Effects of Rate and Timing of Fungicide Applications on Incidence and Severity of Sheath Blight and Grain Yield of Rice

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ABSTRACT

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Incidence and severity of rice sheath blight, caused by *Rhizoctonia solani*, were monitored in 1989 and 1990 from the green ring growth stage to maturity in nonsprayed, inoculated plots and inoculated plots sprayed with propiconazole and other fungicides at different rates and growth stages. Single green ring applications of propiconazole at 0.18, 0.32, or 0.48 kg a.i./ha and sequential green ring and boot sprays (0.18 + 0.18 and 0.32 + 0.32 kg a.i./ha) effectively reduced disease incidence over time. Severity of sheath blight over time, expressed as percent lesion height to total sheath height, was increased by green ring applications. With the loss of fungicidal activity over time, lesions on treated tillers progressed upward at a faster rate and reached higher levels than on nonsprayed tillers. Single boot applications at 0.18, 0.32, or 0.48 kg a.i./ha; boot applications of propiconazole at 0.32 kg a.i./ha followed by heading applications of either benomyl, iprodione, or pencycuron; or boot and heading sprays of benomyl (0.57 + 0.57 kg a.i./ha) had little effect on disease incidence. In contrast, disease severity was significantly reduced by all boot and heading treatment combinations. Disease progress measured as incidence or severity was reduced most effectively by the application of pencycuron at boot and heading (0.18 + 0.18 kg a.i./ha). Consistent positive yield responses compared with the nonsprayed control resulted from all boot and heading applications, whereas green ring applications generally resulted in a negative yield response. Yields were significantly negatively correlated with areas under the disease progress curves (AUDPC) based on weekly severity measurements. Yields were not correlated with AUDPC for disease incidence over time.

Sheath blight, caused by *Rhizoctonia solani* Kühn (*Thanatephorus cucumeris* (Frank) Donk) (15) anastomosis group 1 IA (AG-1 IA), is a major disease of rice (*Oryza sativa* L.) in the United States (6,12). The disease has also increased in importance worldwide, causing serious losses in both temperate and tropical rice-producing countries (14,17). Major factors associated with the increased occurrence of sheath blight include the widespread cultivation of high-yielding but highly susceptible long-grain cultivars, the high tillering capacity of these mostly semidwarf cultivars which creates a favorable microclimate for disease development, and the tendency to apply higher rates of nitrogen fertilizers resulting in increased susceptibility (12). Another important contributing factor, relevant to the rice-producing areas of the southern United States, is the use of soybean (*Glycine max* (L.) Merr.) as a rotation crop with rice. Aerial blight of soybean, caused by the same intraspecific group of *R. solani*, sustains sheath blight epidemics in rice by increasing the numbers of sclerotia in field soil that serve as primary inoculum (1,16).

In the United States, control strategies for this potentially devastating disease have centered around the use of foliar fungicides (6,11,31). Due to the absence of satisfactory levels of resistance in existing cultivars or the ineffectiveness and/or impracticality of recommended cultural control measures, rice growers are restricted to the use of chemicals for disease management (6).

Benomyl (Benlate), iprodione (Rovral), propiconazole (Tilt), thiabendazole (Folatec), and copper plus sulfur (Top-Cop) are currently registered for commercial use in the United States. Evaluation of these fungicides for sheath blight control performance (6,10,11) are based on determination of disease incidence and estimation of visual canopy damage (0–9 scale) (6,9). These assessments are usually made once at the end of the growing season.

Although these measures are adequate and efficient for field screening of new products, disease assessment at several times during the growing season is essential to understand how fungicides impact disease progress over time. Disease progress curves can be used to approximate the length of residual fungicidal activity. Also, the effect of timing of application, an important factor in chemical control of sheath blight (3), can be assessed more precisely when disease measurements are made throughout the season. Despite these benefits, no published accounts are available on how sheath blight epidemics are affected by fungicides used in the United States.

Time-course evaluations require a disease assessment method suitable for weekly assessments. Traditional sheath blight ratings, determined at the whole-plot level, do not fulfill this requirement, so other methods must be adopted.

Results are reported from a 2-yr study on the effects of rate and timing of application of propiconazole and other selected fungicides on sheath blight incidence over time, disease severity over time, and grain yield of rice. A sheath blight severity assessment method suitable for this type of study is described.

MATERIALS AND METHODS

Experiments were conducted at the Louisiana State University Rice Research Station, Crowley, LA, during the 1989 and 1990 growing seasons. Experimental units were plots 1.2 by 2.4 m (1989) and 1.2 by 4.9 m (1990) consisting of seven drill strips with 18-cm row spacings and 35-cm alleys. The plots were drill-seeded with rice cv. Lemont on 28 April 1989 and 24 April 1990 with 112 kg of seed per hectare. At planting, 670 kg/ha of 20-10-10 (1989) and 13-13-13 (1990) NPK fertilizer was drilled over the test area. Propanil (Prostar 4E) at 4.5 kg a.i./ha (1989) or propanil plus bentazone (Basagran) at 0.75 kg a.i./ha (1990) were applied for weed control immediately before applying the permanent flood. In 1989, the plots received a 112 kg/ha application by airplane of 21% ammonium sulfate fertilizer 1 wk after the green ring stage (first internode starting to elongate). In both years, carbofuran (Furadan 3G) at 0.6 kg a.i./ha was applied 1 wk after flooding to control the rice water weevil (*Lissorhoptrus oryzophilus* Kushel).

Inoculation. At maximum tillering stage (5 June 1989 and 11 June 1990), the plots were inoculated with *R. solani* isolate LR 172 grown for 20–30 days on an autoclaved rice grain/rice hull (1:2) mixture. Approximately 40 ml of inoculum (13 ml/m^2) was distributed evenly over each plot in 1989. In 1990, the amount of inoculum per square meter was doubled to increase the potential for a higher disease pressure.

