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# Efficacy of Selected Insecticides Applied to Hybrid Rice Seed

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## Abstract

Hybrid rice and insecticide seed treatments targeting rice water weevil, *Lissorhoptrus oryzophilus* Kuschel, have altered the landscape of rice production. The effect of reduced seeding rates on seed treatment efficacy in hybrid rice has not been studied. During 2011 and 2012, an experiment was conducted at seven locations to determine the relationship between low seeding rates used in hybrid rice and efficacy of selected insecticidal seed treatments as measured by rice water weevil densities and yield. Labeled rates of thiamethoxam, chlorantraniliprole, and clothianidin were compared with higher rates of these products to determine if labeled rates provide an acceptable level of control of the rice water weevil. Study locations were divided into low, moderate, and high groups based on rice water weevil larval densities. All seed treatments and seed treatment rates reduced rice water weevil densities. However, there was no observed yield or economic benefit from the use of an insecticidal seed treatment in areas of low pressure. Differences in yield were observed among seed treatments and seed treatment rates in moderate and high pressure locations, and all seed treatments yielded better than the untreated plots, but these differences were not always economical. All seed treatments showed an economic advantage in areas of high weevil pressure, and there were no differences among seed treatment products or rates, suggesting that currently labeled seed treatment rates in hybrid rice are effective for rice water weevil management.

**Key words**: *Lissorhoptrus oryzophilus*, seed treatment, hybrid, insecticide efficacy

Rice, *Oryza sativa* L., is an important crop for global food production (Khush 1997). As a result, China and other countries began focusing on increased rice production per hectare in the 1970s (Li and Yuan 2000). Hybrid rice was developed to address the need for increased production per unit of land area (Li and Yuan 2000). Characteristics of hybrid rice include increased tiller production, panicle length, and spikelet number per panicle, resulting in ∼15–25% yield increases over conventional inbred lines (Zhende 1988, Li and Yuan 2000, Bond and Walker 2011). Higher grain yields in hybrid rice are due to an increased accumulation of dry matter in the early and middle stages of development (Zhende 1988, Yamauchi 1994). Conventional rice production relies on an accumulation of assimilates after heading for yield (Zhende 1988). Hybrid rice currently accounts for >50% of the production area in China (Yuan 2003). It was commercialized in the United States during 2000 and accounted for ∼25% of rice production by 2010 (Bond and Walker 2011). Hybrid rice is planted at a lower seeding rate than inbred varieties because of its high tillering capacity. The seeding rate for hybrid rice production is 28–44 kg/ha, and 56–123 kg/ha for conventional rice (Bond et al. 2005).

The rice water weevil, *Lissorhoptrus oryzophilus* Kuschel, is the most widely distributed and destructive early season insect pest of rice 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 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. 2002, Saito et al. 2005, Zou et al. 2004a).

Adult rice water weevils overwinter in bunchgrass or in leaf litter in wooded areas. They emerge from overwintering sites in early spring and begin to feed on the foliage of semiaquatic grasses such as rice, leaving narrow longitudinal scars parallel to the veins of leaves (Sooksai and Tugwell 1978, Cave et al. 1984, Shang et al. 2004, Zou et al. 2004). This damage is only economically important in rice under severe infestations (Stout et al. 2009).

Adult oviposition in leaf sheaths, at or below the water line, commences at flood establishment peaking at 1–2 wk after flooding

(Stout et al. 2002, 2009; Wu and Wilson 1997). 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). Yield losses from larval feeding typically approach 10%, but can exceed 25% under severe infestations (Stout et al. 2000). Larval feeding reduces root tissue, growth, tiller production, and yield (Sooksai and Tugwell 1978, Cave and Smith 1983, Grigarick 1984, Hesler et al. 2000, Stout et al. 2002). The reduction in growth and tiller production is especially important in hybrid rice production because of its dependence on rapid growth during the vegetative stage in order to increase dry matter accumulation (Zhende 1988). Larval feeding also results in reduced shoot biomass, resulting in an overall reduction in total leaf area, total plant photosynthesis, and stem carbohydrate levels (Zou et al. 2004). Hybrids depend on tiller production to obtain the desired panicle density, whereas conventional rice production relies on higher seeding rates to achieve the desired panicle density (Zhende 1988).

Insecticide seed treatments were labeled for rice water weevil control in the United States in 2010 (Adams et al. 2015). These seed treatments provide effective control of the rice water weevil during the early developmental stages of rice (Adams et al. 2015). The currently labeled insecticidal seed treatments for control of the rice water weevil in Mississippi are chlorantraniliprole at 98–390 ml/100 kg seed (Dermacor X-100, E.I. DuPont de Nemours), clothianidin at 125 ml/100 kg seed (NipsIt INSIDE, Valent Agricultural Products), and thiamethoxam at 248 ml/100 kg seed (Cruiser 5FS, Syngenta Crop Protection; Catchot et al. 2013). Thiamethoxam and clothianidin are applied at fixed rates per seed. However, the rate of chlorantraniliprole per seed varies depending on the seeding rate, so the rate per ha remains approximately the same over all seeding rates. Because rice water weevils are attracted to thin stands, the low seeding rates associated with hybrid rice can increase the susceptibility to damage by the rice water weevil (Stout et al. 2009). The production of primary and secondary tillers is vital to overall yield in hybrid rice, as tillers account for 85–90% of productive panicles (Bond et al. 2008). In contrast, tiller production only accounts for 30–40% of productive panicles in conventional rice (Zhende 1988). Hybrid rice production systems may be more susceptible to rice water weevil injury than conventional rice production systems because rice water weevil impacts early season tiller production (Stout et al. 2009), and the reduced seeding rate may result in a concentrated number of larvae on the root mass of an individual plant. Reduced seeding rate also results in a reduction in the amount of insecticide active ingredient applied per hectare with seed treatments such as thiamethoxam and clothianidin that have a fixed rate per unit weight of seed. The objective of this study was to determine the impact of rice water weevil on hybrid rice and the impact of reduced seeding rates on the efficacy of insecticide seed treatments targeting rice water weevil in rice by comparing the labeled rate of each insecticide with higher rates.

