

Residual and Systemic Efficacy of Chlorantraniliprole and Flubendiamide Against Corn Earworm (Lepidoptera: Noctuidae) in Soybean

A. Adams,¹ J. Gore,^{2,3} A. Catchot,¹ F. Musser,¹ D. Cook,² N. Krishnan,¹ and T. Irby⁴

¹Department of Biochemistry, Molecular Biology, Entomology and Plant Pathology, Mississippi State University, MS 39762 (caa109@msstate.edu; acatchot@entomology.msstate.edu; Fmusser@entomology.msstate.edu; nkrishnan@entomology.msstate.edu),

²Delta Research and Extension Center (DREC), Mississippi State University, Stoneville, MS 38776 (jgore@drec.msstate.edu; dcook@drec.masstate.edu), ³Corresponding author, e-mail: jgore@drec.msstate.edu, and ⁴Department of Plant and Soil Sciences, Mississippi State University, MS 39762 (tirby@pss.msstate.edu)

Received 15 April 2016; Accepted 2 September 2016

Abstract

Experiments were conducted in Mississippi from 2013 to 2015 to determine the systemic and residual efficacy of chlorantraniliprole and flubendiamide against corn earworm, *Helicoverpa zea* (Boddie), in soybean. Both insecticides were applied at V4 and R3. Ten leaves that were present at the time of application and 10 newly emerged leaves that were not present at the time of application were collected to measure residual and systemic efficacy, respectively. Ten pods were removed from each plot at R5.5. For all assays, corn earworm larvae were placed on plant material. Chlorantraniliprole appeared to provide systemic control of *H. zea*, but was dependent on soybean growth stage at the time of application. In the V4 experiment, chlorantraniliprole resulted in greater mortality than the control on new leaves at 7 d after treatment, but not at 14 d. In the R3 experiment, chlorantraniliprole resulted in greater than 90% mortality on new leaves at all evaluation intervals. Mortality of *H. zea* on new leaves was <17% for flubendiamide and was not different than the control. Both insecticides resulted in significant mortality of *H. zea* on leaves that were present at the time of application for at least 31 d after application. Chlorantraniliprole resulted in greater mortality than flubendiamide at 24 and 31 d. Neither insecticide resulted in mortality of *H. zea* feeding on reproductive structures. These results suggest that chlorantraniliprole moves to new vegetative structures but not to reproductive structures of soybean, and that flubendiamide does not move systemically.

Key words: corn earworm, chlorantraniliprole, soybean, flubendiamide

Soybean, *Glycine max* (L.) Merr., is the most valuable row crop commodity in the midsouthern region of the United States in terms of planted area and total commodity value. In 2014, soybean accounted for nearly 6 million planted hectares valued at over US\$7 billion in the midsouth states of Mississippi, Arkansas, Missouri, Louisiana, and Tennessee (<https://quickstats.nass.usda.gov/#222BF8F2-C461-3830-B4D5-9CECBBBD6F202>, Accessed Aug 21, 2016). Corn earworm, *Helicoverpa zea* (Boddie), is the most costly insect pest of soybean production in the midsouthern and southeastern United States in terms of lost yield and control costs (Musser et al. 2015). During 2014, damage caused by corn earworm larvae resulted in over US\$61 million economic cost in terms of lost yield and control costs in midsouth soybean production (Musser et al. 2015).

Corn earworm is a widely distributed polyphagous pest of numerous cultivated crops (Fitt 1989, Swenson et al. 2013). Corn, *Zea mays* (L.), is preferred for oviposition compared to other plant hosts (Johnson et al. 1975). When corn senesces, corn earworm adults

often begin to oviposit in soybean and can cause considerable economic damage (Johnson et al. 1975, Kogan 1979, Swenson et al. 2013, Musser et al. 2015). Infestations generally occur during the R1 to R3 growth stages (Fehr and Caviness 1977) in open canopied fields (Johnson et al. 1975, Swenson et al. 2013). Larval feeding may result in defoliation, delayed pod fill, and decreased seed number per pod, ultimately resulting in yield loss (Eckel et al. 1992a). Severity of damage from larval feeding depends on four factors: larval age, plant growth stage, timing of damage, and the ability of the plant to compensate for feeding (Swenson et al. 2013). All larval instars prefer to feed on blooms over leaves or pods (Mueller and Engroff 1980). An individual larva can consume more pods during the early reproductive growth stages of soybean because more small pods and immature seeds are present compared to later growth stages when individual pods are more developed and larger (McWilliams 1983).