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Fungicide application. Propiconazole (Tilt 3.6 EC) was applied at 0.18, 0.32, and 0.48 kg a.i./ha at either the green ring stage (15 June 1989 and 1990), early boot stage (1- to 5-cm panicle in the boot) (2 July 1989 and 29 June 1990), or sequentially at green ring and early boot. Propiconazole was also applied as an early boot spray (0.32 kg a.i./ha) followed by a heading (70–80% of panicles emerged) (17 July 1989 and 18 July 1990) application of either benomyl (Benlate 50 DF) at 0.57 kg a.i./ha, iprodione (Rovral 50WP) at 0.57 kg a.i./ha, or pencycuron (Monceren 50WP) at 0.18 kg a.i./ha. Sequential sprays at boot and heading of both benomyl and pencycuron were also included (Table 1). The chemicals were applied in water at 189 L/ha with a backpack CO_2-sprayer equipped with a two-nozzle boom. Nonsprayed, inoculated or noninoculated plots served as control treatments. The treatments were arranged in a randomized complete block design with six (1989) or five (1990) replications.

Disease assessment and yield determination. Twenty-five tillers were randomly chosen at each of four locations per plot and the number of diseased tillers was counted. Disease incidence was then expressed as the percentage of diseased tillers out of 100 tillers per plot. Incidence was assessed weekly from green ring to maturity in control plots and plots that received a green ring fungicide application. For treatments that did not include a green ring application, weekly incidence assessments started at the early boot stage. These treatments were "control" treatments up to the early boot stage; therefore, disease incidence progress before that stage was assumed to be the same as that of the control treatment.

Tillers with early developing, water-soaked lesions on the lower first and/or second sheath near the waterline were flagged. In 1990, five tillers per plot were flagged at the green ring stage and monitored up to maturity for the control treatment and those treatments that included a green ring propiconazole application. In addition, four (1989) or five (1990) tillers per plot were flagged at the early boot stage and monitored up to maturity for all treatments. For each flagged tiller, the height of the uppermost sheath lesion and the total sheath height were measured from the soil level. Disease severity at each assessment was determined by expressing lesion height as a percentage of the total sheath height.

Three days (1989) or 1 day (1990) before harvest, each plot was given a whole-plot 0–9 rating where 0 represented no disease and 9 indicated plots with most of the plants dead at maturity. A detailed description of this rating system is given by Groth et al (6).

On 21–22 August 1989 and 16 August 1990, the center four rows of each plot (1.5 and 3.5 m^2, respectively) were harvested with a small-plot combine. Yields were recorded after correction of rough grain weights to 12% moisture.

Data analysis. Disease progress curves for incidence and severity were plotted separately using the weekly assessment data. The area under the disease progress curves (AUDPC) was calculated by trapezoidal integration as described by Shaner and Finney (30). AUDPC values were divided by the total duration of the assessment period and are referred to as relative AUDPC (rAUDPC). For the treatments for which disease incidence was not assessed before the early boot stage, the disease incidence values of the control treatment before that stage were used to theoretically extend the incidence progress curves over the entire assessment period. Relative AUDPCs for incidence could then be directly compared statistically over all treatments.

Statistical data analysis was performed using the procedures available in the SAS

Table 1. Sheath blight incidence and severity in Lemont rice plots sprayed with foliar fungicides at different rates and at different plant growth stages

Treatment	Rate (kg a.i./ha)	Timing[u]	Mean percent diseased tillers at maturity[v]		Mean disease rating at maturity[w]		rAUDPC for disease incidence[x] (GR to maturity)		rAUDPC for disease severity[y]		
									B to maturity		GR to maturity
			1989	1990	1989	1990	1989	1990	1989	1990	1990
Uninoculated control			5 f[z]	12 f	0.5 e	1.2 e					
Inoculated control			95 a	95 a	4.2 bc	6.6 ab	60.0 a	72.5 a	68.5 ab	65.8 cd	73.4 a
Propiconazole	0.18	GR	85 a–d	92 a–c	4.3 a–c	7.6 a	46.1 b–d	47.0 de	61.9 bc	75.0 ab	70.8 a
Propiconazole	0.32	GR	76 cd	86 a–d	4.5 a–c	7.2 ab	38.7 de	50.6 c–e	68.9 ab	76.2 a	71.3 a
Propiconazole	0.48	GR	78 b–d	80 a–e	5.2 a	6.6 ab	43.8 c–e	42.9 e	76.3 a	75.9 a	67.2 a
Propiconazole	0.18	B	92 ab	93 ab	4.3 a–c	7.2 ab	59.3 a	67.2 ab	64.8 b	69.1 bc	
Propiconazole	0.32	B	90 a–c	85 a–d	3.8 c	7.0 ab	52.6 a–c	56.7 b–d	53.4 d	61.1 d	
Propiconazole	0.48	B	92 ab	80 a–e	3.7 c	6.2 b	56.2 ab	56.1 b–e	55.5 cd	59.8 d	
Propiconazole	0.18	GR + B	91 a–c	78 b–e	5.0 ab	7.2 ab	38.2 de	47.4 de	64.9 b	70.9 a–c	72.4 a
Propiconazole	0.32	GR + B	72 d	75 de	4.5 a–c	7.4 ab	35.4 e	42.6 e	66.7 b	73.4 ab	72.0 a
Propiconazole + benomyl	0.32 +0.57	B + H	83 a–d	83 a–d	2.5 d	2.2 de	58.0 a	63.2 a–c	50.2 de	52.9 e	
Propiconazole + iprodione	0.32 +0.57	B + H	78 b–d	67 de	1.8 d	2.6 d	53.6 a–c	53.5 b–e	54.4 cd	53.1 e	
Propiconazole + pencycuron	0.32 +0.18	B + H	87 a–d	80 a–e	2.2 d	2.8 d	58.7 a	60.4 a–d	50.9 de	48.0 ef	
Benomyl	0.57	B + H	78 b–d	76 c–e	2.0 d	4.4 c	52.5 a–c	63.3 a–c	47.8 de	52.4 e	
Pencycuron	0.18	B + H	52 e	63 e	1.7 d	1.5 de	37.9 de	61.8 a–d	43.9 e	44.5 f	

