Effect of Silicon Rate and Host Resistance on Blast, Scald, and Yield of Upland Rice

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ABSTRACT

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Blast-resistant, partially resistant, and susceptible cultivars of rice were planted in soil amended with Si at 0, 500, or 1,000 kg/ha at two locations in eastern Colombia to assess differential responses to leaf blast, neck blast, and leaf scald, and to examine the quantity and quality of grains harvested. Leaf and neck blast on partially resistant and susceptible cultivars were reduced by Si as the rate of Si was increased. Depending on the location, the level of severity of leaf and neck blast on partially resistant cultivars, when fertilized with Si at 500 or 1,000 kg/ha, was lowered to that of resistant cultivars without Si. At both locations, yields were increased by as much as 42%, depending on the cultivar, by Si applied at 1,000 kg/ha. In general, high rates of Si reduced the number of broken grains harvested. Grain discoloration, regardless of cultivar or location, was reduced by as much as 70% at the high rate of Si. The application of Si to complement host resistance to blast and scald appears to be an effective strategy for disease management in rice and provides the added benefit of improving the quantity and quality of rice yields.

Additional keywords: *Magnaporthe grisea*

Upland rice is grown in Asia, Africa, and Latin America on nearly 19 million hectares, making up 12% of the total worldwide production of rice (19). It is the dominant type of rice culture in parts of Africa and Latin America. Rice blast is particularly severe on rice grown in upland ecosystems due to increased susceptibility to blast by plants grown under non-flooded conditions (1,21). In the upland ecosystem, rice blast is controlled primarily through the planting of resistant cultivars and through cultural practices, such as the avoidance of excessive nitrogen fertilization and planting early in the season (1,12,30). Fungicides are also employed for the control of rice blast, but they are practical only in more industrialized countries due to their relatively high cost (19).

Cultivars of rice (*Oryza sativa* L.) with complete resistance to rice blast, caused by *Magnaporthe grisea* (Hebert) Barr, have been deployed successfully to manage this disease, especially in areas where blast is sporadic or low in severity (1,3,21). However, individual resistant cultivars have become susceptible to blast within a short time after their introduction due to the emergence of pathogenic races of *M. grisea* that are no longer affected by resistance genes in the host (8,9,25). This is a result of inherent variability in populations of *M. grisea*, or of a failure to select and advance breeding lines in the presence of populations of *M. grisea* that are representative of those encountered in commercial fields (7-9,23). Cultivars that are partially resistant to blast have also been utilized to control blast in irrigated lowland rice in tropical regions, but they have performed poorly in areas with greater blast severity, such as irrigated lowland rice in temperate regions and upland rice systems (2,3). Under conditions that are highly conducive to the development of rice blast, additional disease control strategies, such as cultural practices or fungicides, are necessary (3,8).

Upland rice is cultivated on acid soils, typically Oxisols and Ultisols, that are

highly weathered. These soils are nutrient-poor due to leaching processes brought about by heavy annual rainfall (24,34). Among the elements deficient in these soils is silicon (Si), which has been shown to be essential for maximum growth and yield of a number of plant species, including *O. sativa* (14,16). Differential accumulation of Si has been documented among rice cultivars grown under flooded and upland conditions (13,33).

Silicon is also known to reduce the severity of important diseases of rice such as blast; brown spot, caused by *Cochliobolus miyabeanus*; sheath blight, caused by *Thanaophorus cucumeris*; stem rot, caused by *Magnaporthe salvinii*; and leaf scald, caused by *Monographella albescens* (10,11,14,16,21,28). Increased levels of Si in the rice plant are associated with decreased levels of grain discoloration at harvest, and Si has been reported to reduce shattering of seeds in rice and to increase the number and weight of filled grains (14,24,27,28,33). The physiological mechanisms behind these phenomena are poorly understood (4-6,20,21), and the ability of Si fertilizers to complement inherent host resistance has not been well-studied.

The purpose of this study was to evaluate disease and yield responses in blast-resistant, partially resistant, and blast-susceptible cultivars of rice grown under upland conditions when fertilized with Si fertilizer at two rates, and to determine if fertilization with Si could complement inherent host resistance so as to reduce leaf and neck blast severity to levels comparable to blast-resistant cultivars not fertilized with Si. The effects of fertilization with Si on yield, yield quality, and the concentration of Si in plant tissue were also evaluated. Portions of this work have been reported previously (25-27).

