Evaluation of Predatory Mite (Acari: Phytoseiidae) Releases to Suppress Spruce Spider Mites, *Oligonychus ununguis* (Acari: Tetranychidae), on Juniper

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ABSTRACT A laboratory trial evaluated four phytoseiid species for their potential as biological control agents of spruce spider mite, *Oligonychus ununguis* (Jacobi) (Acari: Tetranychidae). An augmentative biological control approach, using the predatory mites *Neoseiulus fallacis* Garman and *Galendromus occidentalis* Nesbitt (Acari: Phytoseiidae), was evaluated for reducing pest mite densities and injury, and economic costs on *Juniperus chinensis* 'Sargentii' A. Henry (Cupressaceae) in an outdoor nursery. Sequential releases of predator species, individually and in combination, were tested and compared with two commonly used miticides, a low-toxicity miticide, horticultural oil, and a conventional miticide, hexythiazox. Timing of treatments was based on grower-determined need, and predator release rates were based on guidelines in literature received from producers of beneficial organisms. Predator releases were more expensive and provided less effective suppression of spruce spider mites, resulting in greater spider mite injury to plants, compared with conventional pesticides. However, spider mite damage to plants did not differ in an economically meaningful way between treatments. Unsatisfactory levels of control seem related to under estimations of actual spider mite abundance based on grower perceptions and the beat sampling technique used to estimate predator release rates. These data suggest that when initial populations of spruce spider mite are high, it is unlikely that sequential releases of predator species, individually or in combination, will suppress spider mite populations. In this trial, augmentative biological control was 2.5–7 times more expensive than chemical controls.

KEY WORDS augmentative biological control, natural enemies, ornamentals, integrated pest management, cost analysis

IN MANAGED ORNAMENTAL SYSTEMS, such as production nurseries, landscapes, and golf courses, insects and other pests frequently outbreak and cause aesthetic and economic damage to plants. The horticulture industry has, and continues to, rely heavily on the use of synthetic pesticides to control these pests (Hudson et al. 1996). More recently, increasing societal concerns over the effect of pesticides on the environment and human health and increasing government regulations on pesticide use have resulted in increased emphasis on the development and implementation of alternative, less toxic pest control measures (Garber et al. 1996).

Biological control is an alternative pest management approach that has received increasing interest in recent years. Biological control is the use of natural enemies to suppress insect, mite, disease, or weed pest populations below damaging levels. Natural enemies include predatory and parasitic arthropods and pathogens. In many ecosystems, endemic populations of natural enemies maintain pest populations below damaging levels. However, in intensively managed or disturbed systems, such as production nurseries, natural enemies are often absent or populations are too low to suppress pest populations below damaging levels (Ehler and Kinsey 1995). In situations where natural enemies are scarce and pesticides do not disrupt natural enemy–prey interactions, augmentative biological control is a viable pest management option. Augmentative biological control is the release of commercially available or insectary-reared natural enemies to suppress pest populations (Raupp et al. 1993, Van Driesche and Bellows 1996).

Most studies evaluating augmentative biological control against pest insects and mites of ornamentals have been done in protected structures or controlled environments such as greenhouses (Boys and Burbutis 1972, Simmonds 1972, Hamlen and Lindquist 1981, Van de Vrie 1985, Gough 1991, Smith et al. 1993, Cashion et al. 1994, Raupp et al. 1994, Zhang and

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Sanderson 1995, Pratt and Croft 1998, 2000b) or laboratories (Boyne and Hain 1983) and have documented varying levels of success. Of the handful of studies that have been conducted in outdoor nursery or landscape environments, success, measured by reduced pest densities, has also been variable (Raupp et al. 1994; Ehler and Kinsey 1995; Dreistadt and Flint 1996; Pratt and Croft 1998, 2000b; Skirvin and De Courcy Williams 1999; Shrewsbury and Smith-Fiola 2000; Pratt et al. 2002). Of these studies, only a few have examined the use of phytoseiids to control ornamental pest mites (Pratt and Croft 1998, 2000b; Skirvin and De Courcy Williams 1999; Pratt et al. 2002). With the limited number of studies evaluating augmentative biological control, there is still much to understand about the use of predatory mites as control agents for phytophagous spider mites, especially in outdoor environments.

The study described herein examines augmentative biological control, using predatory mites in the genera *Neoseiulus* and *Galendromus* (Acari: Phytoseiidae), as an alternative approach for managing spruce spider mite, *Oligonychus ununguis* (Jacobi) (Acari: Tetranychidae), feeding on junipers, *Juniperus chinensis* 'Sargentii' A. Henry (Cupressaceae), in a simulated nursery environment. This study system was selected for several reasons. Spruce spider mites are one of the most destructive conifer feeding spider mites in the United States, attacking a wide range of needled evergreen species grown in nurseries, landscapes, and forest systems (Johnson and Lyon 1988, Raupp and Hoitink 1996). Preferred host plants include spruce, pine, hemlock, juniper, and arborvitae (Johnson and Lyon 1988, Lehman 1998). Spruce spider mites overwinter as eggs on the bark and needles of its hosts, have multiple generations per season, and are active during the spring and fall months when temperatures are cooler (Johnson and Lyon 1988). Spruce spider mite feeding results in damage to plants in the form of stippling on and browning of needles, needle drop, branch dieback, and ultimately tree death (Johnson and Lyon 1988, Davidson and Raupp 1999). This damage results in loss of aesthetic and economic value to the infested evergreens (Hamlen and Lindquist 1981). Current control strategies for spruce spider mites emphasize the use of chemical pesticides (Shetlar and Herms 1997, Davidson and Raupp 1999), which vary in their level of toxicity and effectiveness.

