Role of Syrphid Larvae and Other Predators in Suppressing Aphid Infestations in Organic Lettuce on California's Central Coast

HUGH A. SMITH,[1,2] WILLIAM E. CHANEY,[3] AND TIFFANY A. BENSEN[4]

ABSTRACT Organic lettuce, *Lactuca sativa* L., growers on the Central Coast of California rely on conservation biological control to manage *Nasonovia ribisnigri* Mosley (Hemiptera: Aphididae) and other aphid pests of lettuce. In 2006, we carried out five replicated field trials to determine the importance of syrphid larvae in the suppression of *N. ribisnigri* and other aphids infesting organic romaine lettuce. We used Entrust, a spinosad-based insecticide approved for use on organic farms, to suppress syrphid larvae in aphid-infested romaine. Romaine treated with Entrust was unmarketable at harvest because of aphid infestation, whereas insecticide-free romaine was marketable. Syrphid larvae composed 85% or more of total predators in most trials, and they were the only predators consistently recovered from romaine that was infested with aphids early and largely aphid-free by harvest. The species mix of nonsyrphid predators varied from site to site. Applications of Entrust suppressed nonsyrphid predators in two trials, and so was an imperfect tool for selectively suppressing syrphid larvae. The relative importance of syrphid larvae and other predators in the conservation biological control of aphids in organic romaine is discussed. We conclude that syrphid larvae are primarily responsible for the suppression of aphids in organic romaine on California's Central Coast.

KEY WORDS   conservation biocontrol, organic agriculture, insectary crops, aphid predators, Syrphidae

In 2005, >200,000 acres of lettuce (head and leaf) were grown in California, which produces roughly three quarters of the lettuce consumed in the United States (NASS 2006). More than 14,000 acres of organic leaf lettuces were produced in California in 2005 (Klonsky and Richter 2007). At least 70% of California's lettuce, both conventional and organic, is grown in the state's Central Coast region (California Farm Bureau 2006, Klonsky and Richter 2007).

Nasonovia ribisnigri (Mosley) (Hemiptera: Aphididae) became established in California in 1998, and it has become the most important insect pest of lettuce on the Central Coast (Chaney 1999). *N. ribisnigri* infests the inner leaves of the lettuce head, making it unmarketable (MacKenzie and Vernon 1988, Liu 2004). In addition to *N. ribisnigri*, the foxglove aphid, *Aulocorthum solani* (Kaltebach); green peach aphid, *Myzus persicae* (Sulzer); and potato aphid, *Macrosiphum euphorbiae* (Thomas), are pests of California lettuce. Conventional growers suppress populations of *N. ribisnigri* and other aphids with a range of insecti-cides, including organophosphate, carbamate, and neonicotinoid materials.

Fieldwork in 2005 revealed that at least 13 species of syrphid larvae are involved in suppressing aphid infestations to below economically damaging levels in organically grown lettuce on California's Central Coast (Smith and Chaney 2007). Organic growers typically interplant flowering insectary plants with lettuce to provide floral resources to syrphid adults and enhance their activity. Other predators are found in organically grown romaine in this region, but their importance relative to syrphid larvae in suppressing aphids has not been demonstrated previously (Colfer 2004, Smith and Chaney 2007). Parasitism of *N. ribisnigri* is rarely observed because the aphid colonizes inner portions of the plant that are largely inaccessible to parasitoids. Green peach aphid and potato aphid tend to infest the outer leaves of the romaine head, and they are parasitized. Entomogenous fungi have been observed to impact infestations of *N. ribisnigri* during the early spring rains but rarely during peak lettuce production (May–November) (Smith and Chaney 2007).

Our objective in this study was to evaluate the importance of syrphid predation in suppressing populations of *N. ribisnigri* and other aphids in organically grown romaine on California's Central Coast. In addition, we were interested in the importance of other predators relative to syrphid larvae in suppressing aphids. We used Entrust, a spinosad-based insecticide

[1] Corresponding author: University of California Cooperative Extension, 624 West Foster Rd., Santa Maria CA 93455.
[2] Current address: Connecticut Agricultural Experiment Station, 153 Cook Hill Road, Windsor, CT 06095 (Hugh.Smith@po.state.ct.us).
[3] University of California Cooperative Extension (emeritus), 1432 Abbott St., Salinas CA 93901.
[4] Department of Biology P.O. Box 1848, University of Mississippi, University, MS 38677.

