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Evaluation of large-scale releases of western predatory mite for spider mite control in cotton

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Abstract

We evaluated economically feasible release rates of the western predatory mite, *Galendromus occidentalis*, for spider mite control in organically and conventionally managed commercial cotton fields. An important feature of the experimental design was the evaluation of predatory mite releases at a large spatial scale; the majority of plots were near 2 ha. Predatory mite releases did not enhance the density of the western predatory mite, and populations of western predatory mites remained very low throughout the growing season. However, predatory mite releases did appear to reduce the seasonal abundance of spider mites. Nevertheless, spider mite densities exceeded economic thresholds in many of the release plots, and neither early releases (3–6 nodes per plant) or late releases (>7 nodes per plant) enhanced seed cotton yields. We discuss some potential factors that could have limited the impact of the released predatory mites.

Keywords: *Galendromus occidentallis*; *Tetranychus urticae*; *T. pacificus*; *T. turkestani*; *Gossypium hirsutum*; Large-scale augmentation; Spider mite biological control

1. Introduction

Augmentation of natural enemies can be an important approach to improving biological control in agricultural systems. While augmentative biological control is generally more expensive than other approaches such as classical biological control due to its repetitive nature, it may be an especially important approach for improving biological control in annual cropping systems, where natural enemy populations may encounter difficulty in colonizing and persisting naturally (Obrycki et al., 1997). To enhance the use of augmentative biological control by the agricultural industry, large-scale evaluation of this technique under conditions similar to those encountered in grower fields is necessary. In this paper, we evaluate augmentative biological control of spider mites in cotton at a large-scale and under grower-field conditions.

Spider mites in the genus *Tetranychu*s, including *T. pacificus* McGregor, *T. turkestani* Ugarov and Nikolski, and *T. urticae* Koch, are important pests of cotton in the San Joaquin Valley of California. This mite complex can reduce both yields and lint quality, especially when spider mites establish early in the growing season (Canerday and Arant, 1964; Furr and Pfrimmer, 1968; Mistric, 1969; Wilson, 1986; Wilson et al., 1983, 1991). Many growers control spider mites with selective acaricides. However, the realized and potential development of acaricide resistance and the high costs associated with multiple acaricide applications have created a need for other spider mite management options.

Augmentative releases of predaceous phytoseiid mites for spider mite control have been shown experimentally to reduce spider mite densities in many perennial crops (Croft and MacRae, 1992; Flaherty et al., 1985; Helle and Sabelis, 1985; Hoy et al., 1982; McMurtry, 1982; Nyrop et al., 1998) and some annual row crops such as cotton (Osman and Zohdi, 1976; Tijerina-Chavez, 1991) and field corn (Pickett and Gilstrap, 1986; Pickett et al., 1987). Naturally occurring phytoseiid mite populations tend to be more abundant in perennial agricultural

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systems where conditions are considered to be more conducive for population persistence (these habitats have less disturbance and more abundant overwintering sites; McMurtry, 1982). For this reason, there have been fewer attempts to use predaceous mite releases in annual cropping systems. However, by inoculating annual crops such as cotton with predaceous mites early in the cropping cycle each season, it may be possible to improve spider mite biological control substantially.

In this study, we evaluate large-scale releases of the western predatory mite *G. occidentalis* to improve the biological control of spider mites in organic and conventional cotton grown in the San Joaquin Valley of California.

2. Materials and methods

2.1. 1996 Research

Spider mite populations were monitored in 28 grower fields; 20 fields were organically managed and eight fields were conventionally managed. These fields were located throughout the San Joaquin Valley of California in Merced, Madera, and Kern Counties. Within each field, three square 2 ha plots were marked. Plots were a minimum of 61 m apart and to the extent possible were arranged such that plots were not upwind from each other (the predominant wind is from the northwest, so plots were arranged from the southwest to the northeast corners of fields). This arrangement was chosen to minimize the wind-aided dispersal of predatory mites between plots. Plots were randomly assigned to one of three treatments: (1) early release of *G. occidentalis* (3 May to 25 May), made when the cotton plants had between one and six nodes, (2) late release of *G. occidentalis* (6 June to 7 August), made when plants had seven or more nodes, and (3) no-release control. Each field had all three treatments and was a complete block. We used weekly spider mite sampling to time our releases. In each field, we randomly sampled a minimum of 20 plants for the presence of spider mite populations. Presence of mites on plants was determined by inspecting the lower leaf surfaces with a Coddington 10× Magnifier hand lens (Bausch & Lomb, Rochester, NY).

If at least 20% of the plants or leaves were infested with spider mites, a predatory mite release was made approximately a week later. A plant was considered infested with spider mites if it contained at least one spider mite (egg or motile stages). If the plants within a field that exceeded the 20% infestation threshold had 1–6 nodes, it was considered an early release. Fields that did not exceed the 20% infestation threshold until plants had more than seven nodes only received a late release. Where mite populations persisted in the fields that received early releases, a late release in an adjacent plot was made once plants had seven or more nodes. If mite populations declined after the early release, a late release was not made. Releases were not made into fields that did not reach the 20% infestation threshold.

