FIELD AND FORAGE CROPS

Impact of Water Management on Efficacy of Insecticide Seed Treatments Against Rice Water Weevil (Coleoptera: Curculionidae) in Mississippi Rice

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ABSTRACT Two experiments were conducted at the Delta Research and Extension Center in Stoneville, MS, during 2011 and 2012 to determine the impact of water management practices on the efficacy of insecticidal seed treatments targeting rice water weevil, Lissorhoptrus oryzophilus Kuschel. Larval densities and yield were compared for plots treated with labeled rates of thiamethoxam, chlorantraniliprole, and clothianidin and an untreated control. In the first experiment, plots were subjected to flood initiated at 6 and 8 wk after planting. Seed treatments significantly reduced larval densities with the 8-wk flood timing, but not the 6-wk flood timing. Overall, the treated plots yielded higher than the control plots. In the second experiment, the impact of multiple flushes on the efficacy of insecticidal seed treatments was evaluated. Plots were subjected to zero, one, or two flushes with water. All seed treatments reduced larval densities compared with the untreated control. Significantly fewer larvae were observed in plots that received one or two flushes compared with plots that did not receive a flush. All seed treatments resulted in higher yields compared to the untreated control and one flush treatments. When two flushes were applied, yield from the thiamethoxam and clothianidin treated plots was not significantly different from those of the control plots, while the chlorantraniliprole treated plots yielded significantly higher than the control. These data suggest that time from planting to flood did not impact the efficacy of seed treatments, but multiple flushes reduced the efficacy of thiamethoxam and clothianidin.

KEY WORDS Lissorhoptrus oryzophilus, flood, flush, seed treatment

The rice water weevil, Lissorhoptrus oryzophilus Kuschel, is the most widely distributed and destructive early season insect pest of rice, Oryza sativa L., in the United States (Cave et al. 1984, Way 1990, Saito et al. 2005). Native to North America (Saito et al. 2005), this insect has been associated with rice since the crop was introduced into the United States (Bowling 1957). In 1976, the rice water weevil was accidentally introduced into Japan (Pathak and Khan 1994). It has now spread to major rice producing regions of Asia, and is now regarded as a global threat to rice production (Pathak and Khan 1994, Heinrichs and Quisenberry 1999, Stout et al. 2002b, Zou et al. 2004a, Saito et al. 2005).

Adult rice water weevils overwinter in bermudagrass or in leaf litter in wooded areas and emerge from overwintering in early spring (Shang et al. 2004). After emergence from overwintering, adults feed on the leaves of rice and other aquatic grasses and sedges in flooded or unflooded fields (Tindall and Stout 2003). Adults feed on the upper surface of the foliage, leaving narrow longitudinal scars parallel to the venation of rice leaves (Sooksai and Tugwell 1978, Cave et al. 1984, Zou et al. 2004b). Feeding by the adult is not economically important.

Oviposition in rice commences upon establishment of the flood (Stout et al. 2002b). Peak oviposition generally occurs 1 to 2 wk after the flood is established (Wu and Wilson 1997). Rice water weevil adults oviposit in leaf sheaths at or below the water line (Stout et al. 2002b). Following eclosion, larvae mine leaf sheaths for a short period before crawling down the plant to feed on the roots (Grigarick and Beards 1965, Bowling 1972, Cave et al. 1984, Wu and Wilson 1997). Larvae progress through four instars and a pupal stage on roots before emerging as adults (Cave and Smith 1983). Larval and pupal stages of this insect are spent almost entirely in flooded or water-saturated soils, where larvae feed on or in the roots of their hosts (Zhang et al. 2006). Feeding by rice water weevil larvae results in stunted root systems, reduced tillering, reduced number of grains per panicle, and reduced grain weight (Zou et al. 2004b). Yield losses from larval feeding typically approach 10%, but can exceed 25% under severe infestations (Stout et al. 2000).