Soybean can compensate for feeding injury incurred during early reproductive growth stages (R1–R3; Eckel et al. 1992b). However,

the ability of soybean to compensate for larval damage is dependent on environmental conditions, and damage during the early growth stages may result in delayed pod set (Eckel et al. 1992b). The ability of a soybean plant to compensate in early growth stages is important, but the possible delay in maturity may be problematic for soybean not planted during the optimal planting window. Damage incurred during later growth stages (R4–R5) limits time for compensation, and yield losses are more directly related to pod removal and seed consumption (Thomas et al. 1974, McPherson and Moss 1989).

Foliar applications of insecticides are important for the management of lepidopteran insect pests in the southern United States. Widespread foliar applications of insecticides in multiple crops has led to resistance development and inconsistent control with most chemical classes, including chlorinated hydrocarbons, organophosphates, carbamates, pyrethroids, and benzoylphenylureas (Sparks 1981, Brown et al. 1998, Temple et al. 2006, Jacobson et al. 2009, Lai and Su 2011). The diamide class of insecticides was introduced in 2008 (U.S. Environmental Protection Agency [EPA] 2008). It has a novel mode of action and is classified as a ryanodine receptor modulator (MoA Group 28; Insecticide Resistance Action Committee [IRAC] 2015). Two representatives from this insecticide class are chlorantraniliprole, (Prevathon, DuPont Crop Protection, Newark, DE), an anthranilic diamide, and flubendiamide, (Belt, Bayer CropScience, Raleigh, NC), a phthalic acid diamide (Lahm et al. 2009). Since their introduction, these two active ingredients have been important in the management of lepidopteran insect pests in multiple crops.

Chlorantraniliprole is xylem-mobile, allowing the insecticide to move upwards throughout the plant (Lahm et al. 2007). It is often applied to the soil as seed treatments, soil drenches, or through chemigation in multiple crops such as brassicas and other vegetables (Lahm et al. 2007, Kuhar et al. 2008, Palumbo 2008, Ghidui et al. 2009, Schuster et al. 2009, Cameron et al. 2015). With those applications, the insecticide is taken up by the roots and provides effective control of lepidopteran and other insect pests on the foliage. It is currently registered in the United States for use as an in-furrow spray at planting, transplant water treatment, hill drench at planting, surface band at planting, soil shank injection at planting, through drip irrigation, and by foliar application (Lahm et al. 2007, Cameron et al. 2015). Chlorantraniliprole is also effective as a seed treatment in managing *Lissorhoptus oryzophilus* (Kuschel) infestations in rice, *Oryza sativa* (L.) (Adams et al. 2016). However, chlorantraniliprole has not been confirmed to move to other plant structures when applied as a foliar application. In contrast, flubendiamide is only labeled for foliar applications and is not known to move systemically to other plant structures. Similar to chlorantraniliprole, flubendiamide has greater residual efficacy compared to other insecticides (Hardke et al. 2011). Therefore, the objectives of this study were to determine the systemic and residual efficacy of chlorantraniliprole and flubendiamide against corn earworm through laboratory bioassays when applied as a foliar application to soybean.

Materials and Methods

Multiple experiments were conducted at the R.R. Foil Plant and Soil Sciences Research Center in Starkville, MS, and the Delta Research and Extension Center in Stoneville, MS, during 2013, 2014, and 2015 to evaluate the residual and systemic efficacy of chlorantraniliprole and flubendiamide in soybean. Efficacy was evaluated in lab

bioassays by infesting larvae from lab colonies on to leaf tissue collected from field plots sprayed at V4 and R3 growth stages. A greenhouse experiment was conducted during the fall of 2014 and spring of 2015 to evaluate the efficacy of chlorantraniliprole when applied to individual plant structures.