Phytoseiid mites are the major group of predators that attack tetranychid spider mites (Hoy 1982, McMurtry and Croft 1997), and many are commercially available from suppliers of biological control agents (Hunter 1997). Predator species used in this study were selected based on reports from the literature on their life histories and ability to reduce densities of mites in the Tetranychidae family, the *Oligonychus* genus, or both. McMurtry and Croft (1997) categorized phytoseiid mites into four life style types based on their life history and morphological characteristics. Type I are specialized predators of *Tetranychus* species, type II are selective predators that feed on mites in the family Tetranychidae, type III are generalist predators, and type IV are specialists on pollen but may also feed on mites (McMurtry and Croft 1997).

Both type I and type II phytoseiids have been used frequently in augmentation programs (McMurtry and Croft 1997). For our study, we selected genera of mites classified as type II, *Neoseiulus* and *Galendromus.* Although type I predators, mainly represented by *Phytoseiulus persimilis* Athias Henriot, have high intrinsic rates of increase and numerical response, they are known to specialize on pest mites in the genus *Tetranychus,* and there are few reports in the literature of *P. persimilis* feeding on *Oligonychus* species (McMurtry and Croft 1997). Type II predators are selective for mites in the Tetranychidae family (McMurtry and Croft 1997), and there are numerous studies documenting type II predators, mainly *Neoseiulus* and *Galendromus* species, feeding on *Oligonychus* species (McMurtry and Croft 1997, Croft et al. 1998, Pratt and Croft 2000b). Moreover, *Neoseiulus fallacis* (Garman) has been reported to feed on and suppress populations of our study herbivore, *O. ununguis,* in both natural and manipulated ornamental systems (Boyne and Hain 1983; Kramer and Hain 1989; Pratt et al. 1999, 2002; Pratt and Croft 2000a). In addition, Pratt and Croft (2000c) found higher densities of *N. fallacis* overwintered on conifers and evergreen shrubs than other plant types. *Neoseiulus fallacis* also has a relatively high intrinsic rate of increase (McMurtry and Croft 1997). Production nurseries are highly managed and many of the management practices disrupt natural enemy dynamics. Type II phytoseiids are known to be highly adapted to disturbed habitats (McMurtry and Croft 1997).

This study is the first to evaluate the feasibility of using grower monitoring practices along with augmentative predatory mite release rates recommended by commercial suppliers to control spruce spider mites on ornamentals in an outdoor environment. The objectives of this study were to evaluate augmentative releases of predatory mites and their ability to suppress naturally occurring spruce spider mite populations on container-grown junipers in a nursery environment at densities encountered by nursery managers using recommended predator release strategies; and to evaluate the cost effectiveness of this approach. In a preliminary laboratory trial, we evaluated four type II predatory mite species [*Galendromus annectans* De León, *G. helveolus* (Chant), *G. occidentalis* Nesbitt, and *N. fallacis* (Acari: Phytoseiidae)] for their potential as biological control agents of spruce spider mites. We then examined the impact of two predatory mite species (*N. fallacies* and *G. occidentalis*), released individually and in combination, on spruce spider mite populations on container-grown junipers (*J. chinensis* 'Sargentii'). Controls were implemented when spider mites reached an unacceptable level determined by a grower. We also compared predatory mite releases with two commonly used miticides, a low-toxicity miticide, horticultural oil, and a conventional miticide, hexythiazox. Finally, we evaluated the effect of these management tactics on reducing spruce spider mite damage to junipers and compared costs of these approaches.

