Effect of Cultural Management Practices on the Severity of False Smut and Kernel Smut of Rice

Steven A. Brooks, United States Department of Agriculture–Agricultural Research Service (USDA-ARS), Dale Bumpers National Rice Research Center, Stuttgart, AR 72160; **Merle M. Anders**, University of Arkansas, Rice Research and Extension Center, Stuttgart 72160; and **Kathleen M. Yeater**, USDA-ARS SPA, College Station, TX 77845

ABSTRACT

Brooks, S. A., Anders, M. M., and Yeater, K. M. 2009. Effect of cultural management practices on the severity of false smut and kernel smut of rice. *Plant Dis.* 93:1202-1208.

False smut (*Ustilaginoidea virens*) and kernel smut (*Neovossia horrida*) are diseases of rice (*Oryza sativa*) that reduce both grain yield and quality. False smut is an emerging disease worldwide that is rapidly gaining in importance, whereas kernel smut has historically been a chronic minor disease with sporadic outbreaks that cause considerable losses. Highly effective disease control was obtained for susceptible cultivars by employing conservation tillage (69% reduction in false smut), continuous rice cropping (88% reduction in false smut), and moderate nitrogen fertility rates (34 and 60% reductions in false smut and kernel smut, respectively). Combining these treatments nearly eliminated smuts from cultivars that were fully susceptible under conventional cultivation practices. Furthermore, using a nursery designed to promote smut diseases, two rice hybrids were identified that possessed kernel smut resistance under the most favorable disease conditions. The genetic basis of the resistance is unknown. However, the utility for disease control is great because hybrids occupy significant portions of production rice acreage.

False smut and kernel smut are fungal diseases of rice (*Oryza sativa* L.) that have a direct effect on grain yield and quality through partial or complete replacement of kernels with spore masses (19). The diseases are largely uninvestigated due to a historical emphasis placed on major diseases, such as blast and bacterial blight. Moreover, the label of “minor disease” for smuts (2,12,15), environmental variability, and length of time required to rate these intractable adult plant diseases has led to a general lack of progress toward disease control.

False smut, caused by *Ustilaginoidea virens* (Cooke) Takah., is an important emerging disease of rice. Unlike true smuts that may replace all or part of a kernel with a mass of black spores, the sori of *U. virens* erupt through the palea and lemma, forming a ball of mycelia, the outermost layers of which are spore producing (19).

The size of an individual sorus may vary from 2 to 10 mm but the rice kernel is always destroyed regardless of the size of the replacing sorus. Once an uncommon disease of rice, false smut has increased in prevalence and importance in the last two decades throughout the rice-growing regions of the world (16,19,20). Of specific importance to this work is the shift from initial identification of the disease in Arkansas in 1997 (3) to detection in all Arkansas rice-producing counties by 1999 (2), and persistence of false smut statewide to the present day (S. A. Brooks, *personal communication and observation*). This emerging trend in the United States and throughout the world has placed a greater need to manage false smut in the future.

Kernel smut (causal agent: *Neovossia horrida* (Takah.) Padwick & A. Khan (syn. *Tilletia barclayana* (Bref.) Sacc. & P. Syd.) has been a chronic problem for U.S.-based rice production. Rightfully considered a minor disease worldwide, it has reached epidemic levels at rare intervals (1,4,6). Though minor in terms of severity and yield loss, kernel smut impacts the quality of parboiled rice. Very strict tolerances are in place for smutty rice (<3%; 17), above which the rice cannot be used for parboiling. The parboiling process liberates spores into the water where uninfected kernels are discolored by the black spores (9). Therefore, kernel smut has economic impact even at low disease levels.

Several studies reported varying degrees of susceptibility to smuts among rice culti-

vars (2,4,6,15) but none of the work used large field plots or sample sizes to account for the inherent variability in these diseases. Because both diseases are highly environmentally influenced and soil nitrogen (N) fertility is an important agricultural factor influencing disease severity (15), any reports of resistance must be interpreted cautiously. Without fertility controls, true resistance cannot be distinguished from escapes. Prior to this report, no useful source of resistance has been identified for either disease (6,12).