Water management practices have a direct effect on rice water weevil behavior in rice production (Webb 1914, Whitehead 1954, Morgan et al. 1989, Thompson et al. 1994, Rice et al. 1999, Stout et al. 2002b).
Presence of the flood is the most important external influence on the interaction between rice water weevil and rice (Grigarick and Beards 1965, Stout et al. 2002b). The rice water weevil is a unique pest because of its ability to thrive under flooded conditions (Pantoja et al. 1993, Rice et al. 1999). Rice is most susceptible to rice water weevil damage in the early stages of development. Delay of the flood in drill seeded rice by 2–4 wk may result in reduced rice water weevil densities and reduced yield losses owing to rice water weevil feeding. Delay of the flood allows rice plants to develop higher levels of tolerance to rice water weevil injury by significantly increasing root mass (Rice et al. 1999; Stout et al. 2000; Stout et al. 2002a, b; Zou et al. 2004a).

Seed treatments have recently been registered for control of the rice water weevil in the United States. The current recommended seed treatments for control of the rice water weevil include thiamethoxam (Cruiser 5FS, Syngenta Crop Protection, Greensboro, NC), chlorantraniliprole (Dermacor X-100, DuPont Crop Protection, Wilmington, DE), and clothianidin (NipsIt INSIDE, Valent Professional Products, Walnut Creek, CA; Catchote et al. 2013). Chlorantraniliprole is a member of the anthranilic diamide class of chemistry and received registration in the spring of 2011 (DuPont 2010). Thiamethoxam and clothianidin are members of the neonicotinoid class of chemistry. Thiamethoxam received registration in the fall of 2010 and clothianidin received registration in the fall of 2012 (Syngenta 2010, Valent 2010).

Following the removal of carbofuran from the rice production market, management of the rice water weevil relied on foliar insecticide applications. These were effective in reducing rice water weevil densities but proper application timing was critical and difficult (Stout et al. 2000). The recent introduction of seed treatments targeting rice water weevil has alleviated timing issues related to foliar insecticide applications. This has resulted in better early season management of the rice water weevil. In rice production, early season insect protection is needed for a longer period compared to corn, Zea mays L., cotton, Gossypium hirsutum L., and soybeans, Glycine max Merr. These crops only need protection from early season pests for the initial 2–3 wk of development (Lentz and Van Tol 2000). Regarding the rice water weevil, oviposition does not occur until flood establishment and maximum larval numbers are not reached until ~3 to 4 wk following the application of the flood (Thompson and Quisenberry 1995, Zou et al. 2004a). Therefore, in the instance of a delayed flood, seed treatments targeting rice water weevil must maintain acceptable levels of efficacy up to 7–10 wk after planting. Persistence of seed treatment activity under different water management regimes in rice production has not been previously investigated.

During the time from planting to flood, flushing may be required. Flushing, a common practice in rice production, is defined as applying water across a rice field to facilitate germination and emergence (Koger et al. 2006). A flush is a form of irrigation where the field is brought to a shallow flood and then drained. Flushing is often needed to alleviate soil crusting, incorporate residual herbicides, or irrigate drought-stressed seedlings. In Mississippi, rice is dry seeded into a firm and flat seedbed. The flood is generally established at the fifth leaf stage in Mississippi. This occurs 4–6 wk after planting, depending on environmental conditions. It is not uncommon for fields to be flushed at least once before establishment of the permanent flood. Under hot and dry conditions, as observed in 2011–2012, multiple flushes with water may be necessary to ensure normal growth and vigor. Though flushing is beneficial from an agronomic standpoint in rice production, its effect on the efficacy of insecticide seed treatments has not been studied. In this paper, we report the results of two studies, consisting of two experiments over 2 yr examining the impact of a delayed flood and flush number on the efficacy and longevity of seed treatments targeting rice water weevil in Mississippi rice production.

Materials and Methods

Two experiments were conducted in 2011 and 2012 at the Delta Research and Extension Center (DREC) in Stoneville, MS, to determine the impact of delayed flooding and the impact of multiple flushes with water between planting and flood on the efficacy of seed treatments against rice water weevil in rice. The soil type at this location for both years and experiments was Sharkey clay (very fine, smectitic, thermic epi-aquerts) (www.websoilsurvey.nrcs.usda.gov). The rice variety “Cocodrie” (Linscombe et al. 2000), seeded at 95 kg/ha, was used for both experiments in both years.