Materials and Methods

Predator Evaluation. A feeding trial was conducted at the Smithsonian Institution Greenhouse Facility (Washington, DC) in 1999 to evaluate the ability of four species of type II phytoseiid mites to feed on spruce spider mite. To further improve the likelihood of success of the augmentative field study, predator species selection was also based on reports of efficacy in suppressing spider mites and life history traits from the literature. A completely randomized experimental design was used with 10 replicates of each of five treatments. Spruce spider mites used in this trial were field collected from infested junipers growing in a landscape in Washington, DC. Treatments included four predatory mite species (*G. annectans, G. helveolus, G. occidentalis,* and *N. fallacis*) and no predators (control) (=five treatments total). Predatory mites were purchased from a commercial supplier of beneficial organisms (IPM Laboratories, Inc., Locke, NY). Voucher specimens of predators were sent to the Systematics Entomology Laboratory (SEL–USDA, Beltsville, MD) to confirm species identification. Feeding trials were conducted in petri dishes (100 mm in diameter by 15 mm in height) containing damp filter paper. A standardized unit of spider mite-free arborvitae, *Thuja occidentalis* 'Woodwardii' L., foliage of the same size (90 by 50 mm) and age, and taken from similar locations on the plant, was placed in each of 50 petri dishes (five treatments × 10 replicates). Twenty spruce spider mites (active stages only) were placed on the foliage in each of the petri dishes. Treatments receiving predatory mites had three predators of the appropriate species placed on the arborvitae foliage, and the control treatment received no predators. Petri dishes were sealed with parafilm to retain moisture and prevent mites from escaping. Three days after infestation with spruce spider mites and predators, petri dishes were examined under a dissecting microscope, and counts were taken on the number of live spruce spider mites remaining.

Efficacy Study. A field study was conducted in the outdoor nursery yard at the University of Maryland Greenhouse Facility (College Park, MD) in 2000 to determine the efficacy of augmentative releases of two predatory mite species, *N. fallacis* and *G. occidentalis,* in suppressing spruce spider mites and to compare these releases to conventional controls using miticides. A randomized complete block design with nine blocks (blocked by initial spider mite density based on beat sample counts), one replicate within each block, and six treatments per replicate (=54 plants total), was used. The six treatments included the following: 1, control (nothing); 2, *G. occidentalis;* 3, *N. fallacis;* 4, *G. occidentalis* and *N. fallacis* (1:1); 5, horticultural oil (low-toxicity miticide); and 6, hexythiazox (conventional miticide).

Containerized junipers, *J. chinensis* 'Sargentii,' growing in no. 3 (=10.4-liter) containers were used in this study. Junipers were growing in a commercial nursery when spider mites became active and were first observed by the grower on 20 May 2002. Plants were transported to the University of Maryland Greenhouse Facility and maintained in their outdoor nursery yard under normal cultural practices. All study plants were the same age (started in the nursery at the same time) and size (=0.42 m^3 of foliage) and had not previously been treated with pesticides. To confirm the presence and density of spider mites and assign plants to treatment blocks based on pretreatment mite densities, we used a beat sampling technique, which is commonly recommended to growers as a method of monitoring mite populations (Davidson et al. 1988, Studebaker 1992, Dreistadt 2001). A sheet of white graph paper (10 by 14 cm) on a clipboard was held under the sampling unit of foliage. The foliage was beat with a 0.5-m dowel 10 times, and the number of active spruce spider mites on the graph paper was counted. To prevent possible bias in sampling method, the same individual "beat" all plants, and foliage was uniformly sampled from a randomly selected side of a plant that was hanging over the container. The volume of foliage sampled by beating was ≈0.035 m^3. This represented ≈1/12 of the total plant canopy. We multiplied the number of spider mites in the beat sample by 12 to estimate the total number of mites on the plant.

Rates of predator releases were based on the supplier recommendation that predators be released at the rate of 10–100 per plant at the first observation of spider mites (IPM Laboratories, Inc.). Beat samples confirmed that spider mites were present on all plants and estimates of spider mite densities per plant ranged from 180 to 5,400. Because spider mite densities seemed high, we elected to use the higher rate of predator release. We selected a sequential release strategy with three releases. Releases were made on 26 May 2000, 9 June 2000, and 6 July 2000.

Predatory mites were purchased from IPM Laboratories, Inc. and arrived in vials of ≈1,000 mites. To confirm the number of predators released onto the plants, the number of predators in each vial of each shipment was determined. The average number of predatory mites per 2.5 ml (=one-half tsp) of carrier was estimated by first rolling the vial to evenly disperse mites within the carrier, removing 3, 2.5 ml samples from each vial, placing each sample into a petri dish, and counting the number of predators in each sample under the dissecting microscope. By knowing the mean number of predators in each 2.5 ml of carrier and the amount of carrier applied to each plant we estimated the number predatory mites released on each of the plants. All plants were misted with water before release of predators to help carrier and mites adhere to plants. Predatory mites were applied using a measuring spoon and by sprinkling known amounts of carrier and mites evenly over the tops of plants. Releases were done early in the day when temperatures were below 25°C. The average number of mites released per plant were: 130 (±1.1 SE), 119 (±0.3 SE), and 93 (±0.4 SE) on 26 May 2000, 9 June 2000, 6 July 2000, respectively.

The low-toxicity miticide treatment was three applications of a 2% horticultural oil (EPA Reg. No. 862-28, Sunspray Ultra-Fine, Sunoco, Philadelphia, PA) and the conventional miticide treatment was one application of hexythiazox at the high label rate of 0.6 ml/3.8 liters of H_2O (EPA Reg. No. 10163-208, Hexygon, Gowan Company, Yuma, AZ). Both were applied using a hydraulic sprayer (DRAMM, Manitowoc, WI). Horticultural oil kills mites by disrupting membranes and respiration (Miller 1989), and hexythiazox is a mite growth regulator (CDMS 2003). Multiple oil applications are recommended for controlling spider mites (Dreistadt 2001). Oil applications were made on 26 May 2000, 9 June 2000, and 6 July 2000. Hexythiazox can be applied only once per cropping cycle according to label restrictions; therefore, only a single application of this product was made on 26 May 2000.