A need exists to manage these two important diseases with an integrated approach that includes disease resistance and cultural management. Fungicides are effective on rice smuts (5,16) but their use is not practical for rice production. Neither disease produces visual symptoms until the grain begins to fill, at which time a fungicide application is too late to prevent yield loss. At growth stages when control with fungicides is achievable, there is no way to determine the degree of disease severity and, thus, determine whether the application is warranted. Therefore, integration of disease-resistant germplasm and cultural management techniques are needed to control these diseases at a production scale.

One of our primary objectives was to identify smut-resistant rice cultivars using a disease nursery where crop management (particularly N fertility) was controlled. The nursery location had a history of natural infestation of rice smuts due to a microclimate favorable for disease and a 7-year history of no fungicide use. The natural infection was critical because artificial inoculation (boot injection or sporidia sprays) is impossible in large plots and not representative of the natural epidemics. The second objective was to determine the effects of crop management practices (rotation, tillage, and fertility) on disease severity to advance our fundamental understanding of the diseases, and to apply that knowledge for disease control on desirable rice cultivars that were also smut susceptible. To address our objectives, we evaluated false smut and kernel smut severity in two field experiments conducted over 3 years. We selected modern rice cultivars that were relevant to rice production in Arkansas, the largest rice-producing state in the United States.

Corresponding author: S. A. Brooks
E-mail: ricegenes@mac.com

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Accepted for publication 14 July 2009.

doi:10.1094/PDIS-93-11-1202

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MATERIALS AND METHODS

Study location. The two experimental sites were located at the University of Arkansas Rice Research and Extension Center in Stuttgart (latitude N 34°27', longitude W 91°24'). The sites are situated within the Grand Prairie region of eastern Arkansas, where the leading crop rotation is a rice-soybean (*Glycine max* (L.) Merr.) rotation, and the Dewitt silt loam (fine, smectitic, thermic, Typic Albaqualf) soil is representative of the region (13). Rice grain smuts were known to occur at the experimental sites and were also commonly reported in production fields of the Grand Prairie (M. M. Anders and S. A. Brooks, *unpublished observations and communications*).

Plant materials. Seed of rice cvs. Wells and Cybonnet was obtained from the University of Arkansas foundation seed program (Stuttgart). Seed of cv. Cypress was provided by Dr. Anna McClung of the United States Department of Agriculture-Agricultural Research Service Dale Bumpers National Rice Research Center (Stuttgart, AR). Seed of rice hybrids 'Clearfield XL 730 (CLXL 730)' and 'XL 723' was provided by RiceTec (Alvin, TX). The cultivars were selected to represent the range of plant types currently used in the southern rice-producing states. The conventional "tall" cv. Wells is the leading inbred cultivar in Arkansas. Cybonnet and Cypress were included to represent semidwarf plant types that also possess stable milling yield. Hybrids were included due to their increasing importance everywhere rice is grown.

Crop rotation experiments (2006–2007). As part of a multiyear, multi-cropping-systems rotation study, the incidence of false smut and kernel smut, and crop yields, were recorded for 2 years. The field experimental layout was a randomized split-strip plot design, where tillage type was the main plot, fertility level was the subplot, and rotation was randomly applied within each of four replicates at the beginning of the study (Fig. 1). Tillage treatments were conventional tillage and no-tillage. Fertility treatments were "standard" (N at 112 kg ha⁻¹ + P₂O₅ at 45 kg ha⁻¹ + K₂O at 67 kg ha⁻¹) and "enhanced" (N at 168 kg ha⁻¹ + P₂O₅ at 67 kg ha⁻¹ + K₂O at 100 kg ha⁻¹) using Agrotain (Agrotain International, L.L.C.) coated urea pellets (46-0-0), triple super phosphate (0-46-0), and muriate of potash (0-0-60). Phosphorus and potassium fertilizers were applied prior to planting and N was applied post emergence. The rotation treatments were continuous rice and rice-soybean, where the latter was "mirrored" so that rice and soybean were present every year (Fig. 1). The rotation experiment had been in place since 2000. The experimental plots, all treatments (including the cv. Wells), and crop management practices were the same every year.