## Materials and Methods

An experiment was conducted over seven locations from 2011–2012 (Table 1) throughout the Mississippi Delta to determine the efficacy of insecticide seed treatments in hybrid rice production systems. Currently labeled rates of insecticide seed treatments were compared with higher rates of the same insecticides to determine their effectiveness at lower seeding rates used in hybrid rice production. Treatments are expressed as ml/100 kg of formulated product and g ai/100 kg and are as follows: Cruiser 5FS (thiamethoxam) at 248 ml; 14.87 g ai/100 kg seed and 587 ml; 35.20 g ai/100 kg seed, Dermacor X-100 (chlorantraniliprole) 326 ml; 20.37 g ai/100 kg seed and 390 ml; 24.37 g ai /100 kg seed, NipsIt INSIDE (clothianidin) at 125 ml; 7.50 g ai/100 kg seed and 260 ml; 15.59 g ai/100 kg seed and an untreated check. The rice hybrid RiceTec XL723 was used at all locations during both years and planted between 2 April and 26 May, the normal planting window for Mississippi (Table 1). The experiment was conducted as a randomized complete block design with seven treatments replicated four times at each location. Seeds were treated in a laboratory-scale rotary seed treater before planting. Plot sizes in all experiments were 1.73 by 4.57 $m^2$ and were drill seeded at 29 kg seed/ha. All agronomic practices were conducted based on Mississippi State University Extension Service recommendations (Buehring 2008).

### Data Collection and Analysis

To determine the effectiveness of the seed treatments, two 10-cm-diameter by 15.2-cm-deep, soil core samples were collected from each plot 4 wk after establishment of the flood (Table 1). Soil core samples were collected by removing the upper vegetative growth from a randomly selected plant on an interior row of the plot. Then a modified bulb planter, 10 cm diameter by 15.2 cm deep, was used to collect the bottom portion of the plant, its root mass, and the surrounding soil. Because of the low seeding rate, only one plant was removed per sample. The individual samples were placed in 3.79 -L Ziploc bags labeled with the corresponding plot information. The samples were transported to the laboratory to be washed through a series of wire mesh 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 rice water weevil larvae were counted (Stout et al. 2001). Larval numbers were entered on a per plot basis. At the end of the season, each plot was mechanically harvested with a plot combine.

**Table 1.** Planting dates, sampling dates, and classification of locations for experiments evaluating on-farm insecticidal seed treatment efficacy on hybrid rice (RiceTec XL 723) in Mississippi during 2011 and 2012

| County | Planting date | Core sample date | Classification | Larvae per core[a] | Yield kg/ha |
|---|---|---|---|---|---|
| Bolivar 1 | 2 April 2012 | 21 June 2012 | Low | 0.50 ± 0.50 c | 15,110 ± 1483 |
| Bolivar 2 | 12 April 2011 | 21 June 2011 | Low | 0.75 ± 0.75 c | 13,520 ± 226 |
| Bolivar 3 | 9 April 2011 | 22 June 2011 | Moderate | 22.75 ± 2.09 b | 11,910 ± 306 |
| Washington 1 | 26 April 2012 | 20 June 2012 | Moderate | 21.75 ± 5.62 b | 8,794 ± 598 |
| Washington 2 | 11 May 2011 | 6 July 2011 | Low | 8.00 ± 0.58 c | 14,109 ± 282 |
| Washington 3 | 2 April 2012 | 22 June 2012 | Moderate | 32.00 ± 1.00 b | 12,002 ± 425 |
| Tunica | 24 May 2011 | 22 June 2012 | High | 80.75 ± 5.29 a | 9,039 ± 655 |

[a] Data presented as the mean (SEM) number of rice water weevil larvae in the untreated control for each location. Means followed by the same letter are not significantly different, Fisher's LSD ($\alpha = 0.05$).

### Data Analysis

All data were analyzed with analysis of variance (ANOVA; PROC GLIMMIX SAS Institute Inc. 2011). Degrees of freedom were calculated using the Kenward–Roger method.

Initial analysis compared larval densities and yield of labeled rates versus higher rates of insecticide seed treatments across all locations using an ESTIMATE statement within PROC GLIMMIX. In the model, larval density and treatment were considered fixed effects. Weevil count data were square root transformed to meet assumptions of normality. Replication(location) and treatment by replication(location) were random terms in the model. Means were estimated using the LSMEANS statement and adjusted according to the Tukey's HSD test and considered significant at $\alpha = 0.05$.

