The Effects of Four Insecticides on the Population Dynamics of the Rice Water Weevil, *Lissorhoptrus oryzophilus* Kuschel[1,2]

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J. Entomol. Sci. 35(1): 48-61 (January 2000)

Abstract The rice water weevil, *Lissorhoptrus oryzophilus* Kuschel, has been managed for the past 30 yrs using the soil insecticide carbofuran. The recent cancellation of the registration for carbofuran in rice has necessitated a shift to management strategies involving other insecticides, including lambda-cyhalothrin, fipronil, and diflubenzuron. Efficacies and effects on population dynamics of three alternatives to carbofuran (lambda-cyhalothrin and diflubenzuron as foliar sprays and fipronil as a seed treatment) were compared in two water-seeded and one drill-seeded field trials. Applications of lambda-cyhalothrin, but not of diflubenzuron or fipronil, resulted in decreases in the densities of rice water weevil adults and eggs. All three insecticides suppressed larval densities to levels comparable to, or lower than, densities in plots treated with carbofuran. All three alternatives to carbofuran differed from carbofuran with respect to their effects on the population dynamics of weevil larvae. Lambda-cyhalothrin, diflubenzuron, and fipronil were more effective than carbofuran at preventing early larval infestation of rice roots, but were less effective at preventing later infestation of roots. Yields from plots treated with fipronil, diflubenzuron, and lambda-cyhalothrin were generally higher than yields from plots treated with carbofuran, probably because prevention of early injury to roots has a more beneficial impact than prevention of later injury. This study also provided evidence for the utility of early planting and delayed flooding for management of the rice water weevil.

Key Words Rice, *Oryza sativa,* rice water weevil, *Lissorhoptrus oryzophilus,* population dynamics, cultural control, lambda-cyhalothrin, fipronil, diflubenzuron

The rice water weevil, *Lissorhoptrus oryzophilus* Kuschel (Coleoptera: Curculionidae), is the major insect pest of rice in the United States (Smith 1983, Way 1990). Although both larvae and adults of this insect feed on rice plants, it is feeding by the larval stage on rice roots which generally causes economic losses. Feeding by larvae of this insect can cause yield losses of up to 70% in Louisiana; yield losses over 10% are typical (Anonymous 1994).

Rice water weevil adults emerge from overwintering sites and invade flooded and unflooded rice fields in early spring (Everett and Trahan 1967, Muda et al. 1981, Smith 1983, Morgan et al. 1984, Palrang et al. 1993). Upon arrival in rice fields, adult weevils feed on the leaves of rice plants, but oviposition generally does not com-

[1]Received 01 December 1998; accepted for publication 16 May 1999.

[2]Approved for publication by the Director of the Louisiana Agricultural Experiment Station as manuscript number 97-17-0156.

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mence until rice fields are flooded (Everett and Trahan 1967, Muda et al. 1981, Smith 1983). Larvae feed externally on the roots and progress through four stadia and a pupal stage (Cave and Smith 1982, Smith 1983). Two, and a partial third, generations occur in southern Louisiana (Gifford and Trahan 1966, Smith 1983).

Application of granular carbofuran (Furadan®; FMC Corporation, Philadelphia, PA) has been, until recently, the only tactic used widely for control of the rice water weevil in rice (Way 1990). However, the registration for use of carbofuran in rice has recently been revoked, and carbofuran will not be available to growers following the 1998 growing season. This loss is expected to cost growers up to $48 million annually unless a suitable replacement can be found (Spradley and Widham 1995). Lambda-cyhalothrin (Karate®, Zeneca Ag Products, Wilmington, DE), a synthetic pyrethroid, fipronil (Icon®, Rhône-Poulenc Ag Company, Research Triangle Park, NC), a phenyl pyrazole, and diflubenzuron (Dimilin®, Uniroyal Chemical Company, Middlebury, CT) have recently been approved for use against rice water weevil in rice.

Use of these alternatives to carbofuran will necessitate several changes in management strategies for the rice water weevil. Carbofuran was used as a larvacide and was applied to flooded soil when weevil larvae attained a density of five or more per core sample in Louisiana, normally 2 wks or more after application of permanent flood. Of the three alternatives to carbofuran, only Icon is targeted against the larval stage. Icon is currently registered as a seed treatment in the United States; thus, a grower will decide at planting whether to treat for rice water weevil with Icon. In contrast, Karate and Dimilin will be used as foliar sprays, Karate as an adulticide and Dimilin as an ovicide. Accordingly, Karate and Dimilin will have their largest impacts on weevils when adults or eggs, respectively, are at their peak abundances, but will be ineffective against weevil larvae. An understanding of the population dynamics of rice water weevils in rice fields is necessary in order for application of these insecticides to be timed correctly. Despite its status as the major insect pest of rice in the US, however, there is a scarcity of published information about the behavior and population dynamics of adult rice water weevils.