To compare the efficacy (short-term effect) of different treatments, spruce spider mites were sampled after each of the three treatment applications on 1 June 2000, 20 June 2000, and 21 July 2000. Populations of spruce spider mite are known to decline when summer temperatures consistently exceed 29°C and increase in late summer or early fall when temperatures are cooler (Lehman 1998). Therefore, spruce spider mites were sampled on 8 September 2000 to determine whether treatments applied in the early summer influenced fall spider mite populations (long-term effect). In addition to sampling by the beat method described above, we removed the area of foliage beaten, placed it in a plastic bag, put the bag in a cooler, and transported the samples to the laboratory where they were run through a mite brush machine (Leedom Engineering, Twain Harte, CA). Dislodged mites were collected on a 12.7-cm-diameter plate covered with a thin film of dishwashing soap (to reduce movement of mites) where they were examined with a dissecting microscope and counted. This ensured an accurate count of spider mite densities. The mite brush machine removed 95 ±1% of spider mites on the juniper foliage (P.M.S., unpublished data). Statistical analysis was performed on the total number of mites (beat sample + brush sample) per 0.035-m^3 foliage sample to determine short- and long-term effects of the treatments.

Damage Rating. Unlike damage to deciduous plants spruce spider mite damage on conifers is permanent and not lost until damaged needles are cast, often more than a year later (Lehman 1998). Therefore, we waited to assess plant damage until spider mites were no longer active and maximum damage had accrued. Four individuals with entomological training conducted plant damage ratings on 28 July 2000. Each rater visually assessed the percentage of leaf area showing visible injury (discoloration) by spider mites with an incremental scale: 0, no spider mite injury; 1, 1–10%; 2, 11–20%; 3, 21–30%; 4, 31–40%; 5, 41–50%; 6, 51–60%; 7, 61–70%; 8, 71–80%; 9, 81–90%; and 10, 91–100% leaf injury. An average damage rating was determined from the four individual ratings. Sclar et al. (1998) used this method to assess mite damage on ornamental plants.

Cost Analysis. To evaluate the feasibility of implementing the control tactics used in this study, a cost analysis and comparison of the predator releases and conventional miticides was conducted using a partial budget analysis. Revenues and costs were estimated on a per plant basis for each treatment for the entire "program." The program consisted of three applications or releases of all treatments except hexythiazox (Hexygon), which has label restrictions of one application per crop cycle. Revenue was based on the market value of *J. chinensis* 'Sargentii.' The market value was determined by surveying three wholesale nurseries in the mid-Atlantic region for their wholesale price for *J. chinensis* 'Sargentii' in a no. 3 container. Costs of the pest management programs included materials and shipping, labor, equipment costs, and depreciation, applicator, and integrated pest management (IPM) training, protective clothing, and other miscellaneous expenses. Since there are no "standards" available to calculate labor and associated costs involved in pesticide applications and predator releases, a custom rate, which should account for these costs, was used (J. Hanson, personal communication). Custom rates were estimated by surveying three independent pesticide applicators and three independent IPM consultants on "how much they would charge" to conduct the treatment programs examined in this study. The average charge was calculated and used as the custom rate in the partial budget analysis.

Statistical Analysis. To determine whether predator species differed in their feeding rate on spruce spider mites in the petri dish trial and whether the six treatments in the field study had an effect on plant injury, data were analyzed using an analysis of variance (ANOVA) (Proc GLM; SAS Institute 1999). To determine whether the six treatments had an effect on spruce spider mite density, a mixed model ANOVA was conducted on the three mite density counts taken in the early summer. Data were log transformed to meet the assumptions of normality and heterogeneity of variance. A repeated measures ANOVA was used with treatment and time as fixed effects and block as a random effect (Proc Mixed; SAS Institute 1999). To determine whether the six treatments applied in the early summer influenced the fall population of spruce spider mites (long-term effects), a mixed model analysis was conducted of mite density counts taken in the fall. Variance partitioning was used to account for heterogenous variances, and the data were log transformed to meet the assumption of normality. For early summer and fall spruce spider mite counts, orthogonal contrasts were conducted to compare treatments, and the Bonferroni method was used to control the comparisonwise error rate. The Kenward–Rogers method was used to calculate the degrees of freedom (SAS Institute 1999).