approved for use in organic lettuce, to suppress syrphid larvae. We compared aphid densities in romaine where syrphids were suppressed with aphid densities in insecticide-free romaine. Pilot studies in previous years indicated that aphid densities would not be affected by Entrust at the rate used. We did not know what impact weekly applications of Entrust would have on the complex of nonsyrphid predators found in organically grown romaine, although some studies have indicated that spinosad has little suppressive effect on predators such as ladybird beetles (Coccinellidae), lacewings (Chrysopidae and Hemerobiidae), and minute pirate bugs (*Orius* spp.). (Eizen et al. 1998, Studebaker and Kring 2003, Miles 2006, Contreras et al. 2006, Arthurs et al. 2007).

Although the focus of this study is the evaluation of conservation biological control of aphids in organically grown romaine, conservation biological control may eventually be applicable in conventional production. There is currently little role for natural enemies in the suppression of *N. ribisnigri* in conventional lettuce because conventional growers rely on insecticide regimes that are not compatible with biological control. Industry standards for conventional produce also make the risk of relying on natural enemies unacceptably high for conventional growers. However, the registrations of many organophosphate and carbamate insecticides are currently under review by the U.S. Environmental Protection Agency. Should the insecticides that conventional lettuce growers currently rely on for aphid suppression become less available in the future, information on conservation biological control of aphids may be useful to conventional growers as well as organic growers. Therefore, clarification of the mechanism by which aphids are suppressed in organic lettuce may enhance future prospects for conservation biological control in conventional production.

Materials and Methods

We suppressed syrphid larvae with the spinosad-based insecticide, Entrust, to evaluate how aphid populations responded to release from syrphid predation. We compared densities of aphids, syrphid eggs and larvae, and other natural enemies of aphids in plots of organic romaine lettuce treated with Entrust to densities in untreated plots at five sites in and near the Salinas Valley in 2006. Separate trials were conducted in fields on certified organic farms in Hollister (April–May), Chualar (August–September), and Watsonville (September–October), and in research plots at the Hartnell College East Campus (June–July) and the Spreckels Industrial Park (July–August).

Insect densities on romaine receiving no insecticide applications were compared with insect densities on romaine receiving the equivalent of 0.182 liters Entrust per hectare (2.50 oz/acre) each week applied with a pressurized CO_2 backpack sprayer. Treatments were applied in 7.62-m (25-foot) sections of crop row, replicated four times, and arranged in randomized complete blocks. Trials on organic farms were confined to one section of the field (two beds wide and 100 feet long). At the Hartnell and Spreckels sites, the trials were carried out in plots of the same dimension. Entrust treatments were initiated 1 wk after transplanting or thinning of romaine. We began sampling the next week. Plots were sampled once a week until harvest.

On the three organic farms, we evaluated natural infestations of *N. ribisnigri* and other aphids attacking romaine. For the Hartnell and Spreckels trials, we transplanted lettuce seedlings infested with *N. ribisnigri.* Trays of lettuce transplants were confined for 3 d within a laboratory colony of *N. ribisnigri* to establish an infestation before transplanting at these two field trials.

Three whole romaine plants were sampled from each plot each week, for a total of 12 plants per treatment per week. Plants were placed in plastic bags and taken to the University of California Cooperative Extension laboratory in Salinas for processing. An 18.9-liter (5-gal) plastic water bottle was modified to function as a collection sieve for insects on the romaine. The lower half of the bottle was cut away, and the central portion of the screw-on cap was replaced with organdy cloth by using a glue gun. The half-bottle was placed in a large sink with the cap end down. Plants were washed over the cut-away end of the bottle so that the water carried all insects into the screw-on cap, where material collected on the organdy. Plants were washed using a hand-held showerhead-type faucet. The cap was removed after the plant had been thoroughly washed, and its contents were examined under a microscope. The number and species of aphid were recorded for each plant, as was the number of syrphid eggs and larvae, the number of parasitized aphids, and the number and type of other predators.

Syrphid larvae were collected from samples and placed individually in a petri dish (100 by 25 cm; Thermo Fisher Scientific, Waltham, MA) for rearing. The larvae were kept in a growth chamber (model MB60-B, Percival Scientific, Perry, IA) with a photoperiod of 16:8 (L:D) h at 20–25 C and 60–75% RH, and they were provided with *N. ribisnigri;* pea aphid, and/or foxglove aphid on pieces of lettuce leaf or faba bean, *Vicia faba* L., leaf every 3 d until pupation. Upon reaching the adult stage, syrphids were allowed 1 d to expel abdominal fluid, then they were frozen, and later pinned and placed in a reference collection. The species of each individual was recorded.

