Crop Protection 87 (2016) 68–77

Contents lists available at ScienceDirect

Crop Protection

journal homepage: www.elsevier.com/locate/cropro

Insecticides applied to soil of transplant plugs for *Bagrada hilaris* (Burmeister) (Hemiptera: Pentatomidae) management in broccoli

Shimat V. Joseph [a,*], Ian Grettenberger [b], Larry Godfrey [b]

[a] University of California Cooperative Extension, 1432 Abbott Street, Salinas, CA 93901, USA
[b] Department of Entomology and Nematology, University of California, Davis, CA 95616, USA

ARTICLE INFO

Article history:
Received 3 February 2016
Received in revised form
29 April 2016
Accepted 29 April 2016

Keywords:
Brassicaceae
Integrated pest management
Seedling tray drench
Salinas Valley
Neonicotinoid

ABSTRACT

Chemical control with insecticides, typically applied as foliar sprays or chemigation, is the primary tactic used to manage *Bagrada hilaris* (Burmeister) (Hemiptera: Pentatomidae). We evaluated the efficacy of 14 insecticides, including both systemic and non-systemic insecticides, against *B. hilaris* applied as a seedling tray drench. Experiments were conducted in both greenhouse and field settings. In all experiments, we used the maximum label rate of insecticides and calculated dose per seedling based on this rate and standard plant density per hectare. Each seedling in the tray received 2-mL insecticide solution, and the seedlings were then exposed to *B. hilaris* adults after transplanting in cages for greenhouse experiments or natural *B. hilaris* populations in the field experiments. A scale system (0–4) was used to evaluate the severity of *B. hilaris* feeding injury on leaves where 0 = no injury and 4 = >75% of the leaf margins with *B. hilaris* feeding injury. We evaluated damage using the rating system, percentage of damaged leaves, number of feeding injury sites, as well as plant height, leaf width, and fresh and dry weight. In the greenhouse experiment, percentage of injured leaves, number of injury sites, and damage rating were significantly lower for transplants treated with acetamiprid, clothianidin, dinotefuran, imidacloprid, and thiamethoxam, and cyclaniliprole compared with the untreated. There was a relationship between feeding injury sites and plant height, leaf width, fresh and dry weight ($R^2 > 0.5$) in both 2015 field experiments. Similarly, the transplants treated with acetamiprid, clothianidin, dinotefuran, imidacloprid, thiamethoxam, thiamethoxam + chlorantraniliprole, imidacloprid + β-cyfluthrin and cyclaniliprole had significantly lower damage ratings than those treated with chlorpyrifos, bifenthrin, tolfenpyrad, flonicamid, cyantraniliprole, spinetoram and the untreated control. For transplanted broccoli, treatment of transplant plugs with neonicotinoid insecticides prior to planting can be an effective method for controlling *B. hilaris*.

1. Introduction

Bagrada hilaris (Burmeister) (Hemiptera: Pentatomidae), commonly referred to as the bagrada bug or painted bug, is a stink bug species invasive in North America and native to old world countries of southern Africa, Middle East and Asia (Reed et al., 2013). *B. hilaris* is a serious pest of a wide array of *Brassica* crops in the Central Coast of California (area northwest of Los Angeles and South of San Jose, CA; Joseph, 2014). It was first detected in North America in 2008 in Los Angeles Co., California (Palumbo and Natwick, 2010) and is now found in Arizona, New Mexico, Texas, Utah, and Nevada (CISR, 2014). This pest threatens a valuable industry, with the value of cruciferous crops in California estimated at ~US$1 billion in 2013 (U.S. Department Agriculture, NASS, 2014). In Monterey Co. alone, cruciferous crops are grown year-round on > 34,390 ha and are valued at > $679 million USD (Monterey County Crop Report, 2014). Yearly losses to *B. hilaris* are estimated in the several millions of US dollars in the region in recent years (SVJ, pers. comm.).

Bagrada hilaris can damage cruciferous crops and reduce yields in several ways. The pest develops high populations on mustard weed species commonly found in ditches, roadsides, and edges of agricultural fields, as well as in unmanaged cruciferous crops, and then invades newly planted fields (Reed et al., 2013; I. Grettenberger, unpublished data). *B. hilaris* damages crops most when attacking germinating or cotyledon stage plants (Palumbo and

* Corresponding author.
E-mail address: svjoseph@ucanr.edu (S.V. Joseph).

http://dx.doi.org/10.1016/j.cropro.2016.04.023

Natwick, 2010). In broccoli and cauliflower, serious economic injury occurs when feeding by *B. hilaris* kills the apical meristematic tissue of the young seedlings, creating a "blind head" (plant without a head; Palumbo and Natwick, 2010). *B. hilaris* feeding also triggers production of multiple adventitious shoots, causing plants to produce unmarketable, undersized broccoli and cauliflower heads. Severe feeding during early stages of plant growth depletes the nutrient reserves of the plant and causes stunting (Huang et al., 2014). *B. hilaris* feeding injury on leaves appears as "starbursts" on leaf surfaces which then develop into necrotic tissue. In California's Central Coast, direct-seeded broccoli plants are vulnerable until approximately the six-leaf stage to *B. hilaris* feeding injury such as stunting, blinds, and many adventitious shoots (I. Grettenberger, unpublished data).

In the pursuit of methods to manage *B. hilaris*, pyrethroid and carbamate insecticides were quickly found to be effective (Palumbo, 2011a, b, c; Palumbo et al., 2015). However, multiple sprays of these insecticides have been needed to manage *B. hilaris*, especially during the vulnerable seedling stages of the plant. This has increased overall insecticide use in cruciferous crops in the Central Coast of California (California Department of Pesticide Regulation, 2016). Although potential biological control agents have been identified in the native range in Asia of *B. hilaris* (Mahamood et al., 2015), their climate matching, importation, non-target host screening, and subsequent field release in the Central Coast will take several years, and success is not guaranteed. Until sustainable tactics are developed and readily available, chemical control will remain the primary tool for *B. hilaris* management in conventionally managed vegetable production. Unfortunately, the Central Coast, pesticide transport into surface waters in suspended sediments was already a problem prior to the surge in sprays targeting *B. hilaris* (Ng and Weston, 2009). Commonly detected pesticides included the pyrethroids bifenthrin and zeta-cypermethrin (Anderson et al., 2003a, b; Anderson et al., 2006; Starner et al., 2006; Ng and Weston, 2009; Schmidt et al., 2010). Detections of even higher pesticide residues would most likely trigger stringent regulations on the use of pyrethroid insecticides. Under these circumstances, there is an urgent need to develop alternative but effective Integrated Pest Management (IPM) approaches that will reduce the use and off-site movement of pyrethroid insecticides. Drenching seedling trays with insecticide is a precise application tactic in which the insecticide dose is placed directly onto the transplant plugs before transplanting. Previously, this technique has proven effective in managing lepidopteran and coleopteran pests of *Brassica* crops (Cameron et al., 2015), but little is known about how well it will control *B. hilaris*. Thus, the major objective of this study was to evaluate the efficacy of insecticides against *B. hilaris* when delivered as a seedling tray drench before planting. We conducted both greenhouse and field experiments to a range of insecticides with both systemic and non-systemic activity. Our results demonstrate the utility of a seedling tray drench for preventing damage by *B. hilaris*, protecting *Brassica* crops, and increasing the sustainability of pest management practices.