[u] Fungicides were applied at the green ring (GR), boot (B), and/or heading (H) growth stage of rice.
[v] Percentage of diseased tillers determined from counts of 25 tillers at each of four randomly chosen locations per experimental unit. Means are from six and five plots per treatment in 1989 and 1990, respectively.
[w] Ratings determined at the whole-plot level based on a scale of 0 = no disease to 9 = severe disease (6). Means are from six and five plots per treatment in 1989 and 1990, respectively.
[x] Area under disease progress curve was calculated based on percentage of diseased tillers determined at weekly intervals from green ring (GR) stage to maturity. Calculated areas were divided by the total duration of the assessment period (58 days in both years), yielding relative values in the range of 0–100.
[y] Relative area under disease progress curve based on percent lesion height determined on 24 and 25 rice tillers per treatment in 1989 and 1990, respectively, at weekly intervals from boot (B) stage to maturity or from green ring (GR) stage to maturity in 1990. Total assessment duration was 41 and 44 days, respectively. Relative AUDPCs for tillers at B stage in both years were adjusted for initial percent lesion height according to analysis of covariance using PROC GLM and the LSMEANS statement available in the SAS computer package (28,29).
[z] Means in columns followed by the same letter are not significantly different according to Fisher's LSD ($P = 0.05$).

computer package (28,29). Analysis of variance (ANOVA) combined with Fisher's least significant difference (LSD) multiple comparison procedure were used to compare treatment rAUDPC and yield means. To compare treatment incidence, severity, and sheath height means at each assessment time within each year, the data were analyzed with repeated measures ANOVA. Incidence and sheath height data were normally distributed; severity data, however, were not. Transformation [arcsine ($y^{1/2}$), log(y), log($y^{1/2}$)] of the severity values (13) failed to normalize the data distributions and stabilize variances. Therefore, nonparametric analyses were performed using PROC RANK and PROC GLM. However, because means obtained by these procedures have no biological meaning, raw means were calculated. Because variations in initial disease severity (disease severity of the tillers at the time of flagging) could be attributable to the variation in subsequent severity assessments or AUDPC values, initial disease severity was considered as a covariable. When the covariable was statistically significant in the overall models, adjusted treatment means were obtained by the LSMEANS statement in PROC GLM (29).

The need for correction for serial correlation (13) was determined based on the sphericity tests obtained through the REPEATED statement in PROC GLM (29). Where appropriate, Greenhouse-Geisser (G-G) adjusted probabilities were adopted (29). Fisher's LSD was calculated for multiple treatment comparisons when a main effect or interaction was significant. PROC CORR was used to determine Pearson's correlation coefficients (28).

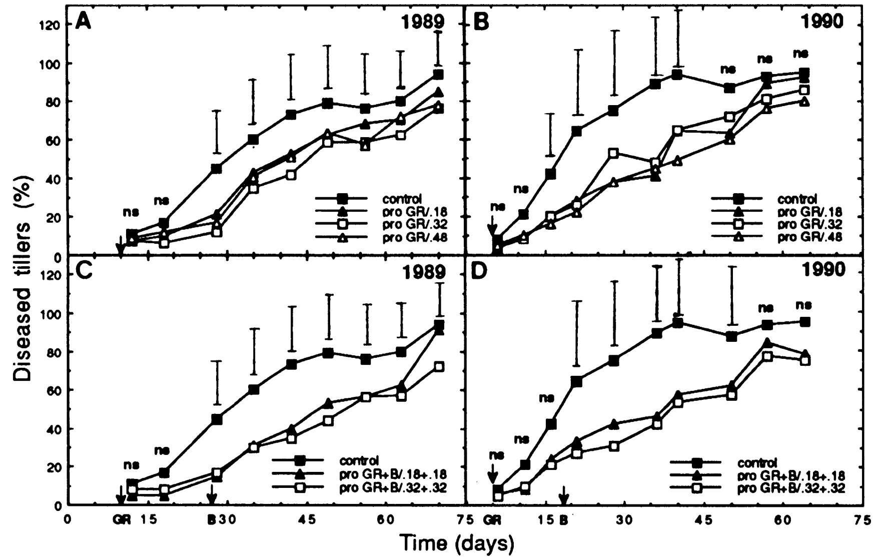

Fig. 1. Effects of rate and timing of fungicide application on sheath blight incidence in Lemont rice in **(A and C)** 1989 and **(B and D)** 1990. Percentage of diseased tillers determined from counts of 25 tillers at each of four randomly chosen locations per experimental unit. Means are from six (1989) and five (1990) plots per treatment. Control = no fungicide application; pro = propiconazole at 0.18, 0.32, or 0.48 kg a.i./ha; GR = green ring growth stage; B = boot growth stage. Arrows indicate timing of application. Day 0 = inoculation day. Days 77–78 (1989) and 66 (1990) = harvest day. Vertical bars indicate Fisher's LSD (P = 0.05); ns = nonsignificant.

