.5-7.5 cm tall plants compared to 15-25 cm tall plants. There was no significant difference in the number of spider mites sampled from among the three plant heights ( $F=0.30$ ;  $df=2,8$ ;  $p=0.74$ ;  $SE=1.08$ ) (Table 9). *T. urticae* may tolerate a wider range of humidities than does *N. fallacis*.

### Dispersal of predator mites

When plots were sampled on October 14, there were more spider mites found in the unflamed plots compared to the flamed plots ( $F=8.35$ ;  $df=1,2$ ;  $p=0.10$ ) (Figure 6). Spider mite levels remained higher in the unflamed plots when the experiment was evaluated again on November 8 ( $F=71.89$ ;  $df=1,2$ ;  $p=0.01$ ) (Figure 6). These results agree with those of Hollingsworth and Berry (1983) who showed a depression in spider mite levels following fall flaming. Fewer predator mites were found in flamed plots on October 14 compared with unflamed plots ( $F=19.67$ ;  $df=1,2$ ;  $p=0.05$ ). As was seen in the first experiment, flaming appears to be detrimental to predator mites. However, there were no significant differences detected in the number of predator mites found between the flamed and unflamed plots on November 8 (Figure 6). Because the majority of predator mites are overwintering in old leaves by this time (Morris et al. 1996), it is difficult to measure differences in the levels of predator mites between flamed and unflamed plots in late fall.

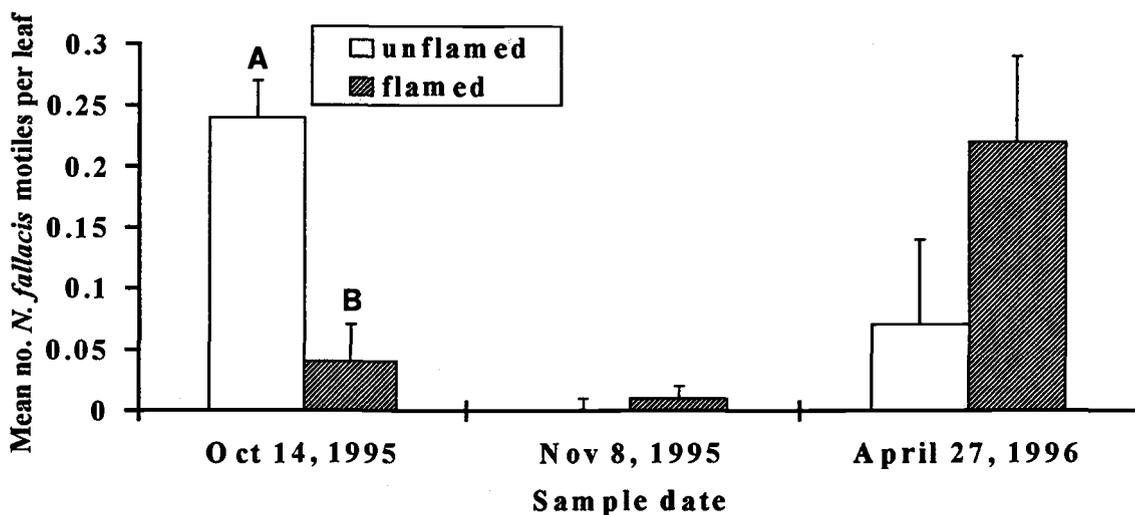
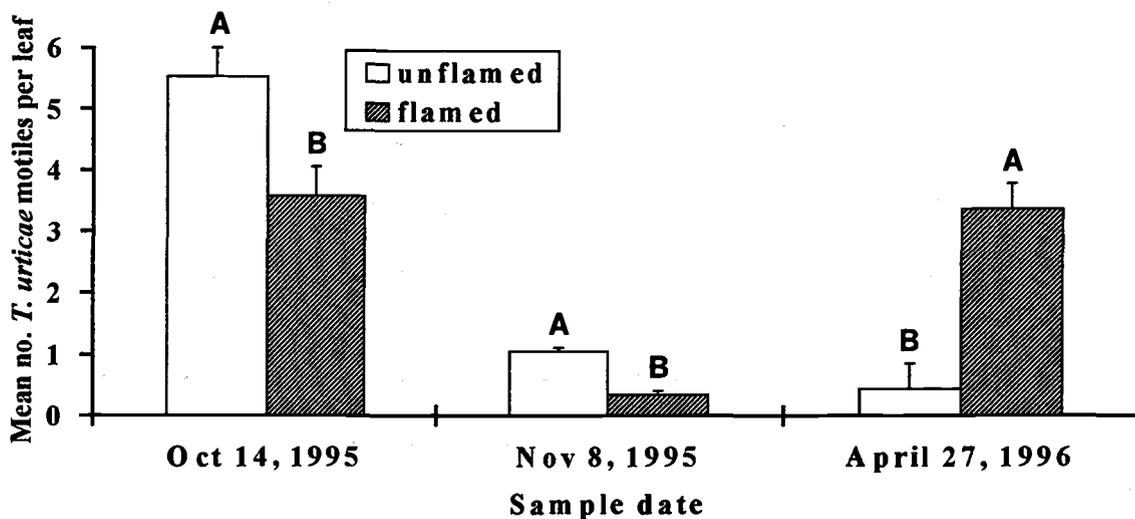
**Table 9.** Mean number of two-spotted spider mite motiles, predator mite motiles and predator mite eggs per leaf on three types of plants (prostrate, 2.5-7.5 cm tall, and 15-25 cm tall).

Plant Type	<i>T. urticae</i> motiles	Mean no. per leaf <sup>1/</sup>		<i>N. fallacis</i> eggs
		<i>N. fallacis</i> motiles		
prostrate	5.10	0.61	a	0.540 a
2.5-7.5 cm tall	6.11	0.21	b	0.100 b
15-25 cm tall	6.13	0.03	b	0.004 b
	SE <sup>2/</sup> = 1.08	SE = 0.12		SE = 0.13

<sup>1/</sup> Sample means were compared with Fisher's Protected LSD (Peterson 1985). Means with the same letter were not significantly different.

<sup>2/</sup> SE = standard error

On April 27, 1996, the situation seen in the fall was reversed. Starting 7 meters from the edge of the unflamed plots and extending out into the flamed areas, more spider mites were found compared to the unflamed plots ( $F=27.27$ ;  $df=1,2$ ;  $p=0.03$ ) (Figure 6). However, in the flamed area immediately adjacent to the unflamed plots and inside the plots themselves, there were few spider mites found. One explanation for this is predator mite dispersal from the unflamed plots (low food) into an area of more abundant food. Predator mite dispersal may explain why there was no significant difference in the number of predator mites detected in the flamed plots compared to the unflamed plots. Although there was a trend indicating more predator mites in the flamed areas, samples were taken 7.5 meters from the edge of the unflamed plots (Figure 6). Because additional samples were not taken further out in the flamed areas, one should not conclude that flamed areas contain more predator mites than unflamed areas. Instead, these data only suggest that predator mites have the ability to disperse a distance of 7 meters by the following spring. Further studies are needed to determine exactly how far predator mites can disperse and how many unflamed areas would be required (as predator mite refugia) to maintain spider mite populations below the treatment threshold throughout the field.



**Figure 6.** Mean number of *T. urticae* motiles and *N. fallacis* motiles in unflamed plots and adjacent flamed peppermint (central Oregon 1995-96). Sample means were compared with Fisher's Protected LSD (Peterson 1985).

## CONCLUSIONS

Propane flaming peppermint in the fall appears to reduce predator mite survival in central Oregon and may uncouple predator populations from their spider mite prey. Although spider mite levels may be reduced initially, fall flaming appears to result in spider mite resurgence the following season. Elimination of predator mites can lead to an unstable predator-prey interaction. If this occurs, spider mites could increase, and if left unchecked, may reach damaging levels before predators are able to re-colonize the field. Allowing portions of peppermint fields to remain unflamed may benefit predator mites by providing refuges for both the predator and its prey, and by temporarily uncoupling predators from their prey.