Two rice cultivars were grown each year and were considered random effects. Rice cv. Wells was grown in both years, whereas cv. Cybonnet (2006) was replaced with hybrid XL 723 in 2007. Rice was drill seeded at the rate of 101 kg ha⁻¹ for the two inbred cultivars and 39 kg ha⁻¹ for hybrid XL 723 using an Almaco grain drill (Almaco, Nevada, IA) and a 19-cm row spacing (6-by-19-m individual plot size; Fig. 1). At the five-leaf growth stage, N fertilizer was applied and a permanent flood 10 cm deep was immediately established and maintained throughout the growing season. Mature rice was harvested with a John Deere 45 combine (Deere & Company, Moline, IL) retrofitted with a Carter weigh bucket (Carter Mfg. Co. Inc., Brookston, IN) for yield measurements.

Analyses of all dependent variables were performed using the GLIMMIX procedure in SAS (version 9.1.3). False smut and kernel smut were lognormally distributed. This probability distribution was specified in the model after the variables were coded by adding (+1) to each value. Yield followed a Gaussian (normal) distribution. Tillage, fertility, rotation, and their interactions were considered fixed effects in the statistical models. The replicated block was random as well as the cultivar within the rotation. Cultivar was a random effect because we were inferring the range of all rice cultivars and we were not implicitly focused on the means results of the specific cultivars included in this study. A compound symmetry covariance structure was fit for each cultivar within rotation across years. The data were originally assessed on a year-to-year basis (*not shown*). The fixed effects showed the same trends in all years of the study. It was decided to utilize the experimental design to analyze the complete experiment using year as the repeated measure. This method allowed for more power to interpret the rotation and the variability of the random cultivar within rotation. The Kenward-Roger degree of freedom method was used in all variable models. Best linear unbiased predictors (BLUPs) and predicted standard errors of cultivar were calculated using the SOLUTIONS option. Estimated means, standard errors, and differences of means in the fixed effects were calculated using the LSMEANS option.

Smut nursery experiments (2007–2008). A smut disease nursery was established in 2007 at a location known to have natural infestation of false smut and kernel smut and a site microclimate that favored long dew periods (M. M. Anders and S. A. Brooks, *unpublished observations*). The nursery year followed a fallow season and the previous crop was rice in 2005. The site was prepared by tilling according to Olk et al. (13). Preplant P and K treatments (standard rate), seeding rates (inbred cultivars and hybrids), and row spacing were the same as above. The field experimental

layout was a randomized complete block design. The nursery was planted with five rice cultivars (inbred cvs. Cybonnet, Cypress, and Wells and hybrids CLXL 730 and XL 723) using a Hege1000 planter (Hege Equipment Inc., Colwich, KS) for nine-row plots measuring 1.5 m wide by 5.5 m long. Fertility treatments (F1 = N at 112 kg ha⁻¹, F2 = N at 157 kg ha⁻¹, F3 = N at 202 kg ha⁻¹, and F4 = N at 246 kg ha⁻¹) of Agrotain (Agrotain International, L.L.C.) coated urea pellets (46-0-0) were applied to all entries and replications (four) at the five-leaf growth stage as a single pre-flood treatment and flooded as previously described. Mature rice was harvested with a Hege 140 combine (Hege Equipment Inc., Colwich, KS), dried, and stored for subsequent yield and disease measurements. The 2008 nursery was located in a field adjacent to the 2007 experiment, which was fallow during the previous (first) year. The previous crop in 2006 was rice. All entries, treatments, and management were identical to the 2007 experiment. Due to an early planting date, the 2008 nursery escaped natural infestation with false smut. Only late-planted experiments exhibited substantial levels of false smut in 2008. Therefore, results presented for 2008 were restricted to kernel smut severities.

Analyses of all dependant variables (false smut, kernel smut, yield, total milling yield, head rice yield [number of milled kernels $\geq 0.75 \times$ premilling length], plant height, and days to heading) were performed using the GLIMMIX procedure in SAS (version 9.1.3). False smut and kernel smut were lognormally distributed. This probability distribution was specified in the model after the variables were coded by adding +1 to each value. The distributions of yield, total milling yield, head rice yield, plant height, and days to heading were Gaussian (normal). The fixed effects in each model were cultivar, fertility, and their interaction. The block effect was random. The Kenward-Roger degree of freedom method was used. Estimated means, standard errors, and differences of means were calculated using the LSMEANS option. Specific hypotheses of cultivar and fertility differences were calculated using the ESTIMATE option.