MATERIALS AND METHODS

Location. Experiments were conducted in 1996 at two locations situated approximately 30 km east of Villavicencio, Colombia. The first location was the Santa Rosa research station, maintained by the Centro Internacional de Agricultura Tropical (CIAT) as a rice breeding nursery. The

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soil type was an Inceptisol with the following characteristics: pH 4.7, cation exchange capacity (CEC) 3.11, 18.3% Al saturation, and approximately 4 ppm plant-available Si. The second site was located approximately 5 km east of Santa Rosa at the Instituto Colombiano Agropecuario's (ICA) La Libertad experiment station. The soil type (Oxisol) at the La Libertad site was representative of upland conditions in the savannas of Colombia. Soil pH was 4.7, and less than 1 ppm plant-available silicon was determined to be present. The CEC was 1.99 and the Al saturation was 79%.

Experimental design and layout. The experimental designs at both locations were split-plots with five replications. Whole plots consisted of three rates of Si, and subplots consisted of three rice cultivars. Wollastonite, a source of calcium silicate that contains 20% elemental Si, was applied 5 days before planting at 0, 2.5, and 5 t/ha, corresponding to 0, 500, and 1,000 kg of elemental Si per hectare. The rice cultivars *Oryzica Llanos 5* (blast resistant), *Linea 2SR* (partially blast resistant), and *Oryzica 1* (blast susceptible) were planted at Santa Rosa, while *Oryzica Sabana 10* (blast resistant), *Linea 2LL* (partially blast resistant), and *IRAT 146* (blast susceptible) were planted at La Libertad. Differences in soil type and pathogen population between Santa Rosa and La Libertad dictated the choices of cultivars used at the experimental locations. The cultivars planted at La Libertad, japonica types, were bred specifically for the savanna ecosystem at that location and were thus chosen for that location instead of the indica-type cultivars planted at Santa Rosa (which could not have been grown at La Libertad). Although the cultivars at both locations were different, they represented a range of susceptibilities to the populations of *M. grisea* inherent at each location. *Oryzica 1*, *Linea 2SR*, and *Oryzica Llanos 5* have approximately 30% genetic similarity. *Linea 2SR* was selected from plants (*Oryzica 1*) in a field that appeared to be more resistant to blast. *Oryzica Llanos 5* is resistant to all genetic lineages of *M. grisea* present at Santa Rosa, *Linea 2SR* is susceptible to only one lineage, and *Oryzica 1* is susceptible to three of the six lineages. *Oryzica Sabana 10* and *Linea 2LL* are sister lines derived from the same cross. They differ in that *Oryzica Sabana 10* is resistant to all lineages of *M. grisea* at La Libertad, and *Linea 2LL* is partially resistant to one lineage. *IRAT 146* is unrelated to either *Oryzica Sabana 10* or *Linea 2LL*, and is completely susceptible to one lineage group of *M. grisea*. This methodology served as a model that allowed for twice-replicated testing, by location, of the effects of Si on blast-resistant, partially resistant, and blast-susceptible cultivars of rice.

Whole plots were 5 × 9.36 m and were subdivided into three 5 × 3.12 m subplots

(12 rows per subplot). Spacing between plots in each block was 3 m, and spacing between blocks was 2 m. A border consisting of four rows of the susceptible cultivar (specific to each site) was planted around the entire experimental area, with spacing of 3 m between experimental plots and the border rows.