While spider mites were found in abundance following harvest on all peppermint plant types that were assessed, predators seemed to prefer plants that grow closer to the soil surface. Differences in humidity tolerances may exist between spider mites and predator mites, with spider mites being able to tolerate lower humidities. At harvest, a mint field typically changes from a humid environment with a dense canopy to a more arid habitat of short plants with no canopy, except in areas that were not adequately harvested. The soil surface condition changes from humid and often wet to dry and almost desert-like. This condition is usually exacerbated by less frequent irrigation following harvest. It is hypothesized that taller plants may play an important role in providing a predator-free space (refuge) where spider mites can temporarily escape predation. The net effect of this temporal-spatial asynchrony may be to stabilize the predator-prey interaction as long as it does not last too long.

It would be important to preserve predator mites so that they can re-colonize into areas in which they were reduced or excluded. Although predator mites appeared to disperse from unflamed plots into adjacent flamed areas, further studies are needed to determine if this dispersal rate or distance occurs under most conditions. *N. fallacis* has been shown to disperse throughout strawberry fields from small point sources if enough time is allowed and environmental conditions are adequate (Coop and Croft 1995). For peppermint in central Oregon, regrowth following harvest seldom exceeds 3-8 cm before

the onset of winter. This is less regrowth than what is found in strawberries and peppermint grown in western Oregon. For this reason, predator mite dispersal in central Oregon peppermint may require more time because shorter plants may not provide predator mites with the trajectory to disperse longer distances.

## Assessing the Impact of Selected Pesticides to *Neoseiulus fallacis* and *Tetranychus urticae* on Peppermint

### INTRODUCTION

Spider mites are often maintained below economically damaging levels by their natural enemies (Helle and Sabelis 1985). Of the many natural enemies that are capable of controlling spider mites, predator mites in the family Phytoseiidae are among the most effective (Hoy 1982, McMurtry 1992). Several phytoseiid species have been identified on peppermint in the western U.S. (Hollingsworth and Berry 1983, Hadam et al. 1986). *Neoseiulus fallacis* (Garman) was the most abundant species in my study and effectively controlled spider mites if adequate levels were present.

Since the early 1980s, *Tetranychus urticae* become an increasing pest problem on peppermint in the western U.S., and the majority of fields are treated each season with miticides (Morris and Lundy 1995). Possible explanations for this trend may be resistance development in spider mites to miticides, disruption of *N. fallacis* by pesticides, or a combination of both. During the late 1980s, peppermint growers experienced greater difficulty in controlling spider mites with dicofol. Because resistance to dicofol in spider mites is a common problem in many crops worldwide (Saito et al. 1983, Dennehy and Granett 1984, Dennehy et al. 1988, Roush and Tabashnik 1990, Denholm and Rowland 1992), dicofol resistance in peppermint may have been at least partially responsible for increasing control failures. Although resistance bioassays conducted on spider mites collected from peppermint during the 1960s showed no evidence of dicofol resistance (Berry 1970), further investigation of this issue was warranted because of increasing complaints about dicofol control failures.

The disruption of biological control by pesticides may be another explanation for the increased severity of spider mites on peppermint. Spider mites are usually secondary pests unless their natural enemies are disrupted (Helle and Sabelis 1985, Hoy and Herzog 1985, Croft 1990). Disruption of phytoseiids can occur through habitat manipulation

(Croft and Hoyt 1983, Strong and Croft 1993), lack of a suitable microenvironment (Zhang and Kong 1985, Kramer and Hain 1989, Croft et al. 1993), competition from other species (MacRae and Croft 1994, Zhang and Croft 1995), or application of disruptive pesticides (Croft 1990, Hoy 1990, Malezieux et al. 1992). Most of the common pesticide classes can be disruptive to phytoseiids, including fungicides, herbicides, insecticides, and nematocides (Helle and Sabelis 1985, Croft 1990). Some of the newer classes of insecticides may also be toxic to phytoseiids, e.g. insecticidal soaps (Osbourne and Petitt 1985) and the beta-exotoxin of *Bacillus thuringiensis* (Hoy and Ouyang 1987).

*N. fallacis* may be disrupted by a wide range of pesticides including fungicides, e.g. sulfur (Thiolux), mancozeb (Manzate), benomyl (Benlate) (Nakashima and Croft 1974, Childers and Enns 1975, Hagley and Biggs 1989); herbicides, e.g. terbacil (Sinbar) (Rock and Yeargan 1973); insecticides, e.g. organophosphates (Rock and Yeargan 1971, Watve and Lienk 1975, Croft et al. 1976), carbamates (Croft and Meyer 1973, Croft and Stewart 1973, Croft and Hoying 1975, Brown and Shanks 1976), synthetic pyrethroids (Rock 1979, Strickler and Croft 1981, Whalon et al. 1982); and miticides, e.g. dicofol (Croft 1975, Hislop and Prokopy 1981, Chapman and Penman 1987, Raworth 1990). Fortunately, not all pesticides are incompatible with phytoseiids (Hoy and Cave 1985, Hoy and Ouyang 1986, Croft 1990, Hoy 1990), including *N. fallacis* (Croft 1975, Croft and McGroarty 1977). For example, the acaricides propargite and fenbutatin-oxide are applied to apple orchards at rates that reduce *T. urticae* levels but do not harm *N. fallacis* (Croft 1975, Croft and McGroarty 1977).

The adverse effect of some pesticides can be reduced by resistance development in some phytoseiid species (Fournier et al. 1985, Croft 1990, Hoy 1990). *N. fallacis* is tolerant or resistant to several insecticides, and some of these may be used successfully in pest management programs that rely on this species (Rock and Yeargan 1971, Croft and Nelson 1972, Croft and Stewart 1973, Watve and Lienk 1975). One must be cautious in extrapolating laboratory resistance to commercial field conditions, however. For example, low levels of pesticide resistance in some populations of *N. fallacis* may not be adequate to tolerate field application rates (Strickler and Croft 1981, Whalon et al. 1982).

Because pesticides may negatively impact biological control, it has been suggested that evaluating pesticide selectivity be a part of the pesticide registration process as it is in several European countries (Jepson 1993, Stark et al. 1995). One question is what kind of bioassay should be used. Laboratory bioassays (e.g. slide dips and leaf dips) may measure physiological selectivity in natural enemies to direct contact with pesticides or their residues (Overmeer 1985, Hoy and Cave 1985, Croft 1990, Stark et al. 1995). Laboratory bioassays are often less time consuming and less expensive than field bioassays; however, conventional laboratory bioassays may not adequately predict the effect of pesticides on natural enemies under all field conditions (Overmeer 1985). In the field, the actual risk posed to natural enemies by pesticides may also depend on the crop, agricultural practices, and biological attributes of the natural enemy (Croft 1990, Jepson and Thacker 1990, Jepson 1993, Wiles and Jepson 1995, Stark et al. 1995).

The objectives of this study were to: (1) determine whether *T. urticae* populations collected from peppermint in the western U.S. are resistance to dicofol; (2) evaluate the physiological selectivity of *N. fallacis* to insecticides commonly used in peppermint using a laboratory bioassay; (3) ascertain the ecological selectivity of *N. fallacis* to several pesticides using semi-field bioassays; and (4) determine whether simulated irrigation, following the application of disruptive pesticides, would make these pesticides more selective.