To test for differences in whole plant densities of aphids, syrphid larvae, nonsyrphid predators, and syrphid eggs between the two treatments over time and among trials, we analyzed together the final 5 wk of data from each trial by using a repeated measures analysis of variance (ANOVA) model. Fixed factors in the model were trial and treatment (between subject) and sampling week (within subject). The random effects of block (trial) and treatment × block (trial) were included when associated covariance parameters were estimated to be greater than zero. Significant interactions between factors were followed with tests of simple effects of treatment within trial or week within trial.

Table 1. Results from ANOVA comparing whole plant densities of aphids, syrphid larvae, syrphid eggs, and nonsyrphid predators between untreated plots and plots treated with Entrust and across trials and time

Factors and sources of variation	df		F statistic	P value
	Numerator	Denominator		
Aphid density				
Trial	4	30.1	37.00	<0.0001
Treatment	1	30.1	248.44	<0.0001
Trial × treatment	4	30.1	4.44	0.0062
Sampling wk	4	218	33.84	<0.0001
Treatment × sampling wk	4	218	59.10	<0.0001
Trial × treatment × sampling wk	32	218	10.18	<0.0001
Syrphid density				
Trial	4	15	8.07	0.0011
Treatment	1	15	283.36	<0.0001
Trial × treatment	4	15	6.46	0.0031
Sampling wk	4	222	87.25	<0.0001
Treatment × sampling wk	4	222	37.51	<0.0001
Trial × treatment × sampling wk	32	222	10.98	<0.0001
Syrphid egg density				
Trial	4	15	31.53	<0.0001
Treatment	1	534	17.18	<0.0001
Trial × treatment	4	534	1.68	0.1539
Sampling wk	4	534	48.79	<0.0001
Treatment × sampling wk	4	534	6.04	<0.0001
Trial × treatment × sampling wk	32	534	12.03	<0.0001
Nonsyrphid predator density				
Trial	4	136	3.23	0.0144
Treatment	1	136	8.69	0.0038
Trial × treatment	4	136	8.51	<0.0001
Sampling wk	4	281	32.84	<0.0001
Treatment × sampling wk	4	281	6.21	<0.0001
Trial × treatment × sampling wk	32	283	2.23	0.0003

Aphid parasitism was determined by counts of aphid mummies. We tested for differences in parasitism between treatments and over time separately for each trial with a repeated measures ANOVA model. Treatment (between-subject) and sampling week (within-subject) were fixed factors in the model, and the random effect of block was included when the associated covariance parameter was estimated to be greater than zero. Significant interactions were followed with tests of simple effects of treatment within week.

To examine the numerical relationships between aphid and syrphid larva densities and between aphid and nonsyrphid predator densities across all trials, we applied a multiple linear regression model to the full data set. This model included trial and week as fixed, categorical variables, syrphid larvae, and nonsyrphid predators as fixed, continuous variables and interactions between trial and each continuous variable.

All analyses were performed using the MIXED procedure of SAS (SAS Institute 2002–2003), which estimates parameters using restricted maximum likelihood. A first-order autoregressive covariance model was used to incorporate correlations in the data collected over time. Denominator degrees of freedom were adjusted using the Kenward–Rogers calculation. When necessary to meet the assumption of normality, data were transformed using a natural log transformation, although untransformed least squares means are presented to facilitate interpretation. Statistical significance for all tests was defined as $\alpha \leq 0.05$.

Results

Aphid Densities. *N. ribisnigri* was the predominant aphid species found in each trial, although foxglove aphid, potato aphid and green peach aphid also contributed to infestations. Whole plant densities of aphids were higher in plots treated with Entrust than in untreated plots in each trial, usually beginning on the third or fourth sampling week of a trial (trial × treatment × week interaction; Table 1). The highest average whole plant aphid infestation levels in romaine treated with Entrust were as much as 36 times higher than peak infestation levels in untreated romaine in the same trial (Table 2). At-harvest aphid infestation levels for romaine treated with Entrust ranged from 28.02 ± 9.22 (mean $\pm$ SEM) per plant in the Hollister trial to 140.03 ± 9.22 in the Spreckels trial. Romaine treated with Entrust was unmarketable because of aphid infestation. In contrast, average aphid densities per plant at harvest in untreated romaine ranged from 2.19 ± 9.22 in the Hartnell trial to 9.48 ± 9.22 at the Spreckels site. Untreated romaine was marketable.