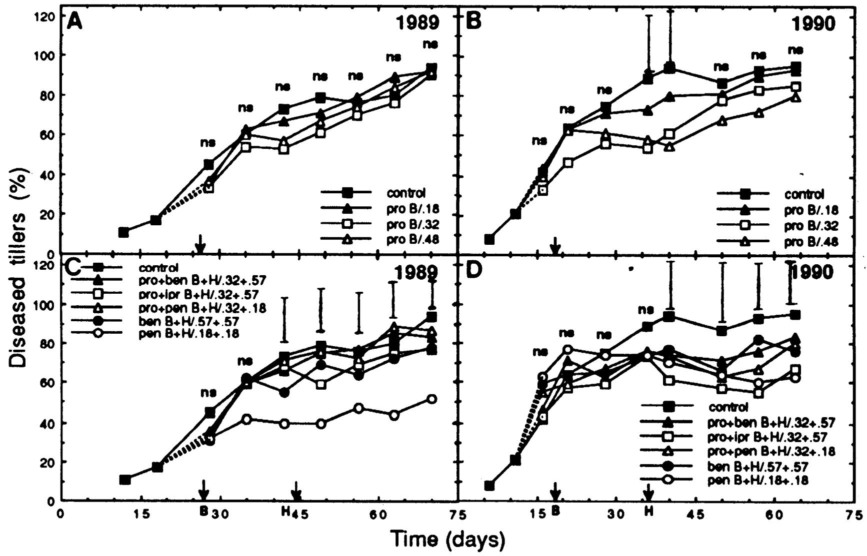

Fig. 2. Effects of rate and timing of fungicide application on sheath blight incidence in Lemont rice in **(A and C)** 1989 and **(B and D)** 1990. Percentage of diseased tillers determined from counts of 25 tillers at each of four randomly chosen locations per experimental unit. Means are from six (1989) and five (1990) plots per treatment. Control = no fungicide application; pro = propiconazole at 0.18, 0.32, or 0.48 kg a.i./ha; ben = benomyl at 0.57 kg a.i./ha; ipr = iprodione at 0.57 kg a.i./ha; pen = pencycuron at 0.18 kg a.i./ha; B = boot growth stage; H = heading growth stage. Arrows indicate timing of application. Dotted lines represent theoretical disease incidence progress for the boot and boot plus heading treatments based on the incidence values of the control treatment. Day 0 = inoculation day. Days 77–78 (1989) and 66 (1990) = harvest day. Vertical bars indicate Fisher's LSD (P = 0.05); ns = nonsignificant.

RESULTS

Fungicide effects on disease progress measured as incidence. The treatment by time interaction in the overall repeated measures ANOVA model was significant in both years with G-G P = 0.0018 in 1989 and G-G P = 0.0001 in 1990. Fisher's LSD (P = 0.05) was used to compare treatments at individual assessment times, as indicated in Figures 1 and 2.

In both test years, disease incidence was consistently lower in plots treated with propiconazole at the green ring stage compared with nonsprayed plots (Fig. 1). Incidence was significantly reduced in plots receiving sequential applications at green ring and early boot stages until maturity (Fig. 1C and D), except for the 0.18 kg a.i./ha treatment in 1989 when a rapid disease incidence increase occurred near maturity (Fig. 1C). Single propiconazole applications at green ring only also significantly reduced disease incidence over time, although the reductions were generally not as great as those observed in sequentially sprayed plots (Fig. 1A and B). Relative AUDPC values for the single and sequential applications were significantly different (P = 0.05) from rAUDPC of the control curves in both years (Table 1).

Single boot applications of propiconazole, propiconazole at boot followed by a heading spray with benomyl, iprodione, or pencycuron, and sequential applications of benomyl at early boot and heading failed to significantly reduce disease incidence over time in 1989 (Fig. 2A and C, Table 1). In 1990, these treatments tended to slow development of the epidemic (Fig. 2B and D), although rAUDPCs were only significantly reduced with single boot applications of propiconazole at 0.32 and 0.48 kg a.i./ha and the combination of propiconazole and iprodione at early boot and heading (Table 1). Pencycuron applied at early boot and heading almost stopped disease incidence increase through maturity in 1989 (Fig. 2C). In 1990, this treatment also prevented an increase in disease incidence over time, but the rAUDPC was not significantly different from the control (Table 1). This can be attributed to the unusually high numbers of diseased tillers before the early boot application compared with the control disease incidence at that time (Fig. 2D).

Fungicide effects on disease progress measured as severity. Disease severities decreased over time when sheath height increased, whereas lesion height remained the same or increased at a lower rate (Figs. 3–5). When sheath heights had reached maximum size (about day 45 in 1989 and day 50 in 1990), disease severities either leveled off or increased. Figure 3C and D shows sheath growth of control and treated tillers flagged at the green ring stage in 1990. For the tillers flagged at early boot in both years, sheath growth curves were very similar. Repeated measures analysis of sheath heights over time indicated no significant differences for any of the treatments in both years. Therefore, treatment comparison using disease severities as proportions of the growing host was valid.

Because the treatment by time interaction was highly significant (G-G $P = 0.0001$ for tillers flagged at early boot in both years; G-G $P = 0.0043$ for tillers flagged at green ring in 1990), multiple comparisons of disease severities at individual assessment times were performed using Fisher's LSD ($P = 0.05$) (Figs. 3–5). Initial severity, entered in the repeated measures model as a covariable, was significant in all analyses with $P = 0.0001$ for tillers flagged at early boot in both years and $P = 0.0241$ for tillers flagged at green ring in 1990. Analysis of covariance of rAUDPCs for the tillers flagged at early boot in both years also showed initial severity to be significant as a covariable ($P = 0.0001$ in 1989 and $P = 0.0267$ in 1990). Therefore, data in Figures 3–5 and rAUDPCs for severity (early boot to maturity) in Table 1 represent treatment means adjusted for initial severity, as obtained by the LSMEANS statement in PROC GLM (29).

In 1990, monitoring of tillers flagged at green ring showed that the application of propiconazole at this growth stage slowed disease progress up the tiller for about 2 wk (Fig. 3A). When early boot applications of propiconazole followed the green ring applications (Fig. 3B), severities were only slightly reduced compared with no early boot application (Fig. 3A). In fact, around the heading growth stage, lesions progressed upward at a faster rate on treated than on control tillers resulting in a significantly higher disease severity at maturity for the sequential 0.18 kg a.i./ha applications. This response also occurred after the single green ring applications (Fig. 3A), but severities of control and treated tillers were not significantly different at maturity. None of the treatment rAUDPC values were significantly different from the control (Table 1). The initial decrease in severity compensated for the increase at the end of the growing season.