## **MATERIALS AND METHODS**

### **Dicofol resistance in spider mites**

Suspected dicofol resistant and susceptible populations of *T. urticae* were collected from peppermint fields in the western U.S. The first bioassay was conducted on a population of *T. urticae* from western Oregon and four populations from central Oregon. Spider mites used in this bioassay were collected directly from infested

peppermint leaves with a small aspirator equipped with a 10 mm micropipette and transferred to lima bean leaf disks. The second bioassay evaluated six populations of *T. urticae*: two from western Oregon, three from central Oregon, and one from Montana. Instead of transferring spider mites directly from peppermint leaves onto leaf disks as was done in the first bioassay, spider mites were transferred from peppermint to lima bean plants and allowed to colonize for 12 to 18 days. This procedure increased the number of adult female spider mites that could be used in the bioassays and addressed the question of whether or not secondary plant compounds in peppermint could influence tolerance levels to dicofol. All other methods were the same as for the first bioassay. For both bioassays, the control was a population of *T. urticae* maintained at Oregon State University which had never been exposed to pesticides (Croft personal communication).

Bioassays were conducted using a bean leaf disk method where pesticides were applied with an air brush sprayer (Miller et al. 1985). Six concentrations of dicofol (4.8, 9.6, 48, 96, 480, and 960 ppm) and a water only control were tested for each bioassay. Three replications of a leaf disk containing over 25 adult female spider mites were used for each concentration. Following pesticide application, the leaf disks were maintained in the laboratory at 24 °C. Mortality was assessed after 48 hours by lightly touching mites with a camel hair brush. Detectable movement was considered evidence of survival. Results were analyzed using standard log-dose probit mortality analysis (Finney 1971).

### **Physiological selectivity to *N. fallacis***

A bean leaf disk bioassay was used to test the selectivity of the following pesticides (both topical applications and leaf residues) to *N. fallacis*: acephate (Orthene 80SP at 0.6 and 1.1 kg ai per ha), chlorpyrifos (Lorsban 4E at 1.1 kg ai per ha) and oxamyl (Vydate 2L at 1.1 kg ai per ha). The predator mites used in this experiment were from laboratory colonies, originally collected from peppermint in central Oregon. Predator mites were transferred to leaf disks with a camel hair brush and each leaf disk was provisioned with 20 adult female *T. urticae* as a food source. Pesticides were applied using an air brush application method (Miller et al. 1985). Insecticides were mixed in the equivalent of 280

liters of water per ha, and a water only treatment served as the control. Three replications of 15 adult female *N. fallacis* for each leaf disk were tested for each concentration. Predators were placed on the leaf disks (1) 24 hours prior to application (topical application), (2) two hours after application, (3) 48 hours after application and (4) 72 hours after application. Mortality was assessed 48 hours after exposure to pesticides by lightly touching predator mites with a camel hair brush. Detectable movement was considered evidence of survival. Mite counts were analyzed by Analysis of Variance (ANOVA) and treatment means were compared using Fisher's Protected LSD test at the  $p=0.05$  level (Peterson 1985).

### **Ecological selectivity to *N. fallacis***

Information on field study sites for selectivity testing are summarized in Table 10. Study sites were located within a 50 km<sup>2</sup> region of central Oregon. For all tests, plots consisted of 38 cm diameter, 51 cm high cylinders made of 1.3 cm PVC pipe. The PVC pipes were placed over plants with a mixed population of *T. urticae* and *N. fallacis* and pushed into the soil to a depth of 5.1 cm. Two rectangular openings (20 cm by 10 cm) were cut into each cylinder for ventilation. A fine mesh screen was placed over the openings to reduce immigration or emigration of mites. Tanglefoot adhesive was applied 5 cm from the top around the inside of each cage to prevent mite escape. In addition to what was already present in the plots, each cage was inoculated with 25 additional *N. fallacis* 48 hours prior to treatment.

Pesticides were applied using a CO<sub>2</sub> backpack sprayer with a single nozzle boom (Teejet 95004 flatfan nozzle). In all experiments, a 0.6 m by 1.2 m wooden frame was placed over each cylinder. Pesticides were applied in the equivalent of 289 liters of water per ha to the area delineated by the frame. Paper liners were placed in the cages and removed after application to eliminate pesticide residues from the inner surfaces. Plots were evaluated by randomly selecting plants from each plot and placing them into plastic bags. Bags were placed into ice-coolers, taken back to the laboratory and processed

**Table 10.** Information on study sites and experimental conditions used in semi-field studies

<u>Location</u>	<u>Variety</u>	<u>Age (yrs)</u>	<u>Field size(acre)</u>	<u>Growth stage (cm)</u>	<u>Experiments</u> <sup>1/</sup>
Culver	Murray Mitcham	4	25	2-10	Physiological selectivity
Madras	Todd's Mitcham	4	40	2-10	Ecological selectivity 1
Culver	Murray Mitcham	3	30	25-35	Ecological selectivity 2
Culver	Murray Mitcham	3	30	5-12	Ecological selectivity 3
Culver	Todd's Mitcham	3	30	5-10	Ecological selectivity 4

<sup>1/</sup> See methods section for description of each experiment

within 48 hrs. Treatments were evaluated by taking six leaves from each plant (two leaves from the top, middle, and bottom), and the number of *T. urticae* and *N. fallacis* motiles and eggs on each leaf were counted with a dissecting microscope. A completely randomized design was used. Mite counts were analyzed by Analysis of Variance (ANOVA) and treatment means were compared using Fisher's Protected LSD test at the  $p=0.05$  level (Peterson 1985).

### ***Ecological selectivity: test 1***

Three insecticides were evaluated for their effect on *T. urticae* and *N. fallacis*. Treatments were: (1) acephate (Orthene 75S, 1.1 kg ai per ha), (2) chlorpyrifos (Lorsban 4E, 2.2 kg ai per ha), (3) esfenvalerate (Asana 0.66EC, 0.05 kg ai per ha), and (4) a water only control. Acephate and chlorpyrifos were included because they are used in mint to control redbacked cutworm (*Euxoa spp.*) (Berry and Fisher 1993). Esfenvalerate was tested because the mint industry was considering the registration of this insecticide. Treatments were applied on May 1. Ambient temperature at the time of application was 24° C. Ten plants from each plot were evaluated on May 13.

***Ecological selectivity: test 2***

Five pesticides were evaluated for their effect on *T. urticae* and *N. fallacis*. Treatments were: (1) methomyl (Lannate 1.8L, 1.0 kg ai per ha), (2) sulfur (Thiolux 80 DF, 3.4 kg ai per ha), (3) carbofuran (Furadan 4L, 2.2 kg ai per ha), (4) malathion (Malathion 5EC, 1.1 kg ai per ha), (5) oxamyl (Vydate 2L, 1.1 kg ai per ha), and (6) a water only control. Carbofuran, malathion, methomyl, and oxamyl were tested because they are currently used, or have been used, to control the mint flea beetle (*Longitarsus ferrugineus*) on peppermint (Morris 1990). Pesticides were applied on June 10. Ambient temperature at the time of application was 21° C. Ten plants from each cage were evaluated on July 3.

***Ecological selectivity: test 3***

In this experiment, one insecticide, one herbicide and one fungicide were evaluated. Treatments were (1) ethoprop (Mocap 6EC, 6.7 kg ai per ha), (2) propiconazole (Tilt 3.6EC, 583 mls of product per ha), (3) paraquat (Gramoxone Extra 2.5 EC, 1166 mls of product per ha), and (4) a water only control. Ethoprop is being considered for registration on mint to control soil arthropod and nematode pests, paraquat is often applied to mint in early spring to manage weeds, and propiconazole is applied in the spring in western Oregon to manage peppermint rust (*Puccinia menthae*). Treatments were applied on May 1. Ambient temperature at the time of application was 24° C. Twenty plants from each cage were evaluated on May 15.