Seed treatments and their use rates for both studies included thiamethoxam (Cruiser 5FS, Syngenta Crop Protection) at 245 ml/100 kg of seed, chlorantraniliprole (Dermacor X-100, E.I. DuPont de Nemours) at 130 ml/100 kg of seed, and clothianidin (NipsIt INSIDE, Valent Agricultural Products) at 124 ml/100 kg of seed. Seed were treated in a laboratory-scale rotary seed treater prior to planting. Plots in both studies during each year measured 1.73 by 4.57 m and were drill seeded at 95 kg/ha.

Impact of Delayed Flood. An experiment was conducted to determine the impact of a delayed flood on the efficacy of insecticidal seed treatments targeting rice water weevil. Treatments were in a split-plot arrangement within a randomized complete block design with four replications in 2011 and eight replications in 2012. The number of replications was increased from four to eight to increase statistical power. The main-plot factor was time to flood and included timings of 6 and 8 wk after planting. The sub-plot factor was seed treatment and included the three seed treatments and rates previously described plus an untreated control.

Plots were planted 11 May 2011 and 26 April 2012 for the 8-wk timing, and 24 May 2011 and 10 May 2012 for the 6-wk timing. All plots were flooded 30 June 2011 and 22 June 2012. During the time from planting to flood establishment rainfall events of 2.74 and 2.95 cm occurred on 26 May 2011 and 22 June
2011. Total precipitation was 8.56 cm from time of planting to flood establishment for 2011. In 2012, total precipitation was 2.21 cm from 3 May 2012 to 20 May 2012. From 31 May 2012 to 12 June 2012 total precipitation was 18.03 cm. Total precipitation from time of planting to flood establishment for 2012 was 21.39 cm. Plots received one flush on the 7 June 2011 and 10 May 2012. Planting dates were varied for different flood timings so that all treatments could be flooded at the same time. Rice water weevil adults migrate into fields and begin oviposition upon establishment of the flood (Everett and Trahan 1967, Rice et al. 1999, Stout et al. 2000), and rice water weevil adult densities can vary greatly from week to week. Planting all treatments on the same date and establishing the flood at different dates would likely bias the results because some plots may have been exposed to different levels of rice water weevil densities. Planting at different dates and establishing the flood on the same date ensured that all plots were exposed to similar densities of rice water weevil. Infestation occurred naturally with the establishment of the flood. Plots were sampled on 1 August 2011 and 19 July 2012. All plots were mechanically harvested for yield on 6 October 2011 and 20 September 2012.

Impact of Multiple Flushes. An experiment was conducted to determine the impact of multiple flushes with water on the efficacy of seed treatments targeting rice water weevil. Treatments were in a split-plot arrangement within a randomized complete block design with four replicates in 2011 and eight replicates in 2012. The number of replications was increased from four to eight to increase statistical power. The main-plot factor was flush number prior to flood establishment. Treatments included zero, one, or two flushes. The sub-plot factor was seed treatment and included the treatments and rates previously described. Plots were planted on 24 May 2011 and 10 May 2012. The first flush was applied on 7 June 2011 and 18 May 2012. During 2011, plots received a total of 4.55 cm of rainfall from planting to the first flushing with a major rainfall event occurring on 26 May 2011, totaling 2.74 cm. In 2012, plots received a total of 0.48 cm of rainfall from planting to the first flush. The second flush was on 15 June 2011 and 13 June 2012. In 2011, a rainfall event occurred on 22 June 2011 of 2.95 cm and the total precipitation from planting to flood establishment of 6.76 cm. In 2012, plots received 18.92 cm of rainfall from the first and second flush, totaling 19.43 cm from time of planting to flood establishment. The plots receiving only one flush were flushed at the time of the second flush in the two-flush treatments. Rice plots for each flush treatment were planted in separate bays. The last bay (lowest elevation) was flushed two times with the middle bay being flushed one time and the first bay only receiving the permanent flood. Rice water weevil infestations occurred naturally with the establishment of the flood. The flood was established on 30 June 2011 and 22 June 2012. Plots were sampled 4 wk after flood establishment on 1 August 2011 and 19 July 2012. Plots were mechanically harvested on 6 October 2011 and 20 September 2012.