Western predatory mites, *G. occidentalis*, were purchased from Sierra Ag (Fresno, CA), a company that retails predatory mites reared in the San Joaquin Valley. Predatory mites were released at ca. 5000 mites per ha. We chose this release rate because the cost to release 5000 mites per ha is similar to the cost of a single acaricide application. Arthropods including spider mites, predatory mites, western flower thrips, *Frankliniella occidentalis* (Pergande), minute pirate bugs (*Orius* spp.), and the bigeyed bugs (*Geocoris* spp.), were sampled in each plot once before predatory mite releases were made. Following predatory mite release, arthropods in all plots were monitored approximately every week through June and every two weeks from July through September, except as noted below. Populations were monitored by sampling 80 mainstem leaves from the node above the cotyledons when the plants had fewer than nine nodes, and then by sampling 40 eighth-node mainstem leaves (eight mainstem nodes below the plant terminal) when the cotton had developed at least nine nodes. Arthropods were separated from the leaves using a leaf washing technique (Leigh et al., 1984) and were stored in 70% alcohol. This leaf sampling technique provided substantial numbers of mites (all stages), thrips (all motile stages), minute pirate bugs (nymphal stage), and bigeyed bugs (eggs). Since not all of the fields we monitored met the minimum 20% spider mite density requirement, we completed a total of 18 early releases and 11 late releases. Our experimental approach allowed us to test the efficacy of predaceous mites in many locations and at a wide range of initial spider mite densities and release dates (Table 1).

To reduce the time necessary to process leaf samples, we counted only the larger stages of mites. Stages of mites were separated by using two mesh sieves: a mesh sieve with 260 μm diameter pores to collect adult and larger immature mite stages (i.e., deutonymphs) and a mesh sieve with 100 μm diameter pores to collect all other smaller stages (i.e., eggs, larvae, and protonymphs). To estimate the fraction of spider mite and predatory mites that we quantified in the 88 mesh sieve (260 μm diameter pores), we used data from a field cage experiment that contained substantial populations of both spider mites and predatory mites (Colfer et al., 1998, 2003). By quantifying all mite stages in both sieves and using linear regression through the origin, we developed a relationship between the proportion of spider mites and phytoseiid mites found in the top sieve and the total mite populations (spider mites: top sieve = total$\{x\}$0.32, $r^2 = 0.95$, $P < 0.0001$; phytoseiid mites: top sieve = total$\{x\}$0.57, $r^2 = 0.96$, $P < 0.0001$). Thus, the regression analysis demonstrated that quantifying the

Table 1
Summary of predatory mite release sites, dates, and initial percent of leaves infested with spider mites for 1996 and 1997

Site #	County	Early release (ER) date	Late release (LR) date	% plants infested (ER, LR)
Conventional 1	Kern	5/03/96	None	25
Conventional 2	Kern	5/03/96	None	30
Conventional 3	Kern	5/03/96	None	30
Conventional 4	Kern	5/03/96	None	25
Conventional 5	Kern	5/04/96	None	20
Conventional 6	Merced	5/25/96	6/19/96	25, 85
Conventional 7	Merced	5/25/96	None	25
Conventional 8	Merced	5/25/96	6/25/96	30, 50
Conventional 9	Merced	5/9/97	6/6/97	45, 55
Conventional 10	Kern	None	5/30/97	20
Conventional 11	Yolo	None	6/8/97	20
Organic 1	Merced	5/10/96	6/06/96	25, 95
Organic 2	Madera	5/10/96	6/06/96	45, 100
Organic 3	Madera	5/10/96	6/07/96	45, 100
Organic 4	Madera	5/11/96	6/12/96	25, 100
Organic 5	Madera	5/24/96	6/20/96	20, 100
Organic 6	Madera	5/24/96	6/20/96	20, 90
Organic 7	Madera	5/24/96	6/12/96	60, 100
Organic 8	Madera	5/11/96	6/12/96	20, 65
Organic 9	Madera	5/25/96	None	35
Organic 10	Madera	5/25/96	None	45
Organic 11	Kern	None	8/7/96	35
Organic 12	Kern	None	7/29/97	30
Organic 13	Kern	None	7/29/97	25

larger stages of mites provides a good estimate of total mite populations. We present data based only on counts of larger stages of spider mites and predatory mites. Populations of all arthropods were quantified using a dissecting stereomicroscope. Adult predatory mites found within samples were slide mounted and identified using a phase-contrast compound microscope. This enabled us to quantify not only *G. occidentalis* but also a guild of other phytoseiid mites, some not previously recorded from cotton, that were naturally present in our plots. A maximum of 10 predatory mites were slide mounted if there were more than 10 adult predatory mites within a sample.

In addition to monitoring arthropods, we measured the percentage of leaf area that was damaged due to spider mite and western flower thrips feeding (it was not possible to distinguish spider mite and thrips damage) in a portion of our fields that we were not able to monitor every two weeks (from July to September we sampled mite populations only twice in organic fields 1–10 and conventional fields 6–8). Leaf damage provided an indirect but useful index of cumulative spider mite densities during the mid- and late-season. Most of the leaf damage was likely due to spider mites because thrips tend not to cause substantial leaf damage during the mid- and late-season. The percentage of leaf area damaged by herbivory was quantified twice for these fields (2 August and 4 September).

We also obtained estimates of seed cotton yields in control and release plots. Seed cotton yields were collected by hand picking the lint and seeds from one-meter sections in 10 randomly selected locations in each plot for all fields.