Soil preparation and planting. Dolomitic limestone (CaCO₃Mg) was incorporated into the soil approximately 20 days prior to planting at both locations to increase alkalinity. At Santa Rosa, phosphorus, potassium, magnesium sulfate, and borax were preplant incorporated at rates of 60, 30, 60, and 0.6 kg/ha, respectively. Phosphorus (100 kg/ha), potassium (45 kg/ha), and zinc sulfate (25 kg/ha) were incorporated prior to planting into each plot at La Libertad. Silicon, in the form of wollastonite (CaSiO₃) (R. T. Vanderbilt, Norwalk CT), was broadcast according to rate by hand and incorporated prior to planting with a tractor-mounted disk. Agricultural lime (CaCO₃) was applied to those plots treated with calcium silicate at 2.5 t/ha and those not treated with wollastonite to adjust the Ca level to that of the treatment with 5 t of calcium silicate per hectare. All rice cultivars were drill-seeded at a rate of 80 kg/ha to a depth of 3 cm. Row spacing was 0.26 m. Planting date at Santa Rosa was 25 May; however, the test was destroyed due to heavy rains following planting and had to be reseeded on 14 June. At La Libertad, plots were planted on 24 May.

At both locations, nitrogen was applied 17, 30, 50, and 70 days after planting (DAP) at rates of 17, 10, 27, and 46 kg/ha, respectively. The Santa Rosa site received an additional 30 kg of potassium at 30 DAP, while potassium at 45 kg/ha and magnesium sulfate at 25 kg/ha were applied at 30 DAP at La Libertad.

Propanil and bentazone were applied at labeled rates for control of weeds, and deltamethrin and chlorpyrifos were applied as needed for insect control.

Data collection and analysis. Prior to the appearance of disease, five main tillers per subplot were tagged at the base of the main tiller with a 2.5-cm section of plastic tubing of 2.5 cm diameter that had been coated with fluorescent paint. At each location, severity of leaf blast for each cultivar was evaluated at a single date, near maximum tillering, by visually estimating the percent diseased leaf area of each leaf of the five marked tillers. Severity of leaf scald was evaluated at a single point in the growing season by selecting five sites within each subplot and randomly choosing five leaves from the middle portion of the plant canopy. Scald severity was rated visually as the percent diseased leaf area (DLA) of the five selected leaves. Severity of neck blast was estimated on 50 randomly selected panicles per plot using the following formula (17): Severity = [(10 ×

N_1) + (20 × N_3) + (40 × N_5) + (70 × N_7) + (100 × N_9)]/50 panicles. The numbers N_1 to N_9 represent the number of panicles with scores of 1, 3, 5, 7, or 9, respectively, scored at each evaluation. These values were then multiplied by a weighting factor. The scale, developed by the International Rice Research Institute, is as follows: 0 = no symptoms; 1 = lesions on pedicels and branches; 3 = lesions on branches and panicle axis; 5 = lesions partially surrounding base of panicle; 7 = lesions completely surrounding base of panicle, with greater than 30% of grains filled; and 9 = lesions completely surrounding base of panicle, with fewer than 30% of grains filled (19). Neck blast was evaluated at growth stage 9, or the mature grain stage. Evaluation dates for neck blast varied according to cultivar.

Subplots were harvested by hand on 18 September at La Libertad, and on 22 October at Santa Rosa. A 3 × 2 m section was marked in each subplot using a wire frame, and only those tillers within the frame were cut. Yields of rough rice (kg/ha) were determined from grain harvested in the 6 m² portion of each subplot and were adjusted to reflect a 12% moisture content. Grain discoloration was estimated using a 0 to 6 pictorial scale, where 0 = grains with no discoloration and 6 = grains completely discolored.

Milling quality of rough rice was determined by placing a 125-g sample from each subplot in a de-huller (H. T. McGill and Co., Houston, TX). Brown rice yields were calculated, followed by further milling to remove the bran layer from grains. Yields of white rice were determined, after which samples were sorted using a Carter-Day Model XT-3 dockage tester (Carter-Day Inc., Minneapolis, MN). Samples were divided into two classes, whole and broken, and the percentage of grains falling into each class was calculated by dividing the weight of grains in a given class by the sample size. All sample weights were adjusted to 12% moisture content.

Leaf tissue samples were collected at the time of evaluation for leaf blast severity at both locations to determine Si concentration of plants in unamended and Si-amended plots. Additionally, roughly 500 g of stem tissue was collected and dried at harvest time. Dried tissue was ground to pass through a 40-mesh screen using a Thomas-Wiley mill (Thomas Scientific, Swedesboro, NJ). Silicon content of tissue samples was determined by first digesting 0.1 g of dried tissue, followed by automated colorimetric analysis (15). Results obtained from automated colorimetric analysis, expressed in absorbance units (mV), were converted to percentages reflecting decagrams (dag) of Si per kg of plant tissue.