On tillers that were recently diseased when flagged at the early boot stage in 1990 and subjected to the same single

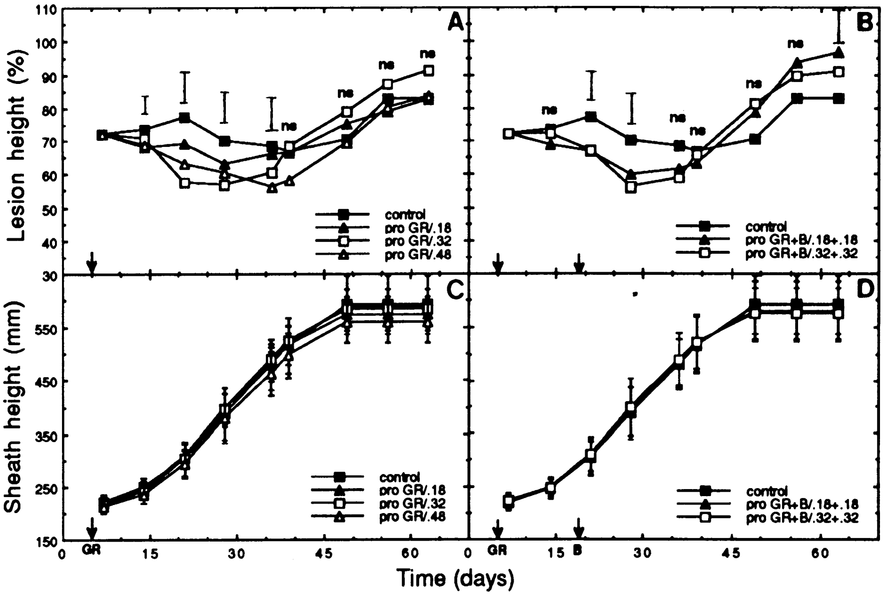

Fig. 3. (A and B) Effects of rate and timing of fungicide application on severity of sheath blight in Lemont rice in 1990. Lesion height is expressed as percentage of total sheath height and was determined on 25 rice tillers per treatment from green ring growth stage to maturity. Treatment means on each day were adjusted for initial disease severity according to analysis of covariance using PROC GLM and the LSMEANS statement available in the SAS computer package (28,29). Vertical bars indicate Fisher's LSD ($P = 0.05$); ns = nonsignificant. **(C and D)** Sheath growth of the rice tillers on which disease severity was monitored. There were no significant differences in sheath height over time for any of the treatments ($P = 0.05$). Vertical bars indicate standard deviations. Control = no fungicide application; pro = propiconazole at 0.18, 0.32, or 0.48 kg a.i./ha; GR = green ring growth stage; B = boot growth stage. Arrows indicate timing of application. Day 0 = inoculation day. Day 66 = harvest day.

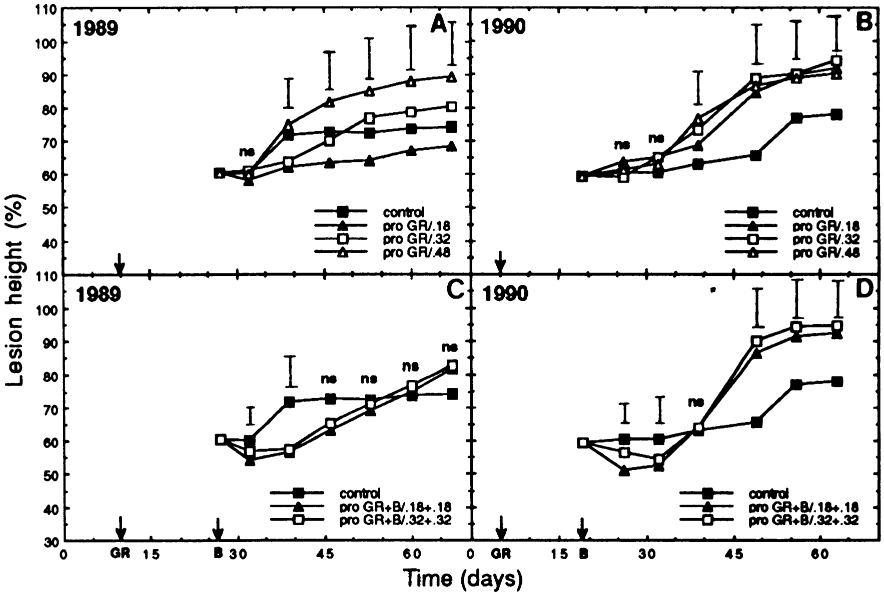

Fig. 4. Effects of rate and timing of fungicide application on severity of sheath blight in Lemont rice in **(A and C)** 1989 and **(B and D)** 1990. Lesion height is expressed as percentage of total sheath height and was determined on 24 (1989) and 25 (1990) rice tillers per treatment from boot growth stage to maturity. Treatment means on each day were adjusted for initial disease severity according to analysis of covariance using PROC GLM and the LSMEANS statement available in the SAS computer package (28,29). Control = no fungicide application; pro = propiconazole at 0.18, 0.32, or 0.48 kg a.i./ha; GR = green ring growth stage; B = boot growth stage. Arrows indicate timing of application. Day 0 = inoculation day. Days 77–78 (1989) and 66 (1990) = harvest day. Vertical bars indicate Fisher's LSD ($P = 0.05$); ns = nonsignificant.

or sequential propiconazole applications (Fig. 4B and D), the rapid increase in severity started earlier and reached significantly ($P = 0.05$) higher levels than on control tillers. Relative AUDPCs for these treatments were significantly higher than for the control curve (Table 1). For tillers flagged at the early boot stage in 1989, the same general trends were observed, except that with increasing rates of single green ring application, severities later in the season were increasingly higher (Fig. 4A). In 1990, there was no such differential response (Fig. 4B).

When the effects of sequential applications of propiconazole (Fig. 4C and D) are compared with the effects of single early boot applications (Fig. 5A and B), it shows that disease severity over time following an early boot application is affected by a preceeding green ring application. About 3 wk after the early boot spray (day 53 in 1989, day 39 in 1990), mean disease severity for tillers that were treated previously at green ring was approximately equal to the mean control severity. In contrast, on tillers that were not previously sprayed at green ring, mean disease severity 3 wk after early boot application was lower than on control tillers. This effect was significant for the 0.32 and 0.48 kg a.i./ha rate. The early boot applications were actually rendered less effective by a preceeding green ring application. In 1989, single 0.32 and 0.48 kg a.i./ha early boot sprays of propiconazole significantly reduced disease severity up to maturity (Fig. 5A and Table 1). In 1990, fungicidal activity from single early boot applications did not restrict disease development up to maturity (Fig. 5B and Table 1). The single 0.18 kg a.i./ha early boot application resulted in the same adverse effect on disease progress as discussed for green ring applications.