***Ecological selectivity: test 4***

The effect of irrigation on pesticide toxicity was evaluated in this experiment. Acephate (Orthene 75S, 1.1 kg ai per ha), chlorpyrifos (Lorsban 4E, 2.2 kg ai per ha), and oxamyl (Vydate 2E, 1.1 kg ai per ha) were tested for their effect on *N. fallacis*. A water only treatment served as the control. Irrigation, 2.5 cm of simulated overhead irrigation, was included in the experiment to determine if it would affect pesticide toxicity to *N. fallacis*.

Thirty minutes after pesticides were applied, irrigation was simulated using a garden sprinkling can. Treatments were applied on May 15 and evaluated 5 days later by sampling ten plants from each cage.

## RESULTS AND DISCUSSION

### Dicofol resistance in spider mites

Comparison of  $LC_{50}$  values showed a 17.8- and a 19.1-fold increase in tolerance to dicofol for *T. urticae* populations GR-91 and BA-91, respectively (Table 11). Located in central Oregon, both fields had a history of annual dicofol use and dicofol alone was unable to reduce spider mites to below the treatment threshold of 5 mites per leaf. One spider mite population from western Oregon (RE-91) and two spider mite populations from central Oregon (DO-91 and CL-91) showed similar  $LC_{50}$  values to the susceptible control population (LAB) (Table 11). All three susceptible spider mite populations were collected from peppermint fields that had never received a dicofol application.

In the second bioassay, comparison of  $LC_{50}$  values showed a 107.3-fold increase in tolerance to dicofol for *T. urticae* from one peppermint field in western Oregon (LU) and a 16.1-fold increase in one population from Montana (MT) (Table 12). For the three central Oregon fields, there was a 2.6-, 5.0- and 23.7-fold increase in dicofol susceptibility for the WAM, BAR-2 and BAR-3 populations, respectively (Table 12). All five spider mite populations were collected from peppermint fields treated annually with dicofol for more than eight years. In all five cases, at least one additional propargite application was required to reduce spider mite populations to below damaging levels. One spider mite population from western Oregon (CHA), which had never received a dicofol treatment, showed a similar susceptibility to dicofol as the control population (LAB) (Table 12).

**Table 11.** Results of probit analysis testing dicofol on *T. urticae* from Oregon peppermint fields (1991)

Population <sup>1/</sup>	n <sup>2/</sup>	LC <sub>50</sub> ppm ai (95% CL)	Slope	RR <sup>3/</sup>
LAB	1033	27 (14 - 52)	0.87	1.00
RE-91 (WO)	354	49 (32 - 69)	1.20	1.81
DO-91 (CO)	384	23 (4 - 46)	1.72	0.85
CL-91 (CO)	219	45 (19 - 76)	1.04	1.67
GR-91 (CO)	371	480 (296-890)	1.38	17.80
BA-91 (CO)	323	516 (310-1505)	0.80	19.10

<sup>1/</sup> WO=western Oregon, CO=central Oregon

<sup>2/</sup> Number of individuals used in the bioassay

<sup>3/</sup> Resistance ratio=LC<sub>50</sub> of field population / LC<sub>50</sub> of control population

**Table 12.** Results of probit analysis testing dicofol on *T. urticae* from Oregon and Montana peppermint fields (1992)

Population <sup>1/</sup>	n <sup>2/</sup>	LC <sub>50</sub> (ppm ai) (95% CL)	Slope	RR <sup>3/</sup>
LAB	781	15 (12-17)	3.76	1.00
CHA (WO)	799	17 (14-20)	3.29	1.17
BAR-2 (CO)	903	353 (272-470)	1.49	23.69
BAR-3 (CO)	744	74 (52-101)	1.51	5.00
MT (MT)	561	240 (182-311)	1.64	16.13
LU (WO)	813	1601 (970-4045)	1.20	107.34
WAM (CO)	419	38 (20-58)	1.51	2.57

<sup>1/</sup> WO=western Oregon, CO=central Oregon, MT=Montana

<sup>2/</sup> Number of individuals used in the bioassay

<sup>3/</sup> Resistance ratio=LC<sub>50</sub> of field population / LC<sub>50</sub> of control population

### Physiological selectivity to *N. fallacis*

Topical applications of acephate, chlorpyrifos and oxamyl to *N. fallacis* on bean leaf disks resulted in 100% mortality within 24 hours ( $F=2116$ ,  $df=4,10$ ,  $P<0.01$ ,  $SE=0.15$ ) (Table 13). Mortality also was 100% when *N. fallacis* were placed on bean leaf disks 2 hours ( $F=507$ ,  $df=4,10$ ,  $P<0.01$ ,  $SE=0.26$ ) and 48 hours ( $F=240$ ,  $df=4,10$ ,  $P<0.01$ ,  $SE=0.39$ ) after acephate, chlorpyrifos and oxamyl were applied. At 72 hours, some *N. fallacis* survived the two rates of acephate (39% and 7%, respectively) although survival was still significantly lower than the control ( $F=54.95$ ,  $df=4,10$ ,  $P<0.01$ ,  $SE=0.55$ ). Survivors showed little more than slight leg extensions and could not move about on the leaf disks. The 1.1 kg ai per ha rate of chlorpyrifos and oxamyl continued to result in 100% mortality when *N. fallacis* were placed on leaf disks 72 hours after application. Because of its moderate residual activity (Frank et al. 1984), acephate may have dissipated earlier than for chlorpyrifos or oxamyl. Alternatively, predator mites may have developed resistance to acephate. Organophosphate resistance in *N. fallacis* is well-documented (Rock and Yeorgan 1971, Croft 1975, Croft 1990).

### Ecological selectivity to *N. fallacis*

#### *Ecological selectivity: test 1*

Insecticide treatments did not significantly alter levels of *T. urticae* motiles ( $F=2.10$ ;  $df=3,12$ ;  $P=0.12$ ;  $SE=0.33$ ) or eggs ( $F=1.28$ ;  $df=3,12$ ;  $P=0.33$ ;  $SE=1.23$ ) compared to the water only treatment (Table 14). However, applications of chlorpyrifos and esfenvalerate reduced *N. fallacis* by 94% and 100%, respectively ( $F=5.47$ ;  $df=3,12$ ;  $P<0.01$ ;  $SE=0.05$ ) (Table 14). Although not significantly different, fewer *N. fallacis* motiles were recovered from plots treated with acephate. *N. fallacis* eggs were reduced ( $F=16.71$ ;  $df=3,12$ ;  $P<0.01$ ;  $SE=0.02$ ) in plots treated with acephate, chlorpyrifos and esfenvalerate by 68%, 94% and 100%, respectively (Table 14).

**Table 13.** Effect of selected pesticides on *N. fallacis* using laboratory bioassays

Treatment	Rate applied <sup>1/</sup> kg ai per ha	<u>Mean no. live <i>Neoseiulus fallacis</i> per leaf disk</u>			
		<u>Time of application</u> <sup>2/</sup>			
		0 hours	2 hours <sup>3/</sup>	48 hours <sup>3/</sup>	72 hours <sup>3/</sup>
water only	-	15.33 a	13.00 a	13.67 a	11.66 a
acephate	0.6	0.00 b	0.00 b	0.00 b	5.33 b
acephate	1.1	0.00 b	0.00 b	0.00 b	0.68 c
oxamyl	1.1	0.00 b	0.00 b	0.00 b	0.00 c
chlorpyrifos	1.1	0.00 b	0.00 b	0.00 b	0.00 c
Standard Error		0.15	0.26	0.39	0.55

<sup>1/</sup> Insecticides mixed in equivalent of 114 liters of water; leaf disks sprayed to wet

<sup>2/</sup> Insecticides applied topically to mites placed on disks prior to application. Mean separation by Fisher's Protected LSD (Peterson 1985). Means with the same letter are not significantly different.