All data collected were analyzed by analysis of variance (ANOVA). Treatment and cultivar means were compared using

Fisher's protected least significant difference test (FLSD). Single degree of freedom contrasts were used to make comparisons between specific whole plot (Si rate) and subplot (cultivar) means. Tests for linear correlation were performed between means for content of Si in plant tissue (leaf and stem) and disease severity (blast and scald). A test for linear correlation between rate of Si and means for yield and yield quality was also performed. All analyses were conducted using SAS version 6.12 (SAS Institute, Cary, NC).

RESULTS

Leaf blast. The interaction between rate of Si and rice cultivar was significant ($P \leq 0.05$) at both Santa Rosa and La Libertad, requiring the analysis of Si means by cultivar. The severity of leaf blast tended to be greater at Santa Rosa than at La Libertad, although total DLA was approximately 2 and 6%, respectively, on the susceptible cultivars at the two locations (Tables 1 and 2). The application of Si at 500 and 1,000 kg/ha significantly reduced severity of leaf blast from 1.8 to 0.5% on Linea 2SR and from 5.9 to 1.6% on Oryzica 1 as compared to these cultivars without Si. However, no significant reduction was seen in disease severity, regardless of rate, for the blast-resistant cultivar Oryzica Llanos 5, where the highest DLA did not exceed 0.06% where Si was not applied.

To determine if the application of Si to a blast-susceptible cultivar could suppress leaf blast levels to those of partially resistant or resistant cultivars that had not been

treated with Si, means of selected cultivar-Si combinations were compared by single degree of freedom contrasts (Tables 1 to 3). The combination of Oryzica 1 plus Si at either 500 or 1,000 kg/ha did not reduce the severity of leaf blast to the same statistical level as that for the resistant cultivar, Oryzica Llanos 5. However, the severity of leaf blast did not differ significantly between the combination of Oryzica 1 plus Si at 500 or 1,000 kg/ha and the partially resistant Linea 2SR without Si. Leaf blast severity on Linea 2SR plus Si at 500 or 1,000 kg/ha was reduced to levels not significantly different from those on Oryzica Llanos 5 without Si.

At La Libertad, leaf blast was significantly reduced on all cultivars by the application of Si at either 500 or 1,000 kg/ha (Tables 1 and 2). Disease severity did not differ for Si between 500 and 1,000 kg/ha for Oryzica Sabana 10, Linea 2LL, or IRAT 146.

Applications of Si at 500 and 1,000 kg/ha reduced the severity of leaf blast on the blast-susceptible cultivar IRAT 146 to the same statistical level as Oryzica Sabana 10 without Si ($P \leq 0.05$) (Tables 1 to 3). Severity of leaf blast was lower for IRAT 146 plus Si at 500 and 1,000 kg/ha compared with Linea 2LL without Si.

Leaf scald. At both locations, the interaction between Si rate and cultivar was not significant ($P \leq 0.05$); therefore Si treatment means are averaged across all cultivars (Tables 1 and 2). For all cultivars, the severity of leaf scald was significantly different at each rate of Si. Disease was

reduced at Santa Rosa by 23% at 500 kg/ha, and by 41% at 1,000 kg/ha. At La Libertad, scald severity was reduced by 32 and 42%, respectively, at 500 and 1,000 kg/ha.

Neck blast. The interaction between Si rate and cultivar was significant ($P \leq 0.05$); therefore, Si treatment means are reported by cultivar. Generally, the severity of neck blast was higher at the Santa Rosa site than at La Libertad (Tables 1 and 2). At both locations, fertilization of blast-resistant cultivars Oryzica Llanos 5 or Oryzica Sabana 10 with Si at any rate did not result in significant decreases in the severity of neck blast. For Linea 2SR and Oryzica 1, severity of neck blast decreased 37 and 28%, respectively, at Santa Rosa in plots fertilized with 1,000 kg/ha of Si compared with plots not fertilized with Si. No significant decrease in disease was found at the lower application rate.