Based on the initial analysis, each location was classified based on larval density of the untreated control into low, moderate, or high weevil density (Table 1). All insect density levels were analyzed independently. Seed treatment was considered as a fixed effect in the model. Replication (location) and location were random effects in the model for low and moderate weevil densities. Replication was the only random effect in the high-density location because there was only one location at this density. Means were estimated using the LSMEANS statement and adjusted according to the Tukey's HSD test and considered significant at $\alpha = 0.05$.

An economic analysis was conducted to determine the economic benefit of insecticide seed treatments in hybrid rice under varying levels of rice water weevil densities. This analysis was based on returns above expenses and based on a 1-yr, short-run decision according to the Mississippi State University 2012 rice planning budget (Mississippi State University, Department of Agricultural Economics [MSUES] 2011). The budget did not account for cost of land, management, or general farm overhead (MSUES 2011). Estimates were calculated on the cost per ha for growing straight levee rice that was flood irrigated at 27 ha-cm (US$1,632/ha), in the Mississippi Delta, for the 2012 growing season (MSUES 2011). This budget included one foliar application of lambda-cyhalothrin (US$20.23/ha) to control rice stink bug, *Oebalus pugnax* F., infestations later in the season when rice water weevils are not economically important (MSUES 2011). Seed treatment prices were obtained from three chemical and seed distributors in the Mississippi Delta. The averages of these prices were used for the economic analysis, and their 2013 costs are as follows: Cruiser 5FS (thiamethoxam) at US$0.34/ml, Dermacor X-100 (chlorantraniliprole) at US$0.36/ml, and NipsIt INSIDE (clothianidin) at US$0.25/ml. Seed price was set at US$271/ha. The market value for rough rice yield was based on a 5-yr average value of US$0.28/kg (National Agricultural Statistics Service [NASS] 2013). All specified expenses were deducted from the gross income to obtain net return per ha. The model for economic return was the same as for yield and weevil density for each of the weevil density classes.

### Economic Injury Levels of Rice Water Weevil Density

In addition to ANOVA, regression analysis was used to examine the relationship between rough rice yield and weevil densities per plot (PROC GLIMMIX SAS Institute Inc. 2011). Preliminary analysis showed that no additional yield loss occurred for weevil densities exceeding 60 weevils per core. Knowing this density is rare and well above an economic injury level, observations with weevil densities exceeding 60 larvae per core were deleted from the regression analysis. In the final model, rice water weevil density was a fixed effect in the model, and rough rice yield was the response variable. Replication(location) and location were random effects in the model. The Kenward–Roger method was used to estimate the appropriate degrees of freedom in the model. The slope of the regression line relating rough rice yield and rice water weevil densities represents yield reduction per rice water weevil larvae per core.

The linear relationship between rice water weevil larvae and yield reduction was used to determine the *EIL* for larval feeding in hybrid rice according to the relationship developed by Pedigo et al. (1986):

$$EIL = C/\ (V \times b \times K)$$

where $C$ is the control cost, $V$ is the crop value, $b$ is the damage per pest, and $K$ is the proportional reduction in pests from a control tactic. The $C$ component was set between US$10 and US$35/ha to account for the potential range of insecticide seed treatment costs. The $V$ component was set between US$0.16 and US$0.48/kg based on a potential range of market values for rough rice yield. The $b$ component was obtained through the regression analysis described above. The $K$ term was estimated by comparing the number or rice water weevil larvae per core sample in all treated plots at currently labeled rates and untreated plots averaged across all locations and set at 52% control. The mortality from higher than labeled rates of insecticide seed treatments were not used to estimate EIL.

## Results

### Overall Analysis

An analysis of the interaction between rice water weevil density and seed treatment was significant ($F = 4.64$; df = 12, 129.3; $P < 0.01$), so each weevil density was analyzed independently. The contrast of high seed treatment rates versus currently labeled rates was also significant for weevil density ($t = 3.09$; df = 129.3; $P < 0.01$). Similar to the results for weevil density, the interaction of insect density and treatment on yield ($F = 2.79$; df = 12, 123.5; $P < 0.01$) and the contrast of high rates versus labeled rates on yield ($t = -2.5$; df = 123.5; $P = 0.01$) were significant. Similarly, the interaction of pressure and treatment on net return ($F = 2.85$; df = 12, 128.5; $P < 0.01$) and the contrast of high rates versus labeled rates on net return were significant ($t = 6.62$; df = 128.6; $P < 0.01$). Significant differences in rice water weevil larval densities in untreated plots were observed across locations ($F = 67.22$; df = 6, 18; $P < 0.01$) (Table 1).

### Low Rice Water Weevil Pressure

In the three locations with low rice water weevil densities, seed treatment had a significant effect on rice water weevil density ($F = 2.51$; df = 6, 61; $P = 0.03$; Table 2). However, rough rice yield ($F = 0.46$; df = 6, 61; $P = 0.84$) and net economic return ($F = 0.61$; df = 6, 33; $P = 0.71$) were not significantly different from the untreated control (Table 2). Only, the high rate of chlorantraniliprole significantly reduced larval densities below the untreated control but did not provide significantly different control from all other seed treatments. The high rate of chlorantraniliprole reduced larval densities by 83% from the untreated control.