Sampling and disease rating. Rice grain from entire experimental plots (an experimental plot unit was represented by each cultivar by fertility interaction) was weighed post harvest and analyzed for moisture content using a Seedburo GMA-128 (Seedburo Equipment Co., Chicago) grain moisture analyzer. Yield (kg ha⁻¹) values were adjusted to and reported at 12% moisture content. False smut sori were recovered by size separation with a 4 mm-diameter hand sieve from 1- to 1.5-kg subsamples of grain. Large sori remained in the sieve, whereas the smaller sori that passed through were found by sorting the

grain in large trays. Disease severity was reported as number of sori per kilogram of seed harvested. The total grain from each experimental plot was subsampled into 50-g allotments. Four 50-g subsamples of harvested seed were used to rate kernel smut severity for each experimental plot. This sampling technique was determined to be optimal upon calculation of coefficient of variation among random 50-g subsamples. Each subsample was wrapped in Miracloth (Calbiochem, La Jolla, CA) and soaked overnight in 0.27 M KOH to clear the hulls (palea and lemma) accord-

ing to Lee et al. (11). Smutted kernels were identified visually over a light box. Kernel smut severity was reported as the number of symptomatic kernels per kilogram of seed harvested.

RESULTS

False smut severity was evaluated in 2006 and 2007 under a variety of crop management systems. Tillage, fertility, and rotation significantly affected disease severity. Least squared means (LSM) of log-transformed false smut data for each treatment are presented in Table 1. No-

tillage soil management significantly reduced the number of sori compared with the number of sori in the tilled plots. Similarly, the standard fertility treatment reduced the number of sori compared with enhanced fertility across all rotation and tillage treatments. Rotation had the greatest effect on false smut severity of all three treatments, where continuous rice dramatically reduced the number of sori compared with the rice-soybean (R-SB) rotation. There was also a significant tillage-rotation interaction. No-tillage (NT) reduced false smut severity by 46% in the

Fig. 1. Field design of one of the four replicates from the rice rotation experiment (not drawn to scale). Tillage treatments indicated at the top and fertility treatments at the bottom. Relevant crop rotations (3 of 10) indicated at right. Cultivar names listed in right-most column but span all treatments (i.e., plots shaded in gray); * indicates a cultivar change from Cybonnet in 2006 to XL723 in 2007.

rice-soybean rotation (NT × R-SB versus T × R-SB); however, the treatment was more effective in continuous rice (R-R) and reduced disease by 69% (NT × R-R versus T × R-R). Alternatively, there was an 86% reduction in disease severity from the continuous rice rotation in conventionally tilled (T) soil (T × R-R versus T × R-SB). The effectiveness of the continuous rice treatment was increased to 92% when no-tillage plots are compared (NT × R-R versus NT × R-SB).

Means of the severity of false smut are presented using estimates of variance from the zero Y-intercept (BLUPs; Table 2). Differences in severity could not be statistically calculated because this assessment focuses on the variability between the cultivars within rotations, and defined disease ratings could not be made (all were susceptible). However, the relative position of each cultivar in relationship to the Y-intercept was made for purposes herein (Cybonnet, Wells, XL 723; highest to lowest within the R-R rotation). Covariance parameter estimates calculated the variance due to random effects in the model (*not shown*). Variance from cultivar (0.06208) was low and variance due to year (0.4320) was high. Both variance estimates support the expectations and are explained below.

For kernel smut, fertility was the only significant main effect and there was a significant tillage by rotation interaction. Differences of LSM of the log-transformed data showed significant differences between fertility treatments (Table 1). At standard fertility, disease severity was approximately 60% less than that observed under enhanced fertility. The continuous rice rotation effectively reduced disease severity in the no-tillage system (NT × R-R versus NT × R-SB) but conventional tillage negated the effect from rotation (T × R-SB versus T × R-R). There was a 34% reduction in kernel smut severity from the no-tillage treatment within the continuous rice rotation (NT × R-R versus T × R-R) but no-tillage had little effect within the rice-soybean rotation (NT × R-SB versus T × R-SB). These differences resulted in a significant interaction but similar multiple comparison groupings due to overlap of standard errors at the 95% confidence interval.