Syrphid Densities. Syrphid larvae composed between 85 and 96% of predators collected from untreated romaine in the Chualar, Hartnell, Hollister, and Watsonville trials and 63% of the predators collected from untreated romaine at Spreckels (Table 3). Syrphid larvae were the only predator group recovered from untreated romaine at all five sites. Usually by the third week and always by the final (harvest) week of sampling for each trial, whole plant densities of syrphids were significantly higher in untreated plots

Table 2.   Simple effect test results and untransformed least squares means ± SEM for whole plant aphid densities between treatments within each sampling week at each trial

	Sampling wk				
	1	2	3	4	5
Chualar					
Entrust	16.79 ± 9.22	50.01 ± 9.22	116.13 ± 9.22	43.55 ± 9.22	52.85 ± 9.22
Untreated	15.93 ± 9.22	16.53 ± 9.22	22.35 ± 9.22	2.42 ± 9.22	2.47 ± 9.22
F, P value	0.56, 0.456	16.83, <0.0001	33.82, <0.0001	59.61, <0.0001	60.12, <0.0001
Hollister					
Entrust	23.67 ± 9.22	63.01 ± 9.22	65.29 ± 9.22	63.78 ± 9.22	28.02 ± 9.22
Untreated	19.12 ± 9.22	69.77 ± 9.22	60.97 ± 9.22	0.72 ± 9.22	6.05 ± 9.24
F, P value	0.03, 0.859	0.02, 0.877	0.00, 0.992	95.15, <0.0001	12.27, 0.001
Hartnell					
Entrust	4.41 ± 9.22	10.38 ± 9.22	21.62 ± 9.22	28.64 ± 9.22	79.85 ± 9.22
Untreated	1.48 ± 9.22	5.43 ± 9.22	14.56 ± 9.22	1.36 ± 9.22	2.19 ± 9.22
F, P value	3.51, 0.061	3.01, 0.083	8.83, 0.003	49.55, <0.0001	100.25, <0.0001
Watsonville					
Entrust	42.71 ± 9.22	51.35 ± 9.22	64.25 ± 9.22	161.19 ± 9.22	64.24 ± 9.22
Untreated	40.42 ± 9.22	33.34 ± 9.22	32.98 ± 9.22	8.71 ± 9.22	5.70 ± 9.22
F, P value	0.03, 0.871	3.15, 0.077	3.99, 0.046	67.15, <0.0001	58.14, <0.0001
Spreckels					
Entrust	5.80 ± 9.22	9.54 ± 9.22	39.51 ± 9.22	96.84 ± 9.22	140.03 ± 9.22
Untreated	2.43 ± 9.22	16.63 ± 9.22	50.74 ± 9.22	23.89 ± 9.22	9.48 ± 9.22
F, P value	2.43, 0.120	0.03, 0.853	0.03, 0.867	19.97, <0.0001	65.59, <0.0001

Statistical differences for pairs of means were determined by $\alpha < 0.05$ with df = 1, 520.

compared with Entrust plots (trial × treatment × week interaction; Table 1). The highest average whole plant syrphid densities in untreated romaine ranged from 2.75 ± 0.58 (at Spreckels during the last week) to 9.08 ± 0.58 (at Hartnell in the fourth week) (Table 4). The highest average whole plant syrphid densities in romaine treated with Entrust ranged from 0.17 ± 0.58 (at Spreckels in the fourth week) to 2.84 ± 0.58 (at Hartnell, also in the fourth week).

Syrphid Egg Densities. Average whole plant densities of syrphid eggs differed statistically between treatments in three of the five trials but only during certain weeks (trial × treatment × week interaction; Table 1). Average whole plant densities of syrphid eggs were significantly higher in romaine treated with Entrust than in untreated romaine during weeks 4 and 5 of the Watsonville trial (week 4: Entrust = 8.70 ± 0.74, un-

treated = 2.82 ± 0.74; week 5: Entrust = 5.92 ± 0.74, untreated = 0.53 ± 0.74), and during the last sampling week at the Hartnell trial (Entrust = 1.84 ± 0.74, untreated = 0.42 ± 0.74). Syrphid egg densities were higher in untreated romaine during the third week at the Spreckels trial (Entrust = 0.08 ± 0.74, untreated = 1.25 ± 0.74). Whole plant densities of syrphid eggs averaged 2.46 ± 0.26 at the Chualar trial and 2.97 ± 0.26 at the Hollister trial.