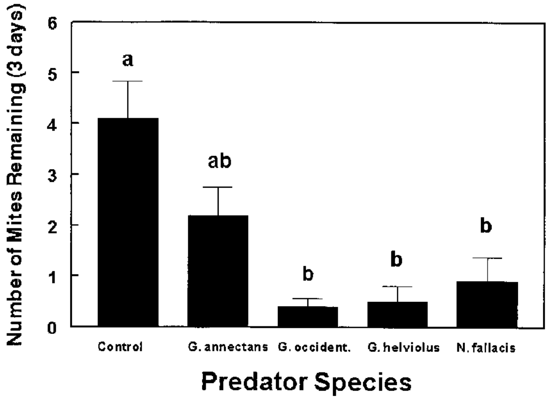

Fig. 1. Number of spruce spider mite remaining in petri dishes after exposure (3 d) to four predatory mite species and a control with no predator. Predator species were *G. annectans*, *G. occidentalis*, *G. helveolus*, and *N. fallacis*. Bars with different letters are significantly different at $\alpha = 0.05$.

Results

Predator Evaluation. The ability of predators to kill spruce spider mite was significantly different among species ($F = 10.13$; df = 4, 45; $P = 0.0001$) (Fig. 1). Significantly fewer spruce spider mites remained after 3 d when exposed to *G. occidentalis*, *G. helveolus*, and *N. fallacis* compared with no predator. There were no differences in feeding between these three predator species. There was no significant difference between the number of spruce spider mites remaining when exposed to the predatory mite *G. annectins* and the control.

Efficacy Study. Analysis of precount spider mite densities indicated a significant block effect ($F = 7.99$; df = 8, 40; $P = 0.0001$) and no significant treatment effect ($F = 0.63$; df = 5, 40; $P = 0.6747$). A repeated measures analysis of spruce spider mite densities on the three sampling dates after each treatment application indicated there was no significant sampling date by treatment interaction ($F = 1.74$; df = 10, 90; $P = 0.0836$). Therefore, we examined the main effects of sampling date and treatment. There was a significant date (pooled across treatment) effect ($F = 1778.5$; df = 2, 66; $P = 0.0001$) and treatment (pooled across date) effect ($F = 8.15$; df = 5, 63; $P = 0.0001$) on spider mite density. Spider mite densities on junipers receiving predator treatments did not differ from each other or the control (Fig. 2). However, three applications of horticultural oil and a single application of hexythiazox did significantly reduce spider mite densities from the control or any of the predator treatments, except hexythiazox did not differ from the combined release of the two predator species (Fig. 2). Horticultural oil and hexythiazox did not differ from each other (Fig. 2). By the third sampling date, populations of spider mites had collapsed in all treatments, including control. This was not surprising because spruce spider mite is a cool-season mite and by 26 July, the third sampling date, daytime temperatures averaged >29°C. Spruce spider mite densities in the early fall (8 September 2000) revealed no significant long-term effect of any treatment on spider mites ($F = 1.56$; df = 5, 29; $P = 0.2015$). Means and standard errors were as follows: control, 36.3 ± 17.4; *G. occidentalis*, 38.0 ±15.1; *N. fallacies*, 58.6 ± 35.3, *G. occidentalis* and *N. fallacies*, 72.5 ±26.2 SE); oil, 17.3 ± 8.5; and hexythiazox, 88.6 ± 41.0.

Damage Rating. When injury to junipers from spruce spider mite feeding was evaluated, there were significant differences in damage ratings among plants receiving the various mite management treatments ($F = 4.10$; df = 5, 207; $P = 0.0014$). Damage ratings ranged from 5.2 to 6.1 where 0 indicated no spider mite injury and 10 indicated 91–100% injury. Junipers treated with horticultural oil and hexythiazox had significantly lower damage ratings than the control and predator treated junipers. There was no difference in damage rating between the control and predator

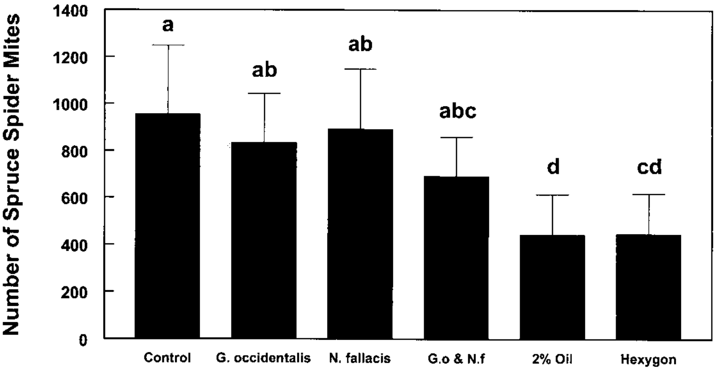

Fig. 2. Spruce spider mite densities (no. of spider mites/0.035 m^3 of foliage) on container-grown junipers after spider mite management treatments. Treatments were control (no predator), *G. occidentalis* (predator), *N. fallacis* (predator), *G. occidentalis*, and *N. fallacis* at 1:1, 2% horticultural oil (low-toxicity miticide), and hexythiazox (Hexygon) (conventional miticide). Three treatment applications or releases were made, except for Hexygon, which was applied once due to label restrictions. Treatment means are of spruce spider mite post counts pooled over three sampling dates. Bars with different letters are significantly different at $\alpha = 0.05$.