Data Collection and Analysis. To determine the effectiveness of the seed treatments in both experiments, 2.10 cm in diameter × 15.2 cm in depth core samples were collected from each plot 4 wk after establishment of the flood, based on information by Thompson et al. (1994) that concluded larval densities peaked at 32 d after flood. Samples included removing upper vegetative growth from plants located in the interior of the plot, then using a modified bulb planter to collect the bottom portion of the plant, its root mass, and the surrounding soil. Approximately three to four plants were removed from each plot for each sample. Samples were taken from the interior rows of each plot. Samples were placed in 3.79-liter Ziploc bags and taken to the laboratory to be washed through a series of screens separating larvae from the root mass. Larvae were collected in a 40 mesh screen basket. The basket was placed in a 10% NaCl solution and the number of rice water weevil larvae was determined (Stout et al. 2001). The 10% NaCl changes the specific gravity of the water, allowing the rice water weevil larvae to float. At the end of the season, each plot was mechanically harvested with a plot combine. All data were analyzed with analysis of variance (PROC Mixed of SAS, Littell et al. 1996). For both experiments, the main-plot factor, the sub-plot factor, and their interactions were considered fixed effects in the model. Weevil count data were square root-transformed to meet model assumptions. Years were considered environmental or random effects, allowing for inferences to be made over a range of environments (Carmer et al. 1989, Blouin et al. 2011). Replication nested in year and replicate by water treatment nested within year were random terms in the model, and served as the error terms for the main-plot and sub-plot factors, respectively.

Results

Impact of Delayed Flood. A significant interaction between flood timing and seed treatments was observed for rice water weevil densities (F = 3.87; df = 3, 66; P = 0.01; Table 1). This interaction resulted from differences in larval densities observed between the untreated control for the 6-wk flood timing and the untreated control for the 8-wk flood timing. There

| Treatment | Mean ± SE no. larvae per core |
|-----------|-------------------------------|
|           | 6 wk                          | 8 wk                          | Seed treatment mean |
| Thiamethoxam | 16.25 ± 3.03b                | 14.83 ± 2.90b                | 15.42 ± 2.06       |
| Chlorantraniliprole | 14.00 ± 1.20b                | 14.67 ± 2.34b                | 14.53 ± 1.29       |
| Clothianidin | 14.00 ± 2.51b                | 15.17 ± 2.98b                | 14.55 ± 1.91       |
| Untreated control | 20.67 ± 4.56b                | 42.42 ± 11.65a               | 31.54 ± 6.52       |
| Mean       | 16.23 ± 1.54                  | 21.71 ± 3.51                 |                   |

Means followed by the same letter are not significantly different (x = 0.05).

Untransformed data presented, but statistics are based on square root-transformed data.

Table 1. Impact of flood timing and insecticide seed treatment on mean (SEM) numbers of rice water weevil larvae per core for 2011–2012.
were no significant differences in larval densities between the treated plots and the untreated plots for the 6-wk flood timing. Larval densities in the untreated plots for the 8-wk flood timing were significantly higher than all other seed treatment–flood timing combinations (Table 1). When the permanent flood was established at 6 wk after planting, densities of rice water weevil larvae ranged from 14.00 to 16.25 in the treated plots and 20.67 in the untreated plots. For the 8-wk flood treatment, densities of rice water weevil larvae ranged from 14.67 to 15.17 in the treated plots compared with 42.42 for the untreated plots.

There was no significant interaction between flood timing and seed treatments for yield ($F = 0.58$; df = 3, 66; $P = 0.63$; Table 2). However, flood timing ($F = 9.16$; df = 1, 11; $P = 0.01$) and seed treatment ($F = 9.07$; df = 3, 66; $P < 0.01$) were both significant for yield. Plots flooded at 6 wk after planting yielded significantly higher than plots flooded at 6 wk after planting. Plots flooded at 8 wk yielded 7,723 kg/ha rough rice yield compared with 7,330 kg/ha rough rice yield in plots flooded at 6 wk. Across flood timings, all seed treatments resulted in significantly higher yields than the untreated control (Table 2). Yields ranged from 7,610 to 7,845 kg/ha rough rice yield for the treated plots compared with 6,960 kg/ha rough rice yield for the untreated plots.

