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Authors: Joseph, Shimat V., and Iudice, Shanna

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Evaluation of seedling tray drench of insecticides for cabbage maggot (Diptera: Anthomyiidae) management in broccoli and cauliflower

Shimat V. Joseph^{1,*}, and Shanna Iudice²

Abstract

The larval stages of cabbage maggot, *Delia radicum* (L.) (Diptera: Anthomyiidae), attack the roots of cruciferous crops and often cause severe economic damage. Although lethal insecticides are available to control *D. radicum*, efficacy can be improved by the placement of residues near the roots where the pest is actively feeding and causing injury. One such method is drenching seedlings with insecticide before transplanting, referred to as “tray drench.” The efficacy of insecticides, when applied as tray drench, is not thoroughly understood for transplants of broccoli and cauliflower. Thus, a series of seedling tray drench trials were conducted on transplants of these 2 vegetables using cyantraniliprole, chlorantraniliprole, clothianidin, bifenthrin, flupyradifurone, chlorpyrifos, and spinetoram in greenhouse and field settings. In the greenhouse trials, the severity of *D. radicum* feeding injury was significantly lower on broccoli and cauliflower transplants when drenched with clothianidin, bifenthrin, and cyantraniliprole compared with untreated controls. In broccoli field trials, incidence and severity of feeding injury was lower in seedlings drenched with cyantraniliprole and clothianidin, as well as a clothianidin spray at the base of seedlings, than the use of spinetoram, chlorpyrifos, flupyradifurone, and chlorantraniliprole. In a cauliflower field trial, tray drench application of cyantraniliprole significantly reduced the severity of *D. radicum* feeding injury in seedlings than untreated controls. Also, the fresh weight of plant shoots was significantly greater in cyantraniliprole tray drenched plants than untreated controls. In a different tray drench trial with cauliflower, the severity of cabbage maggot injury was significantly lower on plants that received cyantraniliprole at wide plant spacing of 30.5 cm (high dose) than narrow spacing of 17.8 cm (low dose) compared with untreated controls. The implications of these results on *D. radicum* management for transplanted cruciferous crops and impact on the environment are discussed.

Key Words: Brassicaceae; *Delia radicum*; cyantraniliprole; clothianidin; bifenthrin; central coast of California

Resumen

Los estadios de larvas del gusano de la col, *Delia radicum* (L.) (Diptera: Anthomyiidae), atacan las raíces de los cultivos crucíferos y a menudo causan graves daños económicos. Aunque hay insecticidas letales disponibles para controlar *D. radicum*, su eficacia puede mejorarse mediante la colocación de residuos cerca de las raíces donde la plaga se alimenta activamente y causa lesiones. Uno de estos métodos es empapar las plántulas con insecticida antes del trasplante, lo que se conoce como “empapado en bandeja.” La eficacia de los insecticidas, cuando se aplica como bandeja de empapado, no se conoce completamente para los trasplantes de brócoli y coliflor. Por lo tanto, se realizaron una serie de ensayos de empapado de bandejas de plántulas en trasplantes de estas 2 verduras usando ciantraniliprole, clorantraniliprole, clothianidin, bifenthrin, flupyradifurone, clorpirifos y spinetoram en el invernadero y campo. En los ensayos de invernadero, la gravedad de la lesión por alimentación de *D. radicum* fue significativamente menor en los trasplantes de brócoli y coliflor cuando se empapó con clothianidin, bifenthrin y ciantraniliprole en comparación con los controles no tratados. En los ensayos de campo de brócoli, la incidencia y la gravedad de las lesiones por alimentación fueron menores en las plántulas empapadas con ciantraniliprole y clothianidin, así como en un rocío de clothianidin en la base de las plántulas, que el uso de spinetoram, clorpirifos, flupyradifurona y clorantraniliprol. En un ensayo de campo de coliflor, la aplicación de ciantraniliprol en la bandeja redujo significativamente la gravedad de la lesión por alimentación de *D. radicum* en plántulas que los controles no tratados. Además, el peso fresco de los brotes de las plantas fue significativamente mayor en las plantas empapadas en bandejas de ciantraniliprole que en los controles no tratados. En un diferente ensayo de empapado en bandeja con coliflor, la gravedad de la lesión del gusano de la col fue significativamente menor en las plantas que recibieron ciantraniliprol con un espaciado amplio de la planta de 30.5 cm (dosis alta) que el espaciado estrecho de 17.8 cm (dosis baja) en comparación con los controles no tratados. Se discuten las implicaciones de estos resultados en el manejo de *D. radicum* para cultivos crucíferos trasplantados y el impacto en el medio ambiente.

Palabras Claves: Brassicaceae; *Delia radicum*; ciantraniliprol; clothianidina; bifentrina; costa central de California

The cabbage maggot, *Delia radicum* (L.) (Diptera: Anthomyiidae), is a serious insect pest of cruciferous crops worldwide (Coaker & Finch 1971) as well as California’s central coast (Johnsen & Gutierrez 1997; Joseph & Martinez 2014). Moreover, cruciferous crops are valued at about USD \$1 billion in 2016 in California, USA (USDA, NASS 2017). In the central coast

of California and coastal region south of San Jose, California, USA, the major crops grown are broccoli (*Brassica oleracea* var. *italica* Plenck), and cauliflower (*B. oleracea* L. var. *botrytis*) (both Brassicaceae). Broccoli and cauliflower are valued at \$410 and \$204 million USD where they are cultivated on 19,795.6 and 7,650.6 ha, respectively, in Monterey County,

¹University of Georgia, Department of Entomology, Griffin, Georgia 30223, USA; E-mail: svjoseph@uga.edu (S. V. J.)