2. Materials and methods

2.1. Greenhouse experiment

We conducted a greenhouse experiment to test the efficacy of an insecticide seedling tray drench for management of *B. hilaris*. The experiment was conducted at the Monterey County University of California Cooperative Extension (UCCE) facilities in Salinas, CA. Broccoli seeds ('Marathon') were planted in 256-cell seed trays (one seed per cell) filled with potting media (Sun Gro, Sunshine Mix #4 Aggregate Plus, Agawam, MA). The potting media contained Sphagnum peat moss, coarse perlite with gypsum and dolomitic limestone, starter fertilizer, and gypsum. Based on manufacturer-provided information, the pH of the media is initially between 4.6 and 5.2, and 14 d after saturation, pH is between 5.5 and 6.5. Seedlings were grown in a commercial greenhouse (Growers Transplant Inc., Salinas, CA) for 5 wks and then transferred to the UCCE greenhouse, where they remained for the duration of the experiment. *B. hilaris* adults used in the experiment were collected from perennial pepperweed (*Lepidium latifolium* L.) and shortpod mustard [*Hirschfeldia incana* (L.) Lagr.-Fossat] in San Ardo, CA. *B. hilaris* were maintained on potted broccoli plants and heads in a controlled environmental chamber at ~20 °C, ~45% relative humidity, and 16:8 L:D for two days before they were used in the experiment.

The experiment was conducted in three separate trials, each with slightly different treatments. Both contact and systemic insecticides currently in use or that have potential for registration were included in the experiment (Table 1), even though the non-systemic insecticides were unlikely to perform well against *B. hilaris* via application as a seedling tray drench. In the first trial, we tested five insecticide treatments: clothianidin, chlorpyrifos, bifenthrin, cyantraniliprole, and spinetoram, plus an untreated control. In the second trial, we tested five insecticide treatments: acetamiprid, dinotefuran, imidacloprid, thiamethoxam, and thiamethoxam + chlorantraniliprole, plus an untreated control. In the third and final trial, the treatments used in the second trial were repeated with the addition of imidacloprid + β-cyfluthrin, tolfenpyrad, flonicamid, and cyclaniliprole.

To expose plants to *B. hilaris*, one pot of each treatment was randomly chosen and placed on a plastic tray (45 cm × 34 cm) in a collapsible mesh cage (catalog # 1466AV, Bioquip, Rancho Dominguez, CA). Each cage therefore contained one replicate of each treatment tested in the respective trial. Plants were randomly arranged within cages. The first trial was repeated twice (two "subtrials"), and each time, treatments were replicated 10 times (10 cages, six pots per cage) for a total of 20 replicates per treatment. In the second trial, treatments were replicated 10 times (six pots per cage). For the third trial, all treatments were replicated 10 times (10 pots per cage). Because all treatments from the second trial were repeated in the third trial, treatments from the second trial were replicated 20 times across trials, but those that were new in the third trial were only replicated 10 times.

To determine the insecticide dose per transplant plug, we first calculated the number of plants per ha based on standard planting practices in the Central Coast and then used the highest recommended field application rate per ha to determine dose per plant (Table 1). Growers typically plant broccoli transplants on 101.6 cm wide beds, with two rows per bed and 15.2–17.8 cm spacing between plants within rows. We used 17.8-cm spacing for our calculations, which would yield 110,668 plants per ha in the field. We injected 2 mL of the insecticide solution into the potting media of each transplant plug using a 6-mL syringe without a needle. The water volume per plug was determined after conducting preliminary tests to establish how much water the transplant plug could absorb and retain. After we applied the insecticide solution, the transplants remained in transplant trays for 7 d. At this point, the seedlings (6–7-wk old) were transplanted into 8.9-cm diameter plastic pots filled with potting media.

Seven days after transplanting (14 d after insecticide treatment), plants were exposed to *B. hilaris* for 14 d. In the first and second trials, five adults were initially introduced into each cage, and 7 d later, five more adults were added. Fourteen days after the addition of *B. hilaris*, the experiment ended and plants were evaluated. In the third trial, the *B. hilaris* exposure period was again 14 d, but eight adults were introduced into the cage at the start of the exposure

Table 1
Insecticides evaluated for *B. hilaris* management in both greenhouse and field experiments.

Class	Insecticide	Formulation	Tested rate (g A.I. per ha)
Neonicotinoid	Acetamiprid[a,c,d]	Assail 30 SG	84.02
	Clothianidin[a,b,c,d]	Belay EC	224.05
	Dinotefuran[a,c,d]	Venom	294.64
	Imidacloprid[a,d]	Admire Pro	404.39
	Thiamethoxam[a,c,d]	Platinum SC	55.5
Neonicotinoid + Diamide	Thiamethoxam + Chlorantraniliprole[a,c,d]	Durivo EC	189.60 + 94.05
Neonicotinoid + Pyrethroid	Imidacloprid + Beta-cyfluthrin[a,c,d]	Leverage EC	52.56 + 25.85
Organophosphate	Chlorpyrifos[a,b,c,d]	Lorsban Advanced	1367.12
Pyrethroid	Bifenthrin[a,b,c,d]	Capture LFR	89.61
Pyridazinone	Tolfenpyrad[a,c,d]	Torac EC	237.11
Pyridinecarboxamide	Flonicamid[a,c,d]	Beleaf 50 SG	99.71
Ryanodine receptor activator	Cyantraniliprole[a,b,c,d]	Verimark SC	197.18
	Cyclaniliprole[a,c,d]	IKI 3106 50 SL	59.89
Spinosyn	Spinetoram[a,b,c,d]	Radiant SC	87.52

[a] Insecticides used in greenhouse experiment in 2015.
[b] Insecticides used in field experiment in 2014.
[c] Insecticides used in field experiment 1 in 2015.
[d] Insecticides used in field experiment 2 in 2015.

period, followed by eight more 7 d later. After 14 d (for all three trials), we evaluated plants for damage by counting the number of feeding injury sites on leaves and the number of leaves with injury. In addition, a scale system (damage rating from 0 to 4) was developed to rate the severity of leaf feeding injury. *B. hilaris* individuals tend to feed on the leaf margins, so we focused on the leaf margins for the evaluation. All leaves on a plant were assessed for damage and the scale values were averaged for each plant (treatment replicate). The scale system is as follows: 0 = 0%; 1 = 1–25%; 2 = 26–50%; 3 = 51–75%; and 4 = >75% of the leaf margin with *B. hilaris* feeding injury.

2.2. Field experiments

2.2.1. 2014 experiment

This experiment was conducted in a commercial broccoli field near Gonzales, CA. Similar to the greenhouse experiment, broccoli seeds (‘Heritage’) were planted in a transplant tray and then grown in a commercial greenhouse. We prepared and applied insecticide solutions as described in the greenhouse protocol. In the field experiments, transplant plugs were transplanted within 1 h after insecticides were applied. The insecticides tested and rates used are listed in Table 1. The transplants were hand-planted into plots on 19 August. Each plot consisted of 7.6 m of a 101.6 cm wide bed, and plants were planted in two rows with 17.8 cm spacing between plants. The treatments were arranged in a randomized complete block design with four replications. On 6 October, 10 plants were removed per plot to determine the severity of *B. hilaris* feeding injury on leaves. From the 10 plants, one of the third or fourth leaves from the top (i.e., older leaf) was assessed using the injury scale (0–4) described in section 2.1. The scale values were averaged per plot (treatment replicate). Older leaves, but not the absolute oldest, were chosen for assessment of injury symptoms. These leaves were chosen over younger leaves because older leaves were more damaged; damage to these leaves occurred when plants were young and most susceptible to yield reduction, and plant stunting resulted from damage to these leaves. The oldest leaves were not used because individual injury sites were not distinguishable when damage was assessed. In addition, 20 plants were destructively sampled per plot on 6 October and plant height and fresh weight were measured in the laboratory within a day.