### Moderate Rice Water Weevil Pressure

In the three locations with moderate rice water weevil densities, seed treatment had a significant effect on larval densities ($F = 13.25$; df = 6, 60; $P < 0.01$), rough rice yield ($F = 10.71$; df = 6, 60; $P < 0.01$), and net economic return ($F = 8.51$; df = 6, 78; $P < 0.01$; Table 3). All treatments significantly reduced larval densities compared with the untreated control, but there were no significant differences among the seed treatments. Across all treatments, larval densities were reduced by 59.5% compared with the untreated

**Table 2.** On-farm trials in Mississippi examining the impact of insecticidal seed treatments at the currently labeled rate and an increased rate in hybrid rice (RiceTec XL 723) on mean number of rice water weevil larvae per core, grain yields, and net economic return under low weevil pressure 2011–2012

| Treatment | Rate[a] | Mean ± SEM[b] | | |
|---|---|---|---|---|
| | | No. larvae/core | Yield kg/ha | Net return US$/ha |
| Thiamethoxam | 14.87 | 1.4 ± 0.62ab | 14,303 ± 455 | 2,519 ± 185 |
| Thiamethoxam | 35.20 | 1.3 ± 0.56ab | 14,067 ± 552 | 2,478 ± 184 |
| Chlorantraniliprole | 20.37 | 1.00 ± 0.45ab | 14,218 ± 454 | 2,547 ± 193 |
| Chlorantraniliprole | 24.37 | 0.50 ± 0.16b | 14,652 ± 430 | 2,574 ± 178 |
| Clothianidin | 7.50 | 1.80 ± 0.80ab | 14,577 ± 413 | 2,556 ± 170 |
| Clothianidin | 15.59 | 1.30 ± 0.68ab | 14,617 ± 462 | 2,542 ± 195 |
| Untreated control | – | 3.00 ± 1.15a | 14,174 ± 455 | 2,543 ± 192 |

[a] Rates are expressed in grams of active ingredient per 100 kg seed.
[b] Means followed by the same letter are not significantly different, Tukey's HSD ($\alpha = 0.05$).

**Table 3.** On-farm trials in Mississippi examining the impact of insecticidal seed treatments at the currently labeled rate and an increased rate in hybrid rice (RiceTec XL 723) on mean number of rice water weevil larvae per core, grain yields, and net economic return under moderate weevil pressure 2011–2012

| Treatment | Rate[a] | Mean ± SEM[b] | | |
|---|---|---|---|---|
| | | No. larvae/core | Yield kg/ha | Net return US$/ha |
| Thiamethoxam | 14.87 | 11.72 ± 2.69b | 12,631 ± 311a | 2,037 ± 78a |
| Thiamethoxam | 35.20 | 11.36 ± 2.32b | 13,394 ± 166a | 2,227 ± 54a |
| Chlorantraniliprole | 20.37 | 7.64 ± 1.08b | 12,614 ± 284a | 2,036 ± 77a |
| Chlorantraniliprole | 24.37 | 6.45 ± 1.90b | 13,263 ± 192a | 2,200 ± 56a |
| Clothianidin | 7.50 | 11.72 ± 2.12b | 12,499 ± 318a | 2,068 ± 99a |
| Clothianidin | 15.59 | 11.64 ± 1.67b | 13,143 ± 374a | 2,215 ± 97a |
| Untreated control | – | 24.91 ± 2.43a | 10,803 ± 538b | 1,669 ± 162b |

[a] Rates are expressed in grams of active ingredient per 100 kg seed.
[b] Means followed by the same letter are not significantly different, Tukey's HSD ($\alpha = 0.05$).

control. Larval reduction in treated plots resulted in a 16.4% (2121 kg/ha) increase in rough rice yield, on average, compared with the untreated control. This resulted in a 21.6% (US$461/ha) average increase in net economic return compared with the untreated control. There were no significant differences among the seed treatments pertaining to rough rice yield or economic return.

### High Rice Water Weevil Pressure

Only one location was classified as having a high rice water weevil density. Seed treatment had a significant effect on larval densities ($F = 11.40$; df = 6, 18; $P < 0.01$), rough rice yield ($F = 6.68$; df = 6, 18; $P < 0.01$), and net economic return ($F = 6.11$; df = 6, 18; $P < 0.01$; Table 4). All seed treatments significantly reduced larval densities compared with the untreated control. The high rate of chlorantraniliprole significantly reduced larval densities compared with the labeled rate of thiamethoxam providing 74 versus 39% control, respectively. The labeled rate of thiamethoxam was not significantly different from all other treatments. All treatments, excluding the high rate of chlorantraniliprole, reduced larval densities by 51%. All seed treatments yielded significantly higher than the untreated control, but there were no significant differences among seed treatments. Averaged across all treatments, rough rice yields were 22.6% (2,460 kg/ha) higher compared with the untreated control. The use of an insecticide seed treatment resulted in a significant net economic return, but there were no significant differences among seed treatments. The use of an insecticide seed treatment resulted in a 47.2% (US$692/ha) increase in net economic return averaged across treatments compared with the untreated control

### Economic Injury Levels of Rice Water Weevil Density

Across all locations, there was a significant linear relationship between the number of rice water weevil larvae per core and rough rice yield ($F = 14.55$; df = 1, 15936; $P < 0.01$; Fig. 1) . A reduction of 44.28 ± 11.61 kg/ha per larva per core was observed from the linear equation and served as the *b* component in the *EIL* equation. The *k* term was estimated to be 52% based on average control observed among all locations and labeled seed treatment rates. Based on these values, *EIL*s for rice water weevil larvae in hybrid rice for the Mississippi Delta ranged from 0.7 to 7.4 larvae per core, depending on rough rice price and cost of control (Table 5).