²Vilmorin North America, Salinas, California 93901, USA; E-mail: shanna.iudice@vilmorin.com (S. I.)

*Corresponding author; E-mail: svjoseph@uga.edu

California, USA alone (Monterey County Crop Report 2017). *Delia radicum* oviposit in the soil surrounding the crown area of the crucifer plant and can lay up to 300 eggs under laboratory conditions (Finch 1974). Eggs hatch within 3 d where larvae feed on roots for up to 3 wk. Larvae undergo 3 instars until they pupate in the soil near the root system. All larval stages can destroy the root system of the plant. Feeding symptoms of *D. radicum* appear on the plant as yellowing and stunting, eventually resulting in plant death (Natwick 2009). Within 2 to 4 wk, adult flies emerge from puparium (Harris & Svec 1966). Females start laying eggs once they mate and find crucifer hosts.

Insecticides are used widely to manage *D. radicum* (Judge et al. 1968; Ester et al. 2003; Natwick 2009; Bažok et al. 2012; Joseph 2014; van Herk et al. 2017). Previously, in the central coast of California, organophosphate insecticides, (chlorpyrifos and diazinon) were used for *D. radicum* control. These insecticides also are used to control this pest in other *Brassica* growing regions (van Herk et al. 2017). Because toxic residues have been detected in local aquatic ecosystems, posing a risk to non-target organisms while impacting public health through contaminated water (Hunt et al. 2003), these insecticides are now stringently regulated (CEPA 2013). However, Joseph and Zarate (2015) determined that pyrethroids (e.g., zeta-cypermethrin), and neonicotinoids (e.g., clothianidin) and diamides (e.g., cyantraniliprole) were alternative options for *D. radicum* control. But precise placement strategies of these insecticides to maximize efficacy has not been developed.

In California's central coast, cauliflower is primarily grown as a transplanted crop. The seedlings of cauliflower are raised in nurseries for up to 6 wk before being transplanted in the field. Within a couple of wk after transplanting, *D. radicum* larvae have been found inside the soil of transplanted plugs (SVJ unpublished data). Infestation of *D. radicum* on young plants can cause serious feeding injury because the affected plants struggle to establish themselves and often appear severely stunted and eventually result in plant mortality. Thus, the application of insecticide sprays during early stages of plant development is critical and is recommended within a wk after transplanting. Because cauliflower fields are thoroughly irrigated for several wk following transplant to ensure seedling establishment, an insecticide application often is challenging, as the tractor mounted with spray equipment cannot easily move through wet fields. Broccoli is another major cruciferous crop in the central coast that is transplanted as well as directly sown onto prepared beds.

Drenching insecticide onto transplant plugs (referred as "seedling tray drench") in the nursery has been proven effective in reducing pest

infestation (Cameron et al. 2015; Joseph et al. 2016). However, this method has not yet been examined for *D. radicum* control in cruciferous crops, especially during the early stages of seedling development. Thus, the major objective of this study was to determine the efficacy of insecticides against *D. radicum* when delivered as a seedling tray drench to cruciferous transplant plugs before planting. To this end, greenhouse and field experiments were conducted with potential insecticides with systemic and non-systemic activity as identified in prior laboratory studies by Joseph and Zarate (2015). In addition, we evaluated the utility of a seedling tray drench for preventing damage by *D. radicum* for the protection of *Brassica* crops in order to increase the sustainability of the method for pest management practices.

Materials and Methods

GENERAL METHODS

Seedling tray drench experiments were conducted in greenhouse and agricultural fields in the central coast of California between Jun and Sep in the 2013, 2015, and 2016 growing seasons. For greenhouse experiments, *D. radicum* larvae, mostly second and third instars, were field-collected from roots of broccoli plants in Chualar, California, USA. These broccoli plants were not exposed to insecticides. In all field trials, treatment effects were evaluated after natural infestation of *D. radicum* populations.

For all experiments, the amount of insecticides per transplant tray was determined by number of plants per ha. Plant density can vary by number of rows, row width, and plant spacing as adopted by individual growers. In the central coast, broccoli is transplanted in 2 rows on a 101.8 cm wide bed with 17.8 cm between plants, which translates to 110,668 plants per ha. Cauliflower seedlings are primarily transplanted in a single row on 101.8 cm wide bed at 30.5 cm between plants, which estimates 32,278 plants per ha. Amount of insecticide per transplant plug was calculated after dividing the insecticide amount per ha by estimated plant density per ha. The amount of insecticide required per transplant tray was determined by number of transplant plugs per tray. For all greenhouse and field trials (1, 2, 4), the insecticide solution was injected using a syringe inserted into the soil media of each transplant plug (Fig. 1A). Each transplant plug received 2 mL of insecticide solution that was optimized after several iterations that prevented in-



Fig. 1. (A) Insecticides were delivered using a syringe and (B) inoculation of *Delia radicum* larvae into the base of transplant seedling in the greenhouse.

secticide leaching from the plug during or after application. Moisture content within each plug was less than full capacity before the insecticide solution was injected. For the field trial 3, the insecticide solution was sprayed directly onto the transplant trays using a RL Flo-Master 7.6 L sprayer (Root-Lowell Manufacturing Co., Lowell, Michigan, USA) in the greenhouse. The trays received insecticide solution for up to soil saturation. Treated transplants were planted within 24 h to the field. For basal spray treatments, insecticides were applied using a CO₂ powered, two-nozzle boom (R&D Sprayer, Opelousas, Louisiana, USA) to the crown area of the plant at 30 PSI. This area of the plant was targeted because *D. radicum* adults oviposit eggs on the soil closest to the plant stem. The water volume used for basal spray application was 934 L per ha. No adjuvant such as surfactant or penetrants was added to the spray tank.