Fungicide applications at heading after an early boot spray suppressed severities up to maturity (Table 1 and Fig. 5C and D). Relative AUDPCs for all early boot and heading applications were significantly lower than the control value (Table 1). An early boot spray of propiconazole followed by either benomyl, iprodione, or pencycuron successfully suppressed upward lesion progression in both years. Two applications of benomyl gave similar results. The decrease in sheath blight severity after an early boot application of pencycuron lasted about 1 wk longer than the decrease after the 0.32 kg a.i./ha rate of propiconazole applied at early boot.

Disease assessment at maturity. Disease ratings determined at the whole-plot level and percent diseased tillers at maturity are given in Table 1. They reflect the same general trends as discussed for the severity and incidence data over time. Percent diseased tillers at maturity was highly significantly correlated with rAUDPC for incidence ($r = 0.54$ in 1989; $r = 0.65$ in 1990) (Table 2). Disease ratings were highly significantly correlated with rAUDPC for severity on tillers flagged at early boot ($r = 0.66$ in 1989; $r = 0.81$ in 1990) (Table 2). In contrast, severity determined over time on tillers flagged at green ring in 1990 was not significantly correlated with disease rating. Based on 29 observations, the correlation coefficient for rAUDPC for severity data from green ring to maturity with disease rating was not significant, whereas rAUDPC for severity from early boot to maturity and disease rating were significantly correlated (Table 2). In both years, disease rating and percent diseased tillers at maturity were significantly positively correlated with $r = 0.32$ in 1989 and $r = 0.45$ in 1990. Relative AUDPCs for sheath blight incidence and severity were negatively correlated (Table 2).

Yield response. In 1989, none of the yields were significantly different (Table 3). Disease pressure was relatively low that year, and yield variation among plots within treatments was high. Variation coefficients ranged from 10 to 29%. Nevertheless, a positive yield increase was obtained for all early boot and heading applications (Table 3). Yield was negatively correlated with rAUDPC for sheath blight severity, disease rating, and percent diseased tillers at maturity (Table 2).

In 1990, coefficients of variation within treatments were considerably lower (1.4 to 11%). Plots treated singly at green ring, early boot, and green ring plus early boot generally yielded less than the inoculated control plots (Table 3). This effect was significant only with the single 0.18 kg a.i./ha green ring application of propiconazole. Significant yield increases over the control were obtained from plots receiving an early boot spray of propiconazole at 0.32 kg a.i./ha followed by either benomyl or pencycuron at heading and by two applications of pencycuron (Table 3). Yield was highly significantly negatively correlated with rAUDPC for disease severity on tillers flagged at early boot and with disease rating ($r = -0.72$ and -0.75, respectively) (Table 2). Relative AUDPC for disease severity on tillers flagged at green ring was not correlated with yield. Correlation of yield with percent diseased tillers at maturity was significantly negative with $r = -0.29$ ($P = 0.019$). In both years, yield was not significantly correlated with rAUDPC for disease incidence (Table 2).

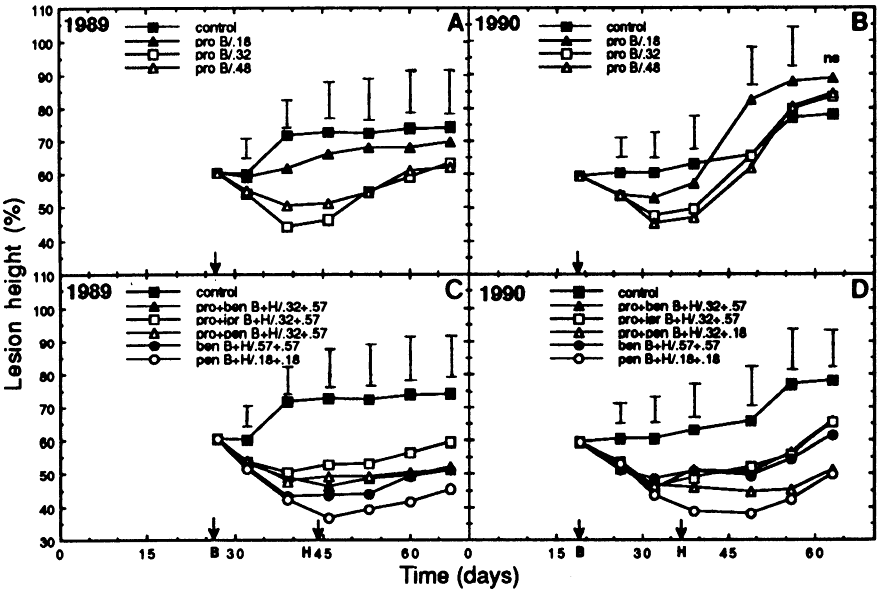

Fig. 5. Effects of rate and timing of fungicide application on severity of sheath blight in Lemont rice in **(A and C)** 1989 and **(B and D)** 1990. Lesion height is expressed as percentage of total sheath height and was determined on 24 (1989) and 25 (1990) rice tillers per treatment from boot growth stage to maturity. Treatment means on each day were adjusted for initial disease severity according to analysis of covariance using PROC GLM and the LSMEANS statement available in the SAS computer package (28,29). Control = no fungicide application; pro = propiconazole at 0.18, 0.32, or 0.48 kg a.i./ha; ben = benomyl at 0.57 kg a.i./ha; ipr = iprodione at 0.57 kg a.i./ha; pen = pencycuron at 0.18 kg a.i./ha; B = boot growth stage; H = heading growth stage. Arrows indicate timing of application. Day 0 = inoculation day. Days 77–78 (1989) and 66 (1990) = harvest day. Vertical bars indicate Fisher's LSD ($P = 0.05$); ns = nonsignificant.