These alternatives to Furadan will have different effects on the temporal pattern of rice water weevil larval infestation than did Furadan. Use of Furadan permitted early larval infestations but, because Furadan had a long residual activity, prevented infestations for several weeks after its application. Dimilin and Karate will normally be applied earlier in the growing season than Furadan, with the first applications being made within 10 d of permanent flood, and therefore should be more effective than Furadan at preventing very early larval infestations. However, because both compounds have relatively short residual activities, Dimilin and Karate will probably be less effective than Furadan at preventing later larval infestations unless multiple applications are made. Icon, like Karate and Dimilin, will be more effective at preventing early season infestation than Furadan because it is applied as a seed treatment, but it, like Dimilin and Karate, may allow later infestations of larvae.

The plant stage at which larval infestations occur is important. Young rice plants have less developed root systems than older plants and are likely to be more vulnerable to root injury than older plants. Using a physiologically-based plant population model, Wu and Wilson (1997) have recently provided evidence that very early injury to rice roots reduces yields to a gerater extent than does later injury. Because the alternatives to Furadan prevent very early injury to rice roots by weevil larvae, they may be more effective than Furadan at preventing yield losses.

In this paper, we report the results of three field comparisons of management strategies involving the use of Karate, Dimilin, Icon, and Furadan. These tests were conducted primarily to compare the efficacies and effects on rice water weevil population dynamics of Furadan, Icon, Karate, and Dimilin. Secondarily, the tests allowed us to test the hypothesis that injury to the roots of young rice plants reduces yield to a greater extent than does injury to roots of older rice plants. Effects on population dynamics were assessed by monitoring populations of rice water weevil adults, eggs, larvae, and pupae.

Materials and Methods

Experiments were conducted at three different sites during the 1998 growing season at the Louisiana State University Rice Research Station in Crowley, LA. The soil at all sites was a silt loam (fine, montmorillonitic, thermic Typic Albaqualf). The rice variety "Cypress" was used for all experiments.

The effects of Karate, Dimilin, Furadan, and Icon were assessed in two water-seeded tests and one drill-seeded test. Untreated and Furadan-treated plots were included in all three experiments. The three comparisons were planted at different times and were, thus, subject to different levels of weevil pressure. In all three tests, Icon was applied as a seed treatment and Karate and Dimilin treatments consisted of two applications of insecticide separated by approximately 1 wk (see below). Treatments were assigned to plots according to a randomized complete block design with five treatments and four replicates per treatment. Plots in all experiments measured 1.5 × 5.5 m and were individually barricaded with metal flashing (approximately 28 cm in height) to prevent movement of insecticides.

Rice culture. Plots for the first water-seeded experiment were initially flooded on 7 April 1998. Pre-germinated seed was hand-sown into plots at a rate of 146 kg per ha on 9 April. The field was drained on 14 April and left unflooded for 9 d, at which time the permanent flood was applied. Fertilizer (23-12-12 N-P-K) was applied at a rate of 114 kg N per ha on 22 April. A second application of fertilizer (23-12-12) at a rate of 34 kg N per ha was made on 27 May. A single post-emergence application of Londax® (E.I. du Pont Nemours and Company, Wilmington, DE) was made to control weeds on 11 May. Entire plots were harvested on 12 August using a Kubota harvester. Yields were expressed as grams of rough rice per plot, adjusted to 12% moisture.

Plots for the second water-seeded experiment were initially flooded on 11 May 1998. Pre-germinated rice was sown by hand on 14 May at a seeding rate of 146 kg per ha. Plots were drained on 16 May and permanent flood was applied on 25 May. A pre-plant application of fertilizer (23 kg N/ha of 7-21-21 N-P-K) was made on 12 May. Urea (114 kg N/ha) was applied to flooded plots on 5 June. Another application of urea (51 kg N/ha) was made on 17 June. Weeds were controlled with a single application of a mixture of Stam® (propanil; Rohm and Haas Company, Philadelphia, PA) and Londax on 21 May. Entire plots were harvested on 3 September. Yields were expressed as grams of rough rice per plot, adjusted to 12% moisture.

For the drill-seeded experiment, rice was seeded using a Kincaid drill on 12 May 1998. Plots were flushed with water on 21 May and 29 May. Permanent flood was applied approximately 3½ wks after planting, on 4 June. Fertilizer (23 kg N/ha of 7-21-21 N-P-K) was pre-plant incorporated on 12 May 1998. A second application of fertilizer (114 kg N/ha of 45-0-0 N-P-K) was made on 17 June. Weeds were controlled with a single application of Stam on 2 June. Four of seven rows in each plot were harvested on 3 September. Partial yields were deemed to be representative of treatment effects on yields because drill-seeding results in an even distribution of plants in a plot.