Insect Rearing

The laboratory colonies of corn earworm used for evaluation in these experiments were established using larvae obtained from non-Bt corn through multiple collections in Starkville, MS, and Stoneville, MS, during 2013, 2014, and 2015. Each collection consisted of at least 300 third instars placed in 36-ml Solo cups (Bio-Serv, Frenchtown, NJ) containing Stonefly *Heliothis* Diet (Product No. 38-0600, Ward's Natural Science, Rochester, NY) with matching lids. At pupation, ~50 pupae were placed in 3.79-liter cardboard containers with matching lids, and the generations since initial field collection were monitored and recorded. Rearing procedures and conditions were similar to those described in Von Kanel et al. (2016). Collected egg sheets from each colony were kept in 3.79-liter Ziploc (S.C. Johnson & Johnson, Inc., Racine, WI) bags until larvae hatched for use in bioassays. All insect assays were conducted at the Mississippi State University insect rearing facility maintained at 25°C, 80% relative humidity (RH), and a photoperiod of 16:8 (L:D) h using larvae from the *H. zea* colony that were the progeny of the first or second generations since initial field collection.

Field Plot Details

Two experiments were conducted to determine the residual and systemic efficacy of chlorantraniliprole and flubendiamide in vegetative plant structures applied as a foliar application to soybean. The experiments were conducted using an indeterminate maturity group (MG) IV soybean variety (Asgrow 4632, Monsanto Company, St. Louis, MO). Plots were 4 rows by 15.24 m. Soybean were planted at 296,532 seeds/ha into raised conventional tilled beds with a 0.97-m row spacing in Starkville, MS, and a 1.02-m row spacing in Stoneville, MS. Seed were treated with a commercial premix of imidacloprid, pyraclostrobin, metalaxyl, and fluxapyroxad (Acceleron, Monsanto Company, St. Louis, MO) to minimize the impact of early season insect pests and seedling diseases. Weed and disease pests were managed according to Mississippi State University Extension Service recommendations. Experiments were separated according to soybean growth stage at the time of application. All plots were treated with a high-clearance multi-boom sprayer (Mudmaster 4WD Multi-Purpose Sprayer, Bowman Manufacturing, Newport, AR) equipped with a compressed air system, and calibrated to deliver 94 liter/ha at 400 kPa through TX-6 ConeJet VisiFlo Hollow Cone Spray Tip nozzles (two nozzles per row; TeeJet Technologies, Glendale Heights, IL).

Leaf Assays for V4 and R3 Applications

During 2013, an experiment was conducted in Starkville, MS, and in 2014 and 2015 in Stoneville, MS, to determine the residual and systemic efficacy of chlorantraniliprole and flubendiamide applied as a foliar application to R3 stage (Fehr and Caviness 1977) soybean. The experiment was conducted as a randomized complete block design with four replications in 2013 and 2014, and six replications in 2015. Treatments consisted of chlorantraniliprole applied at 47.25 g ai/ha, and flubendiamide applied at 70.06 g ai/ha compared with an untreated control. Plants within each plot were flagged at the uppermost node at the time of application to differentiate between treated and nontreated foliage at each of the

evaluation timings. Ten uppermost newly emerged trifoliates were removed from above the flagging at 10, 17, 24, and 31 d after treatment to determine systemic efficacy. Ten leaves from the treated portion of the plants were also removed from within two nodes below the flagging at 10, 17, 24, and 31 d after treatment to determine residual efficacy. All leaves were transported to the laboratory for testing as detailed below. Leaf assays for this experiment were terminated when vegetative growth ceased.

During 2014 and 2015, an experiment was conducted in Starkville, MS, to determine the systemic efficacy of chlorantraniliprole applied as a foliar application to V4 stage (Fehr and Caviness 1977) soybean. The experiment was conducted as a randomized complete block design with four replications and two treatments. Treatments consisted of chlorantraniliprole applied at 47.25 g ai/ha compared with an untreated control. Ten uppermost newly emerged trifoliates were removed at 7 and 14 d after treatment. The newly emerged leaves were removed from the uppermost node above the flagging to ensure that they were not present at the time of application to determine systemic efficacy. They were then transported to the laboratory for testing as detailed below.