DISCUSSION

The assessment method used to monitor sheath blight severity over time proved suitable for demonstrating the effects of fungicide application on disease progress up the tiller. Significant correlations of rAUDPC for severity on tillers flagged at early boot with disease rating at maturity and with plot grain yield suggested that monitoring of lesion heights on four or five tillers per experimental unit from early boot stage to maturity represented disease development at the whole-plot level. In contrast, lack of such correlation for tillers flagged at green ring indicated that monitoring of tillers that became diseased around green ring stage was less representative for disease development at the whole-plot level. A possible explanation for this would be that the frequency of tillers that become diseased at green ring is smaller than at early boot, as shown in the incidence progress curves, so that disease severity progress on tillers that became diseased around the early boot stage would be more representative for the whole plot.

Application of propiconazole at green ring successfully delayed disease incidence increase. Without a green ring spray, approximately 40% of the tillers were infected at the early boot stage. Early boot applications of propiconazole could do little to prevent further disease progress. A boot application of propiconazole combined with a heading application of benomyl, iprodione, or pencycuron suppressed disease incidence during the grain filling stages of rice in 1990 but not in 1989. The same happened for early boot and heading applications of benomyl. Early boot applications of pencycuron in both years stopped disease progress almost completely, even though they were applied at only two-thirds of the recommended rate, and a subsequent heading spray kept incidence low through maturity. Pencycuron is a protectant fungicide, and the possibility for being redistributed downward may be higher than for the systemic fungicides propiconazole and benomyl. This would give greater protection of the lower sheaths at application times, such as early boot and heading, when fungicide penetration into the canopy is limited by the upper foliage.

Although beneficial in reducing sheath blight incidence over time, green ring applications of propiconazole resulted in increased severity compared with the control. Disease severity increased more rapidly on treated tillers than on nontreated tillers following the loss of fungicidal activity. This response was consistent in both 1989 and 1990 and was also observed during a preliminary experiment in 1988 (E. Van Eeckhout, *unpublished*). We interpret these results as an indication of decreased microbial antagonism attributable to fungicidal activity.

Propiconazole is a broad-spectrum fungicide (4,6) that will probably affect many nontarget fungi. Riesen and Close (19) demonstrated that significantly fewer isolates of the endophytic fungi *Didymella phleina* Punith. & Årsvoll, *Alternaria* spp., and *Cladosporium* spp. were obtained from barley leaf blades after a first propiconazole treatment. Significantly more isolations of *Alternaria* spp., *Epicoccum purpurascens* Ehrenb., and *Stemphylium botryosium* Wallr. after the second spraying was linked to a significant delay in the decline of green leaf area in treated plots.

Differential sensitivity of phylloplane fungi to propiconazole is very likely because in vitro activity against fungal plant pathogens covers a broad range of genera. For example, reported EC_{50} values for 19 species ranged from less than 0.1 to 6.0 ppm (4). In vitro sensitivity of *R. solani* was intermediate (4), although differences among various isolates may occur (10). Antagonists of *R. solani* that are more sensitive to fungicide application may not recover as fast as the pathogen, which could then develop at a faster rate. Also, because of its high intrinsic growth rate, *R. solani* could possibly outcompete antagonists that are equally sensitive to fungicidal activity but have lower growth rates. Recent evidence that propiconazole can restrict growth of certain bacteria that exhibit antibiosis in vitro against *R. solani* (M. C. Rush and A. S. Prabhu, *unpublished*) suggests that a reduction of bacterial phylloplane antagonists by fungicide application may also be involved.

Species composition and relative prevalence of antagonistic microorganisms on rice leaves can undoubtedly differ from field to field and year to year. This could explain why in 1989 increasing propiconazole dosages, applied singly at green ring, caused increasing sheath blight severities, while in 1990, all rates were equally detrimental. It could also explain why in 1990, single early boot applications resulted in increased disease severity earlier in the season and to a larger extent than the same applications in 1989. Occasional performance failures of the recommended green ring plus early boot (0.18 + 0.18 kg a.i./ha) or single early boot (0.32 kg a.i./ha) application of propiconazole in the past were attributed to a low rate of application that could not withstand high disease pressure. Higher rates were thought to be necessary (6). Our time-course investigation, however, contradicts this and suggests that the cause of failure may

Table 2. Correlation coefficients and probability levels for sheath blight assessments and yield of Lemont rice sprayed with foliar fungicides

Factor	rAUDPC severity[t] (B to M)	Yield	Percent diseased tillers at maturity[u]	Disease rating at maturity[v]
1989[w]				
rAUDPC incidence[x] (GR to M)	−0.18 0.1036	0.07 0.5323	0.54 0.0001	−0.13 0.2584
rAUDPC severity (B to M)		−0.20 0.0701	0.15 0.1729	0.66 0.0001
Yield			−0.22 0.0503	−0.21 0.0585
Percent diseased tillers at maturity				0.32 0.0040
1990[y]				
rAUDPC incidence (GR to M)	−0.24 0.0522	0.19 0.1158	0.65 0.0001	−0.06 0.6062
rAUDPC severity (B to M)		−0.72 0.0001	0.35 0.0034	0.81 0.0001
Yield			−0.29 0.0189	−0.75 0.0001
Percent diseased tillers at maturity				0.45 0.0002
1990[z]				
rAUDPC severity (GR to M)	0.13 0.4889	0.03 0.8566	0.15 0.4367	0.18 0.3404
rAUDPC severity (B to M)		−0.49 0.0075	0.07 0.7204	0.41 0.0266

[t] Relative area under disease progress curve based on percent lesion height determined on four and five tillers per plot in 1989 and 1990, respectively, at weekly intervals from boot (B) growth stage to maturity (M).
[u] Number of diseased tillers out of 25 counted at each of four randomly chosen locations in each plot.
[v] Ratings determined at the whole-plot level based on a scale of 0 = no disease to 9 = severe disease (6).
[w] Correlation coefficients based on 81 observations (all treatments included).
[x] Relative area under disease progress curve based on percentage of diseased tillers determined at weekly intervals from green ring (GR) growth stage to maturity (M).
[y] Correlation coefficients based on 66 observations (all treatments included).
[z] Correlation coefficients based on 29 observations (control treatment and treatments receiving GR application included).

lie elsewhere.