Insecticide treatments and pest sampling. Adults were sampled by placing a 30.5-cm diam ring over plants and counting the number of adults observed within the ring. Rings were constructed of Tygon® tubing and defined an area of 0.073 m^2. Adult counts began 1 d after permanent flood and were made every 1 to 4 d thereafter for approximately 25 d. Adults were always sampled between 0800h and 1200h. Adults were sampled from all plots. Three adult counts were taken per plot, and data from the three counts were averaged for analysis.

Densities of eggs in plots were estimated in the second water-seeded test only by periodically removing five plants from each plot and storing plants in 95% alcohol for later analysis. Eggs in leaf sheaths were stained using the method of Gifford and Trahan (1969) and counted under a dissecting microscope. Densities of eggs were expressed as number of eggs per plant.

Densities of rice water weevil larvae and pupae in plots were estimated by taking three soil cores from each plot and counting the number of immature rice water weevils associated with roots. Core samples were taken using a metal cylindrical sampler (9.2 cm in diam, with a depth of 7.6 cm). Core samples contained from 1 to 10 rice plants (core samples generally contained more plants when plants were small). Samples were processed by placing them in screen-mesh sieve buckets (40-mesh) and washing soil from roots. Buckets were then placed into basins of salt water, and larvae and pupae were counted as they floated to the surface of the salt solution. Immature rice water weevils were sampled at approximately weekly intervals beginning 10 to 14 d after flooding and ending approximately 5 to 6 wks after flooding. For analysis, numbers of larvae and pupae were summed and numbers of immatures from the three cores from each plot were averaged.

Timings of Karate and Dimilin applications were based on intensive adult sampling, with first applications of Dimilin and Karate made when densities of rice water weevil adults reached an arbitrary treatment threshold of one adult weevil per 0.073 m^2. Second applications of Dimilin and Karate were made approximately 1 wk after the first. Dimilin was applied at a rate of 0.14 kg AI per ha; Karate, at a rate of 0.034 kg AI per ha. Dimilin and Karate were applied using a backpack, CO^2-powered sprayer. Treatment dates for Dimilin and Karate were as follows: water-seeded experiment 1, 4 May and 11 May, 1998; water-seeded experiment 2, 27 May and 2 June, 1998; drill-seeded experiment, 8 June and 15 June, 1998.

Icon (0.0425 kg AI/ha) was applied as a seed treatment using methods recommended by the manufacturer. Broadcast applications of Furadan (0.68 kg AI/ha) were made to appropriate plots when larval densities exceeded five per core (the treatment threshold recommended by the Louisiana State University Agricultural Experiment Station). Treatment dates for Furadan were as follows: water-seeded experiment 1, 21 May 1998; water-seeded experiment 2, 19 June; drill-seeded experiment, 19 June.

Analyses of data. All data were analyzed using the PROC GLM of SAS (SAS Institute 1989). The effects of insecticide treatments on adult and larval densities were analyzed in two ways. Repeated-measures analysis of variance, with sampling date as the within-subjects factor (SAS Institute 1991), was performed using non-transformed adult and larval counts. Separate analyses were conducted for adult and larval data from each of the three experiments. In addition, analyses of variance were conducted using total numbers of adults and larvae found in plots over the course of each experiment. Total numbers of adults or larvae were obtained by summing the average numbers of adults per ring from 9 to 10 samples for each plot or by summing the average number of larvae per core from 5 samples for each plot. Data were log-transformed before analysis, and Duncan's multiple range test was used for mean separations.

Eggs were found in densities sufficient for analysis on 5 June, 9 June, and 15 June 1998. Egg data from each of these dates were analyzed separately for treatment and block effects using two-way analysis of variance. Egg densities were log-transformed before analysis.

Yield data were analyzed for treatment and block effects using a two-way analysis of variance on non-transformed yields. Mean separations were conducted using Duncan's multiple range test. In addition, a specific test for differences in yields from plots treated with Furadan and with the three other insecticides was conducted. Data from the two water-seeded tests were pooled and yields from plots treated with Furadan were compared with yields from plots treated with Icon, Dimilin, and Karate using the CONTRAST statement in PROC GLM (SAS Institute 1989).

Results

Effects of insecticides on adult densities. Rice water weevil adults invaded plots more rapidly, and were more abundant, in the drill-seeded and second water-seeded experiments than in the first water-seeded experiment, undoubtedly because of the earlier planting date for the first water-seeded experiment (see Thompson et al. 1994). Threshold for treatment with Dimilin and Karate was reached within 4 d after permanent flood for the drill-seeded and second water-seeded tests, but was not reached until 11 d after permanent flood for the first water-seeded test.