**Impact of Multiple Flushes.** There was no interaction between number of flushes and seed treatments observed for densities of rice water weevil larvae ($F = 0.99$; df = 6, 90; $P = 0.44$). However, the main effects of flush number ($F = 8.65$; df = 2, 20; $P < 0.01$) and seed treatment ($F = 17.48$; df = 3, 90; $P < 0.01$) were significant for rice water weevil densities (Table 3). Flushing one or more times resulted in significantly lower densities of rice water weevil larvae compared with no flushes. Across all flush treatments, all seed treatments significantly reduced larval densities compared with the untreated control (Table 3). The average numbers of rice water weevil larvae ranged from 14.16 to 14.86 in seed treatment plots compared with 25.03 in the untreated control (Table 3).

A significant interaction between number of flushes and seed treatments was observed for yield ($F = 8.14$; df = 6, 90; $P < 0.01$; Table 4). All of the treated plots that received zero or one flush yielded significantly more compared with the untreated control that received zero or one flush. Plots treated with chlorantraniliprole that received two flushes produced significantly more rough rice yield than plots treated with thiamethoxam, clothianidin, or the untreated plots that received two flushes. Yields ranged from 7,957 to 8,127 kg/ha of rough rice for the treated plots that did not receive a flush compared with 6,837 kg/ha of rough rice for the untreated control that did not receive a flush. The application of one flush did not negatively impact yield for treated plots. Yields ranged from 7,650 to 8,064 kg/ha of rough rice for the treated plots that received one flush compared with 6,994 kg/ha of rough rice for the untreated control that received one flush. As flush number increased from 0 and 1 to 2, thiamethoxam and clothianidin were negatively impacted based on rough rice yield, producing 7,326 and 7,402 kg/ha, respectively. When two flushes were applied thiamethoxam and clothianidin were not significantly different from the untreated control. Plots treated with chlorantraniliprole that received two flushes were not negatively impacted and yielded 8,242 kg/ha of rough rice compared with 7,465 kg/ha for rough rice for the untreated control that received two flushes. Additionally, no differences were observed among chlorantraniliprole treatments across flush treatments.

**Discussion.**

In Mississippi, the flood is generally established between 4 and 6 wk after planting. Flood establishment at 8 wk is not a common agronomic practice in Mississippi except in instances where rice development is delayed. With the commercialization of Clearfield rice in 2002, the need for early flood establishment for red rice control was reduced (Roel et al. 1999, Bond and Walker 2011). Delaying the flood by 2–4 wk allows rice plants to accumulate more biomass and become more tolerant to injury before rice weevil infestations occur (Rice et al. 1999, Stout et al. 2002a, Zou et al. 2004c).

Water management practices have a strong influence on the relationship between rice and rice water weevil (Hesler et al. 1992), but little information exists about the impact of water management on current seed treatments. In a study by Stout et al. (2001), the efficacy of fipronil (Icon, BASF Corporation, Research Triangle Park, NC) was lower in delayed flooded plots (34 days after planting) than in early flooded plots (20 days after planting). It was proposed that the efficacy of fipronil had deteriorated before larval densities were determined. In the current experiment, rice water weevil densities in the untreated plots were higher for the 8-wk flood timing compared with the 6-wk flood timing. This is in contrast to the findings by Rice et al. (1999), who observed that delaying the flood resulted in lower densities of rice water weevil larvae infesting rice plants. All seed treatment were efficacious at the 8-wk flood timing and larval densities in the treated plots were lower than those observed in the untreated plots. However, none of the seed treatments provided control at the 6-wk flood timing.