## Discussion

Rice water weevil infestations are generally more severe in low seeding rate scenarios (Thompson and Quisenberry 1995, Rolston and Rouse 1964, and Stout et al. 2009). Rice planted at low seeding rates with insecticidal seed treatments was exposed to a wide range of rice water weevil densities in this study. High rice water weevil larval densities such as those observed in Tunica, though not common in Mississippi, have been observed in other situations (Adams et al. 2015). In 2011, rice water weevil numbers were believed to be unusually high in various locations throughout the Mississippi Delta (Adams et al. 2015). Typically, rice water weevil densities fall into the low and moderate classes described in this study (Adams et al. 2015).

High and labeled rates of seed treatments were significantly different when all insect densities were analyzed together, but not

**Table 4.** On-farm trials in Mississippi examining the impact of insecticidal seed treatments at the currently labeled rate and an increased rate in hybrid rice (RiceTec XL 723) on mean number of rice water weevil larvae per core, grain yields, and net economic return under high weevil pressure 2011–2012

| Treatment | Rate[a] | Mean ± SEM[b] | | |
|---|---|---|---|---|
| | | No. larvae/core | Yield kg/ha | Net return US$/ha |
| Thiamethoxam | 14.87 | 49.50 ± 5.42b | 10,511 ± 316a | 1,357 ± 91a |
| Thiamethoxam | 35.20 | 41.00 ± 9.75bc | 11,073 ± 161a | 1,485 ± 46a |
| Chlorantraniliprole | 20.37 | 42.00 ± 5.26bc | 10,722 ± 580a | 1,408 ± 167a |
| Chlorantraniliprole | 24.37 | 20.75 ± 1.25c | 11,150 ± 716a | 1,525 ± 207a |
| Clothianidin | 7.50 | 41.50 ± 8.51bc | 10,904 ± 301a | 1,485 ± 86a |
| Clothianidin | 15.59 | 32.00 ± 4.45bc | 11,070 ± 379a | 1,524 ± 109a |
| untreated control | – | 80.75 ± 5.30a | 8,445 ± 154b | 772 ± 42b |

[a] Rates are expressed in grams of active ingredient per 100 kg seed.
[b] Means followed by the same letter are not significantly different, Tukey's HSD ($\alpha = 0.05$).

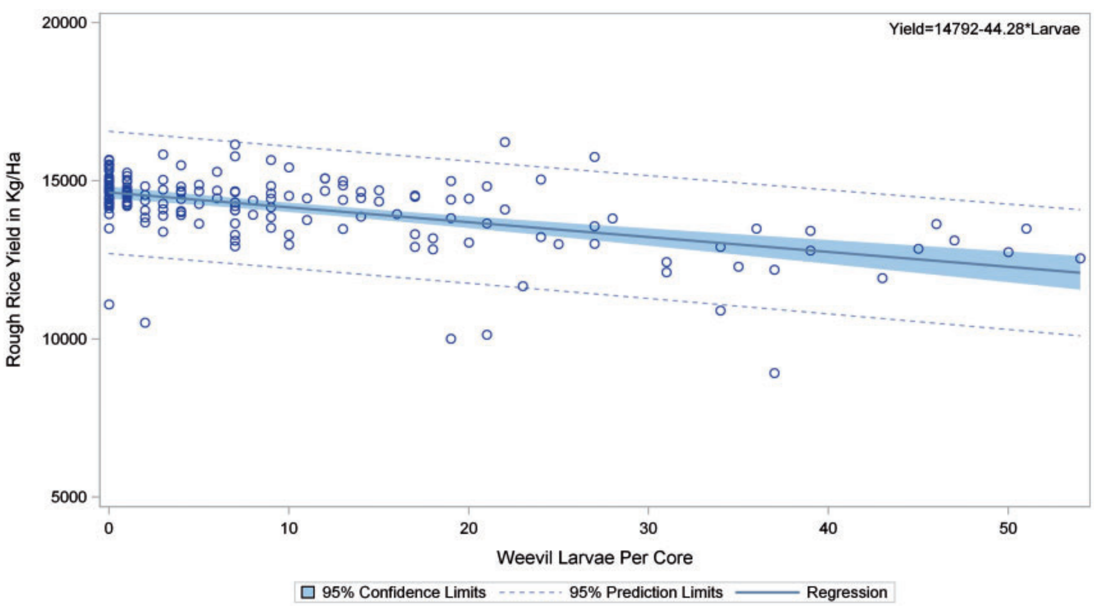


**Fig. 1** Rough rice yield response to increasing numbers of rice water weevil larvae per core in on-farm trials in hybrid rice (RiceTec XL 723) in Mississippi during 2011–2012. Each point represents one replicate of a treatment at one location. The equation was generated from raw data using location and replication within location as a random effects. To show the data fit in this graph, yield of each point was adjusted to make all replicates of all locations have the same yield potential, thereby graphically correcting for the random effects.