Karate was the only insecticide that reduced densities of adults (Fig. 1). As Figure 1a illustrates, the effect of Karate on adult populations was short-lived, and plots were quickly re-invaded following treatment. Statistical analyses of the adult data did not always show an overall significant treatment effect because the period of residual activity was short relative to the period in which adults were sampled and because of high densities of adults. However, significant time X treatment effects were found in the repeated-measures analyses for both water-seeded tests (data not shown), indicating that, as expected, the effect of treatment varied with sampling date. When data from adult counts taken within 2 wks of initial insecticide applications were analyzed separately, a significant effect of Karate application on adult densities was found in the two water-seeded experiments but not the drill-seeded experiment (statistics not shown; Fig. 1b). The failure to detect effects of Karate in the third experiment was probably due to low replication and very high weevil densities in this experiment.

Effects of insecticides on egg densities. Low densities of rice water weevil eggs (less than one egg per plant for all treatments) were found both 1 d and 3 d after establishment of permanent flood (Fig. 2), suggesting that either a small number of eggs was laid before flooding or that female weevils begin ovipositing quickly after flood waters were applied. Densities of eggs were still low 11 d after permanent flood (9 d after the first application of Dimilin and Karate and 3 d after the second application), with an overall mean density of 0.56 eggs per plant (Fig. 2). Egg densities on this date were highest in Karate-treated plots, although a significant effect of treatment was not found in the analysis of variance ($P > 0.05$). Egg densities steadily increased over the next two sampling dates (Fig. 2). Fifteen days after permanent

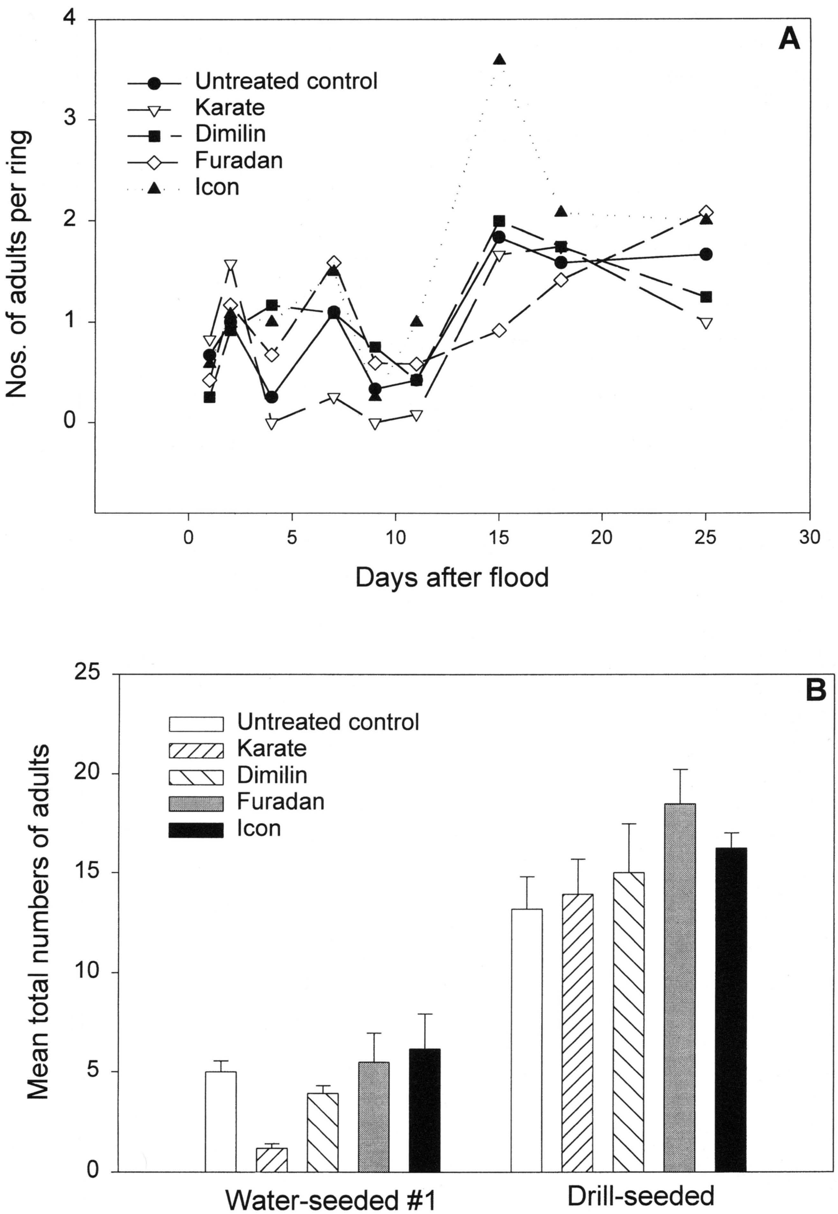

Fig. 1. Effects of four insecticides (and untreated control) on densities of adult water weevils. A: Mean (±S.E.) numbers of adults found per sampling ring over nine sampling dates in the second water-seeded experiment. B: Mean total numbers of adults (±S.E.) found in sampling ring over five sampling dates in water seeded experiment #1 and the drill-seeded experiment.