Larval densities in the untreated control were higher at the 8-wk flood timing compared with the 6-wk flood timing. The differences between treatments were significant for rice water weevil densities (Table 2). The application of one flush did not negatively impact yield for treated plots. Yields ranged from 7,650 to 8,064 kg/ha of rough rice for the treated plots that received one flush compared with 6,994 kg/ha of rough rice for the untreated control that received one flush. As flush number increased from 0 and 1 to 2, thiamethoxam and clothianidin were negatively impacted based on rough rice yield, producing 7,326 and 7,402 kg/ha, respectively. When two flushes were applied thiamethoxam and clothianidin were not significantly different from the untreated control. Plots treated with chlorantraniliprole that received two flushes were not negatively impacted and yielded 8,242 kg/ha of rough rice compared with 7,465 kg/ha for rough rice for the untreated control that received two flushes. Additionally, no differences were observed among chlorantraniliprole treatments across flush treatments.
The plants in the untreated plots with the 6-wk flood timing yielded higher than those in the plots that received the 6-wk flood timing and should have accumulated more root mass, making them more tolerant to rice water weevil injury. In addition, all seed treatments resulted in higher yields than the untreated control. These data suggest that with an economical weed management strategy, growers can apply a flush or two flushes had a negative impact on yield in the thiamethoxam- and clothianidin-treated plots. The water solubility of thiamethoxam (4100 mg liter$^{-1}$) and clothianidin (340 mg liter$^{-1}$) (Pesticide Properties DataBase [PPDB] 2013) may be the reason for the yield losses observed in this study. Yields for plots treated with chlorantraniliprole that received two flushes were not significantly different compared with the chlorantraniliprole-treated plots that received zero or one flush, suggesting that chlorantraniliprole provided better protection when multiple flushes were applied. This could be contributed to the water solubility of chlorantraniliprole (0.88 mg liter$^{-1}$) (PPDB 2013) being much lower than the neonicotinoids. During a flush, the entire field is brought to a shallow flood with large quantities of water and drained immediately. The additional water may have moved thiamethoxam and clothianidin out of the root zone preventing or reducing uptake by the plants resulting in yield loss.

These data suggest that currently labeled seed treatments reduce overall rice water weevil densities in conditions that require multiple flushes with water prior to flooding. However, when multiple flushes were applied in plots treated with thiamethoxam or clothianidin significant yield losses were observed. When using thiamethoxam or clothianidin in hot and dry conditions that require multiple flushes with water, supplemental applications with a foliar insecticide may be needed to protect rice yields.

**Acknowledgments**

We wish to thank all the faculty and staff at the Delta Research and Extension Center for their time and support of this experiment, and the Mississippi Rice Promotion Board for their generous funding of this project.

**Table 3. Impact of flush number and seed treatment on the mean (SEM) number of rice water weevil larvae per soil core 2011–2012**

| Seed treatment  | Mean ± SE no. larvae per core |
|-----------------|-------------------------------|
|                 | 0 Flush | 1 Flush | 2 Flushes | Mean |
| Thiamethoxam    | 19.25 ± 2.74 | 12.92 ± 3.23 | 11.33 ± 1.43 | 14.50 ± 1.38b |
| Chlorantranilprole | 17.00 ± 2.12 | 12.83 ± 2.80 | 12.64 ± 2.02 | 14.53 ± 1.33b |
| Clothianidin    | 16.92 ± 2.46 | 13.83 ± 3.24 | 13.83 ± 1.71 | 14.86 ± 1.45b |
| Untreated control | 32.58 ± 9.71 | 22.67 ± 5.71 | 19.76 ± 1.99 | 24.42 ± 3.86a |
| Mean            | 21.44 ± 2.73a | 15.56 ± 1.92b | 14.39 ± 0.97b | |

Means followed by the same letter are not significantly different ($z = 0.05$).
Untransformed data presented, but statistics are based on square root-transformed data.

**Table 4. Impact of flush number and seed treatment on the mean (SEM) rough rice yields 2011–2012**

| Seed treatment  | Mean ± SE yield (kg/ha) |
|-----------------|-------------------------|
|                 | 0 Flush | 1 Flush | 2 Flushes | Mean |
| Thiamethoxam    | 8.083 ± 296ab | 7.836 ± 372ab | 7.326 ± 171c | 7.749 ± 173 |
| Chlorantranilprole | 8.127 ± 253ab | 8.064 ± 342a | 8.242 ± 140ab | 8.147 ± 146 |
| Clothianidin    | 7.957 ± 330ab | 7.650 ± 385b | 7.402 ± 135c | 7.669 ± 174 |
| Untreated control | 6.537 ± 246c | 6.994 ± 276c | 7.465 ± 83c | 7.094 ± 131 |
| Mean            | 7.751 ± 158 | 7.636 ± 178 | 7.608 ± 85 | |

Means followed by the same letter are not significantly different ($z = 0.05$).
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Received 11 December 2014, accepted 24 March 2015.