**Table 5.** Economic injury levels expressed as average number of rice water weevil larvae per core in hybrid rice for Mississippi under various control costs and market values of rough rice

| Rough rice price (US$/kg)[a] | Cost of control (US$/ha)[b] | | | | | |
|---|---|---|---|---|---|---|
| | 10 | 15 | 20 | 25 | 30 | 35 |
| 0.16 | 2.1 | 3.2 | 4.2 | 5.2 | 6.3 | 7.4 |
| 0.24 | 1.4 | 2.1 | 2.8 | 3.5 | 4.2 | 4.9 |
| 0.32[1] | 1.1 | 1.6 | 2.1 | 2.6 | 3.2 | 3.7 |
| 0.4 | 0.8 | 1.3 | 1.6 | 2.1 | 2.5 | 3 |
| 0.48 | 0.7 | 1.1 | 1.4 | 1.8 | 2.1 | 2.5 |

[a] Average market value of rough rice from 2008–2012.
[b] Range of control costs based on labeled rates of insecticide seed treatment prices, as reported by three MS seed retailers, seeded at 29 kg/ha. Average insecticide seed treatment costs per ha for Mississippi for 2013 are as follows: Cruiser 5FS US$24.45/ha, Dermacor X-100 US$34.03/ha, and NipsIt INSIDE US$9.06/ha.

when each level of pressure was analyzed independently. On closer examination of the data, the trend of higher weevil control, higher yields, and higher economic returns is visible at the moderate and high weevil densities. However, the differences are small, suggesting that statistical power was likely the major limitation to detecting changes between rates of an insecticide.

In areas of low rice water weevil pressure, the use of seed treatments in hybrid rice does not provide an economic benefit; however, results also suggest that the use of the insecticide seed treatments provide enough protection from rice water weevil injury so that there is no significant cost for the insecticide seed treatment in hybrid rice. Furthermore, under moderate and high rice water weevil pressure, currently labeled rates of insecticide seed treatments in hybrid rice provide control that results in positive yield and economic benefits. There was no evidence that any of the seed treatment products were better than any others for rice water weevil control.

Overall, when locations were grouped based on weevil density, all seed treatments and rates reduced larval densities by ~58% on average. All seed treatments and seed treatment rates reduced rice water weevil densities below the untreated control. However, as larval densities increased from low to moderate to high, yield increases of 1.8, 16.4, and 22.6%, respectively, were observed on average in treated plots over the untreated control. A similar trend was observed for net economic returns. When treated plots were compared with the untreated control within each level of infestation, the net economic return was −0.003, 21.6, and 47.2%, respectively. These data suggest that the use of an insecticidal seed treatment is not always beneficial in hybrid rice, especially where rice water weevil pressure is low, as observed at three locations in this study. Also, as rice water weevil densities increase, so does the value of the insecticidal seed treatment.

Yield losses exceeding 20% from rice water weevil larval feeding have been reported in the southern United States (Stout et al. 2000), and no tools currently exist to predict the severity of rice water weevil infestations before flooding. Because there was no economic cost to applying a seed treatment even in situations where the weevil density was low, seed treatments are recommended in all rice producing areas of Mississippi. In areas of moderate and high weevil pressure, currently labeled rates of insecticides performed similar to higher rates in regards to yield and net economic return. These data suggest that currently labeled rates of insecticidal seed treatments are effective in management of the rice water weevil in low seeding rate production systems.

Previous studies conducted by Stout et al. (2009) have indicated that low seeding rates may be subject to greater levels of rice water weevil infestation on a per-plant or per-area basis. Those studies were conducted with conventional varieties. They hypothesized that low seeding rates may be more vulnerable to yield losses from rice water weevil larval infestations and may suffer from proportionally greater yield losses from rice water weevil injury than rice seeded at higher rates. In this study, yield loss per larva per core was 0.30% for hybrid rice, similar to the lower end reported by Zou et al. (2004), who reported yield losses ranging from 0.38 to 4.12% per larva per core. Though our seeding rates were 29 kg/ha compared with their seeding rate of 112 kg/ha, our yield losses were no greater on a per larva basis. This may be attributed to the higher yield potential of hybrid rice cultivars and their ability to compensate for rice water weevil injury (Horgan and Crisol 2013). It is important to realize that a direct comparison is impossible based on different methodologies, cultural practices, location, and flooding regimes. Also, across all locations and treatments, we used a constant seeding rate, whereas previous research by Stout et al. (2009) varied seeding rate densities. Furthermore, previous studies used conventional cultivars, whereas this study was composed of a single hybrid cultivar. Further research should be done to better understand the relationship between seeding rate and rice water weevil larval densities in hybrid rice, but based on this study, hybrid rice cultivar susceptibility to rice water weevil injury appears to be similar to inbred varieties.