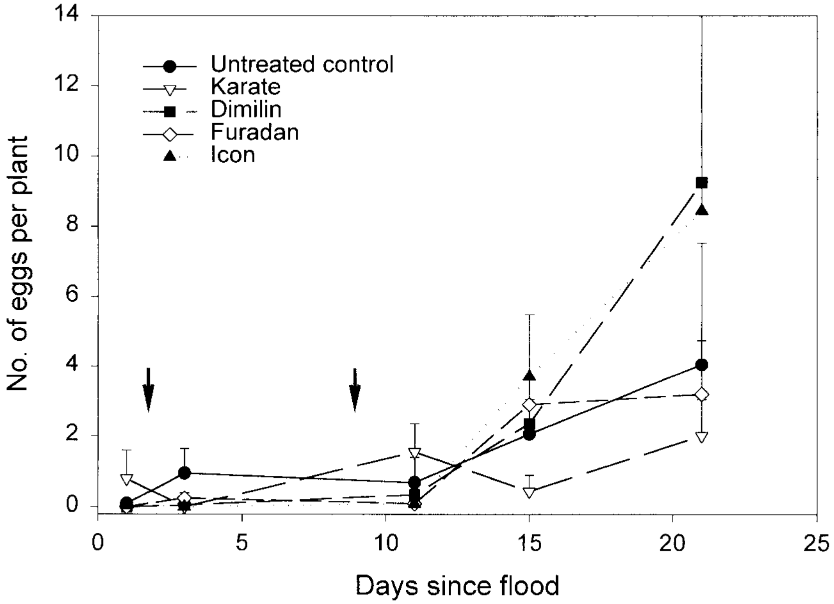

Fig. 2. Effects of four insecticides on densities of rice water weevil eggs in the second water-seeded experiment. Densities are expressed as mean (±S.E.) number of eggs per plant. Arrows signify dates on which Karate and Dimilin were applied.

flood (7 d after the second application of Dimilin and Karate), egg densities were significantly lower in the Karate-treated plots (Fig. 2; $P < 0.05$ for treatment effect) than in the other plots. Egg densities were again lowest in Karate-treated plots 21 d after permanent flood (Fig. 2), although the differences between plots in egg densities were not significant ($P > 0.05$).

Effects of insecticide applications on immature stages. In the first water-seeded test, the total numbers of larvae sampled from plots treated with Dimilin, Karate, Furadan, and Icon were lower than the total number of larvae sampled from untreated plots (Tables 1, 2). Karate and Dimilin were more effective at suppressing larval densities than Furadan and Icon in this experiment, although all insecticides reduced larval densities by at least 50% (Table 2, Fig. 3a). The temporal pattern of larval suppression differed for the different insecticide treatments, as evidenced by a significant time by treatment interaction in the repeated-measures analysis. Larval densities in Karate-, Icon- and Dimilin-treated plots were lower than densities in Furadan-treated plots for the first four sampling dates, but higher than densities in Furadan-treated plots on the last sampling date (Fig. 3a).

In the second water-seeded test, both the Icon and Karate treatments were very effective at reducing larval densities below those found in untreated plots, with total numbers of larvae found in these plots less than a third of the total number of larvae found in untreated plots (Tables 1, 2). Control provided by these two insecticides was also significantly better than control provided by Furadan or Dimilin in this experiment

Table 1. Results of repeated-measures analyses of variance of larval counts through time and results of two-way analyses of variance of total larval counts from two water-seeded experiments and one drill-seeded experiment. Treatments in all experiments consisted of different insecticides, and the "time" factor in the repeated-measures analyses is date of larval sampling. *, $P < 0.05$; **, $P < 0.01$; ***, $P < 0.001$

Source of variation	Experiment								
	Water-seeded #1			Water-seeded #2			Drill-seeded		
	df	*MS*	*F*	df	*MS*	*F*	df	*MS*	*F*
Repeated-measures analysis									
Between-subjects									
Block	3	5.8	0.4	3	45.3	2.1	3	33.4	0.8
Treatment	4	95.6	5.7**	4	269.6	12.7***	5	387.7	9.3***
Error	12	16.7		12	21.2		15	41.5	
Within subjects									
Time	3	54.5	9.2***	4	452.0	50.9***	4	925.5	52.4***
Time*Block	9	35.0	5.9***	12	15.1	1.7	12	23.7	1.3
Time*Treatment	12	20.7	3.5**	16	48.9	5.5***	20	46.8	2.6**
Error(time)	36	5.9		48	8.9		60	17.7	
ANOVA of larval totals									
Block	3	0.07	0.6	3	0.05	2.03	3	0.04	1.62
Treatment	4	0.3	2.5	4	0.28	12.2***	5	0.49	21.0***
Error	12	0.1		12	0.02		15	0.20	