<sup>3/</sup> *N. fallacis* placed on leaf disks at specified times following insecticide application

**Table 14.** Effect of selected insecticides on *T. urticae* and *N. fallacis* motiles and eggs (Madras, Oregon)

Treatment	Rate applied kg ai/ha <sup>1/</sup>	<u>Mean no. per leaf</u>			
		<u>May 13, post treatment</u>			
		<u><i>T. urticae</i></u>		<u><i>N. fallacis</i></u>	
		Motiles <sup>2/</sup>	Eggs	Motiles	Eggs
water only	-	0.69 a	2.31 a	0.25 a	0.21 a
acephate	1.10	1.64 a	3.62 a	0.13 ab	0.02 b
chlorpyrifos	2.20	1.33 a	5.65 a	0.02 bc	0.01 b
esfenvalerate	0.05	0.58 a	4.31 a	0.00 bc	0.00 b
Standard error		0.33	13.12	0.05	0.05

<sup>1/</sup> Insecticide rate applied in equivalent of 280 liters of water per ha.

<sup>2/</sup> Mean separation by Fisher's Protected LSD (Peterson 1985). Means with the same letter are not significantly different.

Both esfenvalerate and chlorpyrifos were highly toxic to *N. fallacis* in both laboratory and field bioassays; however, some survival of *N. fallacis* was observed in fields treated with chlorpyrifos. In the field bioassay, acephate was less disruptive to *N. fallacis* than in the laboratory bioassay. The higher survival of *N. fallacis* in field plots treated with acephate and chlorpyrifos may be related to ecological selectivity. Untreated areas on peppermint plants may result from uneven spray droplet distribution and provide refuges where predators can escape the adverse effects of some pesticides. However, because *N. fallacis* (both motiles and eggs) was reduced more than spider mites, secondary spider mite outbreaks may result from applications of acephate and chlorpyrifos.

### ***Ecological selectivity: test 2***

Significantly more *T. urticae* motiles ( $F=7.51$ ;  $df=5,30$ ;  $P<0.01$ ;  $SE=1.87$ ) and eggs ( $F=19.01$ ;  $df=5,30$ ;  $P<0.01$ ;  $SE=13.15$ ) were observed in plots receiving carbofuran compared to the other treatments (Table 15). Applications of methomyl, oxamyl and carbofuran significantly reduced *N. fallacis* motiles ( $F=4.67$ ;  $df=5,30$ ;  $P<0.01$ ;  $SE=0.08$ ) by 60%, 67% and 96%, respectively (Table 15). In this study, neither malathion nor sulfur affected predator mite levels. Although not significantly different ( $F=1.91$ ;  $df=5,30$ ;  $P=0.12$ ;  $SE=0.07$ ), there was a trend showing lower numbers of *N. fallacis* eggs in plots treated with all pesticides compared with the control (Table 15).

Results from this experiment suggest that application of carbofuran may result in increased spider mite levels through disruption of *N. fallacis*. Such results were observed when carbofuran was applied to peppermint in the fall. Similar results were observed in other studies conducted in pear with *Galendromus occidentalis* and in strawberries with *N. fallacis*. (Westigard et al. 1972, Brown and Shanks 1976). Although oxamyl and methomyl reduced populations of *N. fallacis* in this study, they did not reduce them to the extent carbofuran did. Predator mites may re-establish more rapidly after an application of oxamyl or methomyl; however, lower predator mite levels may result in spider mite outbreaks later in the season.

**Table 15.** Effect of pesticides on *T. urticae* and *N. fallacis* motiles and eggs (Lower Bridge, Oregon)

Treatment	Rate applied kg ai/ha <sup>1/</sup>	Mean no. per leaf			
		July 3, Post treatment evaluation			
		<i>T. urticae</i>		<i>N. fallacis</i>	
		Motiles <sup>2/</sup>	Eggs	Motiles	Eggs
water only	-	4.22 b	25.44 b	0.360 a	0.25 a
methomyl	1.0	6.67 b	28.98 b	0.145 b	0.09 a
malathion	1.1	4.00 b	14.17 b	0.402 a	0.12 a
sulfur	3.3	5.29 b	31.20 b	0.383 a	0.18 a
carbofuran	2.2	15.61 a	162.13 a	0.013 c	0.01 a
oxamyl	1.1	4.58 b	13.23 b	0.119 b	0.03 a
Standard Error		1.87	13.15	0.076	0.066

<sup>1/</sup> Insecticide rate mixed in equivalent of 280 liters of water per ha.

<sup>2/</sup> Mean separation by Fisher's Protected LSD (Peterson 1985). Means with the same letter are not significantly different.

**Table 16.** Effect of a fungicide, herbicide and insecticide on *T. urticae* and *N. fallacis* motiles and eggs (Lower Bridge, Oregon)

Treatment	Rate applied <sup>1/</sup> kg or ml per ha	Mean no. per leaf			
		Post treatment evaluation, May 15, 1994			
		<i>T. urticae</i>		<i>N. fallacis</i>	
		Motiles <sup>2/</sup>	Eggs	Motiles	Eggs
water only	---	0.104 a	0.21 a	0.25 a	0.28 a
propiconazole	583 ml	0.004 a	0.25 a	0.30 a	0.34 a
paraquat	1166 ml	0.040 a	0.06 a b	0.06 b	0.04 b
ethoprop	6.7 kg	0.010 a	0.00 b	0.00 b	0.00 b
Standard Error		0.04	0.07	0.04	0.05

<sup>1/</sup> Pesticide rate applied in equivalent of 280 liters of water per ha.

<sup>2/</sup> Mean separation by Fisher's Protected LSD (Peterson 1985). Means with the same letter are not significantly different.

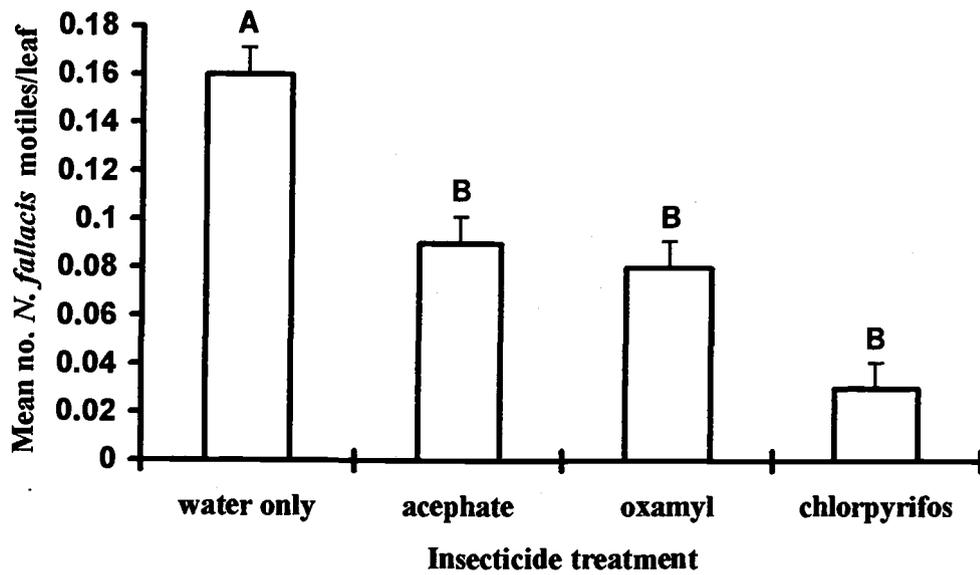
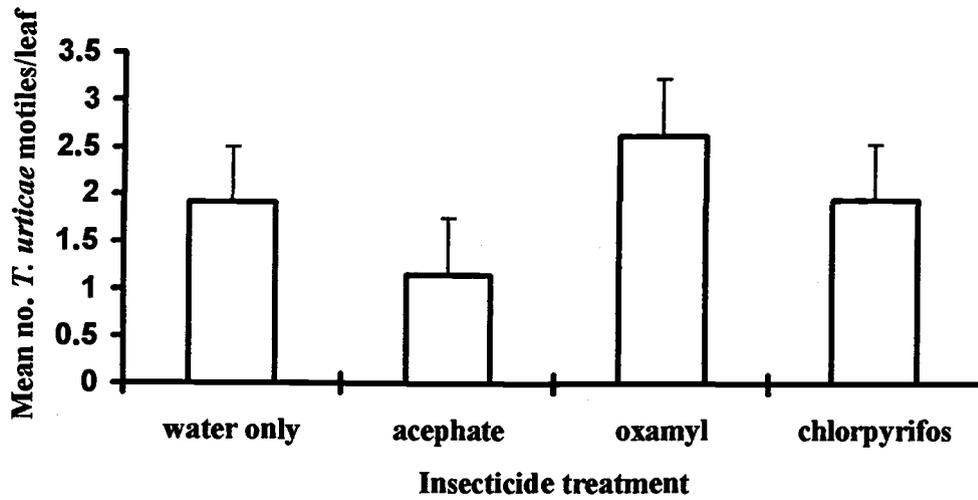
### ***Ecological selectivity: test 3***