Nearly all the predatory mite releases (28 out of 29) were made using a mechanical release device that was developed and evaluated for predatory mite releases in strawberries by Giles et al. (1995). The handling system consisted of an insulated storage reservoir that kept a mixture of predatory mites in a vermiculite carrier stationary and chilled, a rotating metering plate, and an air-cleared ejection port. The components were mounted on a stationary tractor tool bar and electrically powered by the tractor's 12 V battery. Several modifications to the original Giles et al. (1995) design were made including: (1) the inclusion of 'blue ice' ice packs inside the distributors and improved insulation to keep predatory mites chilled and immobile, (2) the use of removable plastic 11.35 L container to hold the predatory mite–vermiculite mixture, (3) replacement of the 12 rpm 12 V dc permanent magnet gearmotor with a 4.5 rpm 12 V dc gearmotor in order to decrease the flow rate and make the distributor more appropriate for the large size of most cotton fields, (4) replacement of the air compressor with a blower which was able to withstand the large amounts of dust typically encountered in cotton fields, (5) addition of wind guards that attach to the sides of each release device to improve the placement accuracy of the mixture onto the cotton, and (6) replacement of rotating plates with sliding plates to decrease flow rates (thereby reducing the frequency of refilling containers, which was especially important in large cotton fields) and to reduce costs needed to construct mechanical release devices. These modifications made the release devices more suitable for the harsh conditions encountered in cotton. Purchased predatory mites were stored in a corn grit carrier in a concentrated form. We combined the corn grit carrier with chilled, moistened vermiculite (temperature: ca. 6 °C, relative humidity: ca. 15% dry basis, vermiculite source: WR Grace, Boca Raton, FL). The predatory mite–corn grit–vermiculite mixture was combined and homogenized by slowly rotating the 11.35 L containers 10 times before being placed into the insulated storage reservoir. To verify that the flow rate of predatory mites was constant over the release duration, 50 ml samples of vermiculite were collected during the first and second half of the release procedure during nine releases. These samples were chilled and the numbers of motile predatory mites per sample were later quantified in the laboratory. The last release on 7 August 1996 was made by hand due to the large size of the cotton plants.

Acaricides and insecticides were sprayed on the conventional blocks. Conventional sites 1–5 received two applications of abamectin (Zephyr, Syngenta Crop Protection, Greensboro, NC), conventional sites 4 and 5 also received one application of chlorpyrifos (Lorsban, Dow AgroSciences LLC, Indianapolis, IN), and conventional blocks 6–8 received one application of dicofol (Kelthane, Dow AgroSciences LLC, Indianapolis, IN).

2.2. 1997 research

The experimental design and methods used during the 1997 predatory mite releases were the same as those described for 1996 except for the following differences. Spider mite populations were monitored in ten grower fields, six of which were organically managed and four of which were conventionally managed. Fields were located throughout the San Joaquin Valley in Merced, Fresno, and Kern Counties, with one additional field in the Sacramento Valley in Yolo County. Because not all of the fields met the minimum 20% spider mite density requirement to trigger releases, a total of one early release and five late releases in two organically managed fields and three conventionally managed fields were made (Table 1). Three of the six releases were made with the mechanical release devices and the remaining three were performed by hand. To avoid having acaricides sprayed on release plots in conventionally managed fields, we asked conventional growers to withhold acaricide applications in experimental plots unless spider mite densities reached damaging levels. This approach reduced the amount that plots were sprayed. To reduce the amount of economic risk associated with not using acaricides, we reduced the size of the release and control plots to 0.4–0.8 ha and reduced the separation between plots to 26–61 m. Arthropods were monitored using the same techniques as described for 1996 except that we collected leaf samples (50 per plot) approximately every two weeks after conducting the releases. Leaf damage and yield data were not collected.

Similar to 1996, acaricides and insecticides were sprayed on some of the conventional blocks in 1997. Conventional site 9 received one application of dicofol and one application of chlorfenapyr (Alert, BASF, Mount Olive, NJ), and conventional site 10 received one application of chlorpyrifos late in the season.

2.3. Statistical analysis

To evaluate the influence of predaceous mite releases on predatory mite and spider mite abundance, we calculated the cumulative number of mites from all samples over the season for each plot after predatory mite releases had been performed. We chose this approach because not all fields were sampled at the same time, and therefore repeated measures ANOVA was not possible. For spider mites, we also calculated the total number of mite-days (# mites per day) from the first sample after release to the last sample of the season. Predatory mite-days were not calculated because predatory mite abundance was too low for this approach to be a reliable representation of predatory mite populations. The number of samples included in calculating cumulative spider mites and cumulative predatory mites was always smaller for late releases vs. early releases. Therefore, direct statistical comparisons between early and late releases could not be made. Cumulative arthropod abundances, percentage of leaf area damaged by herbivory, and seed cotton yields were analyzed with 2-factor ANOVA, with field or block as one factor and release treatment as the second factor (JMP Statistical Discovery Software for Microsoft Windows; SAS Institute, Cary, NC). For the mite-days and cumulative mite abundance data, we performed the analysis with the data from 1996 and 1997 combined and separated. Year was treated as a block for the analysis of combined data. To evaluate the flow rate of predatory mites in the mechanical release device, we compared the observed flow rate during the first and second half of the release periods with the expected flow rate (number of predatory mites per 50 ml vermiculite carrier) using paired *t* tests. Comparisons of cumulative predatory mite abundances in organically versus conventionally grown cotton fields and cumulative predatory mite abundances in fields sprayed with miticide versus fields not sprayed were analyzed using Kruskal–Wallis rank–sum tests (Sokal and Rohlf, 1995).