Syrphid Species. Eight syrphid species and one syrphid parasitoid species (*Diplazon* sp.: Ichneumonidae) were reared from larvae collected during the course of these trials. Each of these species had been recovered during a survey of syrphids in organic romaine in 2005 (Smith and Chaney 2007), with the exception of *Sphaerophoria contigua* Maquart. *Sphaerophoria sulfuripes* (Thomson), *Allograpta obliqua*

Table 3.   Abundance of all predators and percentages of predator groups in each treatment by trial

Trial	Total no.	% total no.						
		Syrphid larvae	Dwarf spider	Minute pirate bug	Ladybird beetle	Lacewing	Rove beetle	Bigeyed bug
Chualar								
Untreated	258	85	7	3	—[a]	—	4	—
Entrust	16	81	13	6	—	—	—	—
Hollister								
Untreated	189	88	—	—	10	2	—	—
Entrust	77	47	1	—	34	18	—	—
Hartnell								
Untreated	233	96	3	—	<1	1	—	—
Entrust	65	80	8	—	8	4	—	—
Watsonville								
Untreated	229	91	2	<1	—	<1	6	—
Entrust	50	40	10	8	4	6	32	—
Spreckels								
Untreated	109	63	2	30	4	1	—	—
Entrust	17	18	—	12	53	12	—	6

[a] —, not collected.

Table 4. Simple effect test results and untransformed least squares means ± SEM for whole plant syrphid larva densities between treatments within each sampling week at each trial

	Sampling wk				
	1	2	3	4	5
Chualar					
Entrust	0.00 ± 0.58	0.50 ± 0.58	0.25 ± 0.58	0.33 ± 0.58	0.00 ± 0.58
Untreated	0.25 ± 0.58	3.29 ± 0.58	8.96 ± 0.58	3.50 ± 0.58	2.32 ± 0.58
F, P value	0.44, 0.509	29.42, <0.0001	127.34, <0.0001	35.69, <0.0001	24.08, <0.0001
Hollister					
Entrust	0.00 ± 0.58	0.00 ± 0.58	0.09 ± 0.58	0.73 ± 0.58	2.19 ± 0.58
Untreated	0.00 ± 0.58	0.00 ± 0.58	0.76 ± 0.58	6.49 ± 0.58	6.66 ± 0.58
F, P value	0.00, 1.000	0.00, 0.996	2.40, <0.0001	65.62, <0.0001	37.58, <0.0001
Hartnell					
Entrust	0.09 ± 0.58	0.00 ± 0.58	1.25 ± 0.60	2.84 ± 0.58	0.25 ± 0.58
Untreated	0.00 ± 0.58	0.66 ± 0.58	2.86 ± 0.58	9.08 ± 0.58	5.98 ± 0.58
F, P value	0.05, 0.825	2.85, 0.094	8.68, 0.004	44.31, <0.0001	80.76, <0.0001
Watsonville					
Entrust	0.17 ± 0.58	0.42 ± 0.58	0.25 ± 0.58	0.41 ± 0.58	0.42 ± 0.58
Untreated	0.76 ± 0.58	2.81 ± 0.58	5.30 ± 0.58	5.46 ± 0.58	3.34 ± 0.58
F, P value	2.11, 0.149	19.22, <0.0001	43.36, <0.0001	60.67, <0.0001	32.55, <0.0001
Spreckels					
Entrust	0.00 ± 0.58	0.00 ± 0.58	0.00 ± 0.58	0.17 ± 0.58	0.08 ± 0.58
Untreated	0.08 ± 0.58	0.26 ± 0.58	1.00 ± 0.58	1.68 ± 0.58	2.75 ± 0.58
F, P value	0.05, 0.821	0.44, 0.510	4.33, 0.040	11.3, 0.001	29.04, <0.0001

Statistical differences for pairs of means were determined by $\alpha < 0.05$ with df = 1, 520.

(Say), *Toxomerus marginatus* (Say), and *Allograpta exotica* Wiedemann were the most common species reared. *Syrphus opinator* Osten Sacken, *Platycheirus stegnus* (Say), *Eupeodes americanus* Wiedemann, and *Sphaerophoria continua* were recovered in low numbers.