GREENHOUSE TRIALS

In 2015, broccoli and cauliflower trays were obtained from a commercial greenhouse in King City, California. Broccoli 'Heritage' transplants were 5 wk old, whereas cauliflower 'Herman' transplants were 7 wk old. Transplant trays were transferred from the commercial greenhouse to the University of California Cooperative Extension Monterey County greenhouse in Salinas, California. Insecticides and their rates used in the trials are listed in Table 1. Tray drench treatments were: (1) clothianidin, (2) bifenthrin, (3) chlorpyrifos, (4) spinetoram, (5) cyantraniliprole, and (6) untreated check. Treatments were replicated 15 times in a completely randomized design. After injecting insecticides to transplant plugs, they were planted into 10.2 × 10.2 × 10 cm (L:W:D) green plastic pots using a potting mix substrate (Sun Gro, Sunshine Aggregate Plus Mix 4, Agawam, Massachusetts, USA). Ten field-collected, second and third-instar, *D. radicum* were released at the base of each pot (Fig. 1B). Field collected larvae were sub-sampled (10 larvae per 10 plants) and identified using the taxonomic key described in Brooks (1951) to confirm *D. radicum*. Plant roots were evaluated for severity of injury at 4 wk after inoculation using a scale system, where a root was scored 0 = not infested; 1 = infested or > 90% root hairs present;

2 = 80 to 90% root hairs present; 3 = 70 to 79% root hairs present; 4 = 60 to 69% root hairs present; 5 = 50 to 59% root hairs present or < 25% root destroyed; 6 = 40 to 49% root hairs present or 25 to 49% root destroyed; 7 = 30 to 39% root hairs present or 50 to 74% root destroyed; 8 = 20 to 29% root hairs present or > 75 to 89% root destroyed; or 9 = no root hairs present or > 90% root destroyed (Joseph 2016).

FIELD TRIALS

Trial 1

In 2013, trial 1 was conducted in a commercial, transplanted field of 'Heritage' broccoli in Gonzales, California. As part of grower practice, transplant plugs were planted at 17.8 cm spacing between plants in 2 rows. The field was transplanted on 5 Jul, and the trial was set up on same d and time. The insecticide and their rates used in this trial are listed in Table 1. The treatments were: (1) cyantraniliprole (tray drench), (2) chlorantraniliprole (transplant water), (3) cyantraniliprole (tray drench then basal spray), (4) chlorantraniliprole (tray drench), (5) chlorpyrifos (tray drench), (6) spinetoram (tray drench), (7) clothianidin (tray drench), (8) flupyradifurone (tray drench), and (9) untreated check. These treatments were replicated 4 times in a randomized complete block design. The experimental plot consisted of a 7.62 m × 101.6 cm (L:W) raised bed (about 15 cm tall). For tray drench treatments, insecticides were injected into the soil of broccoli seedling plugs as described in the previous section. These treated plugs were then immediately planted in 2 rows into the designated experimental plots. The insecticide treatments that involved tray drench and transplant water were treated on 5 Jun, and the seedlings were sprinkler irrigated immediately after transplanting. For transplant water treatments, 4 mL of insecticide solution was drenched into the 3 × 3 × 6 cm (L:W:D) holes on the bed, which were created before the plugs were planted. On 20 Jul (2 wk after transplant), seedlings in 1 treatment where cyantraniliprole (Verimark®) was applied as tray drench also received basal spray of a different formulation (Exirel®) of the same active ingredient, cyantraniliprole using CO₂ powered, 2 nozzle sprayer directed toward the crown area of the seedlings. The experimental plot area received

Table 1. Insecticides tested, rates and trials where they were used in during experiments in 2013-2016 in the Salinas Valley of California.

Brand name	% active ingredient	Active ingredient	Rate of formulation tested (L per ha)	Methods tested*				
				Greenhouse trial	Field trial 1	Field trial 2	Field trial 3	Field trial 4
Verimark SC ¹	18.66	Cyantraniliprole	0.986	TD	TD, TW	TD	—	TD ^a
Verimark SC ¹	18.66	Cyantraniliprole	0.913	—	—	—	TD	—
Exirel ¹	10.2	Cyantraniliprole	1.497	—	—	BS ^c	—	BS
Verimark + Exirel ¹	18.66 + 10.2	Cyantraniliprole	0.986 + 1.497	—	TD + BS ^b	—	—	—
Coragen ¹	18.4	Chlorantraniliprole	0.511	—	TD, TW	—	—	—
Radiant SC ²	11.7	Spinetoram	0.730	TD	TD	TD, BS ^c	—	—
Success ²	22.8	Spinosad	0.438	—	—	—	C	—
Belay EC ³	23.0	Clothianidin	0.438	—	—	BS ^c	—	—
Belay EC ³	23.0	Clothianidin	0.877	TD	TD	TD	—	—
Capture LFR ¹	17.15	Bifenthrin	0.497	TD	—	—	—	—
Lorsban Advanced E ²	40.2	Chlorpyrifos	0.175 /304.8 m row	TD	TD	—	—	—
Sivanto ⁴	17.09	Flupyradifurone	2.045	—	TD	—	—	—

*Trials 1 and 2 were conducted on broccoli, whereas trials 3 and 4 were conducted on cauliflower transplants. Thus, the seed rate for broccoli was 110,668 transplants per ha at 17.8 cm spacing between plants, and for cauliflower, the seed rate was 32,278 plants per ha at 30.5 cm spacing. The abbreviations TD = tray drench; TW = transplant water; BS = basal spray, and C = chemigation.