3. Results

For all the results presented below, data from 1996 and 1997 were combined unless otherwise stated.

3.1. Influence of releases on G. occidentalis populations

Releases of *G. occidentalis* did not increase cumulative predatory mite abundance in release plots compared to control plots (early release: $F = 0.01$, $df = 1$, $P = 0.92$, late release: $F = 0.9$, $df = 1$, $P = 0.36$, Fig. 1). Also, *G. occidentalis* comprised a small percentage of the total phytoseiid species assemblage across the field sites in control and release plots during both 1996 and 1997 (Tables 2 and 3, respectively). In most fields, densities of predatory mites were very low throughout the season (<1 mite per sample of 40 or 80 leaves on average). These densities were far below those observed in agroecosystems where predatory mites have been shown to play an important role in spider mite control (Flaherty et al., 1985; Hoy et al., 1982; McMurtry, 1982). Neither farming technique (conventional vs. organic) nor application of miticides significantly affected cumulative predatory mite abundance ($\chi^2 = 0.65$, $df = 1$, $P = 0.42$; $\chi^2 = 0.01$, $df = 1$, $P = 0.93$, respectively).

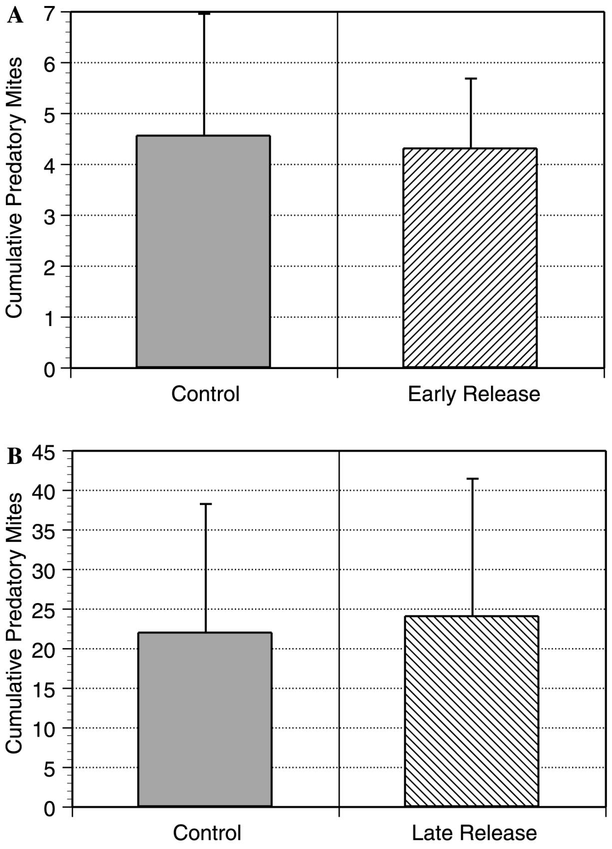

Fig. 1. Mean (±S.E.) cumulative number of predatory mites in plots that (A) received an early release (plant with 3–6 nodes) and (B) plots that received a late-release (plant with $\geqslant 7$ nodes) of 5000 western predatory mites per hectare compared to no-release control plots.

3.2. Influence of releases on spider mite populations

Before releases were performed, spider mite densities were similar in the early release and control plots (early release: 76.8 ± 22.7 mites per leaf sample, control: 83.4 ± 23.4, mean ± S.E.; $F = 0.17$, $df = 1$, $P = 0.68$). Initial mite densities before treatments were applied were, by chance, somewhat greater in the late release plots than in the associated control plots, making the test more conservative (late release: 232.7 ± 49.0 mites per leaf sample, control: 118.9 ± 24.6, mean ± S.E.; $F = 4.2$, $df = 1$, $P = 0.06$).

The early release of *G. occidentalis* reduced the number of spider mite-days by 35% compared to control plots ($F = 4.7$, $df = 1$, $P = 0.044$; Fig. 2). Cumulative spider mite abundance in the early release plots was also 24% below control plots; however, this difference was marginally non-significant ($F = 3.65$, $df = 1$, $P = 0.071$). In spite of these reductions, spider mite densities exceeded economic injury levels in many of the release plots.

To investigate the impact of early release of *G. occidentalis* on spider mite population dynamics further, we analyzed each year separately, and we examined early season (April–June) vs. mid- and late-season (July–September) cumulative spider mite abundance separately as well. Cumulative spider mite densities for the whole season were 20–25% lower in release plots compared to control plots during both 1996 and 1997, although these differences were not significant (1996: control: 1191 ± 290, early release: 861 ± 175, $F = 3.4$, $df = 1$, $P = 0.08$; 1997: control: 3580 ± 2074, early release: 2770 ± 1862, $F = 14.6$, $df = 1$, $P = 0.16$). When

Table 2
1996 phytoseiid mite species composition across all field sites

Phytoseid spp.	Control (%)	Early release (%)	Late release (%)	Totals (%)
Galendromus occidentalis	7.7	6.4	9.0	23.1
Euseius quetzali	2.5	11.5	38.5	52.5
Neoseiulus californicus	6.4	7.7	2.5	16.6
Neoseiulus setus	1.3	1.3	2.5	5.1
Phytoseiulus persimilis	0	0	1.3	1.3
Typhlodromus caudiglans	0	0	1.3	1.3
Totals	17.9	26.9	55.1	

Identifications were based on adult females ($n = 77$).