Table 1. Partial budget analysis of conventional, low-toxicity, and biological pest management programs for spruce spider mite on container-grown junipers

	Conventional (hexythiazox)	Low-toxicity (horticultural oil)	Biological		
			G. occidentalis	*N. fallacis*	*G. o.* and *N. f.*
Revenue (wholesale value)					
Juniper	\$11.75	\$11.75	\$11.75	\$11.75	\$11.75
Costs					
Materials/ship	\$0.50	\$1.40	\$11.79	\$10.45	\$11.12
Labor[a]	\$1.50	\$4.50	\$2.70	\$2.70	\$2.70
Total costs	\$2.00	\$5.90	\$14.49	\$13.15	\$13.82
Net[b]	\$9.75	\$5.85	−(\$2.74)	−(\$1.40)	−(\$2.07)

Revenue and costs were estimated on a per plant basis for the entire "program." The program consisted of the three predator releases or miticide applications of all treatments except hexythiazox (Hexygon), which was applied once due to label restrictions.

[a] Labor was calculated from the custom rate an independent pesticide applicator (conventional and low toxicity) or private IPM consultant (biological) would charge for their services.

[b] Net profit or loss (=revenue − costs).

treated junipers. Means and standard errors were as follows: control, 6.1 ± 0.17; *G. occidentalis,* 5.9 ± 0.16; *N. fallacies,* 5.9 ± 0.16; *G. occidentalis* and *N. fallacies,* 5.9 ± 0.17; oil, 5.4 ± 0.32; and hexythiazox, 5.2 ± 0.20.

Cost Analysis. When comparing the costs associated with the conventional (hexythiazox), low-toxicity (horticultural oil), and augmentative biological control (predators) programs, we found that the biological control measures were dramatically more expensive to implement than the conventional and low-toxicity measures (Table 1). Also, the horticultural oil treatment at three applications was more expensive than the single application of hexythiazox. The partial budget analysis of the pest management programs conducted in this study demonstrated that augmentative biological control was clearly not an economically feasible approach because they resulted in a net loss, whereas the conventional and low-toxicity approach resulted in a net profit (Table 1).

Discussion

In screening four phytoseiid species to identify which predator species might be successful in our augmentative field study, we found three (*G. occidentalis, G. helveolus,* and *N. fallacis*) of the four species tested equally reduced spruce spider mite populations. This was not surprising because type II phytoseiid mites in the genus *Neoseiulus* and *Galendromus* are known to feed on tetranychid spider mites, including those in the genus *Oligonychus* (McMurtry and Croft 1997, Croft et al. 1998). Of the few studies examining the efficacy of phytoseiids in suppressing spruce spider mite, *N. fallacis* was used successfully under controlled laboratory (Boyne and Hain 1983, Kramer and Hain 1989, Pratt et al. 1999) and field conditions (Boyne and Hain 1983), further supporting our selection of *N. fallacis* as a likely candidate for augmentative control of spruce spider mite.

At the time the field study was initiated, we could not predict key environmental conditions of temperature and relative humidity that could influence predator performance. Therefore, we sought predators that differed somewhat in thermal and humidity requirements for releases of single species and a combination of two species. Pratt and Croft (2000b) examined life history traits of phytoseiids and found that *G. occidentalis* tolerates relative humidity levels as low as 28% (Pratt and Croft 2000b), whereas others reported that *N. fallacis* performs best at relative humidities >70% (Boyne and Hain 1983, Kramer and Hain 1989, Pratt and Croft 2000b). In addition, we thought it best to select predators that differed somewhat in other life history traits. *G. occidentalis* is classified as a specialist predator with no preference for prey eggs or larvae, and *N. fallacis* is known to be a generalist that prefers prey eggs to larvae (Schausberger and Croft 2000a, b, Blackwood et al. 2001). There is little data on the efficacy or life history traits of *G. helveolus* on spider mite pests of ornamentals. Based on the results of our trial and other phytoseiid life history characteristics, we selected *G. occidentalis* and *N. fallacis* as the two predators to use in the augmentative field study.

The primary objective of this study was to determine whether augmentative release of the two predatory mite species, individually or in combination, could reduce pest mite densities and injury, and whether it is cost-effective compared with conventional miticides in a nursery environment using a method likely to be implemented by nursery growers. Timing of treatments was based on when the growers first determined they had a spider mite infestation, and predator release rates were based on guidelines received from suppliers of beneficial organisms. Predator releases were less efficacious at suppressing spider mite populations and more expensive compared with conventional control measures. However, all treatments resulted in plants receiving spider mite injury.