Collected leaf material from the V4 and R3 studies were placed in 0.95-liter Ziploc (S.C. Johnson & Johnson, Inc.) bags labeled by plot and transported to the Mississippi State University insect rearing facility. All plant material was transported in a cooler with cold packs to minimize desiccation from heat. In the laboratory, entire newly emerged trifoliates with ~2.54-cm-long leaflets from the upper canopy and 5 cm leaf disks from the lower canopy were placed in 100- by 15-mm petri dishes (Product No. 431760, Fisher Scientific, Norcross, GA), labeled by plot, containing a 1% water agar (Product No. 7060, Frontier Agricultural Sciences, Newark, DE) solution to prevent desiccation. Two corn earworm neonates obtained from the colony described above were placed onto the surface of each leaf. After infestation, a lid was placed onto the top of every petri dish and sealed with a single piece of 1.27 by 10 cm Parafilm M All-Purpose Laboratory Film (Product No. 13-374-12, Fisher Scientific, Norcross, GA). Infested petri dishes were then placed in a rearing chamber maintained at 25°C, 80% RH, and a photoperiod of 16:8 (L:D) h. Mortality was rated after 3 d of initial exposure. Mortality was defined as larvae that failed to respond to a probe or to right themselves after being flipped onto their dorsal surface.

Mortality data were analyzed with analysis of variance (PROC GLIMMIX, SAS Institute Inc. 2012). In the V4 experiment, insecticide treatment and days after treatment were considered fixed effects in the model. Year and replication nested in year were random terms in the model. In the R3 experiment, treatment, days after treatment, and leaf position were considered fixed effects in the model. Year, replication nested in year, and replication by leaf position nested in year were random terms in the model. Degrees of freedom were calculated using the Kenward–Roger method. Means were estimated using the LSMEANS statement and adjusted according to the Tukey's HSD test and considered significant at $\alpha = 0.05$.

Pod and Seed Assays for the R3 Application

In 2014 and 2015, additional bioassays were conducted within plots treated at the R3 growth stage. This experiment was conducted to determine if chlorantraniliprole or flubendiamide translocated to the reproductive structures of soybean. Ten soybean pods were removed from the top 1/3 of plants in treated and untreated plots at the R5.5 growth stage (28 d after treatment; Fehr and Caviness 1977). This portion of the plant was chosen because greater than

90% of *H. zea* oviposition occurs in the top 1/3 of the soybean canopy (Adams 2015, Dill 2015).

Collected pods were handled as previously described for leaves. In the laboratory, pods were separated into seed and pod hulls. To prevent mold growth that occurred in preliminary studies, the seed and pod hulls were surface sterilized with a 10% sodium hypochlorite (Clorox Regular-Bleach¹, The Clorox Company, Oakland, CA) solution by soaking for 5 min followed by rinsing with water through a 100-mesh sieve for 5 min. Seeds and pod hulls were then allowed to air dry on a paper towel (Brawny, Georgia-Pacific Consumer Products, Atlanta, GA). Seeds were placed in 36-ml Solo cups containing a 1% water agar solution to prevent desiccation. One entire pod hull was placed in petri dishes according to the methodology previously described for leaves. In total, 30 seeds and both sides of the pod hull were used per plot per treatment. To reduce control mortality and more closely simulate what occurs in the field, larvae were reared on untreated diet for 5 d prior to infestation. One second-instar corn earworm was placed onto each seed totaling 30 larvae per treatment per replication. For pod hulls, one corn earworm larva was placed on the inside wall of the seed hull totaling 20 larvae per treatment per replication. After infestation, the cap was placed onto the top of every cup and petri dish lids were sealed as previously described. Infested seed and pod hulls were placed in a rearing chamber maintained at 25°C, 80% RH, and a photoperiod of 16:8 (L:D) h. Mortality was rated 3 d after exposure and determined as previously described.

Mortality data were analyzed as previously described except for the fixed and random effects. In the model, insecticide treatment and reproductive structure were considered fixed effects. Year, replication nested in year, and replication by location nested in year were random terms in the model.