At Santa Rosa, the addition of Si at 500 and 1,000 kg/ha did not suppress the severity of neck blast for either Linea 2SR or Oryzica 1 to levels equivalent to the resistance expressed by the blast-resistant cultivar Oryzica Llanos 5 without Si (Tables 1 to 3). However, the addition of Si at 1,000 kg/ha reduced neck blast severity on Oryzica 1 to that of Linea 2SR without Si ($P \leq 0.05$).

At La Libertad, fertilization of partially resistant and susceptible cultivars at either rate of Si significantly reduced disease compared with cultivars not fertilized with Si (Tables 1 and 2). Severity of neck blast was reduced by 74 and 92% on Linea 2LL

Table 1. Severity of leaf blast, leaf scald, and neck blast on blast-resistant, partially resistant, and blast-susceptible cultivars of rice treated with Si at 500 or 1,000 kg/ha at Santa Rosa, Colombia, in 1996

Silicon rate (kg/ha)	Leaf blast % DLA ^v			Leaf scald % DLA ^w All cultivars ^y	Neck blast % severity ^x		
	Oryzica Llanos 5	Linea 2SR	Oryzica 1		Oryzica Llanos 5	Linea 2SR	Oryzica 1
0	0.06 a ^z	1.8 a	5.9 a	8.3 a	2.8 a	33.0 a	55.1 a
500	0.04 a	0.8 ab	3.0 b	6.4 b	4.4 a	28.0 ab	48.7 a
1,000	0.01 a	0.5 b	1.6 b	4.9 c	2.4 a	20.5 b	39.4 b

^v Percent diseased leaf area (DLA) estimated visually on all leaves of five tillers per subplot.

^w Percent DLA estimated visually on five leaves at five randomly selected sites within a subplot.

^x Percent neck blast severity estimated on 50 randomly selected panicles per subplot using a 0 to 9 rating scale.

^y Means for leaf scald averaged across all cultivars.

^z Means within a column followed by the same letter do not differ significantly according to Fisher's protected least significant difference test (FLSD) ($P \leq 0.05$).

Table 2. Severity of leaf blast, leaf scald, and neck blast on blast-resistant, partially resistant, and blast-susceptible cultivars of rice treated with Si at 500 or 1,000 kg/ha at La Libertad, Colombia, in 1996

Silicon rate (kg/ha)	Leaf blast % DLA ^v			Leaf scald % DLA ^w All cultivars ^y	Neck blast % severity ^x		
	Oryzica Sabana 10	Linea 2LL	IRAT 146		Oryzica Sabana 10	Linea 2LL	IRAT 146
0	0.4 a ^z	1.8 a	2.2 a	4.0 a	14.8 a	9.1 a	16.0 a
500	0.1 b	0.3 b	0.3 b	2.7 b	10.4 a	2.4 b	8.0 b
1,000	0.03 b	0.3 b	0.1 b	2.3 c	12.8 a	0.72 b	5.7 b

^v Percent diseased leaf area (DLA) estimated visually on all leaves of five tillers per subplot.

^w Percent DLA estimated visually on five leaves at five randomly selected sites within a subplot.

^x Percent neck blast severity estimated on 50 randomly selected panicles per subplot using a 0 to 9 rating scale.

^y Means for leaf scald averaged across all cultivars.

^z Means within a column followed by the same letter do not differ significantly according to Fisher's protected least significant difference test (FLSD) ($P \leq 0.05$).

at 500 and 1,000 kg/ha, respectively, and by 50 and 64% on IRAT 146 at the same rates ($P \leq 0.05$).

Neck blast severity was reduced on IRAT 146 and Linea 2LL treated with Si at 500 and 1,000 kg/ha to levels significantly lower than those observed on Oryzica Sa-

bana 10 without Si ($P \leq 0.05$). No differences in severity were found between the cultivars where Si was not applied.