Table 2. Mean total numbers of larvae (±S.E.) sampled from five soil cores taken over a five week period in untreated plots and in plots treated with Karate, Dimilin, Icon, and Furadan in two water-seeded experiments and one drill-seeded experiment. Means followed by same letter are not significantly different (Duncan's multiple range tests on log-transformed total larval counts)

	Mean total number of larvae		
Treatment	Water-seeded #1	Water-seeded #2	Drill-seeded
Untreated control	34.73 ± 4.29 a	56.64 ± 7.61 a	70.13 ± 7.38 a
Karate	11.43 ± 4.94 b	16.79 ± 5.29 c	26.84 ± 7.44 ab
Dimilin	10.98 ± 4.17 b	47.50 ± 7.59 ab	40.81 ± 4.09 ab
Furadan	16.80 ± 3.32 ab	27.79 ± 3.22 b	53.42 ± 5.24 a
Icon	15.03 ± 1.15 ab	15.60 ± 2.92 c	7.87 ± 1.40 c

(Table 2). Larval suppression due to applications of Dimilin, Karate, and Icon was more effective early in the season than late in the season; Furadan-treated plots showed the opposite trend (indicated by a significant time by treatment interaction in the repeated-measures analysis) (Fig. 3b).

In the drill-seeded experiment, treatment with all four insecticides resulted in a reduction in the number of larvae found in plots, but there were significant differences in the effectiveness of the different insecticides (Tables 1, 2). Icon gave the best control of larvae in this experiment, with total numbers of larvae found in Icon-treated plots about 90% lower than total numbers of larvae found in untreated plots. Larval suppression due to the other treatments ranged from 24% (Furadan) to 62% (two applications of Karate) (Table 2). Once again, the insecticides differed in their effects on larval population dynamics, with early larval densities in Furadan-treated plots higher than early larval densities in all other plots (Fig. 3c).

Effects of insecticide applications on rice yields. In both water-seeded tests, yields were lowest in untreated plots, intermediate in plots treated with Dimilin, Karate, and Furadan, and highest in plots treated with Icon (Table 3). Yields from Icon-treated plots were significantly higher ($P < 0.05$) than yields in control plots in both experiments. In the first water-seeded experiment, yields in Karate- and Dimilin-treated plots were significantly higher than yields from untreated plots, but yields from Furadan-treated plots were not significantly higher than yields from control plots. In the second experiment, yields from Karate- and Furadan-treated plots but not from Dimilin-treated plots were significantly higher than yields from control plots.

A combined analysis of yields from the two water-seeded tests was performed to test the hypothesis that treatment with insecticides that prevent early infestation of rice roots (i.e., Karate, Dimilin, and Icon) have a larger positive impact on rice yields than treatment with Furadan. Average yields from Dimilin-, Karate-, and Icon-treated plots were significantly higher ($P = 0.05$) than average yields from Furadan-treated plots.

In the drill-seeded test, significant differences in yields were not found, although