Table 3
1997 phytoseiid mite species composition across all field sites

Phytoseid spp.	Control (%)	Late release (%)	Totals (%)
Galendromus occidentalis	4.6	3.8	8.4
Euseius quetzali	34.6	23.1	57.7
Neoseiulus californicus	1.5	0	1.5
Neoseiulus fallacis	16.9	13.1	30.0
Phytoseiulus persimilis	1.5	0	1.5
Typhlodromus caudiglans	0	0.8	0.8
Totals	59.1	40.8	

Identifications were based on adult females ($n = 128$).

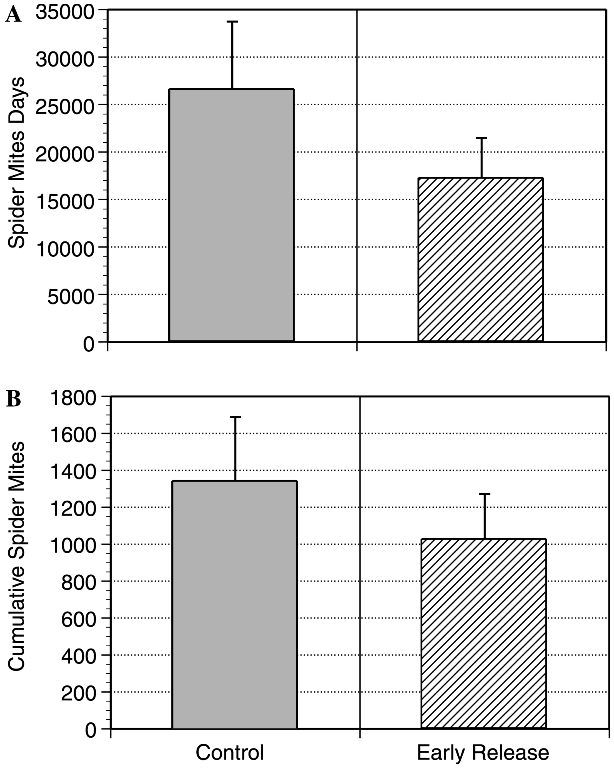

Fig. 2. Mean (±S.E.) number of (A) spider mite days, and (B) cumulative number of spider mites in no-release control plots and plots that received an early release (plant with 3–6 nodes) of 5000 commercially reared western predatory mites per hactare.

we examined only early season cumulative spider mite numbers, we found that there was no difference in spider mite abundance between early release and control plots (early release: 690.2 ± 147.5, control: 686.2 ± 196.5; $F = 0.002$, $df = 1$, $P = 0.96$). However, cumulative spider mite abundance was marginally nonsignificantly lower in early release plots compared to the control plots for the mid- and late-season (early release: 386.5 ± 210.4, control: 733.6 ± 327.6; $F = 4.1$, $df = 1$, $P = 0.058$).

There was a non-significant trend towards fewer spider mite-days and cumulative mites in the plots that received late releases of *G. occidentalis* compared to control plots (mite-days: $F = 1.8$, $df = 1$, $P = 0.20$; cumulative abundance: $F = 2.1$, $df = 1$, $P = 0.17$; Fig. 3). These tests have only moderate inferential strength, however, because they had low statistical power (mite-days: power = 0.16, cumulative abundance: power = 0.22). As observed in the early release fields, spider mite densities exceeded economic injury levels in many of the late-release plots. When we examined the impact of predatory mite releases on cumulative spider mite abundance for 1996 and 1997 separately, we found that there were no statistically significant differences between late-release plots and control plots (1996: late release 648 ± 257, control 793 ± 306, $F = 0.6$, $df = 1$, $P = 0.45$;

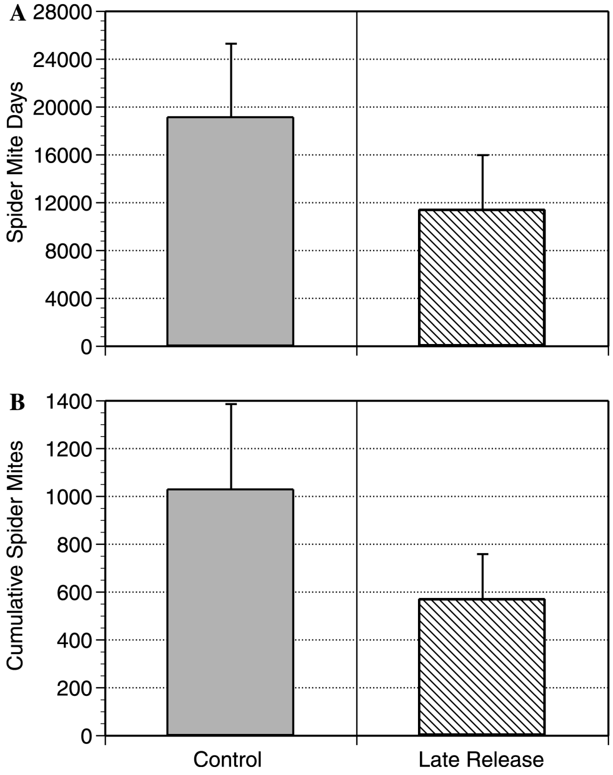

Fig. 3. Mean (±S.E.) number of (A) spider mite days and (B) cumulative number of spider mites in no-release control plots and plots that received a late-release (plant with ⩾ 7 nodes) of 5000 commercially reared western predatory mites per hactare.