The *EIL* concept remains as one of the most important components of an integrated pest management program. It was proposed over 50 yr ago by Stern et al. (1959) and put into a mathematical formula by Pedigo et al. (1986). The yield loss estimates from rice water weevil injury per larva were calculated to produce *EIL*s across varying market prices and control costs. Based on the data collected in this study, the 5-yr commodity average price, and the average control cost, the *EIL* is 2.7 larvae per core in hybrid rice. This is similar to the estimate of 3.2 larvae per core in conventional rice (Espino et al. 2009). In the overall analysis when pressure was contrasted by treatment, this difference was significant. In this study, the average larval density was 3 larvae per core in the untreated control in the low pressure locations. The inability to detect a significant yield difference under low pressure is based on the lack of overall statistical power because only three versus seven locations were analyzed.

Foliar applications of insecticides are also effective in reducing rice water weevil densities and protecting yields, but proper application timing is critical and difficult (Stout et al. 2000, Hummel et al. 2014). Based on the larval densities observed in this study, the rice water weevil is a severe early season pest of rice in Mississippi. Five of the seven locations, or 71% of the fields, were above the *EIL*. Furthermore, it is not uncommon to observe 10–30 larvae per core in untreated plots on a regular basis in Mississippi rice production (Adams et al. 2015). Considering that there was no economic loss from the use of insecticidal seed treatments under low pressure, preventative insecticidal seed treatments are appropriate for rice water weevil control in Mississippi hybrid rice production. However, 50–60% control against rice water weevil. Higher rates of these treatments resulted in lower weevil densities, higher yield, and a higher net return when all pressure levels were analyzed together, so it appears that currently labeled seed treatment rates do not provide absolute control when used on hybrid rice. In areas with historically high rice water weevil pressure, the use of an insecticide seed treatment, in combination with early monitoring of rice fields, timely application(s) of a foliar insecticide, early planting, and delayed flooding may all be required for effective rice water weevil management in hybrid rice production.

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## References Cited

**Adams, A., J. Gore, F. Musser, D. Cook, A. Catchot, T. Walker, and G. A. Awuni. 2015.** Impact of water management on efficacy of insecticidal seed treatments against rice water weevil (Coleoptera: Curculionidae) in Mississippi rice. J. Econ. Entomol. 108: 1078–1085.

**Bond, J. A., and T. W. Walker. 2011.** Differential tolerance of Clearfield® rice cultivars to imazamox. Weed Technol. 25: 192–197.

**Bond, J. A., T. W. Walker, P. K. Bollich, C. H. Koger, and P. Gerard. 2005.** Seeding rates for stale seedbed rice production in the Midsouthern United States. Agron. J. 97: 1560–1563.

**Bond, J. A., T. W. Walker, B. V. Ottis, and D. Harrell. 2008.** Rice seeding and nitrogen rate effects on yield and yield components of two rice cultivars. Agron. J. 100: 393–397.

**Bowling, C. C. 1957.** Seed treatment for control of the rice water weevil. J. Econ. Entomol. 50: 450–452.

**Bowling, C. C. 1972.** Note on the biology of rice water weevil, *Lissorhoptrus oryzophilus*. Ann. Entomol. Soc. Am. 65: 990–991.

**Buehring, N. 2008.** Rice growth and development, pp. 80, *In* Rice Growers Guide, Mississippi State University Extension Service Publication 2255. Mississippi State, MS.

**Catchot, A., D. Cook, J. Gore, F. Musser, D. Dodds, C. Allen, R. Jackson, E. Larson, B. Layton, R. Luttrell, et al. 2013.** Insect control guide for agronomic crops, Mississippi State University Extension Service. Publication 2471. Mississippi State, MS.

**Cave, G. L., and C. M. Smith. 1983.** Number of instars of the rice water weevil, *Lissorhoptrus oryzophilus* (Coleoptera: Curculionidae). Ann. Entomol. Soc. Am. 76: 293–294.

**Cave, G. L., C. M. Smith, and J. F. Robinson. 1984.** Population dynamics, spatial distribution, and sampling of the rice water weevil on resistant and susceptible rice genotypes. Environ. Entomol. 13: 822–827.

**Grigarick, A. A. 1984.** General problems with rice invertebrate pests and their control in the United States. Prot. Ecol. 7: 105–114.

**Grigarick, A. A., and G. W. Beards. 1965.** Ovipositional habits of the rice water weevil in California as related to a greenhouse evaluation of seed treatments. J. Econ. Entomol. 58: 1053–1056.

**Heinrichs, E. A., and S. S. Quisenberry. 1999.** Germplasm evaluation and utilization for insect resistance. *In* S. L. Clement and S. S. Quisenberry (eds.), Global plant genetic resources for insect-resistant crops. CRC, Boca Raton, FL.

**Hesler, L. S., M. J. Oraze, A. A. Grigarick, and A. T. Palrang. 2000.** Numbers of rice water weevil larvae (Coleoptera: Curculionidae) and rice plant growth in relation to adult infestation levels and broadleaf herbicide applications. J. Agric. Urban Entomol. 17: 99–108.

**(MSUES) Mississippi State University, Department of Agricultural Economics. 2011.** Rice 2012 planning budgets, Budget report No. 2011-04. Mississippi State University, Department of Agricultural Economics. (http://www.agecon.msstate.edu/whatwedo/budgets/docs/12/MSURICE12.pdf) (accessed 2 October 2015).