2.2.2. 2015 experiments

Two field experiments were conducted near Gonzales, CA in 2015. The insecticide treatments and rates used for both experiments are listed in Table 1. Transplants were planted with 17.8 cm spacing in two rows on a 101.6 cm wide bed. Each block contained one plant of each treatment. Blocks were spaced 1.5-m apart in a randomized complete block design with 20 replications.

For the first experiment, broccoli seeds (‘Patron’) were planted on 10 June. Broccoli seeds (‘Marathon’) were planted for the second experiment on 25 July. Seeds were planted in 256-cell trays filled with potting media. Transplants for the first experiment were grown in the UCCE greenhouse, while transplants for the second experiment were grown in a commercial greenhouse facility (Growers Transplant Inc., Salinas, CA). The transplants were not fertilized in either experiment. The plugs were drenched with insecticides on 2 August for the first experiment and on 28 August for the second experiment. The first experiment was transplanted on 26 August, and the second experiment was transplanted on 4 September. Plants were evaluated for damage by counting the number of *B. hilaris* feeding injury sites and the number of injured leaves. The number of injured leaves was not evaluated in 2014 field experiment because nearly all leaves had *B. hilaris* feeding injury. The leaves were also evaluated using the 0–4 scale system for damage. All the leaves on a plant were assessed for damage and the scale values were averaged for each plant. We measured plant height and width of three leaves. We determined plant fresh weight by cutting plants at the soil surface and weighing them. Plants were then dried in a drying oven at ~105 °C for three days and weighed to determine dry plant weight. In addition, total number of leaves per plant (both injured and uninjured) was quantified to evaluate plant growth.

2.3. Statistical analyses

All analyses were conducted in SAS (SAS Institute, 2012). Where applicable, data were tested for normality using the PROC Univariate procedure of SAS and data were transformed to establish homogeneity of variance. For the greenhouse experiment, the number of feeding injury sites average damage scale value (per plant) was analyzed with analysis of variance (ANOVA) using the general linear model procedure after log-transformation ($\ln[x + 1]$). The proportion of leaves with feeding damage was analyzed with ANOVA after arcsine square root transformation. In the 2014 field experiment, average damage rating value (per plot), plant height, and fresh weight were analyzed with ANOVA without data transformation. For 2015 field experiments number of leaves and feeding injury sites on leaves, average damage scale value (per plant), plant height, leaf width, fresh and dry plant weights were log-transformation (ln[x + 1]) and analyzed with ANOVA. Means were separated using Tukey's HSD method ($\alpha = 0.05$). The relationship between the mean number of *B. hilaris* feeding injury sites and plant height, average leaf width, fresh weight, and dry weight was analyzed with linear regression (JMP 12.01, SAS Institute, 2015). A small number of replicates were not included in the analyses either because data were missing for a specific variable or because the entire plant was destroyed by rodents.

3. Results

3.1. Greenhouse experiment

Percentage injured leaves, number of feeding injury sites, and damage rating were all substantially lower than the untreated when the transplants were treated with the neonicotinoids acetamiprid, clothianidin, dinotefuran, imidacloprid, and thiamethoxam (percentage injured leaves: overall $F = 21.4$, df = 14, 224, $P < 0.001$, Fig. 1A; feeding injury sites: $F = 23.8$, df = 14, 225, $P < 0.001$, Fig. 1B; damage rating: $F = 28.1$, df = 14, 224, $P < 0.001$, Fig. 1C). Damage, assessed with each of the three variables, was also significantly lower than untreated plants for plants treated with imidacloprid + β-cyfluthrin, thiamethoxam + chlorantraniliprole, and cyclaniliprole. For percentage injured leaves, number of feeding injury sites, and damage rating, none of the previous treatments (significantly different than the untreated) were different from each other (Fig. 1B). The one exception was dinotefuran for feeding injury sites, which had lower damage than thiamethoxam + chlorantraniliprole. However, dinotefuran was not significantly different from the other effective treatments. There were no significant differences in percentage injured leaves, injury sites, or damage rating among untreated, chlorpyrifos, bifenthrin, tolfenpyrad, flonicamid, cyantraniliprole, and spinetoram treatments.

3.2. Field experiments

3.2.1. 2014 experiment

Feeding injury rating ranged from 0.76 to 1.63 and did not differ significantly between treatments ($P = 0.427$). Similarly, there was no significant effect of insecticide treatment on plant height ($P = 0.059$), although height was numerically higher for clothianidin-drenched (43.3 cm) than untreated plants (33.3 cm). Fresh weight of plants was significantly greater for plants treated with clothianidin (~2.2×) and bifenthrin (~1.8×) than the untreated, which suggest that these insecticides reduced stunting from *B. hilaris* damage ($F = 2.9$; df = 5, 15; $P = 0.049$; Fig 2).

3.2.2. 2015 experiments

3.2.2.1. Experiment 1. The number of feeding injury sites was significantly lower than the untreated control for plants treated with acetamiprid, clothianidin, dinotefuran, thiamethoxam, thiamethoxam + chlorantraniliprole, imidacloprid + β-cyfluthrin, and bifenthrin ($F = 21.5$; df = 13, 245; $P < 0.001$; Fig. 3A). Plants

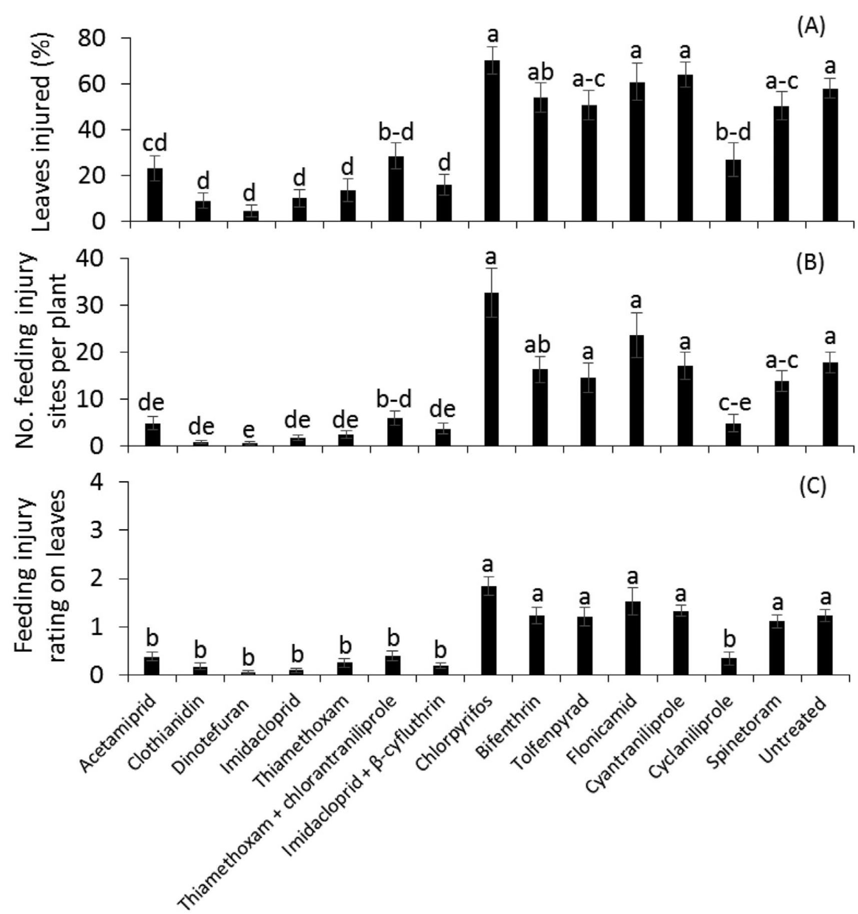

Fig. 1. Effect (mean ± SE) of tray drench application of insecticides on (A) leaves injured by *B. hilaris* feeding, (B) number of feeding injury sites, and (C) feeding injury rating on the leaves in greenhouse experiments. Bars with the same letters for each evaluation parameter are not significantly different ($P > 0.05$).