These results differ somewhat from those of others that evaluated the efficacy of augmentative releases of predatory mites in outdoor nursery environments. To our knowledge only one other study has evaluated augmentative biological control efforts for suppressing spruce spider mite density and damage on woody plants in an outdoor nursery. Pratt et al. (2002) rated control of spruce spider mite by *N. fallacis* on a scale of 1–4, with 1 being unacceptable and 4 being complete control. They found out of four small-scale studies similar to ours, *N. fallacis* provided unacceptable control (=rating of 1) in two cases and acceptable but with plant damage (=rating of 2) in the other two studies. In two large-scale nursery level studies, *N. fallacis* provided acceptable control but with plant damage (=rating of 2) of spruce spider mites. Although two of the Pratt et al. (2002) studies were rated as acceptable, plant damage still occurred in all their trials. It is impossible to say how damage levels compare between our study and those of Pratt et al. (2002). Pratt et al. (2002) suggested that differences in control levels could be related to foliage density and the associated relative humidities of varying plant canopies. *N. fallacis* is known to be sensitive to low relative humidity (Kramer and Hain 1989, Croft et al. 1993).

The remaining few studies conducted in outdoor environments on ornamentals have found that phytoseiids can suppress tetranychid mites compared with controls. Pratt and Croft (1998) released *N. fallacis* and significantly reduced *Panonychus citri,* citrus red mite, populations on *Skimmia japonica* grown in containers. In another study, Pratt and Croft (2000b) demonstrated that three phytoseiid mites, *N. fallacis, N. californicus,* and *G. occidentalis,* reduced densities of twospotted spider mite, *Tetranychus urticae* Koch, on *Malus, acer,* and *Spiraea* species and southern red mite on *Rhododendron* plants.

Even with these demonstrated successes, there is still much to learn to improve the use of augmentative biological control of spider mites in outdoor environments such as nurseries. Several factors might explain the failure of augmentative releases under conditions found in our study. Consideration of these factors should identify areas to focus future research. Many of the reported successes of augmentative biological control of spider mites on ornamentals, both in greenhouse and outdoor environments, have been demonstrated over extended time intervals (Boys and Burbutis 1972, Simmonds 1972). Our study was temporally limited. Spruce spider mite is considered a cool-season mite and temperatures in excess of 29°C are commonly associated with spruce spider mite population decline under field conditions (Lehman 1998). Spruce spider mite populations in our study collapsed in all treatments, including controls, by mid-July when temperatures in the nursery regularly exceeded 30°C. The interval of time from the first release of predators on the junipers to the collapse of spider mite populations was <7 wk. This short time interval afforded limited opportunity for releases of *N. fallacis* and *G. occidentalis* to reduce spruce spider mite populations. *N. fallacis* and *G. occidentalis* are classified as type II predators, known to take longer to establish and reduce pest mite populations, but to be more persistent over time compared with other predator types (McMurtry and Croft 1997, Pratt et al. 2002). Spruce spider mite densities in September, after their summer diapause, did not differ between treatments, indicating early season control measures did not influence fall populations of spruce spider mite. This may have been the result of predator movement out of our nursery because type II predators, as those used in our study, are known to disperse when prey populations decline (McMurtry and Croft 1997). These data suggest that *N. fallacis* and *G. occidentalis* would not provide extended control for spruce spider mites once they diapause.

Our study found no difference in control of spruce spider mite when single or multiple predator species were released. Studies using the same type II predators as our study found that releasing *N. fallacis* and *G. occidentalis* either singularly or in combination in hops had the same effect on twospotted spider mites (Strong and Croft 1995). Alternatively, releasing more than one predator species with different predatory behaviors have been found to have an additive impact on spider mite populations (McMurtry and Croft 1997).

Three related factors may strongly influence the success of an augmentative biological control approach. These are timing of release, initial prey density, and predator release rate or predator: prey ratio (Hamlen and Lindquist 1981, Stiling 1993, Skirvin and De Courcy Williams 1999, Pratt and Croft 2000a). There is little empirical data on predator release rates, especially for managing spider mites in outdoor nurseries. Pratt and Croft (1998, 2000b) and Pratt et al. (2002) have made impressive headway in identifying factors that influence the success of predator releases and in demonstrating that augmentative release of predatory mites for spider mite control in outdoor nurseries can be successful. However, they do not give specific release rates (predator: prey) that have led to these successes. Release rate recommendations are available from extension fact sheets and information bulletins produced by commercial suppliers of beneficials, but recommendations are variable and there are few for ornamentals in nurseries. For greenhouse plants recommendations include: two or three predators per 0.0929 m^2 (1 sq. foot) of foliage; 10–100 predators per plant; or one predator per five prey. In apple systems, recommendations include one predator per 10 or 20 prey; or one predator per 25 prey. One empirical study by Hamlen and Poole (1982) examined different predator: prey ratios to control *T. urticae* using *Phytoseiulus macropilis* (Banks). Predator: prey ratios of 1:5 and 1:10 suppressed spider mite populations below damaging levels, whereas 1:20 and controls (no predators) resulted in significant damage to plants.