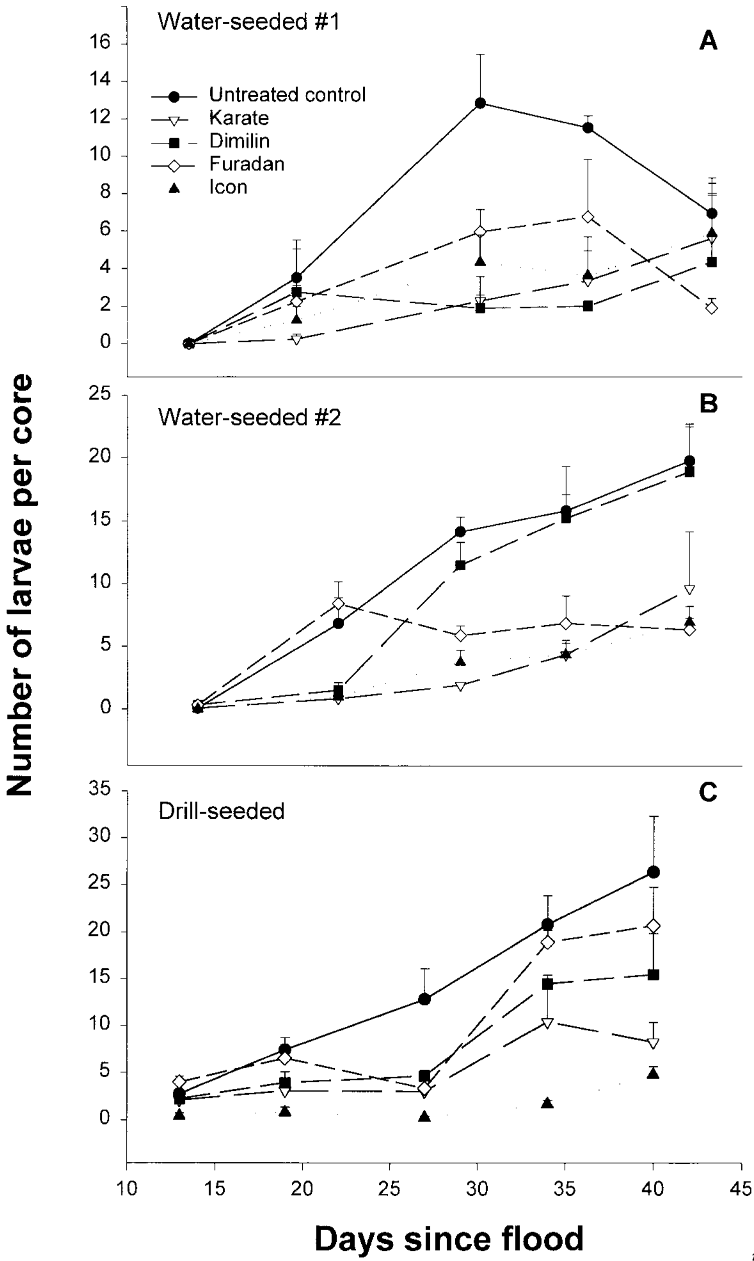

Fig. 3. Mean (±S.E.) number of larvae per core over five sampling dates in untreated plots and in plots treated with Karate, Dimilin, Furadan, and Icon. Data from two water-seeded (A,B) and one-drill seeded experiment (C) are shown.

Table 3. Mean yields per plot (±S.E.) from untreated and insecticide-treated plots in two water-seeded experiments and one drill-seeded experiment. For both water-seeded experiments, yields are from entire 1.5 × 5.5 m plots; for the drill-seeded test, yields are from four rows of 1.5 × 5.5 m plots. All yields are adjusted to 12% moisture. Means followed by the same letter are not significantly different (Duncan's multiple range tests)

	Yields in grams per plot		
Treatment	Water-seeded #1	Water-seeded #2	Drill-seeded
Untreated control	4071.2 ± 137.1 c	3437.4 ± 180.9 bc	2326.6 ± 192.6 a
Karate	4536.8 ± 59.5 ab	4533.9 ± 105.2 a	2009.9 ± 88.6 a
Dimilin	4647.8 ± 274.8 ab	3885.2 ± 151.9 ab	2300.6 ± 114.6 a
Furadan	4135.8 ± 152.3 bc	4199.8 ± 231.7 a	2186.7 ± 135.9 a
Icon	4688.6 ± 116.5 a	4610.1 ± 176.6 a	2330.7 ± 63.0 a

yields from Icon-treated plots were again numerically higher than yields from all other plots (Table 3).

Discussion

The rice water weevil is the most injurious insect pest of rice in the United States, and is a particularly severe pest in southern Louisiana (Smith 1983). In the experiments reported here, yields from untreated plots were, on average, 17% lower than yields from Icon-treated plots (Table 3; Icon plots had the highest yields in all three experiments). A 17% reduction represents a loss of approximately $205 per hectare to farmers (assuming an average yield of 6124 kg/ha and a $9/cwt grain price). Thus, the necessity of effective alternatives to Furadan is evident. In both the water-seeded and drill-seeded tests, treatment of seeds with Icon and treatment of plots with two applications of Karate and Dimilin provided control of rice water weevil larvae that was as good as, or better than, control provided by Furadan. In the first water-seeded test, larval densities were lowest in plots treated with Dimilin; in the second water-seeded test and in the drill-seeded test, larval densities were lowest in plots treated with Icon (Table 2; Fig. 3). Larval densities in Karate-treated plots were always lower than densities in Furadan-treated plots (Table 2; Fig. 3). These results, as well as data from several large-plot tests (Stout et al. 1997, Ring et al. 1997, Muegge et al. 1996), indicate that all three potential alternatives to Furadan will adequately control rice water weevil, provided applications are timed correctly.

The population dynamics of the rice water weevil were differentially affected by the different insecticides (Figs. 1-3). Applications of Karate reduced adult, egg, and larval densities, but applications of Dimilin, Icon, and Furadan reduced larval densities without reducing adult or egg densities. No evidence was found for the presence of lethal or non-lethal effects of Dimilin or Icon on rice water weevil adults or on rice water weevil oviposition. The temporal patterns of egg and larval densities found in this study are similar to those reported by Barbour and Muegge (1995).

Larval densities in Icon-, Dimilin-, and Karate-treated plots were low in the first few larval samplings for all three experiments, but usually were higher in the later samplings (Fig. 3). Larval densities in Furadan-treated plots showed the opposite trend: larval densities were high in the first few samplings, but decreased in the later samplings. The differential effect of Furadan and its alternatives on the population dynamics of rice water weevil larvae is illustrated for the second water-seeded experiment in Fig. 4. In plots treated with Furadan, a high proportion of the total number of larvae sampled from plots were found in the early samplings (14, 22, and 29 d post-flood); whereas, higher proportions of the total numbers of larvae found in plots treated with Icon, Karate, and Dimilin were found in later samplings (35 and 42 d post-flood). This differential effect on population dynamics occurred primarily because Furadan was applied in accordance with Louisiana State University Cooperative Extension guidelines, when larval densities exceeded five per core. The timing of Furadan applications in these experiments reflects the practices of rice producers in the state of Louisiana, where many producers do not apply Furadan until near mid-season.