Nonsyrphid Predators. Whole-plant densities of nonsyrphid predators generally were low in all trials. Average whole plant densities of nonsyrphid predators ranged from zero in multiple weeks to 1.74 ± 0.21 in romaine treated with Entrust during the final week of sampling at the Hollister site. Entrust affected nonsyrphid predators differently depending on trial and sampling week (trial × treatment × week interaction;

Table 1). At the Chualar and Spreckels trials, nonsyrphid predator densities were significantly higher in the untreated lettuce compared with romaine treated with Entrust for the last 3 and 2 weeks of sampling, respectively (Table 5). In contrast, at the Hollister and Watsonville trials, nonsyrphid predators were significantly higher in romaine treated with Entrust than in untreated romaine during the week before harvest. Nonsyrphid predators did not differ statistically between treatments at the Hartnell trial (Table 5).

Nonsyrphid predators collected from organic romaine included dwarf spiders (Linyphiidae), minute pirate bugs (*Orius* sp.), ladybird beetles (Coccineli-

Table 5. Simple effect test results and untransformed least squares means ± SEM for whole plant nonsyrphid predator densities between treatments within each sampling week at each trial

	Sampling wk				
	1	2	3	4	5
Chualar					
Entrust	0.07 ± 0.21	0.00 ± 0.21	0.00 ± 0.21	0.01 ± 0.21	0.16 ± 0.21
Untreated	0.10 ± 0.21	0.16 ± 0.21	0.63 ± 0.21	1.08 ± 0.21	1.16 ± 0.21
F, P value	0.02, 0.893	0.76, 0.384	10.01, 0.002	21.23, <0.0001	7.45, 0.007
Hollister					
Entrust	0.00 ± 0.21	0.00 ± 0.21	0.34 ± 0.21	1.34 ± 0.21	1.74 ± 0.21
Untreated	0.00 ± 0.21	0.01 ± 0.21	0.44 ± 0.21	0.89 ± 0.21	0.51 ± 0.21
F, P value	0.00, 0.994	0.01, 0.910	0.00, 0.991	0.42, 0.516	17.44, <0.0001
Hartnell					
Entrust	0.00 ± 0.21	0.09 ± 0.21	0.00 ± 0.21	0.07 ± 0.21	0.93 ± 0.21
Untreated	0.00 ± 0.21	0.00 ± 0.21	0.00 ± 0.21	0.41 ± 0.21	0.45 ± 0.21
F, P value	0.00, 0.952	0.27, 0.610	0.00, 0.945	1.66, 0.199	3.16, 0.077
Watsonville					
Entrust	0.24 ± 0.21	0.00 ± 0.21	0.00 ± 0.21	0.25 ± 0.21	1.25 ± 0.21
Untreated	0.22 ± 0.21	0.02 ± 0.21	0.16 ± 0.21	0.65 ± 0.21	0.36 ± 0.21
F, P value	0.57, 0.450	0.01, 0.920	0.82, 0.365	1.47, 0.226	6.22, 0.013
Spreckels					
Entrust	0.00 ± 0.21	0.16 ± 0.21	0.01 ± 0.21	0.00 ± 0.21	0.00 ± 0.21
Untreated	0.00 ± 0.21	0.00 ± 0.21	0.40 ± 0.21	1.03 ± 0.21	1.34 ± 0.21
F, P value	0.00, 0.974	0.91, 0.340	2.52, 0.114	15.92, <0.0001	22.81, <0.0001

Statistical differences for pairs of means were determined by $\alpha < 0.05$ with df = 1, 520.

Table 6. Multiple linear regression analysis and parameter estimates ± SE for relationships between aphid (y) and syrphid larva (x) densities and between aphid (y) and nonsyrphid predator (z) densities

Factors and sources of variation	df		F statistic	P value
	Numerator	Denominator		
Trial	4	86.4	5.61	0.001
Syrphid Larvae	1	542	17.92	<0.0001
Nonsyrphid predators	1	493	0.00	0.982
Syrphid larvae × trial	4	567	1.42	0.226
Nonsyrphid predators × trial	4	512	2.60	0.035
Sampling wk	4	467	10.15	<0.0001