1997: late release 453 ± 103, control 1581 ± 1066, $F = 1.22$, $df = 1$, $P = 0.35$).

3.3. Naturally occurring predatory mite populations

Four fields developed substantial densities of naturally occurring predatory mites (Fig. 4). In three of the four fields with substantial predatory mite populations, *Euseius quetzali* McMurtry (Phytoseiidae) was the dominant species. This species has not previously been reported from California cotton. In one of the four fields, *Neoseiulus fallacis* (Garman) (Phytoseiidae), was the dominant species. Predatory mite populations consistently increased late in the season. In all four of these field sites, spider mite populations were negatively correlated with increases in predatory mite populations (Spearmans $\rho = -0.36$, $P = 0.041$), suggesting that naturally occurring predatory mites may have been partially responsible for decreases in spider mite populations.

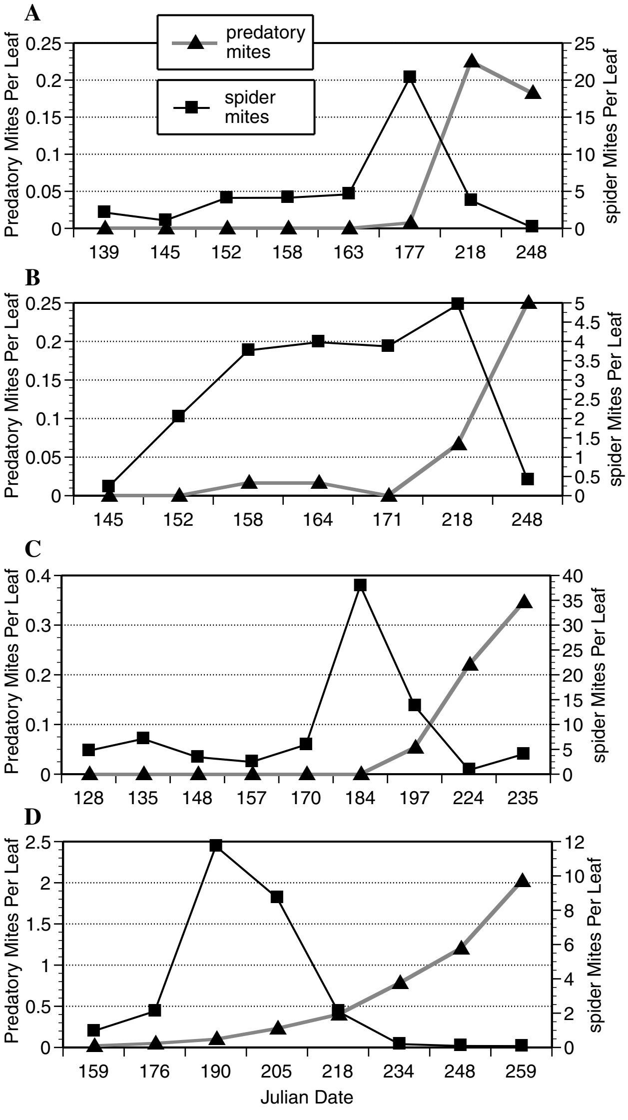

Fig. 4. Predatory mite and spider mite population dynamics in fields with abundant populations of naturally occurring predatory mites: (A) organic 4, (B) organic 7, (C) conventional 9, and (D) conventional 11. In organic 4, organic 7, and conventional 11 the predatory mite *E. quetzali* was dominant, and in conventional 9 the predatory mite *N. fallacis* was dominant.

3.4. Evaluation of mechanical release of *G. occidentalis*

The predaceous mite release rate was fairly constant over the duration of the release period, though there was a slight downward trend (Fig. 5). The release rate for the first half of the release periods was somewhat greater than expected ($t = -2.0$, $P = 0.042$) but the rate for the second half of the release was close to expected ($t = 1.5$, $P = 0.91$). Generally the predaceous mite–vermiculite mixture was placed on or near the cotton seedlings (within 8 cm). The precision of predaceous mite placement was worse in windy conditions (i.e., winds above 10 knots). The placement of predatory mites onto plants was generally better during the late releases than the early releases because cotton plants were larger and therefore were larger ‘targets’.