**Horgan, F. G., and E. Cristol. 2013.** Hybrid rice and insect herbivores in Asia. Entomol. Exp. Appl. 148: 1–19.

**Hummel, N. A., A. Mészáros, D. R. Ring, J. M. Beuzelin, and M. J. Stout. 2014.** Evaluation of seed treatment insecticides for management of the rice water weevil, *Lissorhoptrus oryzophilus* Kuschel (Coleoptera: Curculionidae), in commercial rice fields in Louisiana. Crop Prot. 65: 37–42.

**Khush, G.S. 1997.** Origin, dispersal, cultivation, and variation of rice. Plant Mol. Biol. 35: 25–34.

**Li, J., and L. Yuan. 2000.** Hybrid rice: Genetics, breeding, and seed production, pp. 15–158 *In* J. Janick, (ed.), Plant breeding reviews, Volume 17. J. Wiley. Hoboken, NJ.

**(NASS) National Agricultural Statistics Service. 2013.** Rice - price received, measured in $/cwt. United States Department of Agriculture (USDA), National Agricultural Statistics Service (http://www.nass.usda.gov/).

**Pathak, M. D., and Z. R. Khan. 1994.** Insect Pests of Rice. International Rice Research Institute, Los Banos, Philippines.

**Pedigo, L. P., S. H. Hutchins, and L. G. Higley. 1986.** Economic injury levels in theory and practice. Annu. Rev. Entomol. 31: 341–368.

**PROC GLIMMIX SAS Institute Inc. 2011.** The GLIMMIX procedure, SAS/STAT® 9.3 user's guide. SAS Institute Inc., Cary, NC.

**Rolston, L. H., and P. Rouse. 1964.** Some factors influencing larval infestations of the rice water weevil. J. Kans. Entomol. Soc. 37: 29–35.

**Saito, T., K. Hirai, and M. O. Way. 2005.** The rice water weevil, *Lissorhoptrus oryzophilus* Kuschel (Coleoptera: Curculionidae). Appl. Entomol. Zool. 40: 31–39.

**Shang, H., M. J. Stout, R. C. Pousson, Z. T. Zhang, and J. Cheng. 2004.** Population dynamics of the rice water weevil, *Lissorhoptrus oryzophilus* Kuschel, (Coleoptera: Curculionidae), in Louisiana. J. Entomol. Sci. 39: 623–642.

**Sooksai, S., and P. Tugwell. 1978.** Adult rice water weevil feeding symptoms: number samples required, spatial and seasonal distribution in a rice field. J. Econ. Entomol. 71: 145–148.

**Stern, V. M., R. F. Smith, R. Van Den Bosch, and K. S. Hagen. 1959.** The integrated control concept. Hilgardia 29: 81–101.

**Stout, M. J., W. C. Rice, R. N. Riggio, and D. R. Ring. 2000.** The effects of four insecticides on the population dynamics of the rice water weevil, *Lissorhoptrus oryzophilus*. J. Entomol. Sci. 35: 48–61.

**Stout, M. J., W. C. Rice, S. D. Linscombe, and P. K. Bollich. 2001.** Identification of rice cultivars resistant to *Lissorhoptrus oryzophilus* (Coleoptera: Curculionidae), and their use in an integrated management program. J. Econ. Entomol. 94: 963–970.

**Stout, M. J., M. Rita Riggio, L. Zou, and R. Roberts. 2002.** Flooding influences ovipositional and feeding behavior of the rice water weevil (Coleoptera: Curculionidae). J. Econ. Entomol. 95: 715–721.

**Stout, M. J., D. Harrell, K. V. Tindall, and J. Bond. 2009.** Impacts of seeding rate on interactions between rice and rice water weevils. J. Econ. Entomol. 102: 1837–1845.

**Thompson, R. A., and S. S. Quisenberry. 1995.** Rice plant density effect on rice water weevil (Coleoptera: Curculionidae) infestation. Environ. Entomol. 24: 19–23.

**Way, M. O. 1990.** Insect pest management in rice in the United States, pp. 181–189. *In* B. T. Grayson, M. B. Green, and L. G. Copping (eds.), Pest management in rice. Elsevier Science Publishing Co., Inc., New York, NY.

**Wu, G. W., and L. T. Wilson. 1997.** Growth and yield response of rice to rice water weevil injury. Environ. Entomol. 26: 1191–1201.

**Yamauchi, M. 1994.** Physiological basis for higher yield potential in F1 hybrids., pp. 71–80, *In* S.S. Virman (ed.), Hybrid rice technology: New developments and future prospects. IRRI, Los Banos, Philippines.

**Yuan, L. P. 2003.** Recent progress in breeding super hybrid rice in China, pp. 3–6. *In* S.S. Virmani et al. (ed.), Hybrid rice for food security, poverty alleviation, and environmental protection. Proc. Int. Symp. on Hybrid Rice, 4th, Hanoi, Vietnam. 14–17 May 2002. IRRI, Los Banos, Philippines.

**Zhende, Y. 1988.** Agronomic management of rice hybrids compared with conventional varieties, pp. 217–223, *In* Hybrid Rice. IRRI, Los Banos, Philippines.

**Zou, L., M. J. Stout, and R. T. Dunand. 2004.** The effects of feeding by the rice water weevil, *Lissorhoptrus oryzophilus* Kuschel, on the growth and yield components of rice, *Oryza sativa*. Agric. For. Entomol. 6: 47–53.