Fungicide trials conducted at the Rice Research Station in Crowley, LA, during 1981–1990 (20–27) showed that early applications (green ring + early boot) of seven of 22 fungicides tested did not significantly control sheath blight development, whereas later (early boot + heading) applications of the same compounds at the same rate significantly reduced disease levels compared with the control treatment. Green ring and early boot applications of Rovral in 1987 and BAS 480 OOF in 1990 resulted in a significantly higher percentage of tillers dead at maturity than in nonsprayed plots. In contrast, early boot and heading applications of these compounds at the same rate significantly reduced sheath blight development. These results suggest that disease development after early fungicide application would have to change from an expected initial decrease to an increase at a higher rate for it to result in a disease level at rice maturity comparable to or higher than the disease level in nonsprayed plots. The disease progress curves presented in this paper support this assumption. Disease development following later applications is presumably interrupted by harvest before increased disease development can occur. The fact that fungicides with different modes of action and with mostly broad spectrum activity seem to be involved favors the hypothesis that nontarget antagonistic microorganisms may be affected.

Examples of fungicides that have caused a so-called "boomerang" effect (2) or "iatrogenic" disease (8) were reviewed by Hislop (7) and Bollen (2). Fokkema et al (5) obtained substantial evidence that reduction of the saprophytic mycoflora of rye leaves caused by benomyl resulted in an increased susceptibility to *Cochliobolus sativus* (Ito & Kuribayashi) Drechs. ex Dastur). However, well-documented cases are scarce (2). Hislop (7) mentioned that any chemical applied to plants may alter the microflora either directly, by affecting its components, or indirectly by altering the physiology of the host. In addition, a boomerang effect could be brought about by changes in plant resistance mechanisms after fungicide application (2). Owen and Donzel (18) reported that the overall rate of propiconazole metabolism in rice cell cultures was considerably slower than in wheat cells. They linked this observation to the greater phytotoxicity of propiconazole to rice when compared with wheat and other cereals. Thus, it cannot be ruled out that host physiology may be altered, resulting in increased rice plant susceptibility and/or changed antagonist populations.

Yield responses were significantly negatively correlated with rAUDPC for sheath blight severity and were not correlated with disease incidence over time. This implies that relatively high sheath blight incidences could be tolerated as long as infection remains in the lower part of the canopy. For very susceptible cultivars, this would not apply. Lemont, however, is a susceptible cultivar with some degree of resistance to penetration of the culm, and it can withstand infection on the lower sheaths without severe lodging. Lack of correlation between yield and incidence over time also implies that scouting procedures based solely on determination of disease incidence during the season may not be the most effective basis for recommending fungicide applications. Current recommendations for sheath blight in the United States are to apply a fungicide when 5–10% of the tillers of a susceptible cultivar are diseased at the early jointing stages of growth (6,10). The observations made during this study suggest that sheath blight thresholds that also incorporate disease severity indices might give a more accurate basis for decision making.

Based on this 2-yr investigation, it appears that fungicide application at both early boot and heading stages were imperative for consistent control of sheath blight development and positive yield response. A single early boot application, however, might be effective enough to suppress disease severities up to maturity. This will depend on the interplay of several components: host, pathogen, chemical, biotic, and abiotic environment. As long as the interactions among these components are not fully understood, attempts to develop a system that would forecast the need for an additional heading application are likely to fail. The results of this study indicate that it would be of great interest to elucidate the impact of propiconazole and other fungicides on nontarget phylloplane antagonists on rice and to determine how this impact might be related to sheath blight development.

Table 3. Plot yields of Lemont rice inoculated with *Rhizoctonia solani* and sprayed with foliar fungicides at different rates and at different plant growth stages

			1989		1990	
Treatment	**Rate (kg a.i./ha)**	**Timing[x]**	**Yield[y] (kg/ha)**	**Change from inoculated control (kg/ha)**	**Yield[y] (kg/ha)**	**Change from inoculated control (kg/ha)**
Noninoculated control			6,149 a[z]	+458	8,215 bc	+698
Inoculated control			5,691 a		7,517 d–g	
Propiconazole	0.18	GR	6,065 a	+374	6,635 h	−882
Propiconazole	0.32	GR	5,474 a	−217	7,378 e–g	−138
Propiconazole	0.48	GR	5,606 a	−85	7,058 gh	−458
Propiconazole	0.18	B	5,920 a	+229	7,498 c–g	−19
Propiconazole	0.32	B	5,366 a	−325	7,450 e–g	−67
Propiconazole	0.48	B	5,085 a	−606	7,116 gh	−401
Propiconazole	0.18	GR + B	5,691 a	0	7,271 f–h	−246
Propiconazole	0.32	GR + B	5,064 a	−627	7,130 gh	−386
Propiconazole + benomyl	0.32 +0.57	B + H	6,068 a	+377	8,371 ab	+854
Propiconazole + iprodione	0.32 +0.57	B + H	6,167 a	+476	8,047 b–e	+530
Propiconazole + pencycuron	0.32 +0.18	B + H	6,062 a	+371	8,392 ab	+875
Benomyl	0.57	B + H	6,870 a	+1,179	8,145 b–d	+628
Pencycuron	0.18	B + H	5,905 a	+214	8,467 ab	+950

[x] Fungicides were applied at the green ring (GR), boot (B), and/or heading (H) growth stage of rice.

[y] Yields are averages over six plots per treatment in 1989 and five plots per treatment in 1990. The harvested area per plot was 1.5 m^2 in 1989 and 3.5 m^2 in 1990.

[z] Means in columns followed by the same letter are not significantly different according to Fisher's LSD ($P = 0.05$).

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