Parameter estimates	Significance of slope parameter		
	DF	t value	P value
Syrphid larva			
$y = 2.88(\pm0.09) - 0.091(\pm0.02)*x$	542	−4.23	<0.0001
Nonsyrphid predator × trial			
Chualar: $y = 2.98(\pm0.21) - 0.302(\pm0.11)*z$	505	−2.78	0.006
Hollister: $y = 3.30(\pm0.21) + 0.080(\pm0.09)*z$	486	0.90	0.371
Hartnell: $y = 2.18(\pm0.21) + 0.018(\pm0.17)*z$	487	0.11	0.914
Watsonville: $y = 3.49(\pm0.22) + 0.018(\pm0.12)*z$	510	0.15	0.882
Spreckels: $y = 2.88(\pm0.21) + 0.179(\pm0.13)*z$	546	1.34	0.181

dae), brown lacewings (Hemerobiidae), rove beetles (Staphylinidae), and big-eyed bugs (*Geocoris* sp.). The complex of nonsyrphid predators was different at each site (Table 3).

Parasitism. Aphid mummies were found only in the Hartnell and Watsonville trials. Average whole plant densities of aphid mummies were higher in romaine treated with Entrust (1.43 ± 0.22) than in untreated romaine (0.08 ± 0.22) at the Hartnell trial ($F = 18.71$; df = 1, 6; $P = 0.005$). At the Watsonville trial, average whole plant densities of aphid mummies were significantly higher in romaine treated with Entrust only in week 5 (Entrust = 3.25 ± 0.49, untreated = 0.20 ± 0.49; $F = 21.13$; df = 1, 6; $P = 0.004$).

Aphid Density Relationships with Syrphid Larvae and Nonsyrphid Predators. Regression analysis revealed a significant, negative relationship between aphid and syrphid densities in all trials, but a significant, negative relationship between nonsyrphid predators and aphid densities in the Chualar trial only (Table 6). Of the four other trials, we found no relationship between aphid and nonsyrphid predator densities.

Discussion

On California's Central Coast, several different types of predators are found in organically grown romaine that is infested with *N. ribisnigri* and other aphids. The data presented here and previously (Smith and Chaney 2007) indicate that syrphid larvae are the most abundant predators, often making up >85% of the predators collected from infested romaine and that they can average up to nine larvae per romaine head during the crucial weeks immediately before the harvest of the crop. In addition, syrphid larvae are the only predator group consistently found in all infested romaine fields. Other predators are less abundant, and they are recovered in some fields but not others. Regression analysis presented here suggests that increases in syrphid larvae help explain reductions in aphid numbers and that there is no

relationship between nonsyrphid predators and aphid densities at most sites.

We present data that demonstrates that aphid densities were significantly higher in plots where syrphids were suppressed. Romaine in which syrphids were suppressed was unmarketable because of aphid infestation, whereas untreated romaine was marketable. Our results suggest that syrphids play a major role in the conservation biological control of *N. ribisnigri* and other aphids in organically grown romaine on the Central Coast of California.

We found that although Entrust does not affect oviposition by syrphid females, it does suppress nonsyrphid predators in some instances. Because Entrust apparently reduced the densities of nonsyrphid predators as well as syrphid larvae at the Chualar and Spreckels trials, it was an imperfect tool for demonstrating the effect of selectively removing syrphid larvae from organically grown romaine. Given that minute pirate bugs composed 30% of the predators at the Spreckels trial in untreated romaine, and only 12% where Entrust was applied, it is possible that suppression of minute pirate bugs contributed to the release of aphids from predation in the Entrust treatment. Dwarf spiders and minute pirate bugs in the Chualar trial also may have contributed to aphid suppression. Dwarf spiders are important predators of aphids in wheat, *Triticum aestivum* L. (Harwood et al. 2004, Nienstedt and Poehling 2004), and minute pirate bugs are important predators of soybean aphid (Costamagna and Landis 2007).

The Chualar and Spreckels trials illustrate instances in which predators other than syrphids may contribute significantly to the suppression of aphids in organic romaine. However, unlike the Chualar site, where average syrphid densities were among the highest of all trials 2 wk before harvest, syrphid densities were very low at Spreckels. The Spreckels trial also was unusual in that the aphid infestation in the untreated plots at harvest approached unmarketable levels. Considering the paucity of syrphid larvae, the abundance

of minute pirate bugs, and the poor biological control of aphids achieved at this site, the Spreckels trial may offer an example of interguild predation interfering with suppression of aphids by syrphids in organic romaine. Interguild predation interferes with conservation biological control in some instances (Rosenheim 1998), and further study is required to determine whether the presence of certain nonsyrphid predators reduces the efficacy of syrphids in suppressing aphids in organic romaine.