Greenhouse Study

An experiment was conducted to determine the route of absorption and translocation of chlorantraniliprole in soybean. This experiment was conducted in a greenhouse located at the Clay Lyle Entomology Building in Mississippi State, MS, in September 2014, March 2015, and May 2015. Three soybean seed were planted into a 3.79-liter black blow molded nursery container (Product No: C408, Nursery Supplies, Kissimmee, FL) containing a 80/20 mixture of PRO-MIX ALL PURPOSE GROWING MIX (Premier Tech Horticulture Office USA, Quakertown, PA) and soil that had not been exposed to insecticides. Each pot was fertilized with Miracle-Gro Shake 'N Feed All Purpose Continuous Release Plant Food (The Scotts Miracle-Gro Company, Marysville, OH) at planting. When plants reached V2 they were thinned to one plant per pot.

The experiment was initiated at the V4 growth stage. The experimental design was a randomized complete block design with five treatments and three replications. Treatments consisted of applying chlorantraniliprole as a 2.5% solution independently to the whole main stem, each trifoliolate, every petiole, or entire plant with a number six paint brush compared to an untreated control. Each treatment consisted of 10 plants per replication totaling 150 plants per test. Plants were watered every other day to maintain soil moisture. Special care was taken not to get water onto any plant parts when watering. After 7 d, the uppermost newly emerged trifoliolate was removed from every plant and placed in 0.95-liter Ziploc bags according to treatment and replication. Leaves were transported to the laboratory where they were tested. Testing procedures were identical to those described above in the leaf assay methodology.

Mortality data were analyzed as previously described except for the fixed and random effects. In the model, treatment location was considered a fixed effect. Replication was the random term in the model.

Results

Leaf Assays at the V4 and R3 Applications

Chlorantraniliprole moved to newly emerged leaves when applied as a foliar application to soybean at the V4 growth stage. A significant interaction between treatment and days after treatment was observed for corn earworm mortality ($F = 22.72$; $df = 1, 28$; $P < 0.01$). Chlorantraniliprole resulted in greater mortality of corn earworm compared with the untreated control at 7 d after treatment (Fig. 1). At 14 d after treatment, no significant difference in mortality of corn earworm was observed between chlorantraniliprole and the untreated control.

A significant interaction between treatment, days after treatment, and leaf position was observed for corn earworm mortality on leaves at the R3 application timing ($F = 3.69$; $df = 9, 222.2$; $P < 0.01$). Chlorantraniliprole resulted in 89–96% mortality of corn earworm infested on leaves not present at time of application (upper

canopy) across all evaluation times (Table 1). In contrast, flubendiamide did not move to new vegetative growth and resulted in similar levels of mortality to the untreated growth and resulted in similar levels of mortality to the untreated control in upper leaves. Mortality of corn earworm on leaves present at time of application (lower canopy) was similar between chlorantraniliprole and flubendiamide at 10 and 17 d after treatment (Table 1). Both insecticides resulted in significantly greater mortality of corn earworm than the untreated control on lower leaves at 10 and 17 d after treatment. At 24 and 31 d after treatment, chlorantraniliprole resulted in significantly greater mortality on lower leaves than flubendiamide, providing 19 and 30%, respectively, greater residual mortality of corn earworm compared with flubendiamide, and 90 and 86%, respectively, greater residual mortality compared to the untreated control (Table 1). The residual mortality of chlorantraniliprole at 24 and 31 d after treatment was not significantly different than chlorantraniliprole at 10 and 17 d after treatment (Table 1). Flubendiamide resulted in significantly greater mortality of corn earworm compared with the untreated control on lower leaves throughout the experiment. However, mortality of corn earworm on lower leaves treated with flubendiamide declined significantly at 24 and 31 d after treatment, providing ~30% less mortality compared with chlorantraniliprole at 31 d and ~15% less mortality compared with flubendiamide at 24 d after treatment (Table 1).