Yield and grain quality. The interaction between Si rate and cultivar was not significant at either location; therefore means for yield and grain quality for each

rate of Si are presented across all cultivars. Although yields tended to be higher for all cultivars at Santa Rosa than at La Libertad, responses by the cultivars to fertilization by Si tended to be of a greater magnitude at La Libertad than at Santa Rosa (Table 4). The application of Si at 500 and 1,000 kg/ha to all cultivars significantly increased grain yield, compared with the same cultivars without Si, by 19 and 24% ($P \leq 0.05$), respectively, at Santa Rosa, and by 40 and 72% at La Libertad.

Milling quality of grain harvested from cultivars planted at Santa Rosa was not affected by applications of Si at 500 kg/ha. When applied at 1,000 kg/ha, the percentage of head rice (whole grains) was increased by 20% and the percentage of broken grains was reduced by 15% across all cultivars tested in relation to the same cultivars not fertilized with Si ($P \leq 0.05$) (Table 4). Averaged across all cultivars, fertilization with Si at 1,000 kg/ha reduced grain discoloration by 26%.

At La Libertad, the percentage of head rice was significantly increased ($P \leq 0.05$) on all cultivars by 16% when fertilized with Si at 500 kg/ha, and by 26% when fertilized with Si at 1,000 kg/ha compared with when Si was not applied (Table 4). No differences were found among Oryzica Sabana 10, Linea 2LL, or IRAT 146 at any rate of Si with regard to the percentage of broken grains. Grain discoloration was reduced for all cultivars by 68% in relation to the control at both 500 and 1,000 kg/ha.

Silicon content of plant tissue. Analysis of Si content of leaf tissue collected after evaluations of leaf blast and of stem tissue collected before harvest showed that, at both Santa Rosa and La Libertad, there was no significant interaction between rate of Si and cultivar ($P \leq 0.05$). Means for Si content in leaf and stem tissue are thus presented as averages across all cultivars for each rate of Si (Table 5). At Santa Rosa, Si content of leaf and stem tissue was significantly higher compared with that of tissue collected from plants that had not been fertilized with Si ($P \leq 0.05$). The percentage of Si in leaf tissue increased 41 and 60%, respectively, where Si was applied at 500 or 1,000 kg/ha. The silicon content of stem tissue increased by 15 and 31% at the same rates of Si.

The concentration of Si in plant tissue following the addition of Si fertilizer at La Libertad followed a pattern similar to that found at Santa Rosa. Silicon content of leaf and stem tissue increased by 94 and 60%, respectively, across all cultivars when Si was applied at 500 kg/ha, and by greater than 100% when Si was applied at 1,000 kg/ha (Table 5).

Correlation analyses. At Santa Rosa, the leaf scald was negatively correlated ($P = 0.0001$) with rate of silicon on Oryzica Llanos 5, while no significant correlations were found between Si content in leaf or stem tissue and leaf or neck blast severity

Table 3. Effects of Si fertilizer on the severity of leaf and neck blast for three cultivars of rice at Santa Rosa and La Libertad, Colombia, in 1996^x

Contrast	Blast severity	
	Leaf <i>Pr > F</i>	Neck <i>Pr > F</i>
Santa Rosa		
Oryzica 1 (500) vs. Oryzica Llanos 5 (0) ^y	***z	**
Oryzica 1 (1,000) vs. Oryzica Llanos 5 (0)	**	**
Oryzica 1 (500) vs. Linea 2SR (0)	ns	**
Oryzica 1 (1,000 kg) vs. Linea 2SR (0)	ns	ns
Linea 2SR (500) vs. Oryzica Llanos 5 (0)	ns	**
Linea 2SR (1,000) vs. Oryzica Llanos 5 (0 T)	ns	**
La Libertad		
IRAT 146 (500) vs. Oryzica Sabana 10 (0)	ns	**
IRAT 146 (1,000) vs. Oryzica Sabana 10 (0)	ns	**
IRAT 146 (500) vs. Linea 2LL (0)	**	ns
IRAT 146 (1,000) vs. Linea 2LL (0)	**	ns
Oryzica Sabana 10 (500) vs. Linea 2LL (0)	ns	**
Oryzica Sabana 10 (1,000) vs. Linea 2LL (0)	ns	**

^x Comparisons represent single degree of freedom contrasts between mean values of percent leaf area with disease for selected Si-cultivar combinations from Tables 1, 2, and 4.