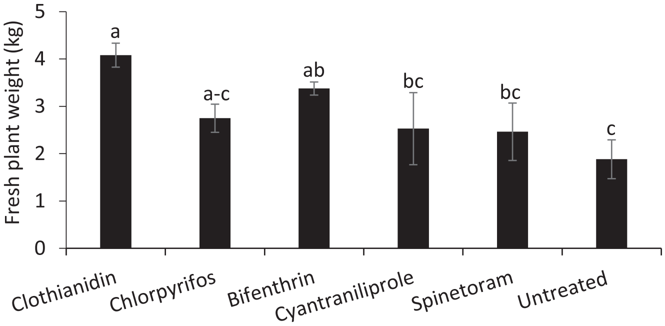

Fig. 2. Effect (mean ± SE) of tray drench application of insecticides on fresh plant weight when applied as tray drench against *B. hilaris* in the 2014 field experiment. Bars with the same letters are not significantly different ($P > 0.05$).

treated with clothianidin had the fewest injury sites, and the number was lower than all treatments other than dinotefuran. Similarly, bifenthrin and cyclaniliprole, as well all treatments containing a neonicotinoid, had significantly lower damage ratings than the untreated control ($F = 30.3$; df = 13, 245; $P < 0.001$; Fig. 3B). Other than plants treated with dinotefuran, plants treated with clothianidin had significantly fewer injury sites than all other treatments. Plant were taller when treated with clothianidin and dinotefuran than flonicamid, spinetoram, tolfenpyrad, but only clothianidin-treated plants were taller than untreated plants ($F = 4.5$; df = 13, 246; $P < 0.001$; Fig. 3C). Plants treated with clothianidin, dinotefuran, thiamethoxam + chlorantraniliprole, and imidacloprid + β-cyfluthrin had wider leaves than plants from a number of other treatments, including the untreated control ($F = 7.5$; df = 13, 246; $P < 0.001$; Fig. 3D). Fresh ($F = 5.8$; df = 13, 247; $P < 0.001$; Fig. 3E) and dry ($F = 8.4$; df = 13, 247; $P < 0.001$; Fig. 3F) plant weight were significantly greater for clothianidin, dinotefuran and imidacloprid + β-cyfluthrin treated plants than untreated plants. Number of leaves was not significantly different than the untreated control for any treatment ($P > 0.05$).

There was a significant negative relationship between number of feeding sites and plant height ($y = 22.2-0.14x$; Fig. 4A), leaf width ($y = 8.1-0.08x$; Fig. 4B), fresh weight ($y = 86.8-1.3x$; Fig. 4C), and dry weight ($y = 11.6-0.16x$; Fig. 4D).

3.2.2.2. Experiment 2. The number of feeding injury sites was significantly lower for plants treated with acetamiprid, clothianidin, dinotefuran, imidacloprid, thiamethoxam, thiamethoxam + chlorantraniliprole, imidacloprid + β-cyfluthrin, chlorpyrifos, and cyantraniliprole than for the untreated control ($F = 26.8$; df = 14, 261; $P < 0.001$; Fig. 5A). Plants treated with dinotefuran had the fewest injury sites, although there were no statistical differences between those treated with dinotefuran, imidacloprid, or thiamethoxam. When the transplants were treated with acetamiprid, clothianidin, dinotefuran, imidacloprid, thiamethoxam, thiamethoxam + chlorantraniliprole, imidacloprid + β-cyfluthrin, chlorpyrifos, and cyantraniliprole, injury ratings were lower than the untreated control ($F = 41.1$; df = 14, 261; $P < 0.001$; Fig. 5B). Similar to number of injury sites, plants treated with dinotefuran had the lowest damage ratings numerically, but they were not significantly different from plants treated with imidacloprid or thiamethoxam. Plant height was significantly higher than the untreated control only for the dinotefuran treatment ($F = 3.8$; df = 14, 251; $P < 0.001$; Fig. 5C); however, dinotefuran-treated plants were not significantly taller than many of the treatments, including all other neonicotinoid insecticides and insecticides from several other classes. A similar pattern was evident for leaf width, with only the dinotefuran treatment significantly different than the untreated control and a number of other treatments not significantly different than the dinotefuran treatment ($F = 4.2$; df = 14, 253; $P < 0.001$; Fig. 5D). Fresh plant weight was significantly greater for plants treated with clothianidin, dinotefuran, imidacloprid, thiamethoxam, and thiamethoxam + chlorantraniliprole than for the untreated control ($F = 5.4$; df = 14, 248; $P < 0.001$; Fig. 5E). The treatments that had greater fresh plant weight than the untreated control were not statistically different from one another. The pattern across treatments for dry plant weight was nearly the same as for fresh plant weight ($F = 9.1$; df = 14, 247; $P < 0.001$; Fig. 5F). The number of leaves was not significantly different among all insecticide-treated plants ($P > 0.05$).

There was a significant negative relationship between mean feeding injury sites and mean plant height ($y = 26.8-0.08x$; Fig. 6A), leaf width ($y = 10.9-0.05x$; Fig. 6B), fresh weight ($y = 90.2-0.6x$; Fig. 6C), and dry weight ($y = 13.3-0.1x$; Fig. 6D).

4. Discussion

These results demonstrate that drenching transplant plugs with neonicotinoid insecticides, and in particular acetamiprid, clothianidin, dinotefuran, imidacloprid, and thiamethoxam, reduce *B. hilaris* feeding damage and promote normal plant growth. Dinotefuran has previously performed better against *B. hilaris* than imidacloprid and thiamethoxam in field trials with foliar sprays (Palumbo et al., 2015), and this result was consistent with our study. When applied to the foliage in the field, performance of clothianidin has been unsatisfactory in preventing *B. hilaris* damage (Palumbo et al., 2013). Changing the application method may improve management of *B. hilaris* with these products. Tray drenches of neonicotinoids have been effective against other pests. For instance, drenches of imidacloprid, thiamethoxam or clothianidin reduced tobacco flea beetle [*Epitrix hirtipennis* (Melsheimer)] feeding damage and number of green peach aphids [*Myzus persicae* (Sulzer)] on tobacco (*Nicotiana tabacum* L.) (Semtner, 2005; Semtner and Srigiriraju, 2005; Semtner and Wright, 2005; Semtner et al., 2008), while chlorantraniliprole was effective against cabbage looper [*Trichoplusia ni* (Hübner)] on cabbage (Cameron et al., 2015). In our study with broccoli, we also tested non-neonicotinoid systemic insecticides as tray drenches including cyantraniliprole and cyclaniliprole, as well as contact insecticides, such as flonicamid, spinetoram, tolfenpyrad, and bifenthrin, but most did not consistently affect *B. hilaris* damage. The contact insecticides were tested in addition to systemic insecticides because these insecticides are commonly used as foliar sprays for various insect pests, including *B. hilaris* on *Brassica* crops, although positive results were not expected.