^aThe cauliflower spacing L (low) = 17.8 cm and H (high) = 30.5 cm spacing.

^bBasal spray was administered after 7 d of planting the transplant seedlings.

^cTwo applications were administered at 7 d interval.

¹FMC Corporation, Philadelphia, Pennsylvania, USA.

²Corteva Agriscience, Indianapolis, Indiana, USA.

³Valent USA, Walnut Creek, California, USA.

⁴Bayer CropScience LP, Research Triangle Park, North Carolina, USA.

a pre-emergence herbicide treatment, but no insecticide was applied for the duration of the trial. All plants were grown at routine grower's standard fertilizer regime.

For evaluation, plant root samples were collected from experimental plots. Roots were extracted using a shovel to reduce root damage. Ten root samples were randomly collected from each plot on 22 Jul (2 wk after transplant) and 7 Aug (5 wk after transplant). Root samples were temporarily stored in the refrigerator at 4 °C. *Delia radicum* larvae were extracted from roots using forceps and quantified. The number of roots injured as a result of *D. radicum* feeding and severity of this injury was determined based on the previously described scale system. Sub-samples of larvae were randomly extracted from these injured roots to determine they were *D. radicum*.

Trial 2

In 2013, the second field trial was set up in a commercial, direct-seeded 'Heritage' broccoli field in Gonzales, California. The field was sown with seeds to stand at 17.8 cm spacing as part of grower practice so that no further thinning operation was required. Treatments were aimed at understanding the utility of the seedling tray drench application compared with basal spray treatment. Seeds were sown in field beds on 1 Jul. To be consistent with seed type and plant age, the same broccoli seeds were obtained from the grower and planted within the wk (on 6 Jul) in transplant trays maintained in the University of California Cooperative Extension Monterey County greenhouse. Seedlings from transplant trays were later used for transplant tray drench treatment in the same trial.

On 24 Jul (3 wk after direct-seed placement in the field), insecticide treatments were applied to transplant plugs. Treatments were: (1) cyantranilipriole (tray drench), (2) cyantranilipriole (basal spray), (3) clothianidin (tray drench), (4) clothianidin (basal spray), (5) spinetoram (tray drench), (6) spinetoram (basal spray), and (7) untreated check. The plants in the untreated check treatment were all transplanted. The experimental plot for this trial was the same size as trial 1 with insecticides and their rates listed in Table 1. Four replicates of each treatment (either basal spray or transplant drench) were designated to experimental plots according to randomized complete block design. To transplant the seedlings into an already direct seeded field, broccoli seedlings in those previously assigned plots for tray drench treatments were uprooted and cleared from the plots before treated-broccoli seedlings were planted on the same plots. Tray drench applications was administered on 24 Jul, whereas basal spray was applied 2 d later. Insecticide solution was injected into transplant plugs as described in the previous section. Broccoli seedlings for the basal spray treatment plots were not removed. A second basal spray application was administered on 6 Aug to treatment pots that already received the first round of basal sprays. Basal sprays were applied at 3 and 5 wk after sowing the seeds because *D. radicum* infestation peaks about 4 wk after sowing seeds (Joseph & Martinez 2014). Plant roots were sampled on 30 Aug (4 wk after transplant) and 17 Sep (6 wk after transplant). Number of samples and evaluation were the same as described in trial 1.

Trial 3

In 2015, trial 3 was conducted on 'Casper' cauliflower in Salinas, California. Seeds were sown on 21 Jul at a commercial greenhouse in Gilroy, California, then moved to another commercial greenhouse in Salinas, California, a wk before transplant. The insecticides and their rates used in this trial are listed in Table 1. Treatments were: (1) untreated check without net, (2) untreated check with net, (3) cyantranilipriole (tray drench), and (4) spinosad (chemigation). On 3 Sep, the

transplant drench application of cyantranilipriole was administered on trays using a backpack sprayer (mentioned earlier) and were transplanted by hand on 4 Sep to field plots in two 101.6 cm (W) beds at 30.5 cm spacing. There were 2 untreated check treatments: uncaged plants (negative control) and caged plants (positive control). Mesh netting fabric, PRO70 weight, from AgroFabric (Seven Springs Farm Organic Farming and Gardening Supply Catalog, Check, Virginia, USA) was used to cage the plants. Plants that received insecticide treatments were not caged but exposed to natural *D. radicum* populations. Chemigation of spinosad was injected into the drip irrigation immediately after the transplant. These treatments were applied to dedicated beds. Because seedlings were covered using a net immediately after transplanting, normal sprinkler irrigation was not deployed, and instead beds were drip irrigated for 6 h after transplant. Transplanted plants were then irrigated 3 to 4 hours, 3 times per wk, as a grower's standard irrigation schedule for this geographic region. Plant root samples were collected from 5 random plots within each treatment bed. Each plot was 7.62 m long and served as replicates. On 13 Oct, mesh cages on untreated check plants were removed 1 mo prior to a predicted harvest date for those transplants. During this 4-wk interval, plants were exposed to natural populations of *D. radicum*, which resulted in fresh attacks by this pest. Ten root samples were randomly collected from each plot on 6 Nov (9 wk after transplant) for *D. radicum* injury evaluation. An additional 10 plants (shoots only) were sampled from each plot to determine fresh weight.