BLUPs were used to estimate the variance from the Y-intercept (zero) for each cultivar (random effect) to present entries from highest to lowest in observed kernel smut severity (Table 2). The differences in mean disease severity could not be statistically evaluated, although Wells displayed much higher mean severity (99.2 and 144.6 infected kernels kg⁻¹, R-R and R-SB rotations, respectively) than Cybonnet or XL 723. Covariance parameter estimates were used to calculate the variance due to random effects in the model (*not shown*). Variance from cultivar (1.5841) was high

and variance due to year (0.01921) was low. Both variance estimates contrast with those from the false smut severity results but fit the expectations and are explained below.

False smut severity was evaluated among five rice cultivars with four fertility treatments in the 2007 nursery. Both cultivar ($P < 0.0045$) and fertility ($P < 0.0001$) were significant main effects. Differences in cultivar LSM for false smut severity across all fertility treatments were calculated by applying the multiple comparison t tests with Tukey-Kramer adjustment (Table 3). To resolve false smut severity at individual fertility levels, disease severities for each cultivar and fertility treatment were plotted in Figure 2. At low fertility (F1 and F2), disease levels were similar across all entries and severity was low (2.6 sori kg⁻¹; mean false smut severity for all cultivars at F1) and the entries appeared resistant. Only at high fertility (F3 and F4)

was susceptibility evident, and separation of all cultivars for disease severity occurred at F4. Because the increasing trend of false smut severity with fertility was true for all cultivars, differences of LSM at each fertility rate were used to determine the general effect of fertility on disease severity (Table 4). The table shows an increase in disease severity with fertility rate; however, the only significant difference in false smut severity was between the F1-F2 and F3-F4 fertility groups.

Severity of kernel smut was also evaluated in the 2007 and 2008 nurseries for five cultivars across four fertility treatments. Both cultivar ($P < 0.0001$) and fertility ($P < 0.0001$) were significant main effects and there were no significant interactions in either year. LSM multiple comparisons of log-transformed data for kernel smut severity across all fertility treatments were used to group entries by disease severity (Table 3). Conventional cultivars

Table 1. Rice smut severity (number of infected kernels per kilogram of harvested seed) comparisons between tillage, fertility, and rotation treatments and their interaction in 2006–2007 crop rotation studies

Treatment ^w	Interaction ^x	Mean	LSM value ^y	LSM groupings ^z
False smut				
Conventional tillage	...	84.0	3.4101	A
No-tillage	...	26.0	1.8945	B
Enhanced fertility	...	66.4	2.7990	A
Standard fertility	...	43.8	2.5056	B
Rice-soybean rotation	...	164.0	4.8120	A
Continuous rice	...	19.1	1.8579	B
Tillage × rotation	T × R-SB	210.9	5.1267	A
	NT × R-SB	114.0	4.4974	A
	T × R-R	29.2	2.0574	B
	NT × R-R	9.0	1.6584	B
Kernel smut				
Enhanced fertility	...	133.0	3.8258	A
Standard	...	53.1	3.1760	B
Tillage × rotation	NT × R-SB	78.0	3.6603	A
	T × R-SB	81.5	3.0543	A
	T × R-R	74.7	3.0519	A
	NT × R-R	49.1	3.0266	A

^w Significant main effects and their interactions for false smut: tillage ($P < 0.0001$), fertility ($P < 0.0410$), rotation ($P < 0.0007$), and the tillage-rotation interaction ($P < 0.0001$); and kernel smut: fertility ($P < 0.0042$) and the tillage-rotation interaction ($P < 0.0001$).

^x T = conventional tillage, NT = no-tillage, R-SB = rice-soybean rotation, and R-R = continuous rice.

^y LSM = least squared means.

^z Letter groupings of differences of LSM were derived from log-transformed data for the multiple comparisons and use of the Tukey-Kramer P value adjustment. Within a treatment group, values followed by the same letter are not significantly different at $\alpha = 0.05$.