Applications of propiconazole, paraquat, and ethoprop did not significantly reduce populations of *T. urticae* motiles compared to the control ( $F=3.28$ ;  $df=3,28$ ;  $P=0.09$ ;  $SE=0.04$ ) (Table 16). However, fewer spider mite eggs were detected in plots treated with ethoprop ( $F=2.83$ ;  $df=3,28$ ;  $P<0.05$ ;  $SE=0.07$ ) (Table 16). *N. fallacis* motiles were reduced by 76% in plots treated with paraquat and by 100% in plots treated with ethoprop ( $F=11.45$ ;  $df=3,28$ ;  $P<0.01$ ;  $SE=0.04$ ) (Table 16). Plots treated with ethoprop and paraquat also showed a 100% and 86% reduction, respectively, in *N. fallacis* eggs ( $F=8.83$ ;  $df=3,28$ ;  $P<0.01$ ;  $SE=0.06$ ).

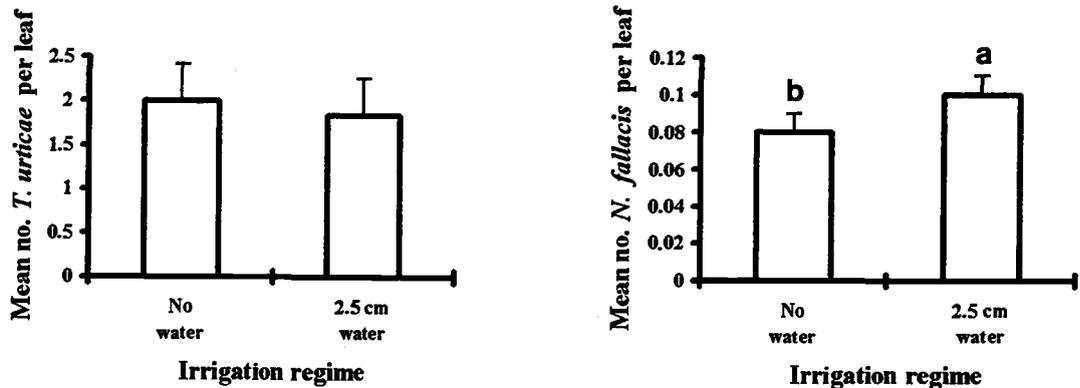
Because broadcast applications of ethoprop may eliminate *N. fallacis* motiles and eggs, alternative application methods or formulations that increase the selectivity of ethoprop may be desirable, e.g. chemigation and granular formulations. Although paraquat greatly reduced *N. fallacis* when applied to peppermint in the spring, paraquat selectivity to mites may be increased if applied during the winter months when predators are dormant. During the dormant season, diapausing adult female predator mites may be more protected from spray residues by overwintering in dead leaves, debris and hollow stems (Morris et al. 1996). In this study, propiconazole did not adversely affect either the number of *N. fallacis* motiles or eggs. Additional studies are required, however, to determine if egg hatch could be reduced by this fungicide. As an example, the fungicide benomyl has been shown to reduce egg viability in *N. fallacis* (Nakashima and Croft 1974).

### ***Ecological selectivity: test 4***

Neither irrigation regime nor pesticide significantly affected the density of spider mites in the plots during this study (Figures 7 and 8). In contrast, predator mite density did depend on the pesticide applied ( $F=20.29$ ;  $df=3,32$ ;  $P<0.01$ ;  $SE=0.011$ ) and irrigation regime used ( $F=5.01$ ;  $df=1,32$ ;  $P=0.03$ ;  $SE=0.008$ ). Predator mites decreased by 81%,



**Figure 7.** Effect of selected pesticides on *T. urticae* and *N. fallacis* motiles (Culver, Oregon). Sample means were compared with Fisher's Protected LSD (Peterson 1985).



**Figure 8.** Effect of simulated irrigation on levels of *T. urticae* and *N. fallacis* motiles (Madras, Oregon). Sample means were compared with Fisher's Protected LSD (Peterson 1985).

50% and 43% in cages treated with chlorpyrifos, oxamyl and acephate, respectively (Figure 7). The addition of 2.5 cm of water applied 30 minutes after pesticide application increased predator mite survival by about 25% (Figure 8). There was no significant interaction detected between pesticide applied and irrigation regime used with respect to predator mite levels.

Pesticides are used to control soil pests on peppermint in early spring. Irrigating the crop soon after pesticides are applied or applying pesticides via chemigation may improve control of soil pests by moving the pesticide from the leaves to the soil. In addition, by reducing the impact of disruptive pesticides on *N. fallacis*, biological control of spider mites may be enhanced. However, the effectiveness of acephate applied to control foliar pests later in the season may be reduced by washing acephate residues off peppermint leaves prematurely.

## CONCLUSIONS

Resistance to dicofol in spider mites and disruption of *N. fallacis* by pesticides have probably contributed to increased spider mite severity in peppermint over the last 20 years. Spider mite resistance to dicofol is well-documented in many agricultural crops (Cranham and Helle 1985, Dennehy et al. 1988, Denholm and Rowland 1992) and has probably played a role in spider mite control failures in peppermint. Although peppermint phenolics and monoterpenes have been shown to increase metabolic breakdown of some insecticides by certain mint pests (Yu et al. 1979, Berry et al. 1981), I hoped to avoid induced metabolism of dicofol by collecting spider mites from peppermint and rearing them on lima bean plants for several generations before conducting the bioassays.

Dicofol is toxic to *N. fallacis* (Croft 1975, Hislop and Prokopy 1981, Chapman and Penman 1987, Raworth 1990) and has probably contributed to spider mite outbreaks in peppermint. According to grower surveys, over 90% of peppermint fields treated with dicofol in the western U.S. were re-treated with propargite (Morris and Lundy 1995). This practice increases selection pressure for spider mite resistance to propargite, the only selective miticide presently registered for use on mint. If propargite were to lose its effectiveness, spider mite management would become more difficult. Using selective miticides at low rates and only in situations where spider mites are temporarily uncoupled from phytoseiid predators is an effective spider mite management strategy on several crops including apples (Croft and McGroarty 1977), almonds (Hoy 1985), and peppermint.

Because pesticides may adversely affect *N. fallacis*, determining the toxicity of various pesticides to this natural enemy would benefit the U.S. mint industry. Pesticides are usually more toxic to natural enemies than their prey (Fournier et al. 1985, Croft 1990); therefore, researchers have suggested that risk assessment of pesticides to natural enemies should be part of the pesticide registration process (Jepson 1993, Stark et al. 1995). Such risk assessment is common in several European countries (Jepson 1993, Stark et al. 1995). What would be desirable is a cost effective laboratory bioassay that would accurately predict pesticide effects on important natural enemies across all crops.