Trial 4

In 2016, trial 4 was conducted on 'Herman' cauliflower transplants in Gonzales, California. Insecticides were applied, and transplants planted on the plots on 18 Aug. Treatments were: (1) untreated check with cage, (2) untreated check without cage, (3) cyantranilipriole at a low rate (17.8 cm spacing), (4) cyantranilipriole at a high rate (30.5 cm spacing), and (5) cyantranilipriole applied as a basal spray (Table 1). The insecticide treatments were assigned to these plots, and they were replicated 4 times in a randomized complete block design. The experimental plot was 15.2 m × 101.6 cm (L:W) raised bed (about 15 cm tall), and a single row of cauliflower seedlings was planted. The basal spray was conducted using a CO₂ powered sprayer at 30 PSI mentioned earlier. Row cover (Agribon®, Berry Global Inc., Evansville, Indiana, USA) material was used to cage the plants. Twenty root samples were randomly collected from each plot on 1 Nov (6 wk after transplant) for evaluation. Number of roots injured from *D. radicum* feeding and severity of injury was determined based on the previously described scale system.

STATISTICAL ANALYSES

All data analyses were conducted using SAS software (SAS 2012). For the severity of *D. radicum* injury on roots of broccoli and cauliflower in the greenhouse, analysis of variance on the severity of injury was conducted with the PROC GLIMMIX procedure with log link function and distribution as negative binomial. Least squares means were separated by pairwise *t*-test ($P < 0.05$) after back-transformation and are reported in the tables. For field trials 1, 2, and 4, PROC GLIMMIX procedure failed to converge on multiple data sets. Severity data (number of *D. radicum* larvae, plant roots injured, and average severity scale) were averaged for replication and subsequently square root transformed after checking normality. Above parameter data were then individually subjected to analysis of variance (ANOVA) using the general linear model procedure in PROC GLM. Means were separated using Tukey's HSD test ($P < 0.05$). For field trial 3, ANOVA on average

severity of injury, number of larvae, and fresh weight data was conducted using the PROC GLIMMIX procedure with log link function and distribution as negative binomial. Least squares means from this trial were separated by pairwise *t*-tests ($P < 0.05$) after back-transformation and are reported in figures.

Results

GREENHOUSE TRIALS

In broccoli, all seedlings were injured by *D. radicum*. The severity of injury was significantly lower in clothianidin, bifenthrin, chlorpyrifos, and cyantraniliprole treatments than spinetoram and untreated check ($F = 9.3$; $df = 5,160$; $P < 0.001$; Fig. 2A). Severity of feeding injury was significantly lower in clothianidin than bifenthrin, chlorpyrifos, and cyantraniliprole. Similarly, the cyantraniliprole treatment had significantly lower levels of feeding injury than bifenthrin treatment. There was no significant difference in injury severity between bifenthrin and spinetoram treatments.

Similarly, in cauliflower, all the seedlings had *D. radicum* injury regardless of insecticide drench treatment. Among various treatments, the severity of feeding injury was significantly lower in clothianidin, bifenthrin, and cyantraniliprole treatments than chlorpyrifos, spinetoram, and untreated check treatments ($F = 5.2$; $df = 5,20$; $P < 0.001$; Fig. 2B). There was no significant difference in injury severity between clothianidin, bifenthrin, and cyantraniliprole.

FIELD TRIALS

Trial 1

At 2 wk after transplant, the tray drench application with cyantraniliprole, chlorpyrifos, spinetoram, and clothianidin treatments significantly reduced *D. radicum* feeding injury than the chlorantraniliprole

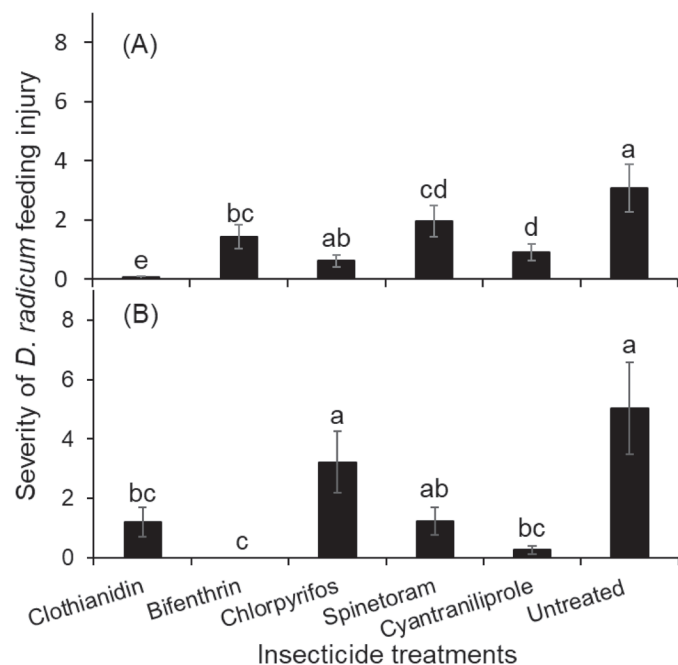


Fig. 2. Least squares means (\pm SE) of severity of *Delia radicum* feeding injury to 5 insecticides and an untreated control in (A) broccoli and (B) cauliflower in the greenhouse. Means with different letters are significantly different between treatments for each commodity according to Tukey's HSD test at $P < 0.05$.