Extension fact sheets and information bulletins stress the importance of timing releases when spider mite populations are "first seen" or when populations are "low" for optimal effectiveness. In greenhouse crops, Hamlen and Lindquist (1981) demonstrated it was important to introduce predators at low densities of spider mites to prevent plant damage because it took from 1 to 3 wk to obtain control. Using *T. urticae* and *P. persimilis* on ornamental nursery plants as their study system, Skirvin and De Courcy Williams (1999) found differential responses (fecundity and movement) of *T. urticae* to plant species. They suggest plants where spider mites reproduce rapidly need to be closely monitored for signs of spider mites or prophylactic, repeated predator releases should be made to prevent plant damage because it takes time for *P. persimilis* to find their prey and build up sufficient populations to suppress a spider mite infestation.

We initiated the augmentative release program when the nursery grower first noted the spruce spider mite infestation. At that time, beat sample estimates of spruce spider mite densities ranged from 180 to 5,400 spider mites per plant. Our release rate averaged 114 predators per plant for each of three sequential releases. These rates result in predator: prey ranges of ≈1:1.6–1:47. Recently, we have found that beat sampling of junipers underestimates actual spruce spider mite densities by a measure of four-fold (P.M.S., unpublished data), suggesting our spider mite densities per plant were actually four times higher than indicated by beat sampling. Relative to the empirical and other release rate information described above, it seems that our study had very high initial densities of spruce spider mite resulting in low predator to prey ratios. These factors may explain the failure of augmentative releases of *N. fallacis* and *G. occidentalis* to suppress spruce spider mite populations in this study.

Strong and Croft (1996) examined the influence of single early season releases of *N. fallacis* and multiple releases throughout the season on twospotted spider mite densities in hops and found that the interaction between spider mite density and timing of predator release(s) were critical. They found naturally occurring populations of predators moved into fields of hops too late to prevent twospotted spider mite outbreaks, but fields that received early season introductions of *N. fallacis* maintained low spider mite densities throughout the season. Although sequential predator releases were conducted in our study, high initial spruce spider mite densities may explain failure of this approach to suppress spruce spider mites. An alternative, potentially more effective approach to examine would be to start early in the season with prophylatic, sequential predator releases, especially because our study and anecdotal information suggest growers usually notice pest populations "too late."

High initial spruce spider mite densities not only influenced the success (or lack of) of augmentative biological control measures but also the conventional and low-toxicity measures. Although conventional and low-toxicity control measures significantly reduced spruce spider mite densities compared with the control and biological control measures, spider mite injury to plants occurred in all treatments. The economic value of ornamental plants is based on their esthetic appearance, which can be directly related to pest feeding injury (Sadof and Raupp 1996). This value is often based on the subjective opinion of plant managers and consumers who tend to have low tolerances for pest damage (Sadof and Raupp 1996). Several studies have been conducted that examine the relationship between ornamental plant value and pest injury to plants (Sadof and Raupp 1987, Coffelt and Schultz 1993, Sadof and Alexander 1993). Most of these studies surveyed retail consumers, rather than wholesale producers or landscape professionals, to determine at what level of plant injury they would no longer purchase a plant. None-the-less, the general consensus of these studies was that once plants reached 10% injury, nearly 100% of consumers refused to buy the plant. All junipers used in our study, regardless of treatment, suffered substantial injury (well beyond 10% discoloration) by the end of the season, suggesting that none of the treatments resulted in a salable plant. These data indicate control measures on ornamentals should be initiated when spider mite populations are low, before economical damage occurs.

Several studies have compared costs of "conventional" and IPM programs in ornamental systems, mainly landscapes, and found costs to be lower under an IPM program (Smith and Raupp 1986, Napit et al. 1988, Stewart et al. 2002). Few studies have conducted partial budget analysis and compared the costs of conventional and biological control measures. To our knowledge, only one cost analysis has been conducted for control of spider mites and that was in a greenhouse study (Smith et al. 1993). Smith et al. (1993) found sequential releases of phytoseiids suppressed twospotted spider mite densities on poplar and was more cost effective than chemical controls. In the partial budget analysis conducted in our study, we used the full market value of the junipers to determine whether the treatments that worked would they be economical. Under this assumption, the biological controls were clearly not economically feasible and horticultural oil was likely not either. Under the pest management programs used in this study and the level of spider mite injury plants incurred, revenues from plants in all treatments would likely be zero, resulting in none of the control measures examined being feasible. Note that if plants were maintained in the production nursery for another growing season, they would likely improve in esthetic appearance and there economic value would increase.

In conclusion, grower-identified need for control measures was too late (spider mite populations were high); beat sampling provided an inaccurate estimate of spider mite populations (underestimated); inadequate release rates (predator:prey ratios) resulted in failure of augmentative predator releases and conventional measures to control spruce spider mites below economically damaging levels; and augmentative predator releases were clearly not economically feasible. To increase the likelihood of success of augmentative releases of predatory mites to control spider mites in outdoor environments, growers need to monitor early and accurately estimate spider mite densities and predator release rates should be pest density based rather than plant density based. Future research should address the development of practical and more accurate methods for growers to monitor and estimate spider mite populations and examine the use of early season prophylatic, sequential predator releases. In addition predator–prey population dynamics should be further examined to determine predator:prey release ratios that provide optimal control of spider mites on a range of plants in outdoor environments.

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