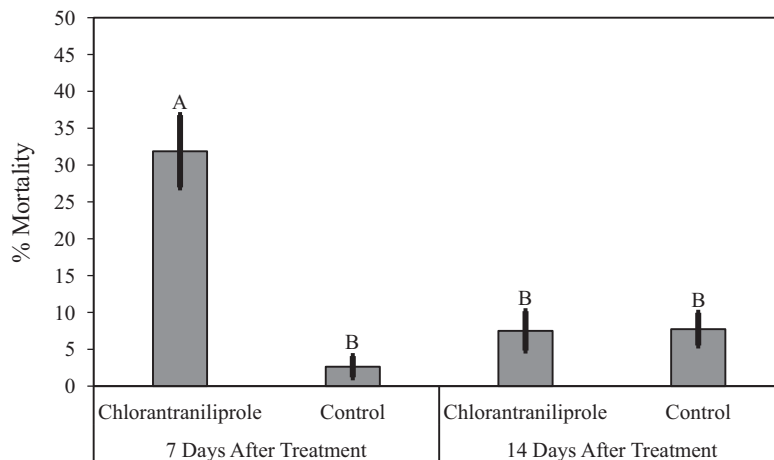


Fig. 1. Mean (SEM) levels of mortality of *H. zea* exposed to leaves that developed after application of chlorantraniliprole at the V4 growth stage during 2013–2015. Bars sharing the same letter grouping are not significantly different ($P < 0.05$).

Table 1. Mean (SEM) levels of mortality of *H. zea* exposed to *G. max* leaves that developed after application and leaves present at time of application when treated with chlorantraniliprole or flubendiamide at the R3 growth stage during 2013–2015

Treatment	Leaf position	Mean \pm SE ^{a,b}				
		10 DAT ^c	17 DAT ^c	24 DAT ^c	31 DAT ^c	Mean
Chlorantraniliprole	Upper	96.02 \pm 1.21a	89.11 \pm 2.52ab	92.88 \pm 2.08a	92.46 \pm 1.80a	92.62 \pm 1.90
Flubendiamide	Upper	15.43 \pm 3.32de	16.34 \pm 2.72de	11.82 \pm 2.30de	12.83 \pm 2.57de	14.11 \pm 2.73
Untreated control	Upper	6.79 \pm 1.50e	10.96 \pm 2.10de	7.49 \pm 1.85e	6.08 \pm 1.36e	7.83 \pm 1.70
Chlorantraniliprole	Lower	98.47 \pm 0.78a	95.00 \pm 2.11a	98.21 \pm 0.86a	94.51 \pm 1.58a	96.55 \pm 1.33
Flubendiamide	Lower	96.67 \pm 1.67a	89.91 \pm 4.28ab	79.56 \pm 4.88b	64.42 \pm 5.67c	82.64 \pm 4.13
Untreated control	Lower	10.50 \pm 1.89de	10.17 \pm 1.91de	8.29 \pm 1.81de	8.86 \pm 2.21de	9.45 \pm 1.96

^a Means followed by the same letter are not significantly different, Tukey's HSD ($\alpha = 0.05$).

^b Means and standard error are expressed as percentage mortality of *H. zea*.

^c DAT—days after treatment.

Pod and Seed Assays at the R3 Application

No significant interaction between insecticide treatment and fruiting structure was observed for corn earworm mortality when chlorantraniliprole or flubendiamide was applied as a foliar application at the R3 growth stage and measured in mortality of corn earworm from feeding on R5.5 seed and pod hulls ($F = 0.94$; $df = 2, 20.13$; $P = 0.41$). There was no significant effect observed for insecticide treatment ($F = 0.42$; $df = 2, 18.83$; $P = 0.67$) or reproductive structure ($F = 4.11$; $df = 1, 5.56$; $P = 0.09$; Fig. 2). Overall, mortality never exceeded 20%, but considerable variability was observed in this experiment, especially on pod hulls. This may be the result of pod hulls not being a preferred feeding site for corn earworm.

Greenhouse Study

A significant effect was observed for treatment location when chlorantraniliprole was applied to vegetative structures in the greenhouse at V4 ($F = 59.88$; $df = 4, 50$; $P < 0.01$). Overall, the application of chlorantraniliprole to the entire plant resulted in significantly greater mortality of corn earworm compared to applying chlorantraniliprole individually to the stem, leaf, or petiole (Fig. 3).

Chlorantraniliprole applied to the whole plant resulted in ~22, 42, 45, and 48% greater mortality compared to the stem, leaf, petiole, and the untreated control, respectively. Chlorantraniliprole applied to the stem resulted in significantly greater mortality of corn earworm than application to the leaf, petiole, or the untreated control. Application to the stem resulted in ~20, 23, and 26% greater mortality than application to the leaf, petiole, and the untreated control, respectively. No significant differences in mortality were observed for applications of chlorantraniliprole to the leaf or petiole compared with the untreated control.