Based on a physiological plant population model, Wu and Wilson (1997) predict that injury by rice water weevil larvae during early stages of rice growth will cause greater reductions in yield than injury during later stages of growth. Two results from our experiments support this prediction. First, plots treated with insecticides that were effective at reducing the levels of very early weevil infestations gave significantly higher yields in the two water-seeded tests than did plots treated with Furadan (Table

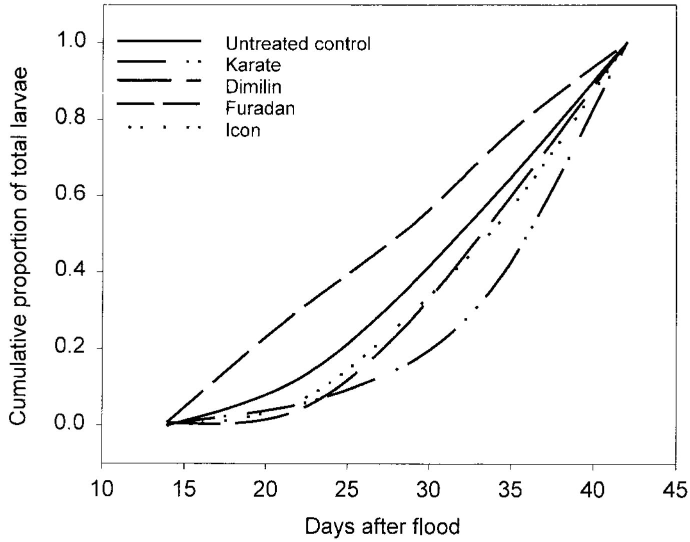

Fig. 4. Cumulative proportions of the total numbers of larvae found in plots over the course of five samplings as a function of treatment and days since flooding. Data are from the second water-seeded test.

3). Second, rice plants in the drill-seeded experiment, in which plants were larger at the time of rice water weevil infestation, appeared to be more tolerant of root injury. This greater tolerance of root injury is evidenced by the failure to observe differences in yields in this experiment despite a wide disparity in weevil pressures, ranging from a total of almost 70 weevils per five samplings in the untreated plots to under 10 weevils per five samplings in the Icon-treated plots (Tables 2, 3).

The results of these experiments indicate that applications of Karate, Dimilin, and Icon may be combined with cultural practices that reduce the level of larval infestations on very young plants. Temporal avoidance of weevils by early planting of fields is one such practice (Thompson et al. 1994). Threshold for treatment with Dimilin and Karate was reached later in the early water-seeded trial than in the later water-seeded trial, and plants in the early water-seeded trial were exposed to 30 to 40% fewer rice water weevil adults and larvae than plants in the late water-seeded trial (Fig. 1b, 3). These differences in the timing and magnitude of weevil pressure may have been responsible for the greater yield reduction in the second water-seeded test than in the first water-seeded test.

Another cultural practice that may contribute to management of the rice water weevil is delaying the establishment of permanent flood. Because female weevils generally do not oviposit until rice fields are flooded (Everett and Trahan 1967, Muda et al. 1981, Smith 1983), delayed flooding alters the time course, if not the absolute level, of rice water weevil infestation of roots. By delaying injury to rice roots until plants are less vulnerable, delayed flooding may increase the tolerance of plants to the rice water weevil. In our drill-seeded experiment, flooding was delayed by approximately 2 wks relative to the water-seeded experiments. This delay in flooding did not reduce weevil pressure—in fact, adult and larval populations were highest in the drill-seeded experiment—but apparently did increase the tolerance of plants to root injury, because no significant differences between yields from treated and untreated plots were found. Rice et al. (1999) recently reported that delaying flooding by 2 to 4 wks in drill-seeded rice resulted in reduced densities of rice water weevil larvae and in reduced yield losses from rice water weevil feeding. Thus, short delays in flooding may be a valuable strategy for rice water weevil control. Unfortunately, even short delays in flooding may not be possible in all rice growing areas. Water-seeding and continuous or near-continuous flooding are practiced in California, southern Louisiana, and Texas for weed control (Way 1990), and altering water management practices for rice water weevil control may compromise weed control in these regions.

Acknowledgments

These research was supported by grants from the Louisiana Rice Research Board and the USDA-CSREES. We thank P. Bollich, B. Henry, and J. Hoffpaur for assistance with experiments.

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