Table 2. Rice smut severity (number of infected kernels per kilogram of harvested seed) comparisons between cultivar and rotation treatments within the 2006–2007 crop rotation studies^z

Variety	Rotation	Mean	Estimate	Standard error
False smut				
Cybonnet	Continuous rice	35.6	0.1712	0.2171
Wells	Continuous rice	17.5	-0.04493	0.2157
XL 723	Continuous rice	5.8	-0.1262	0.2245
Wells	Rice-soybean	189.3	0.02685	0.2248
Cybonnet	Rice-soybean	140.3	-0.02685	0.2248
Kernel smut				
Wells	Continuous rice	99.2	0.8218	0.7649
Cybonnet	Continuous rice	23.1	-0.3218	0.7707
XL 723	Continuous rice	26.0	-0.5001	0.7707
Wells	Rice-soybean	144.6	0.9840	0.9191
Cybonnet	Rice-soybean	19.1	-0.9840	0.9191

^z Estimate = best linear unbiased predictor.

had the highest levels of kernel smut (susceptible; Cybonnet, Cypress, and Wells), whereas hybrids had consistently low disease severities (resistant; XL 723 and CLXL 730). Differentiation of resistant hybrids from susceptible cultivars was achieved at all fertility levels, including F1 (not shown).

Kernel smut resistance in rice hybrids was most evident in consistently low disease severity means from F1 through F4 (i.e., XL 723 in 2007: 6, 24, 30, and 24 infected kernels kg^{-1} for F1 to F4, respectively), whereas the conventional cultivars had higher mean severity values that in-

creased with fertility (i.e., Wells in 2007: 49, 59, 118, and 285 infected kernels kg^{-1} for F1 to F4, respectively). There was a significant (albeit negligible) increase in severity from F1 to F2 ($P = 0.0147$; 18 infected kernels kg^{-1}) in XL 723 but no additional increases in disease severity occurred from F2 through F4 ($P = 1.000$; Fig. 3A). In contrast, a nearly sixfold increase in mean severity from F1 to F4 occurred in the susceptible cv. Wells (Fig. 3B). For all cultivars included in this study, maximum yield was achieved at F2 in both years (not shown). Yields were not significantly increased at higher fertility

rates but kernel smut severity was increased (Table 4, all entries inclusive of R and S). Therefore, overfertilization (higher than F2) of a susceptible cultivar (e.g., Wells) did not improve yield but caused a two- to fivefold increase in disease severity. In contrast, there was a nonsignificant numeric increase in yield from F2 to F4 in the resistant hybrid XL 723 but kernel smut severity values remained consistently low.

Fertility treatments in the smut nursery increased plant height ($P < 0.0001$; 105, 111, 113, and 116 cm for F1 to F4, respectively) and days to heading values ($P < 0.0001$; 86, 88, 90, and 91 days for F1 to F4, respectively). Means of all cultivars at each fertility level were significantly different as determined by differences of means calculated using the LSMEANS option and Tukey's adjustment of P values. Cultivar and fertility did not significantly influence milling yield and fertility did not significantly influence head rice yield (not shown). However, total yield and head rice yields among cultivars varied (not shown). There was no correlation between false smut severity or kernel smut severity with milling yield or head rice yield (CORR procedure, SAS; not shown).

DISCUSSION

False smut and kernel smut are largely understudied diseases of rice. The difficulty in working with these environmentally variable adult plant diseases is evident in the absence of deployed sources of resistance and a sketchy understanding of disease cycles and epidemiology (2,6,12,19). Understanding agricultural practices that influence disease is essential for resistance screening and moderating severity on susceptible cultivars.