The efficacy of tray drench application for broccoli suggests that this application method could be useful for *B. hilaris* management in other *Brassica* crops, and in particular, cauliflower. The insecticide dose received by each transplant plug was based upon the number of plants per ha, which is related to plant spacing, number of rows per bed, and width of a bed. As the number of plants transplanted in a hectare decreases, the amount of insecticide received per plug will increase. In the Central Coast, cauliflower is planted at a greater spacing than broccoli, and only one row of cauliflower is typically planted per bed rather than the two rows used for broccoli in the same-sized bed. This suggests that if the same overall rate of insecticide is used at the field level, each cauliflower transplant will receive a larger insecticide dose than broccoli transplants because of the lower number of plants per ha. Our results show that *B. hilaris* was adequately controlled by the neonicotinoid insecticides when applied to broccoli transplants. Thus, cauliflower transplants, which would receive a higher dose

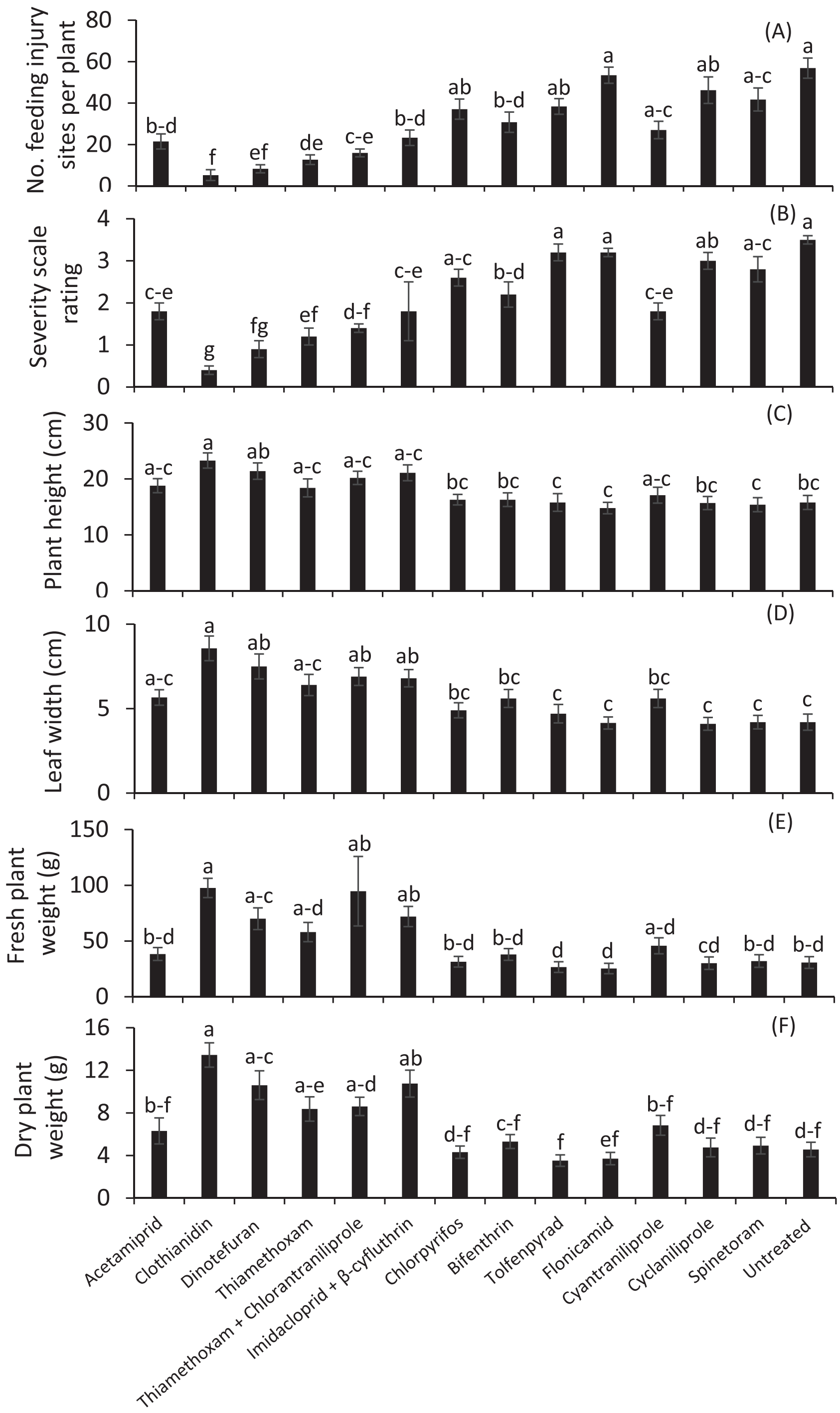

Fig. 3. Effect (mean ± SE) of tray drench application of insecticides on (A) *B. hilaris* feeding injury, (B) injury rating, (C) plant height, (D) leaf width, (E) fresh, and (F) dry weight per plant in the first 2015 field experiment. Bars with the same letters for each evaluation parameter are not significantly different ($P > 0.05$).

than broccoli at the same per ha rate, should perform even better. Future research will investigate the efficacy of lower rates of neonicotinoid insecticides, and in particular dinotefuran and clothianidin, against *B. hilaris* in cauliflower. We may be able to still achieve sufficient control of *B. hilaris* in cauliflower by reducing the amount of insecticide applied on a per-ha basis compared to broccoli, but keeping the rate the same at the individual transplant level.

Drenching transplant plugs could provide several benefits for *B. hilaris* control. First, this tactic applies the insecticide to a small volume of soil in the transplant plug. The plants can quickly uptake and translocate the active ingredient to the foliage of the young plant, targeting the pest in both space and time. This precise delivery of insecticide to plants when they are young and most vulnerable to injury will maximize the utility of the applied volume of insecticide, in contrast to foliar sprays. Second, establishment of *B. hilaris* in the Central Coast has increased insecticide use, especially of pyrethroids. Prior to the arrival of *B. hilaris*, surveys had