It is worth noting that nonsyrphid predators were statistically higher in romaine treated with Entrust in the Hollister and Watsonville trials, but that Entrust-treated romaine was still unmarketable in these trials because of aphid infestation. Numbers of aphid mummies also were higher in romaine treated with Entrust in two trials, presumably because the densities of aphids were much higher in romaine treated with Entrust.

Given the abundance of syrphid larvae and that syrphid larvae are the only predator consistently recovered from organically grown romaine, we argue that syrphid larvae are primarily responsible for suppressing *N. ribisnigri* and other aphids to below economic levels.

Acknowledgments

References Cited

Arthurs, S. P., L. A. Lacey, and E. R. Miliczky. 2007. Evaluation of codling moth granulosis virus and spinosad for codling moth control and impact on non-target species in pear orchards. Biol. Control 41: 99–109.

California Farm Bureau. 2006. California Farm Bureau. (www.cfbf.com/info/agfacfts.cfm).

Chaney, W. E. 1999. Lettuce aphid update. Monterey County Crop Notes, University of California Cooperative Extension, Salinas, CA.

Colfer, R. 2004. Using habitat management to improve biological control on commercial organic farms in California, pp. 55–62. *In* M. S. Hoddle [ed.], Fourth California Conference on Biological Control, 13–15 July 2004, Berkeley, CA. University of California Press, Berkeley, CA.

Contreras, J., V. Quinto, V. Abellan, J. Fernandez, E. Gravalos, C. Moros, and P. Bielza. 2006. Effects of natural insecticides on *Frankliniella occidentalis* and *Orius* spp. Bull. OILB/SROP 29: 331–336.

Costamagna, A. C., and D. A. Landis. 2007. Quantifying predation on soybean aphid through direct field observations. Biol. Control 42: 16–24.

Eizen, G. W., P. J. Elzen, and E. G. King. 1998. Laboratory toxicity of insecticide residues to *Orius insidiosus, Geocoris punctipes, Hippodamia convergens,* and *Chrysoperla carnea,* pp. 1235–1238. *In* P. Dugger and D. Richter [eds.], 1998 Proceedings of the Beltwide Cotton Conference, 5–9 January 1998, San Diego, CA.

Harwood, J. D., K. D. Sunderland, and W.O.C. Symondson. 2004. Prey selection by linyphiid spiders: molecular tracking of the effects of alternative prey on rates of aphid consumption in the field. Mol. Ecol. 13: 3549–3560.

Klonsky, K., and K. Richter. 2007. Statistical review of California Organic Agriculture 2000–2005. Agricultural Issues Center, University of California, Davis, CA. (aic.ucdavis.edu).

Liu, Y.-B. 2004. Distribution and population development of *Nasonovia ribisnigri* in iceberg lettuce. J. Econ. Entomol. 97: 883–890.

MacKenzie, J. R., and R. S. Vernon. 1988. Sampling for the distribution of lettuce aphid, *Nasonovia ribisnigri* (Homoptera: Aphididae), in fields and within heads. J. Entomol. Soc. Br. Columbia 85: 10–14.

Miles, M. 2006. The effects of spinosad on beneficial insects and mites used in integrated pest management systems in greenhouses. Bull. OIL/SROP 29: 53–59. [NASS] National Agricultural Statistics Service. 2006. National Agricultural Statistics Service. (www.nass.usda.gov).

Nienstedt, K. M., and H.-M. Poehling. 2004. Invertebrate predation of ^{15}N-marked prey in semi-field wheat enclosures. Entomol. Exp. Appl. 112: 191–200.

Rosenheim, J. A. 1998. High order predators and the regulation of insect herbivore populations. Annu. Rev. Entomol. 43: 421–47.

SAS Insitute. 2002–2003. SAS, version 9.1. SAS Institute, Cary, NC.

Smith, H. A., and W. E. Chaney. 2007. A survey of syrphid predators of *Nasonovia ribisnigri* in organic lettuce on the Central Coast of California. J. Econ. Entomol. 100: 39–48.

Studebaker, G. E., and T. J. Kring. 2003. Effects of insecticides on *Orius insidiosus* measured by field, greenhouse and Petri dish bioassays. Fla. Entomol. 86: 178–185.