tray drench application (Table 2). Moreover, injury in chlorantraniliprole treatment was not significantly different from the untreated checks. There was no significant difference in severity of injury between any of the treatments at this stage of plant development. At 5 wk after transplant, a number of plant roots injured from *D. radicum* feeding was not significantly different between treatments. But the severity of injury was significantly lower in cyantraniliprole tray drench treatment than the rest of the treatments including untreated check. However, cyantraniliprole applied as tray drench plus basal spray was not significantly different from the stand-alone treatment of cyantraniliprole. Transplant water application did not provide any significant reduction in *D. radicum* feeding on broccoli roots compared with untreated check.

Trial 2

At 4 wk after transplant, *D. radicum* feeding injury on plant roots was significantly lower in tray drench and basal spray treatments with clothianidin and tray drench with cyantraniliprole and spinetoram than untreated check (Table 3). However, 2 wk later, no significant difference in the incidence of feeding injury among any of the treatments (and untreated check) was observed.

Trial 3

At 9 wk after transplant, the severity of the feeding injury by *D. radicum* was significantly lower in cyantraniliprole tray drench and untreated check with caged plants than in untreated check without caged plants and spinosad chemigated treatments ($F = 9.3$; $df = 3,12$; $P = 0.002$; Fig. 3A). The number of *D. radicum* larvae extracted from infested roots was significantly lower in untreated check without caged plants and spinosad chemigated treatments than cyantraniliprole and untreated check with caged plants ($F = 19.8$; $df = 2,12$; $P < 0.001$; Fig. 3B). The fresh weight of plants was significantly lower in untreated check without caged plants and spinosad chemigated treatments than cyantraniliprole and untreated check with caged plants ($F = 10.2$; $df = 3,11$; $P = 0.002$; Fig. 3C). Cages were removed 4 wk before evaluation and roots in previously caged plants exhibited fresh attacks by *D. radicum*.

Trial 4

At 6 wk after transplant, the number of *D. radicum* larvae extracted from roots were significantly lower in untreated check with caged plants than the rest of the treatments ($F = 16.4$; $df = 4,12$; $P < 0.001$; Fig. 4A). The severity of feeding injury was significantly lower at the high application rate of cyantraniliprole compared with the rest of the treatments including untreated check without caged plants ($F = 97.7$; $df = 4,12$; $P < 0.001$; Fig. 4B).

Discussion

We sought to determine the efficacy of insecticides against *D. radicum* when applied to the soil of transplant seedling plugs as a drench before transplanting. The results suggest that drenching transplant plugs with cyantraniliprole and clothianidin reduced *D. radicum* feeding damage. The effect of cyantraniliprole was apparent when the infestation of *D. radicum* was relatively heavy than moderate to mild infestation scenarios when trial 3 was compared with trials 1 and 2. Previously, van Herk et al. (2016) observed inconsistent *D. radicum* control or reduction in damage from multiple trials when tray drench with cyantraniliprole was evaluated on rutabaga, *Brassica napobrassi-*

Table 2. Insecticides evaluated against *D. radicum* in field trial 1 when delivered as tray drench, transplant water, and basal spray to broccoli transplants in 2013.

Treatment	Method*	Mean (\pm SE)	Mean (\pm SE)	Mean (\pm SE no.)	Mean (\pm SE)
		no. roots injured	injury severity	roots injured	injury severity
		22 Jul (2 wk after transplant)		7 Aug (5 wk after transplant)	
Cyantraniliprole	TD	1.3 \pm 0.3 bcd	1.0 \pm 0.0 a	9.8 \pm 0.3 a	2.1 \pm 0.2 b
Cyantraniliprole	TW	3.8 \pm 1.4 abc	1.6 \pm 0.2 a	10.0 \pm 1.4 a	4.4 \pm 0.1 a
Cyantraniliprole	TD + BS	3.5 \pm 1.2 abc	1.1 \pm 0.1 a	10.0 \pm 1.2 a	3.0 \pm 0.3 ab
Chlorantraniliprole	TD	5.8 \pm 0.5 a	1.5 \pm 0.2 a	9.8 \pm 0.0 a	3.7 \pm 0.5 ab
Chlorantraniliprole	TW	4.3 \pm 0.6 ab	1.2 \pm 0.2 a	10.0 \pm 0.0 a	3.9 \pm 0.4 ab
Chlorpyrifos	TD	0.8 \pm 0.8 d	1.0 \pm 0.0 a	10.0 \pm 0.0 a	2.8 \pm 0.8 ab
Spinetoram	TD	1.5 \pm 0.6 cd	1.2 \pm 0.2 a	10.0 \pm 0.0 a	2.9 \pm 0.3 ab
Clothianidin	TD	1.0 \pm 0.4 cd	2.3 \pm 1.3 a	10.0 \pm 0.0 a	3.8 \pm 0.7 ab
Flupyradifurone	TD	2.0 \pm 0.7 bcd	1.6 \pm 0.3 a	10.0 \pm 0.0 a	4.3 \pm 0.1 a
Untreated check	–	3.0 \pm 0.8 abc	1.7 \pm 0.3 a	10.0 \pm 0.0 a	4.2 \pm 0.3 ab
<i>F</i> (df1, df2)		2.9 (9, 27)	0.9 (9, 20)	1.00 (9, 27)	3.2 (9, 27)
<i>P</i>		0.013	0.583	0.464	0.006