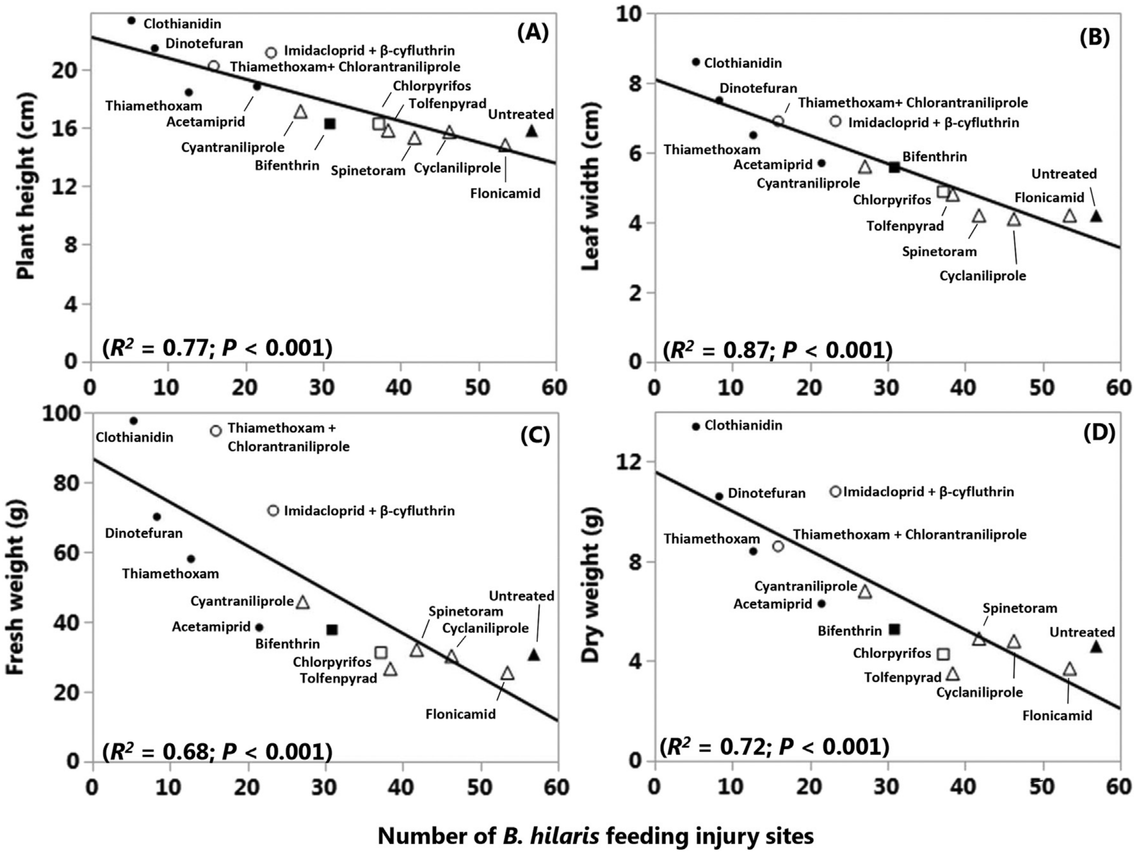

Fig. 4. The relationship between mean number of *B. hilaris* feeding sites and mean (a) plant height, (b) leaf width, (c) fresh, and (d) dry weight. The symbols: ● = neonicotinoid; ○ = combination product with neonicotinoid; ■ = pyrethroid; □ = organophosphate; Δ = reduced-risk insecticides; and ▲ = untreated in the first experiment in 2015.

found pyrethroids in suspended sediments in the lower reaches of major rivers of California's Central Coast (Anderson et al., 2003a, b; Anderson et al., 2006; Starner et al., 2006; Ng and Weston, 2009; Schmidt et al., 2010). Because *B. hilaris* poses a serious but unpredictable threat to newly planted *Brassica* crops, growers have responded with multiple foliar sprays or sprinkler chemigation of pyrethroid insecticides. Drenching transplants could reduce the number of applications to a single application before planting without compromising management of *B. hilaris*. This tactic could prevent economically significant damage during the window of vulnerability for *Brassica* crops when plants are young. Moreover, dinotefuran likely elicits antifeedant properties (Palumbo et al., 2015), which might be reducing the time spent feeding after initial probing by *B. hilaris*. Tray drench application with a follow-up foliar spray with a pyrethroid insecticide could therefore be a good, longer-term IPM strategy. Third, tray drench applications will likely reduce the off-site movement of applied insecticide. Currently, most insecticides are applied as foliar sprays or as sprinkler chemigations in the field, providing opportunities for loss of insecticides via run-off. Certain insecticides such as pyrethroids tend to bind to the soil organic matter (Harris et al., 1981), which can then be transported into waterways. Thus, insecticides drenched on the transplant plug are likely to be absorbed by the roots and not move off-site to the same degree. Finally, seedling tray drench of systemic insecticides is a cost-effective and efficient delivery method of insecticides. The insecticides are precisely placed with minimal loss. Some growers in the Central Coast are chemigating via sprinkler irrigation systems for *B. hilaris* management. Much of the insecticide is applied to the soil rather than the plants and may therefore not provide much activity for bagrada bug management. Seedling tray drench would provide a more efficient method of insecticide and would be compatible with current production methods.

Although application of systemic insecticides as a seedling tray drench would provide benefits for managing *B. hilaris*, there are a few challenges and issues that will need to be addressed if this tactic is to be employed. First, worker safety issues may arise when dealing with restricted insecticides. Depending on the type of restricted insecticide and re-entry period, the transplant date may need to account for the application date to avoid worker safety issues when handling the treated transplants and using the transplanting equipment. Also, the insecticide-contaminated trays will need to be washed properly (triple rinsed) if re-used for new transplants. The only product registered for seedling tray drench to date on *Brassica* crops is cyantraniliprole (Verimark). This product has a short re-entry period of 4 h and after this period, there is no requirement for personal protective equipment such as gloves while handling the treated trays or transplants, although these practices are encouraged (DuPont Crop Protection, 2014). Second, application as a tray drench is not yet a registered use for neonicotinoid insecticides. More research will be required to determine the breakdown pathways of systemic insecticides and if residues in the harvested heads are below established tolerances. Third, if neonicotinoids are consistently used as a tray drench, it could apply a strong selective pressure on *B. hilaris*, and would therefore create a high likelihood for development of resistance. *Bagrada hilaris* can complete a generation in 41 and < 21 d at 24 and 35 °C, respectively (Reed et al., 2013), and there is a strong possibility of overlapping generations as well. Before pursuing seedling tray drench application, pest managers should monitor the size of the local *B. hilaris*