Discussion

The systemic efficacy of chlorantraniliprole against lepidopteran pest species when applied to the root zone has been well documented (Lahm et al. 2007; Kuhar et al. 2008, Palumbo 2008; Ghidui et al. 2009, 2012; Schuster et al. 2009). Although it would be expected, there had been no confirmed reports of systemic efficacy in new soybean growth with chlorantraniliprole when applied as a foliar application. In this paper, it is reported that chlorantraniliprole moved to newly emerged vegetative structures of soybean

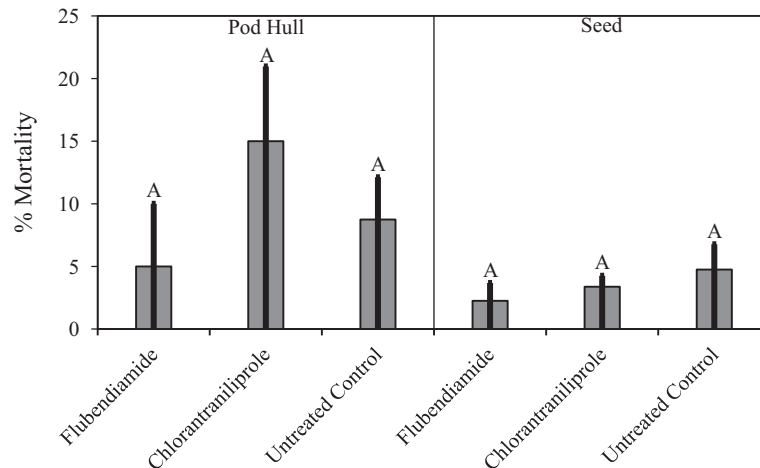


Fig. 2. Mean (SEM) levels of mortality of *H. zea* larvae exposed to *G. max* reproductive structures sprayed with chlorantraniliprole or flubendiamide at the R3 growth stage during 2014–2015. Bars sharing the same letter grouping within a tissue type are not significantly different ($P < 0.05$).

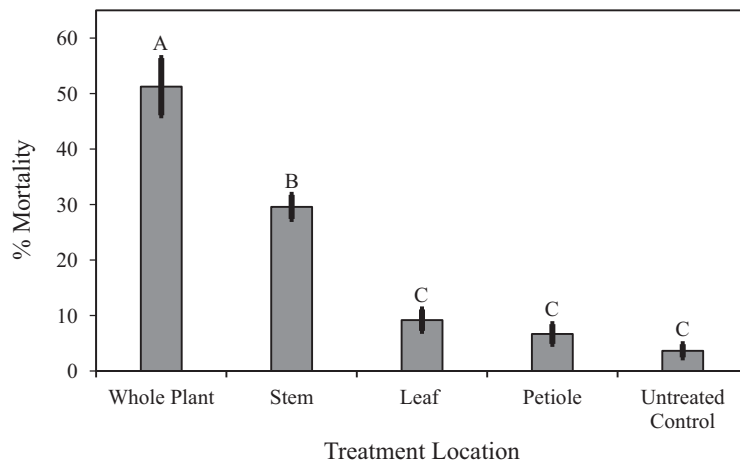


Fig. 3. Mean (SEM) levels of mortality of *H. zea* larvae exposed to *G. max* leaf material in laboratory assays with chlorantraniliprole applied to specific vegetative structures at V4 growth stage in a controlled environment during 2014–2015. Bars sharing the same letter grouping are not significantly different ($P < 0.05$).

based on mortality of corn earworm on leaves that emerged after the insecticide application.