Because such a bioassay is presently unavailable (Stark et al. 1995), risk assessment should be conducted on an individual crop basis, regardless of whether pesticides are included as part of a national program.

One possible drawback of a national program for pesticide risk assessment toward natural enemies would be the lack of specific information. For example, a pesticide may be determined to be safe toward a specific natural enemy and crop, but this does not mean the results are robust enough to be extrapolated to all natural enemies and all cropping systems. Also, a national program may be biased toward certain natural enemies found in major crops and neglect effective natural enemies in minor crops. Would *Phytoseiulus persimilis* be used to determine pesticide susceptibility of all phytoseiids? Pesticides affect different phytoseiid species in different ways (Croft 1990, Fournier et al. 1985) and pesticide susceptibility may vary for sub-populations of a single phytoseiid species (Hoy 1982, Fournier et al. 1985, Croft 1990).

The following factors also may have an impact on how a pesticide affects natural enemies in the field (Croft 1990, Jepson and Thacker 1990, Jepson 1993): (1) properties of the pesticide, e.g. formulation and method of application, (2) natural enemy characteristics, e.g. resistance, behavior, dispersal, and (3) specifics of the cropping system, e.g. physical characteristics, environmental conditions, agricultural practices. In peppermint, the effect of pesticides on *N. fallacis* may depend on pesticide application method and timing, predator-prey interaction, and growing region. For example, if pesticides are applied prior to mid-March, *N. fallacis* may avoid direct contact since it is overwintering in protected habitats. Moreover, because *N. fallacis* is mostly inactive during the winter, it may avoid contact with toxic pesticide residues.

In early spring, *N. fallacis* is usually found feeding on spider mites on lower peppermint leaves. Peppermint leaves that are lower in the canopy are more mature and have fewer secondary plant compounds than leaves higher in the canopy. Such leaves may be more desirable to *T. urticae* (Larson 1983, Larson and Berry 1984). Predators are likely to be protected from pesticide sprays in early spring because their proximity to the soil surface and short internodes on the plant provide a protective umbrella effect. Also, predator mites may escape lethal pesticide levels since they are mainly found on the

underside of leaves. Spider mites prefer the underside of leaves and *N. fallacis* is often associated with spider mites until they are depleted (Croft et al. 1995, McMurtry and Croft 1997).

Pesticide effects on *N. fallacis* may change as the plant grows, spider mite levels decrease, or different pesticide application methods are used. As peppermint grows, new leaves are formed at the apex, lower leaves are lost through senescence, and internodal length increases (Hollingsworth 1980). This growth habit may increase pesticide exposure to *N. fallacis* initially, then reduce the potential for exposure as the canopy thickens. As *N. fallacis* depletes its spider mite prey on lower leaves, it may become more active in search of new prey patches, placing it at greater risk of encountering pesticide spray droplets and toxic residues. Immigration from surrounding crops or non-crop areas may re-establish predator mites in a field following an application of a disruptive pesticide; however, adequate sources of immigrants must exist and their dispersal ability must be adequate (Croft 1990, Jepson 1993). Because *N. fallacis* does not tolerate dry conditions, re-colonization from outside irrigated agroecosystems may not occur in arid growing regions such as central Oregon. Lastly, if peppermint growers chose pesticide application techniques that provide greater spray coverage (e.g. air blast sprayers) fewer pesticide-free refuges may exist for *N. fallacis*.

The following is a protocol to evaluate pesticide effects on *N. fallacis* in peppermint to complement a national pesticide risk assessment program. First, bean leaf disk bioassays could measure physiological selectivity and provide a conservative estimate of risk to *N. fallacis* (equivalent to the Tier I tests described by Jepson (1993)). If no negative effects are observed in the leaf disk bioassays, field trials may be unnecessary. Other researchers have shown that pesticides that were safe in laboratory bioassays were also safe under field conditions (Hislop and Prokopy 1981, Thistlewood and Elfving 1992). Should the bioassays detect a deleterious effect on predators, semi-field experiments could be conducted to assess ecological selectivity (equivalent to Tier II testing (Jepson 1993)). If unacceptable risks occur in semi-field experiments, pesticides could be manipulated to increase selectivity, for example, by changing the pesticide formulation, application rate, application method, and application timing (Croft 1990).

## SUMMARY AND CONCLUSIONS

This study was conducted to address the increasing severity of spider mites on peppermint in the western U.S. Based on observations of peppermint growing practices throughout this region, it was hypothesized that spider mite resistance to dicofol and/or disruption of spider mite biological control by certain agricultural practices may be responsible for this trend. Because miticide costs are increasing and fewer miticides are being registered (Glass 1986), biological control of spider mites in peppermint warranted additional investigation. This view was reinforced by results from preliminary peppermint surveys which suggested that higher levels of phytoseiids were present in mint fields than had been previously reported (Hollingsworth 1980, Hadam et al. 1986).

The first objective was to conduct an extensive phytoseiid survey of peppermint fields throughout the western U.S. From the beginning, the intention was to evaluate the effectiveness of the most abundant native phytoseiid species found in mint. If this species proved to be ineffective, the next most abundant native phytoseiid and combinations of different native phytoseiid species would have been evaluated. Combinations of phytoseiids may improve biological control of spider mites in some cropping systems (Croft and MacRae 1992, MacRae and Croft 1994, McMurtry and Croft 1997). If results using native phytoseiids were unsatisfactory, I was prepared to evaluate exotic phytoseiid species. By evaluating native species first, I hoped to avoid adversely affecting biological control through mechanisms such as competitive exclusion (Ehler and Hall 1982).

Although several phytoseiid species were identified in peppermint, *Neoseiulus fallacis* accounted for greater than 99% of all phytoseiids found. Other phytoseiid species were detected at very low levels and were usually found along field margins adjacent to their preferred plant species. Results of both pesticide exclusion and cage exclusion studies demonstrated that *N. fallacis* was effective in controlling spider mites in peppermint. The results observed in these studies were similar to those observed in commercial peppermint fields (Morris, personal observation).

Propargite worked effectively to control spider mites in the presence of *N. fallacis*, but spider mites soon rebounded in cages that were treated with propargite but lacked predator mites. These data suggest that although propargite is still a valuable tool in mint for managing spider mites, its effectiveness has been somewhat diminished probably as a result of increased spider mite resistance. Increasing the useful life of selective miticides is presently very important because new pesticide registrations are difficult to obtain and fewer miticides are being registered (Glass 1986).

Having established that *N. fallacis* was effective in controlling spider mites in peppermint, ways of improving biological control using this species were then investigated. The first step was to study aspects of overwintering. Since *N. fallacis* were present in the majority of peppermint fields in central Oregon, it was hypothesized that it must be overwintering in mint fields because the humidity was too low for its survival in the surrounding desert environment. Also, a small number of *N. fallacis* were observed on mint leaves throughout the winter.

Studies were conducted to determine where *N. fallacis* overwintered and what kind of habitats it preferred. Results showed that the majority of *N. fallacis* overwintered in dead leaves near the soil surface, with fewer numbers in dead stems and on live leaves. Studies were conducted to evaluate the effect of manipulating the overwintering peppermint habitat on predator mite survival. An experiment was conducted where dead leaves were either added to or removed from plots. Results showed that increasing the amount of dead leaves in the plots enhanced the overwintering survival of *N. fallacis* in central Oregon. Conversely, removal of dead leaves had the opposite effect. These results suggest that adjusting peppermint management practices to allow some dead leaves to remain in mint fields following harvest may improve spider mite biological control.