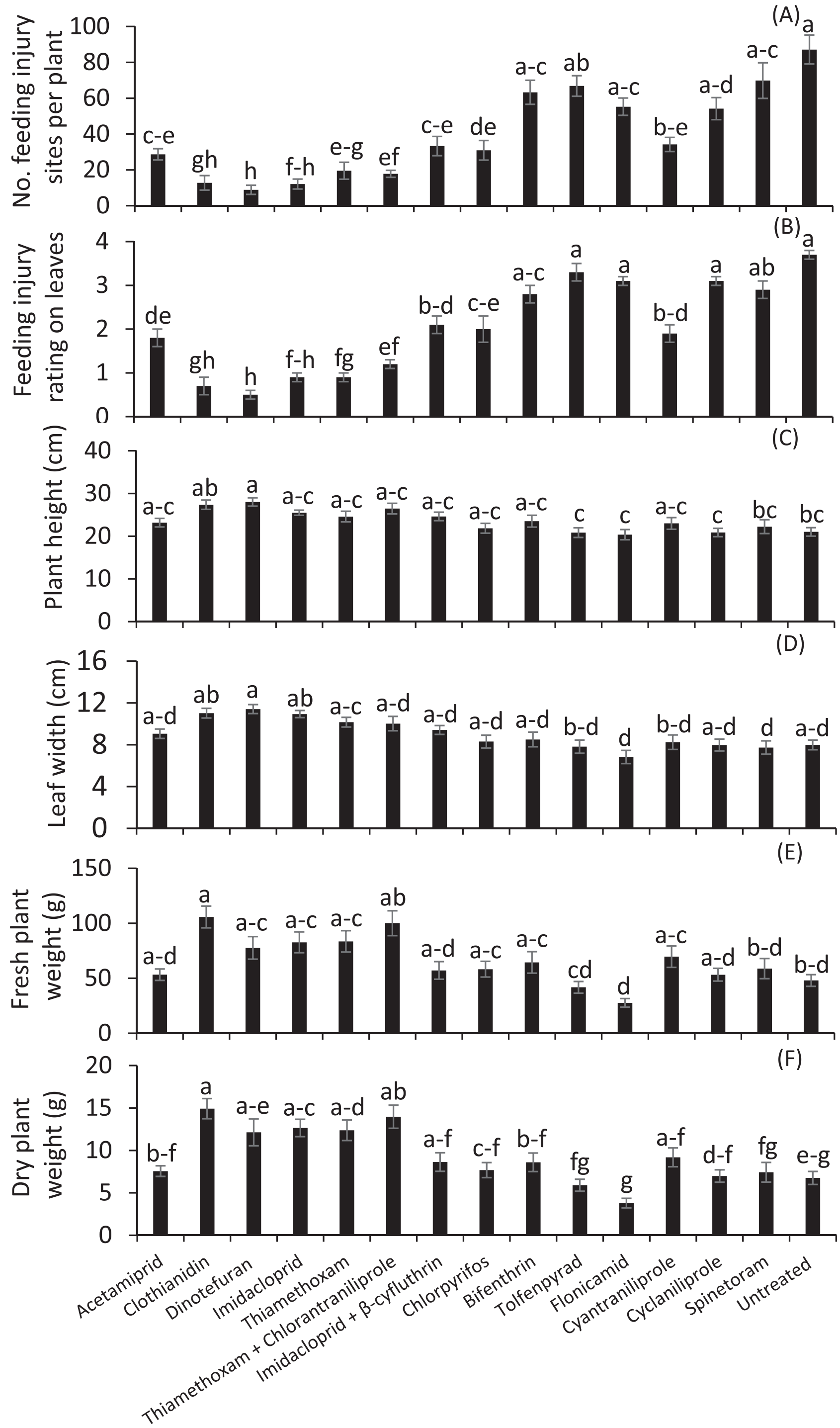

Fig. 5. Effect (mean ± SE) of tray drench application of insecticides on (A) *B. hilaris* feeding injury, (B) injury rating, (C) plant height, (D) leaf width, (E) fresh, and (F) dry weight per plant in the first 2015 field experiment. Bars with the same letters for each evaluation parameter are not significantly different ($P > 0.05$). Bars with the same letter are not significantly different ($P > 0.05$).

population in other fields and in patches of weed hosts outside of fields to identify the expected pest pressure and determine if the management tactic is warranted. This will help reduce the likelihood *B. hilaris* develop insecticide resistance and maintain the viability of these management tools.

Factors such as water volume, time of application, and insecticide properties for tray drenching may influence the efficacy of insecticides. The water volume used to apply the insecticides may be critical for placement of insecticides in the root zone of the plug. The quantity of solution should be low enough that it will not leach from the plug, which would waste insecticide and increase waste management problems. In this study, the ideal water volume was determined after a series of preliminary experiments to identify the maximum volume of insecticide solution that could be applied without leaching loss. The insecticide solution in this study was also injected using a syringe rather than sprayed with overhead

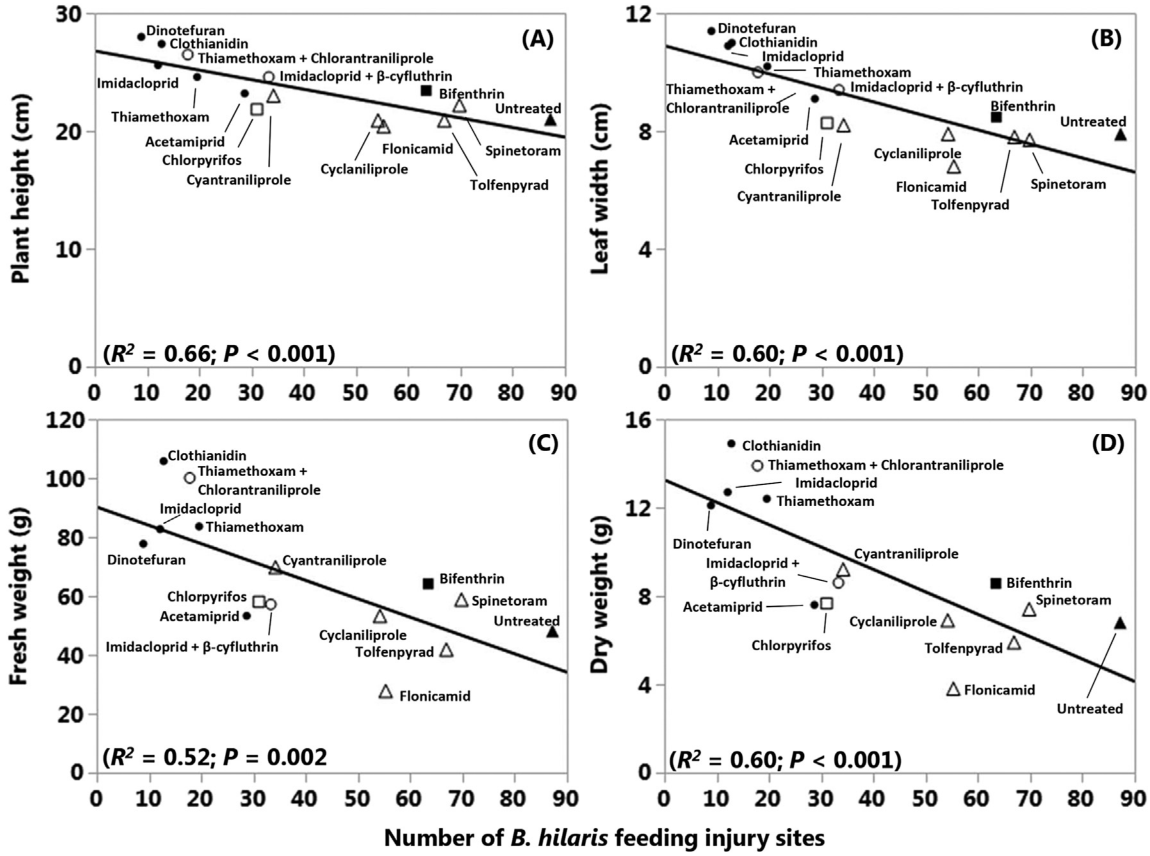

Fig. 6. The relationship between mean number of *B. hilaris* feeding sites and mean (a) plant height, (b) leaf width, (c) fresh, and (d) dry weight. The symbols: ● = neonicotinoid; ○ = combination product with neonicotinoid; ■ = pyrethroid; □ = organophosphate; Δ = reduced-risk insecticides; and ▲ = untreated in the second experiment in 2015.

sprinklers. In a commercial setting, the seedlings in the trays will likely be chemigated, and both the foliage and roots will be exposed to insecticides. The amount of insecticide solution received per seedling will depend on the set-up of the system, frequency, and pressure of the irrigation events. In this study, the interval between tray drench and transplanting was not uniform, although effective insecticides had activity within a time period of 0–3 wks between insecticide application and transplant in the field.

Typically, insecticide properties such as water solubility, and strength of binding with soil particles affect the speed of insecticide movement and their efficacy. Although dinotefuran is highly water soluble (39.8 g/L) and less likely to bind with the soil particles (Koc 30.0) than imidacloprid (514 mg/L; Koc 262.0) and clothianidin (259 mg/L; Koc 160.0) (Sur and Stork, 2003; Tomizawa and Casida, 2005; Ali and Caldwell, 2010), our results show that both dinotefuran and clothianidin can perform well against *B. hilaris* when applied as a seedling tray drench. This suggests that neonicotinoid insecticides move quickly from roots to leaves and affect feeding by *B. hilaris*. However, further research is needed to determine the optimal interval between insecticide application as a drench and transplanting to reduce *B. hilaris* feeding.

In conclusion, this study clearly shows that neonicotinoid insecticides were very effective against *B. hilaris* as a systemic application through a tray drench. Drenching transplant plugs with neonicotinoid insecticides protected plants from *B. hilaris* feeding beyond five weeks, which is the most vulnerable phase of crop development to *B. hilaris* feeding and injury. This suggests that if neonicotinoid insecticides are registered for this application method, it could reduce the need for multiple applications of foliar insecticides beginning at plant emergence. Cauliflower is 100% transplanted in the Central Coast of California while broccoli is ~95% transplanted in the southern half of the California, so tray drenches with neonicotinoids could provide a vital tool to help protect these crops from *B. hilaris*.

Acknowledgments

We appreciate the technical assistance provided by J. Martinez, C. Ramirez, C. Bettiga, E. Bejarano, J. Zarate, R. Ahedo, G. Reyes and G. Fletcher data collection. We thank two anonymous reviewers and the editor for the review of the earlier version of the manuscript. This research was supported by several agro-chemical companies, and 2014 California Department of Food and Agriculture Specialty Crop Block Grant (#SCB14059).