3.5. Influence of releases on leaf damage

The percentage leaf area damaged by spider mite and western flower thrips feeding was similar across control and release plots on both sampling dates in 1996 (5 August: $F = 0.6$, $df = 2$, $P = 0.57$; 4 September: $F = 1.1$, $df = 2$, $P = 0.36$; Fig. 6). However, these data represent the combined feeding damage caused by both spider mites and western flower thrips. Western flower thrips abundance was similar to or greater than spider mite abundance during these two samples (5 August: thrips = 112 ± 33 per leaf sample, spider mites = 114 ±

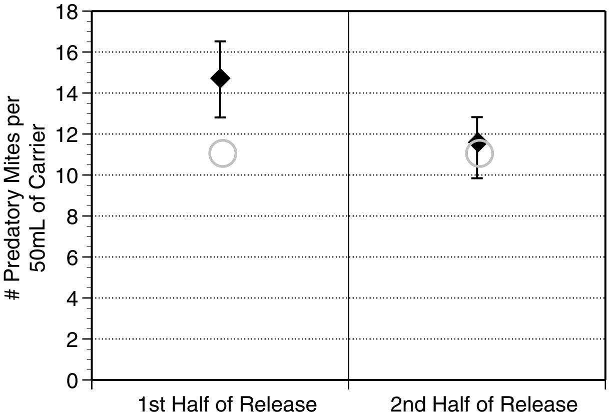

Fig. 5. Mechanical release of western predatory mites, *Galendromus occidentalis*. Mean (±S.E.) observed motile predatory mites (black diamonds) and the expected number of predatory mites (gray, open circles) from 50 mL samples of vermiculite/corncob grit carrier during the first and second half of the releases.

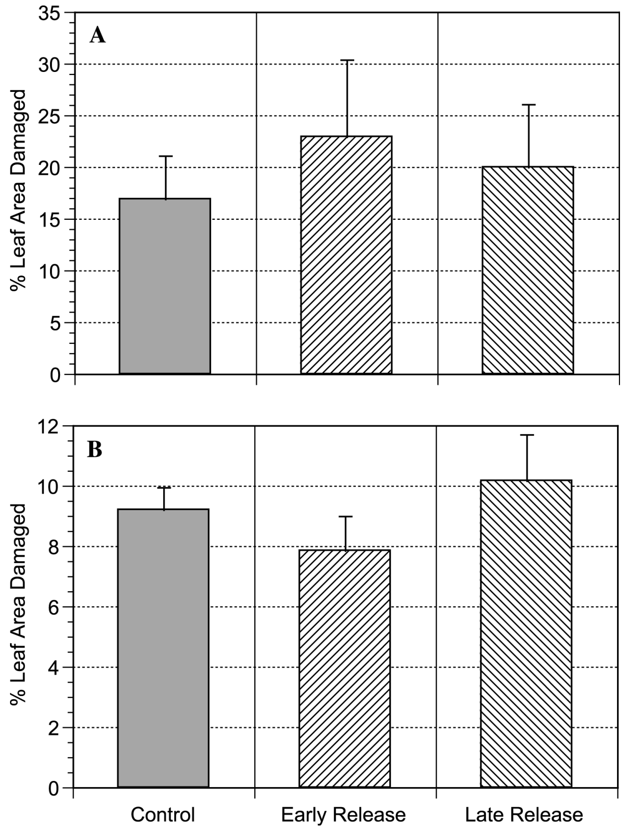

Fig. 6. Percentage of leaf area damaged (Mean ± S.E) by spider mite and western flower thrips feeding in the (A) 5 August 1996 samples and (B) 4 September 1996 samples. These data were collected only in the subset of fields that were sampled less frequently during the middle and late season (see text).

18; 4 September: thrips = 20 ± 3, spider mites = 5 ± 2). However, leaf-scarring by western flower thrips is not typically observed in mid- and late-season cotton (R.G. Colfer and J.A. Rosenheim, pers. observ.).

3.6. *Influence of releases on seed cotton yields*

Seed cotton yields in 1996 were similar in the release and control plots for the grower fields where yields were estimated ($F = 0.15$, $df = 2$, $P = 0.86$; Fig. 7). Although we did not observe heavy spider mite damage to cotton plants within our experimental plots (i.e., severe leaf defoliation and stunting of plant growth), we did observe leaf discoloration and minor defoliation during the early season. This type of moderate damage occurring during the early season is known to cause yield losses (Wilson, 1986; Wilson et al., 1991). However, we did not expect to observe yield differences between release and control plots because spider mite populations were not greatly affected by predatory mite releases, and the differences that were observed occurred later during the season, when plants were less sensitive to mite injury.

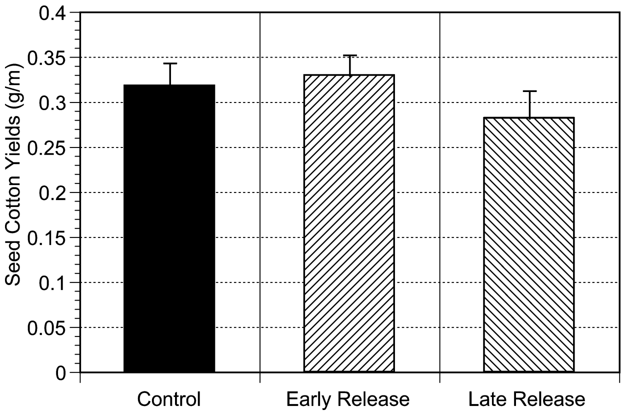

Fig. 7. Mean (±S.E.) seed cotton yields from plots that received an early release (plant with 3–6 nodes), plots that received a late-release (plant with $\geqslant 7$ nodes), and no-release control plots.

4. Discussion

In this study we evaluated economically feasible release rates of the western predatory mite for spider mite control in organically and conventionally managed grower cotton fields. This study was unusual because it evaluated predatory mite releases at a very large scale; the majority of plots were approximately 2 ha. Releases did not enhance populations of the western predatory mite in plots, and populations of western predatory mites remained very low throughout the growing season. While the results show that plots that received an early release of western predatory mites had slightly lower spider mite abundance, spider mite densities exceeded economic thresholds in many of our release plots. Finally, neither early releases (3–6 node stage) nor late releases (>7 node stages) affected seed cotton yields.