The effect of fall applications of carbofuran on spider mite and predator mite levels were assessed. Carbofuran was evaluated because this insecticide is known to be toxic to *N. fallacis* (Brown and Shanks 1976, Croft 1990), and mint growers have relied on it in the past for root weevil control. Carbofuran applied in the fall decreased levels of *N. fallacis* and increased levels of spider mites the following spring. These results also

suggested that using carbofuran for root weevil control probably contributed to the increased severity of spider mites in mint during the 1980s.

Flaming peppermint fields in the fall was also shown to be disruptive to *N. fallacis*. Flamed plots resulted in higher spider mite levels and lower predator mite levels the following spring compared to unflamed plots. Disruption of predator mites by flaming is an example where management of one pest, in this case *Verticillium dahliae*, adversely affects the management of another pest species. The disruptive effect of fall flaming may be reduced if small areas within mint fields are allowed to remain unflamed. More research will be required to determine the size and number of unflamed areas that will provide adequate refugia for *N. fallacis*. Although such areas may allow predator mite survival, allowing unflamed areas to remain in peppermint fields may increase the severity of verticillium wilt. Wilt-infested plant material may spread the disease from unflamed to flamed areas. Additional research is required to understand the true benefit of fall flaming for verticillium wilt control.

From fall until the following spring, *N. fallacis* were shown to disperse 7.5 m from unflamed peppermint plots into adjacent flamed areas. The dispersal ability of *N. fallacis* in mint, however, may depend on other factors that must be investigated including the effect of: (1) height and density of mint regrowth, (2) humidity provided by irrigation or rainfall, (3) prey density and (4) adjacent cropping systems. Moreover, predator mite releases targeting spider mite "hot spots" may provide a more widespread distribution of predators after they deplete their prey and disperse. Information on dispersal would not only be useful for assessing the need for predator mite refugia in mint, but also for improving *N. fallacis* application techniques in augmentation programs for spider mite control.

Mint fields where spider mites never reached treatable levels for three consecutive growing seasons have been observed (Morris, unpublished data). To better understand predator-prey interactions that may lead to such conditions, the spatial patterns of spider mites and predator mites following harvest were examined. Results showed that spider mites more readily colonized upper regions of peppermint plants than did *N. fallacis*. This difference may be related to lower humidities associated with taller plants compared to

plants growing closer to the soil surface. Allowing a refuge in which spider mites may temporarily escape their predators may prevent spider mite extinction via predation and subsequently prevent the extinction of predators by starvation (Nachman 1988).

The stability of spider mite regulation in mint by predator mites may follow the meta-population dynamics model. The following events appear to play a role in increasing the stability of spider mite regulation in mint: (1) asynchronous colonization of mint patches by spider mites and their predators, (2) dispersal of *N. fallacis* into spider mite patches before spider mites have overexploited their food supply, and (3) the temporary uncoupling of predator mites from their prey. Other factors may also contribute to the stability of biological control in mint. For example, *N. fallacis* may avoid extinction by feeding on alternate food sources, as do many other phytoseiid species. Tydeids have been recovered from mint fields but their role as an alternate food source for *N. fallacis* is unclear. *Galendromus occidentalis* is known to feed on tydeid mites in some cropping systems (Hoy et al. 1979, Calis et al. 1988).

Because pesticides are known to have such a profound effect on both pests and their natural enemies (Cranham and Helle 1985, Dennehy et al. 1988, Croft 1990), it was important to evaluate the impact of commonly used mint pesticides on *N. fallacis*. Also, it was necessary to document how widespread spider mite resistance to dicofol was in mint throughout the western U.S. An increasing number of field failures have been reported following treatment of spider mites with dicofol (Morris, personal observation). Various explanations have been suggested throughout the mint industry to explain this phenomenon including the rapid degradation of dicofol in spray tanks due to high pH conditions as well as lack of adequate spray coverage. However, these explanations did not adequately address why growers were experiencing difficulty controlling spider mites with dicofol despite buffering their spray solution and changing their application techniques.

Toxicity of dicofol to *N. fallacis* appears to have contributed to increased spider mite pressure on mint. Dicofol is usually applied in early spring because it has longer residual activity than propargite and because it supposedly works better under cool conditions. The use of non-selective acaricides like dicofol served to uncouple spider

mites from their predators at a crucial time when spider mites were rapidly increasing. Because spider mite populations were often resistant to dicofol, they rapidly resurged to damaging levels in the absence of sufficient predators to control them.

Several pesticides used on mint were shown to adversely affect *N. fallacis* in laboratory and semi-field tests. The negative effects of some pesticides, however, may be reduced by manipulating how a pesticide is used, e.g. changes in formulation, timing or method of application. For example, the application of additional water soon after pesticide application was shown to reduce the disruptive effects of acephate, chlorpyrifos, and oxamyl on *N. fallacis*. In cases where alternatives are not available, more research is required to understand how to use disruptive pesticides more selectively.

Because these results demonstrated the disruptive nature of some pesticides to *N. fallacis*, it makes sense to include pesticide selectivity as part of the registration process. It may be best for individual commodity groups to assume the responsibility for evaluating the selectivity of pesticides of interest to them. Important natural enemies are likely to vary among different crops, and even the same natural enemy may possess unique genetic traits that affect their response to pesticides depending on the crop in which they occur. Unique attributes of the natural enemy in different cropping systems are not likely to be addressed adequately by a national pesticide screening process.

It appears that spider mite severity in mint has been reversed. Results of 1995 pesticide surveys conducted by Oregon State University and Washington State University show miticide use in Oregon and Washington to have declined. In central Oregon, the percentage of peppermint fields treated with propargite and dicofol has decreased from 100% and 57%, respectively, to 88% and 1% (Morris and Lundy 1995, Jepson and Mason 1996). In central Washington, which has an arid climate similar to central Oregon, the percentage of peppermint fields treated with propargite and dicofol has decreased from 66% and 27%, respectively, to 25% and 2% (Morrell et al. 1995, Morris and Lundy 1995). These results suggest that the adverse effects of some pesticides probably contributed to the increase in spider mite problems observed by the mint industry during the 1980s and early 1990s. Peppermint growers appear to have reduced their reliance on miticides due to (1) increased awareness of resistance development, (2) knowledge of the

negative impact of pesticides on spider mite predators, and (3) greater understanding of how to manage spider mites using *N. fallacis*.

The U.S. mint industry is supporting an intensive program to educate growers about mint pest management including biological control (Morris and Lundy 1995). In addition, the mint industry is funding research on the impact of pesticides on *N. fallacis*. Hopefully, this research will lead to the registration of more selective pesticides and determine ways of using disruptive pesticides more selectively. Also, the mint industry has supported the development of a facility to produce *N. fallacis* for commercial release in mint fields. In 1996 and 1997, *N. fallacis* was released on 8,000 and 10,000 acres of mint, respectively, to augment native populations. The mint industry is currently working toward registering additional selective miticides that may be used in conjunction with propargite and *N. fallacis* as part of an overall pesticide resistance management program. Because propargite is the only selective miticide currently registered for use on mint, its loss due to resistance development could seriously jeopardize spider mite biological control on this crop.

To further refine spider mite management on mint, additional research is required to identify and manipulate those factors that affect the stability of biological control. Management of irrigation and overwintering habitat has been documented in this thesis. Another area requiring additional research is the use of moderately disruptive pesticides. Under certain circumstances, such pesticides may actually stabilize predator-prey interactions by preventing predators from over-exploiting their prey. Manipulating the system at this level would require extensive knowledge of predator-prey dynamics. Yet another research avenue would be to study the role of generalist predators in the mint cropping system. It has been shown that certain generalist phytoseiids are able to maintain spider mite populations at low densities in tree fruit agro-ecosystems (Croft and MacRae 1992, MacRae and Croft 1994, Nyrop personal communication) and perhaps generalist insect and mite predators would act in a similar fashion in mint.

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