Table 3. Comparison of disease severities (number of infected kernels per kilogram of harvested seed) among cultivars in the 2007–2008 rice smut nursery study

Variety	Mean	LSM ^y	LSM grouping ^z
False smut 2007			
Cybonnet	21.2	2.51	A
Wells	11.0	1.77	A B
CLXL 730	8.1	1.71	A B
XL 723	6.5	1.57	B
Cypress	5.5	1.33	B
Kernel smut 2007			
Wells	127.5	4.39	A
Cybonnet	107.5	4.52	A
Cypress	63.8	4.04	A
XL 723	20.9	2.70	B
CLXL 730	6.3	1.41	C
Kernel smut 2008			
Cypress	39.1	3.40	A
Cybonnet	98.7	3.16	A B
Wells	16.3	2.33	A B
CLXL 730	6.6	0.96	C D
XL 723	2.6	0.76	D

^y Cultivars are listed (highest to lowest) for disease susceptibility (across all fertility treatments) using differences of least squared means (LSM; multiple comparisons) of the log-transformed disease severity data.

^z Letter groupings of differences of LSM were derived from log-transformed data for the comparisons and use of the Tukey-Kramer P value adjustment. Values followed by the same letter are not significantly different at $\alpha = 0.05$.

Fig. 2. False smut severity shown as mean sori number per kilogram of harvested rice seed (Y axis) for the five rice cultivars and four fertility treatments (X axis) included in the 2007 smut nursery study.

Table 4. Comparison of disease severities (number of infected kernels per kilogram of harvested seed) among fertility levels in the 2007–2008 rice smut nursery study

Fertility	Mean	LSM ^y	LSM group ^z
False smut 2007			
246 kg ha^{-1}	20.9	2.68	A
202 kg ha^{-1}	12.7	2.13	A
157 kg ha^{-1}	5.8	1.36	B
112 kg ha^{-1}	2.5	0.94	B
Kernel smut 2007			
246 kg ha^{-1}	113.5	4.13	A
202 kg ha^{-1}	68.8	3.69	A B
157 kg ha^{-1}	46.8	3.39	B
112 kg ha^{-1}	31.8	2.45	C
Kernel smut 2008			
246 kg ha^{-1}	72.5	3.13	A
202 kg ha^{-1}	20.3	2.15	B
157 kg ha^{-1}	10.5	1.79	B C
112 kg ha^{-1}	7.3	1.23	C

^y Least squared means.

^z Letter groupings of differences of LSM were derived from log transformed data for the comparisons and use of the Tukey-Kramer P value adjustment. Values followed by the same letter are not significantly different at $\alpha = 0.05$.

False smut is increasing in importance worldwide, particularly as hybrid rice begins to dominate production acreage. Although hybrids are perceived as highly susceptible to false smut, economically important hybrids such as XL 723 were no more susceptible than leading inbred cultivars. We believe this false perception is due to changes in hybrid crop management. U.S. rice hybrids possess good blast (*Pyricularia grisea* (Cooke) Sacc.) resistance; 18), which eliminates the need for mid- to late-season fungicide applications. Fungicides also provide some control for smuts and sheath blight (5,16). Therefore, the perception of high susceptibility to false smut in hybrids may simply be due to recognition of a disease that was previously inadvertently controlled. It is important to note that, although false smut severity levels in new hybrids are equivalent to those in established conventional cultivars, the continued release of susceptible germplasm in any form promotes disease incidence in production rice fields worldwide.

Kernel smut has been a chronic minor disease of rice in the United States for more than 50 years (15) with occasional epidemics resulting in significant losses (4,6). Attempts have been made to identify resistance but past studies have failed to identify resistant germplasm (6). The introduction of hybrids to the U.S. rice market in 1999 by RiceTec changed the germplasm base used on production rice acreage. This change introduced kernel smut resistance to production acreage through both RiceTec hybrids tested. The basis for resistance in the hybrids is unknown. Additional work is needed to determine whether major gene resistance, horizontal resistance, or field resistance is responsible for the very low severity of kernel smut in these hybrids. Although the mechanism of resistance is unknown, hybrids represent modern, relevant cultivars with immediate utility for the rice industry. Hybrids had the highest yield potential of any line tested, and also possessed the only sources of resistance to kernel smut disease.