*Tray drench and transplant water applications received on 5 Jul 2013. Ten root samples were collected to assess a number of injured plants and severity of feeding injury. Basal spray received on 20 Jul. Means within columns followed by the same letters are not significantly different according to Tukey's HSD test at $P < 0.05$. The abbreviations TD = tray drench, TW = transplant water, BS = basal spray.

ca (L.) Mill. (Brassicaceae). The rutabaga is a root vegetable, so *D. radicum* feeding on this portion of the plant causes direct feeding damage and negative impact on marketability. On the other hand broccoli and cauliflower are not root vegetables; instead their unopened-flowering heads are harvested. *Delia radicum* damage on broccoli and cauliflower roots impact the yield either when plants do not produce sufficient heads or the development of the heads becomes delayed and asynchronous. The tolerance of these 2 Brassicaceae to *D. radicum* feeding damage can be much higher than rutabaga, where a mild infestation can cause severe economic loss to this latter commodity.

Reduction of *D. radicum* density and feeding damage observed with cyantraniliprole tray drench application has enormous implications on pest management of the vegetable industry in the central coast of California and elsewhere. Cyantraniliprole provides a reliable alternative to organophosphate insecticides, primarily chlorpyrifos and diazanon that are gradually phasing out of the traditional *D. radicum* control toolbox. Although recent studies have identified several effective alternative insecticides, such as pyrethroids and neonicotinoids for *D. radicum* control (Bažok et al. 2012; Joseph & Zarate 2015), *D. radicum* control under field conditions is not only dependent on the insecticidal activity. Several field efficacy trials suggest that *D. radicum*

control or reduction in feeding injury was not realized when effective insecticides were used by the traditional means of insecticide delivery such as basal and foliar spray (Joseph 2014; SVJ unpublished data). Placement of effective insecticides to the root zone region of the plant is critical, because the destructive stages of *D. radicum* inhabit the soil around the root system. In the current study, when those insecticides that exhibited excellent activity against *D. radicum* previous evaluated by Joseph & Zarate (2015) as tray drenches in greenhouse trials, effective control was still evident. Most of the broccoli and cauliflower planted in California's central coast are transplanted rather than directly seeded; the tray drench tactic is a good fit for this cultural practice. Tray drench of insecticides have been effective against other pests such as imidacloprid, thiamethoxam, or clothianidin on feeding damage produced by the tobacco flea beetle, *Epitrix hirtipennis* (Melsheimer) (Coleoptera: Chrysomelidae); green peach aphid density (*Myzus persicae* [Sulzer]; Hemiptera: Aphididae) on tobacco (*Nicotiana tabacum* L.; Solanaceae) (Semtner 2005; Semtner & Srigiriraju 2005; Semtner & Wright 2005; Semtner et al. 2008); chlorantraniliprole against cabbage looper, *Trichoplusia ni* (Hübner) (Lepidoptera: Noctuidae) on cabbage (Cameron et al. 2015); and neonicotinoids against painted bug, *Bagrada hilaris* (Burmeister) (Hemiptera: Pentatomidae) in broccoli (Joseph

Table 3. Insecticides evaluated against *D. radicum* in field trial 2 when delivered as tray drench and basal spray to broccoli transplants in 2013.

Treatment	Method*	Mean \pm SE no. roots injured per 10 plants	
		30 Aug (4 wk after transplant)	17 Sep (6 wk after transplant)
Cyantraniliprole	TD	0.5 \pm 0.5 b	3.0 \pm 1.4 a
Cyantraniliprole	BS	1.5 \pm 0.6 ab	3.3 \pm 1.3 a
Clothianidin	TD	0.8 \pm 0.3 b	7.0 \pm 1.5 a
Clothianidin	BS	0.3 \pm 0.3 b	4.0 \pm 0.4 a
Spinetoram	TD	1.0 \pm 0.0 b	4.3 \pm 1.8 a
Spinetoram	BS	1.8 \pm 1.1 ab	4.8 \pm 1.0 a
Untreated check	–	3.5 \pm 0.5 a	7.0 \pm 1.0 a
<i>F</i> (df1, df2)		3.1 (6, 14)	0.69 (6, 11)
<i>P</i>		0.036	0.741

*Broccoli seeds were sown in field beds and greenhouse trays on 1 and 6 Jul 2013, respectively. Tray drench application was conducted on 24 Jul 2013. Basal spray was applied on 26 Jul and 6 Aug 2013. Means within columns followed by the same letters are not significantly different according to Tukey's HSD test at $P < 0.05$. The abbreviations TD = tray drench, and BS = basal spray.