References

Ali, A.D., Caldwell, D., 2010. Royal palm bug *Xylastodoris luteolus* (Hemiptera-Thaumastocoridae) control with soil applied systemics. Fla. Entomol. 93, 294–297.

Anderson, B.S., Hunt, J.W., Phillips, B.M., Nicely, P.A., de Vlaming, V., Connor, V., Richard, N., Tjeerdema, R.S., 2003a. Integrated assessment of the impacts of agricultural drainwater in the Salinas River (California, USA). Environ. Pollut. 124, 523–532.

Anderson, B.S., Hunt, J.W., Phillips, B.M., Nicely, P.A., Gilbert, K.D., de Vlaming, V., Connor, V., Richard, N., Tjeerdema, R.S., 2003b. Ecotoxicologic impacts of agricultural drain water in the Salinas River, California, USA. Environ. Toxicol. Chem. 22, 2375–2384.

Anderson, B.S., Phillips, B.M., Hunt, J.W., Richard, N., Connor, V., Tjeerdema, R.S., 2006. Identifying primary stressors impacting macroinvertebrates in the Salinas River (California, USA): relative effects of pesticides and suspended particles. Environ. Pollut. 141, 402–408.

Cameron, R.A., Williams, C.J., Portillo, H.E., Marçon, P.C., Teixeira, L.A., 2015. Systemic application of chlorantraniliprole to cabbage transplants for control of foliar-

feeding lepidopteran pests. Crop Prot. 67, 13–19.
California Department of Pesticide Regulation, 2016. Pesticide Use Report 2010-2013 Monterey County. http://calpip.cdpr.ca.gov/main.cfm (accessed 02.02.16.).
CISR Center for Invasive Species Research, 2014. UC Riverside. http://cisr.ucr.edu/bagrada_bug.html (accessed 02.02.16.).
DuPont Crop Protection, 2014. DuPont Verimark® Insecticide Label (United States).
Harris, C.R., Chapman, R.A., Harris, C., 1981. Laboratory studies on the persistence and behavior in soil of four pyrethroid insecticides. Can. Entomol. 113, 685–694.
Huang, T., Reed, D.A., Perring, T.M., Palumbo, J.C., 2014. Feeding damage by *Bagrada hilaris* (Hemiptera: Pentatomidae) and impact on growth and chlorophyll content of Brassicaceous plant species. Arthropod Plant Interact. 8, 89–100.
Joseph, S.V., 2014. Effect of trap color on captures of bagrada bug, *Bagrada hilaris* (Hemiptera: Pentatomidae). J. Entomol. Sci. 49, 318–321.
Mahamood, R., Jones, W., Bajwa, B.E., Rashid, K., 2015. Egg parasitoids from Pakistan as a possible classical biological control agents of the invasive, *Bagrada hilaris* (Heteroptera: Pentatomidae). J. Entomol. Sci. 50, 147–149.
Monterey County Crop Report, 2014. Office of Agricultural Commissioner- Monterey County, California. http://www.co.monterey.ca.us/home/showdocument?id=1581 (accessed 02.02.16.).
Ng, C.M., Weston, D.P., 2009. Pyrethroid Pesticide Transport into Monterey Bay Though Riverine Suspended Solids. UC Water Resources Center Technical Completion Report, Project No.WR1018.
Palumbo, J.C., Natwick, E.T., 2010. The bagrada bug (Hemiptera: Pentatomidae): a new invasive pest of cole crops in Arizona and California. Online. Plant Health Prog. http://dx.doi.org/10.1094/PHP-2010-0621-01-BR.
Palumbo, J.C., 2011a. Control of *Bagrada hilaris* with foliar insecticides on broccoli, 2010. Arthropod Manag. Tests 36. http://dx.doi.org/10.4182/amt.2011.E8. E8 2.
Palumbo, J.C., 2011b. Evaluation of soil systemic insecticides for control of *Bagrada hilaris* on broccoli, 2010. Arthropod Manag. Tests 36. http://dx.doi.org/10.4182/amt.2011.E10. E10 2.
Palumbo, J.C., 2011c. Evaluation of experimental insecticides against *Bagrada hilaris* on broccoli, 2010. Arthropod Manag. Tests 36. http://dx.doi.org/10.4182/amt.2011.E9. E9 2.
Palumbo, J.C., Huang, T., Perring, T.M., Reed, D.A., Prabhaker, N., 2013. Evaluation of pyrethroid and neonicotinoid mixtures for control of *Bagrada hilaris* on broccoli, 2012. Arthropod Manag. Tests 38. http://dx.doi.org/10.4182/amt.2013.E61. E61.
Palumbo, J.C., Prabhaker, N., Reed, D.A., Perring, T.M., Castle, S.J., Huang, T., 2015. Susceptibility of *Bagrada hilaris* (Hemiptera: Pentatomidae) to insecticides in laboratory and greenhouse bioassays. J. Econ. Entomol. 108, 672–682.
Reed, D.A., Palumbo, J.C., Perring, T.M., May, C., 2013. *Bagrada hilaris* (Hemiptera: Pentatomidae), an invasive stink bug attacking cole crops in the southwestern United States. J. Integr. Pest Manag. 4 (3). http://dx.doi.org/10.1603/IPM13007.
SAS Institute, 2012. SAS Version 9.4. SAS Institute Inc., Cary, NC.
SAS Institute, 2015. JMP12.01. SAS Institute Inc., Cary, NC.
Schmidt, K., Lopez, S.G., Krone-Davis, P., 2010. Pesticides and Toxicity to *Hyalella azteca* in Sediments. Central Coast Region Conditional Waiver Cooperative Monitoring Program. Central Coast Water Quality Preservation, Inc.. Follow-up Monitoring Report.
Semtner, P.J., 2005. Aphid, flea beetle, and thrips control on flue-cured tobacco with transplant water and tray drench treatments, 2004. Arthropod Manag. Tests 30, F87.
Semtner, P.J., Srigiriraju, L., 2005. Flea beetle and aphid control on burley tobacco with transplant water and tray drench treatments. Arthropod Manag. Tests 30, F88.
Semtner, P.J., Wright, L., 2005. Flea beetle and aphid control on burley tobacco with transplant water and tray drench treatments. Arthropod Manag. Tests 30, F48.
Semtner, P.J., Wright, L., Jones, N., 2008. Systemic insecticides applied as tray drench and transplant water treatments for insect control on burley tobacco, 2007. Arthropod Manag. Tests 30, F47.
Starner, K., White, J., Spurlock, F., Kelley, K., 2006. Pyrethroid Insecticides in California Surface Waters and Bed Sediments: Concentrations and Estimated Toxicities. http://www.cdpr.ca.gov/docs/emon/surfwtr/swposters/starner_pyreth06.pdf (accessed 23.01.16.).
Sur, R., Stork, A., 2003. Uptake, translocation and metabolism of imidacloprid in plants. Bull. Insectology 56, 35–40.
Tomizawa, M., Casida, J.E., 2005. Neonicotinoid insecticide toxicology: mechanisms of selective action. Annu. Rev. Pharmacol. Toxicol. 45, 247–268.
U.S. Department of Agriculture, NASS, 2015. 2015 California Agricultural Statistics, Vegetable Summary. United States Department of Agriculture, National Agricultural Statistics Service, Pacific Region-California, Sacramento, CA. http://www.nass.usda.gov/Statistics_by_State/California/Publications/California_Ag_Statistics/Reports/2012cas-all.pdf (accessed 02.02.16.).