Fertility has been known to influence the severity of rice grain smuts (15,19). Our data on fertility treatments are in agreement with previous work. Furthermore, we believe that tillage and rotation treatments directly influenced N availability for rice plants. Recently, Olk et al. (13) showed that soil N cycling was inhibited in continuous rice cropping systems, and N availability was low in mid- to late-season growth stages, resulting in yield losses. The phenomenon was attributed to accumulation of lignin-derived phenols in continuous rice systems that bind soil N, thereby inhibiting soil N mineralization and late-season crop growth. Similarly, tillage is known to affect soil C levels (14), and we hypothesize that increased C content in untilled soil also buffers N avail-

ability (7). Numerous reports exist in the literature describing disease control with crop rotation. Unlike other systems, where rotation functions as a biotic or abiotic stress on the pathogen or pathogen population (8), the effects on false smut and kernel smut appear to result from N availability and uptake at different points in the plant's development.

Although N fertility may be the key agricultural factor influencing smut severity, the treatments that alter N availability are easily employed to achieve disease control. For example, the current preferred rice culture system in Arkansas also promotes the highest severity of smuts (rice-soybean rotation, tilled soil, high fertility), particularly for false smut, where we were unable to identify resistance. In an era when carbon sequestration to the soil is of global importance (10), sustainable agriculture practices aimed at soil conservation can also benefit rice producers by controlling these two diseases. By simply avoiding excess fertility rates in this study, a single pre-flood application of N at 157 kg ha⁻¹

reduced both smut diseases on susceptible cultivars and maximized yield.

It is important to note that, although false smut and kernel smut disease severity was positively affected by N fertility, each disease is unique. Genetic differences in disease resistance exemplify this fact, where the conventional cultivars were susceptible to both diseases and the hybrids possessed resistance to kernel smut but not to false smut. No correlation between the two diseases, or each disease with milling yield, was detected. Furthermore, analysis of covariance detected the influence of plant height and days to heading on the kernel smut severity measurement but these control measurements were not detected to be covariates for false smut severity (*not shown*). At this time, we have no explanation for the observed covariates for kernel smut severity beyond pure speculation. We report it here as further evidence of the uniqueness of each disease.

Control measurements of plant height and days to heading were used to demonstrate the efficacy of the fertility treatments

Fig. 3. Kernel smut severity shown as mean number of infected kernels per kilogram of harvested rice seed (right Y axis), and grain yield (left Y axis) at the four fertility levels (X axis) included in the 2007 smut nursery. **A**, Kernel smut and yield trends with fertility for resistant hybrid XL 723; **B**, plot of the same variables for the susceptible conventional cv. Wells.

in the smut nursery but the data also show the precision obtained in a difficult-to-control field experiment. Differences as small as 1 day in heading and 3 cm in plant height were significant, indicating that fertility categories were easily obtained for the phenotypes of interest. Furthermore, we observed good correlation of fertility response trends, degrees of disease severity, and cultivar disease rankings between two experiments conducted over 3 years. Only one cultivar–disease interaction (Cybonnet–kernel smut) displayed a noteworthy difference (2006 rotation study versus 2007–2008 smut nurseries). Cybonnet was included in the nurseries due to low kernel smut severity values in 2006 but a considerable increase in kernel smut severity was observed in 2007 and 2008. This inconsistency is interesting because all other cultivar–disease interactions correspond well, and false smut severity in Cybonnet was also consistent between two year–experiment interactions.

Covariance parameter estimates were used to quantify the variance due to cultivar and year for the rotation study. For false smut, severity variance due to cultivar was low and was consistent with the assessment that all tested cultivars were susceptible. The variance due to year was high for false smut severity, as expected. Severity of false smut was greater in 2006 than 2007. This was attributed to heavy rain storms that shattered false smut sori (much larger than rice grains) from panicles prior to harvest, because high levels of disease severity were observed at grain fill (S.A. Brooks, *field observations*). The trends were reversed for kernel smut severity variance levels. Variance from cultivar was high for kernel smut, which is consistent with the inclusion of both resistant and susceptible cultivars. Variance due to year was low for kernel smut because infected

kernels were no more likely to shatter from the 2007 rain events than noninfected kernels.

ACKNOWLEDGMENTS

We thank J. Gibbons, A. Jackson, Y. Jia, F. Lee, D. McCarty, A. McClung, G. Miller, T. Moss, B. Ottis, T. Sells, J. Stroike, and K. Ueda for their contributions to this project.

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