A surprising combination of results was that early releases of western predatory mites did not increase predatory mite populations but did appear to reduce spider mite populations. If released predatory mites had an impact on spider mites but were unable to persist throughout the growing season, we would expect to have observed the greatest difference in spider mite abundance between release and control plots during the early season. However, we found that spider mite differences between treatments were greatest during the mid- and late-season. Thus, we believe the differences we observed between treatments were probably not caused by a simple direct effect of released predatory mites causing greater mortality to spider mite populations. The differences in spider mite densities we observed between release and control plots were likely caused by either a chance event or a complicated set of effects that was stimulated by predatory mite releases. We base this conclusion on the following evidence: (1) western predatory mite populations remained low and were similar in abundance in the release and control plots, (2) early season spider mite populations were the same across treatments, (3) leaf damage and yields were the same across treatments, and (4) other experiments that we have conducted as an extension of this study have consistently shown that western predatory mite releases, even when made at rates more than an order of magnitude greater than those tested here, do not significantly reduce spider mite populations (R.G. Colfer, unpubl. data).

Western predatory mites are known to be key predators of spider mites in orchard and vineyard agroecosystems in the San Joaquin Valley of California (Flaherty et al., 1985; Hoy et al., 1982, 1984) where they are both important naturally occurring predators and effective in augmentative releases against spider mites. Releases of *G. occidentalis* are commonly made on some commercially managed orchards and vineyards (W. White, pers. com.). For these reasons, and because earlier research suggested that this species might perform well in cotton grown in the San Joaquin Valley (Tijerina-Chavez, 1991), we chose to release *G. occidentalis* in preference to other species of predatory mites. However, we did not observe substantial populations of the western predatory mites in any of the twenty-four grower fields in our experiment. We did, however, observe substantial populations of two other species of phytoseiid mites: *E. quetzali* and *N. fallacis*. Releases of *N. fallacis* have been shown to reduce spider mites in hops, strawberries, peppermint, and ornamental Skimmia (Coop and Croft, 1995; Morris et al., 1999; Pratt and Craft, 1998; Strong and Croft, 1996). *N. fallacis*, a species generally thought to prefer high-humidity environments, may be able to withstand the arid climate of the San Joaquin Valley when the cotton plants are irrigated and the microclimate within the cotton canopy is humid. The importance of *E. quetzali* as a spider mite biological control agent has not been studied (but see Congdon and McMurtry, 1986; McMurtry et al., 1985). Although both of these species reached moderate to high densities in some fields, they were not abundant until late in the cotton growing season. It remains unknown whether they could maintain high densities early in the season when spider mites can be especially detrimental to cotton production.

Our results suggest that there was one or several factors that prevented the western predatory mites from establishing in the cotton agroecosystem. It appears, then, that the lack of overwintering sites for predatory mites does not completely explain why western predatory mite populations do not thrive in the cotton agroecosystem. Some potentially important factors that could have prevented western predatory mite releases from being more successful include: (1) the mechanical release device might have negatively affected predatory mite viability; (2) the commercially reared predatory mites might have been negatively affected by the transition from greenhouse rearing conditions to the outdoor cotton field conditions; (3) release rates may have been too low; (4) the cotton plant itself may not be conducive to predatory mite persistence; and/or (5) interspecific interactions with naturally occurring predatory insects may have negatively affected western predatory mite establishment and persistence. We will report separately experimentation that has evaluated the relative roles of each of these factors.

Research performed by Corbett et al. (1991) and Giles et al. (1995) provide some important insights into why we did not observe the establishment and increase of *G. occidentalis* populations following releases.

In the Corbett et al. (1991) study, releases of western predatory mites were made into strips of alfalfa, *Medicago sativa*, which were located on the edge of cotton plots. First, *G. occidentalis* were more abundant in alfalfa than cotton, and they were more abundant in cotton adjacent to alfalfa than in cotton distant from alfalfa, indicating that *G. occidentalis* populations may be limited on cotton compared to alfalfa due to attributes specific to the cotton plant. Second, *G. occidentalis* populations were not more abundant in alfalfa strips that received a release of predatory mites compared to alfalfa strips that did not, indicating that insectary-reared western predatory mites may not be capable of surviving the environmental conditions found in low-growing crops such as cotton and alfalfa. Third, the release rate of western predatory mites was approximately 10 times greater in the Corbett et al. (1991) study (50,610 mites/ha) compared to our study (5000 mites/ac), suggesting that release rate alone may not have prevented *G. occidentalis* from establishing in cotton in our study.

In the Giles et al. (1995) study, the mechanical release device was evaluated as a technique for releasing the predatory mite *Phytoseiulus persimilis* in strawberries. This study demonstrated that the mechanical release device delivered *P. persimilis* mites evenly and in good condition onto strawberries, suggesting that this device may not have been an important limiting factor.

In conclusion, the release of *G. occidentalis* at low rates was not an effective spider mite control strategy in cotton because releases did not increase the populations of predatory mites throughout the growing season and did not increase yields. Further research is needed to determine which limiting factors are most important in preventing *G. occidentalis* from performing better in the cotton agroecosystem.

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