Ghidiu et al. (2009) reported that two applications of chlorantraniliprole through drip irrigation resulted in season long control of European corn borer, *Ostrinia nubilalis* (Hübner), in bell peppers, *Capsicum annuum* (L), and was as effective as up to nine foliar applications of a standard insecticide program. The systemic efficacy of foliar-applied chlorantraniliprole was variable in the current study, and appeared to be dependent on plant size and stage at the time of application. The differences observed in systemic efficacy between the V4 application and the R3 application could be attributed to rapid node development occurring from the V4 to the R2 growth stage (Pedersen 2004). When applied at V4, it appeared that the vegetative surface area may not have been great enough at the time of application to intercept an adequate amount of chlorantraniliprole to provide any mortality beyond the 7 d rating. Additionally, it is possible that the insecticide becomes diluted within the plant for applications at the V4 stage when vegetative growth is more rapid than later in the season. Although mortality from chlorantraniliprole at the 7 d rating was greater than the untreated control, it was not adequate to provide acceptable control in a field situation at a high corn earworm density. In contrast, soybean at R3 has developed close to its total number of nodes. The size of the plant at the time of application was sufficient to intercept enough chlorantraniliprole to provide systemic control until no new terminal growth was present.

Chlorantraniliprole is xylem mobile and moves throughout the green tissue of plants (Lahm et al. 2007). Because larval mortality from feeding on reproductive structures in chlorantraniliprole-treated plots was not different from untreated plots, it appears that chlorantraniliprole is not phloem mobile. While the primary function of xylem is to transport water and minerals from the roots to aerial portions of the plant (Lucas et al. 2013), the phloem primarily functions as a food and nutrient transport from leaves to storage organs (source to sink; Lucas et al. 2013). Vijayasree et al. (2013) found that chlorantraniliprole residues were undetectable and had completely dissipated from cowpea fruits 10 d after treatment. The finding that larval feeding on reproductive structures resulted in no larval mortality in the current study supports those results.

Based on the results of the greenhouse portion of this study, it appears that absorption and translocation occurs primarily from application to the stem. Application to the leaf or petiole alone did not result in significant levels of mortality. Application to the entire plant appears to have an additive effect and a greater level of efficacy was observed. This further supports the hypothesis that chlorantraniliprole only moves in the xylem. This suggests that applications to the base of plants targeting the stems may provide an alternative application strategy in agricultural systems to overcome coverage issues with over the top applications in crops that produce a large amount of above ground biomass. This concept is similar to soil drench applications for ornamental plants, but will need to be further researched in agricultural systems.

Large monocultures with staggered planting dates are a standard practice in current agriculture systems. The biological and ecological characteristics of the corn earworm allow this insect pest to thrive in the current production landscape (Stinner et al. 1982, Fitt 1989). Chlorantraniliprole and flubendiamide provided long residual mortality of corn earworm when applied at the R3 growth stage and will continue to play an important role in lepidopteran insect pest management. However, the persistence of these insecticides on crop tissues may accelerate the likelihood of resistance development because multiple generations of insect pests will likely be exposed to

lethal concentrations from a single application, thereby increasing selection pressure.

The systemic efficacy of chlorantraniliprole, though variable, may provide greater benefits for overall management of corn earworm and other lepidopteran pests in soybean than flubendiamide (Table 1). However, this will depend on plant size at time of application and the duration of infestation. When soybeans are infested at R1–R3, the systemic efficacy of chlorantraniliprole may prove valuable in protection of crop yields later into the season than flubendiamide. Flubendiamide resulted in good residual mortality on treated leaf tissue. Infestations at growth stage R4–R5 are common in some areas. At R4–R5, soybean has produced the majority of its leaf surface area (Pedersen 2004). Further, accumulation of biomass will be limited and the residual efficacy of flubendiamide should persist for the remainder of the growing season. In this situation, it appears that chlorantraniliprole would not have an appreciable advantage over flubendiamide. In conclusion, both chlorantraniliprole and flubendiamide are valuable tools for lepidopteran insect pest management in soybean. Each insecticide provides good control of corn earworm. Understanding the population dynamics of the pest, growth stage of the plant, and time of year will be beneficial in making an application decision. Additionally, more research is needed to quantify levels of these insecticides in different plant tissues over time and to determine their long-term benefits in determinate soybean varieties.

Acknowledgments

We thank personnel of the Mississippi State University Agricultural and Forestry Experiment Station and the Mississippi State University Extension Service for technical assistance with these experiments. We also thank the Mississippi Soybean Promotion Board and Mississippi soybean producers for their generous funding of this research. This material is based upon work that is supported by the National Institute of Food and Agriculture, U.S. Department of Agriculture, Hatch Project under 223813, MIS-721140.

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