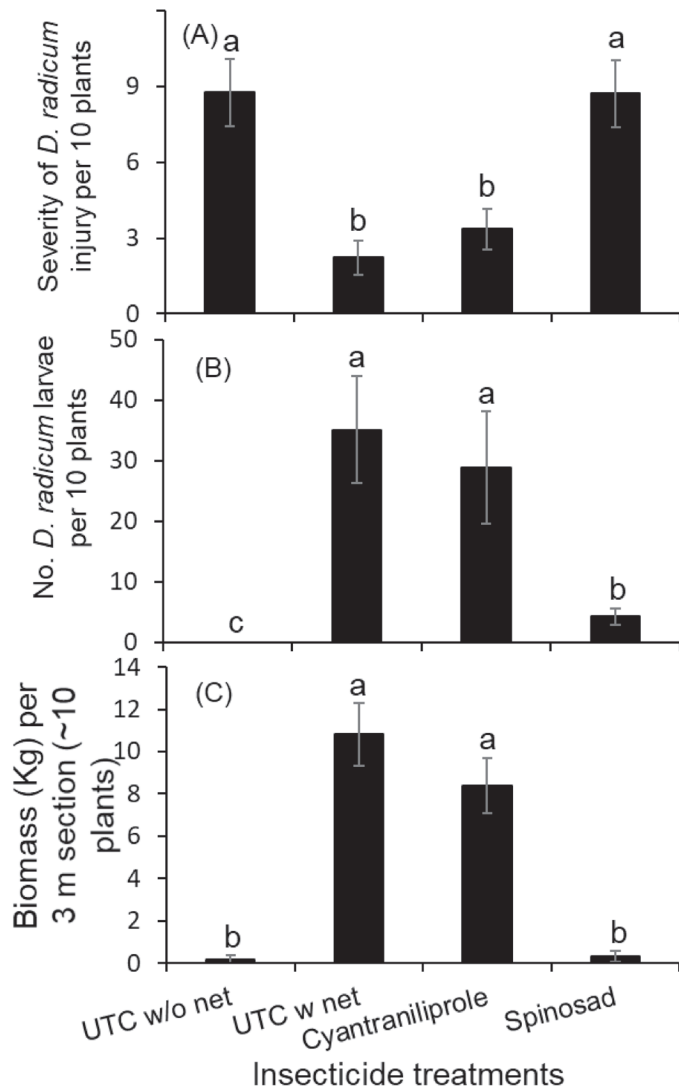


Fig. 3. Least squares means (\pm SE) of (A) severity of *Delia radicum* feeding injury, (B) *Delia radicum* larvae, and (C) fresh weight of 10 cauliflower plants in the field trial 3 conducted in 2015. Means with different letters are significantly different between treatments for each parameter according to Tukey's HSD test at $P < 0.05$.

et al. 2016). Clearly, our study shows that insecticide delivered as seedling tray drench can effectively reduce the severity of *D. radicum* infestation and allows the plant to develop normally, especially under heavy infestation scenarios as evident in trial 3 (Fig. 3).

In addition, there are some other attributes that favor adoption of cyantraniliprole for *D. radicum* control. First, this insecticide has a 4 h, short re-entry period that tremendously benefits field workers, and greenhouse personnel who directly handle this insecticide. Second, the personal protection equipment requirements for cyantraniliprole is minimal because it only requires a long-sleeved shirt, and pants and shoes. Once the tray drench application has been administered in the greenhouse, it can be transplanted rather quickly with reduced unintended insecticide exposure. Field workers transplanting cyantraniliprole-treated plugs often handle them while planting, and extensive personal protection equipment requirements such as wearing coverall suits can discourage field workers from normal routine operations in the field. Finally, in California's central coast, insecticides usually are applied as a foliar or basal spray immediately after planting, and these

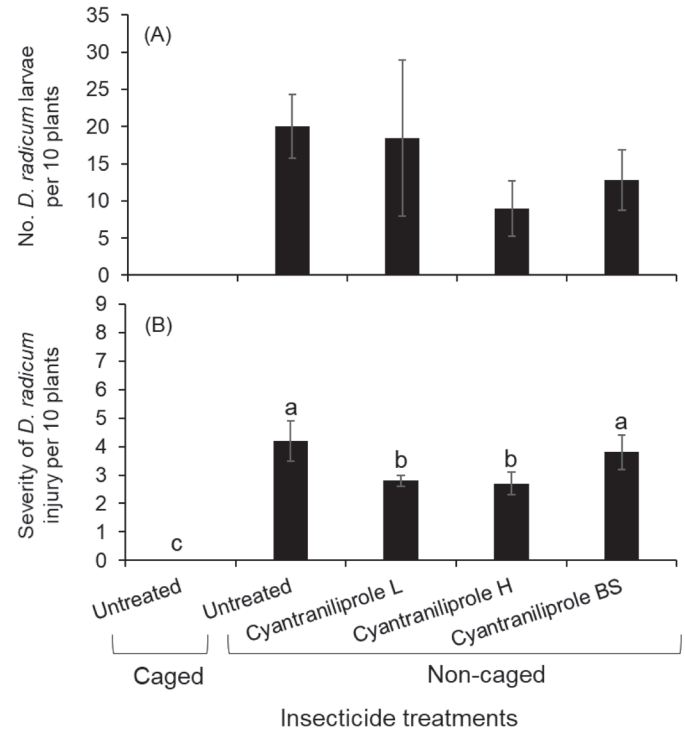


Fig. 4. Mean (\pm SE) of (A) *Delia radicum* larvae and (B) severity of *Delia radicum* feeding injury of 20 cauliflower plants in the field trial 4 conducted in 2016. Means with different letters are significantly different between treatments for each parameter according to Tukey's HSD test at $P < 0.05$. Where no differences were observed, no letters are given.

applications often are impossible to administer at the recommended time frame because the fields are heavily irrigated as soon as the transplanting is completed. Moreover, spray equipment, usually mounted on a tractor, is heavy and application is considerably challenging to accomplish on wet fields. The tray drench of an effective insecticide opens up a new pragmatic pest management strategy replacing traditional foliar spray application.

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