^y Numbers in parentheses are rates of Si in kg/ha.

^z *** = 0.01 or 0.0001; ns = not significant.

Table 4. Yield and yield quality of grains from blast-resistant, partially resistant, and blast-susceptible cultivars of rice treated with Si at 500 or 1,000 kg/ha at Santa Rosa and La Libertad, Colombia, in 1996

Location	Rough rice yield Si rate (kg/ha)	Grain quality		
		Percent ^x		Discoloration rating ^y
	(kg/ha) ^w	Head rice	Broken rice	
Santa Rosa				
0	2,836.8 a ^z	28.7 a	30.2 a	2.73 a
500	3,356.5 b	27.8 a	29.9 a	2.33 ab
1,000	3,516.0 b	34.6 b	25.8 b	2.03 b
La Libertad				
0	1,772.4 a	12.8 a	43.3 a	3.8 a
500	2,507.6 b	14.9 b	42.3 a	1.2 b
1,000	3,056.1 c	16.1 c	41.4 a	1.2 b

^w Yield of rough (unmilled) rice estimated from 6 m² sections of each subplot and averaged across three cultivars of rice for each rate of Si.

^x Percentage of grains in two classes, head rice (whole grains) and broken, from a 125-g sample, averaged across three cultivars of rice for each rate of Si and replicated five times.

^y Grain discoloration of rough rice, rated on a 0 to 6 pictorial scale, where 0 = clean grains and 6 = completely discolored grains. Data shown are means taken across three cultivars of rice for each rate of Si and replicated five times.

^z Means within a column followed by the same letter do not differ significantly according to Fisher's protected least significant difference test (FLSD) ($P \leq 0.05$).

Table 5. Accumulation of Si in leaf and neck tissue by cultivars of rice planted at Santa Rosa and La Libertad, Colombia, in 1996

Si rate (kg/ha)	Santa Rosa		La Libertad	
	Leaf ^x	Neck ^y	Leaf ^x	Neck ^y
0	2.2 a ^z	2.6 a	1.8 a	1.5 a
500	3.1 b	3.0 b	3.5 b	2.4 b
1000	3.5 c	3.4 c	4.1 c	3.4 c

^x Percentage of Si in leaf matter determined from samples taken at the time of leaf blast evaluation.

^y Percentage of Si in panicles and stems determined from samples taken at harvest.

^z Means within a column followed by the same letter do not differ significantly according to Fisher's protected least significant difference test (FLSD) ($P \leq 0.05$).

(Table 6). A negative correlation ($P = 0.02$) was determined between Si levels in leaf tissue and leaf blast severity at La Libertad. Severity of blast and scald was more strongly correlated with Si content in plant tissue on the partially blast-resistant and blast-susceptible cultivars at both locations. Negative correlations between Si in leaf tissue and severities of both leaf blast ($P = 0.02$) and leaf scald ($P = 0.001$) were found at Santa Rosa on Linea 2SR. Leaf blast, leaf scald, and neck blast severities on Linea 2LL were negatively correlated ($P \leq 0.01$) with Si content in leaf tissue and stems at La Libertad. Susceptible cultivars at both locations had negative correlations between blast severity (leaf and neck) and Si content, while leaf scald severity was negatively correlated with Si content in leaf tissue only at Santa Rosa.

Yields were positively correlated ($P \leq 0.05$) with the rate of Si applied at both locations (Table 7), as were levels of Si in leaf and stem tissue. The percentage of whole grains collected was positively correlated with Si application rate, and the number of broken grains was negatively correlated with Si rate at Santa Rosa. No correlations between Si rate and milling quality were found at La Libertad.

DISCUSSION

The data presented in this study provide evidence that applications of Si to Si-deficient soils, depending upon the application rate and disease pressure, can decrease leaf and neck blast in partially resistant and susceptible cultivars of rice to levels observed for resistant cultivars grown without supplemental Si. It is clear that the response of partially resistant and susceptible cultivars to fertilization with Si, for the rates tested, is dependent upon the overall severity of disease at a given location. Higher inherent severity of disease at specific sites may require larger amounts of Si fertilizer to reduce leaf and neck blast as

effectively as blast-resistant cultivars. Where conditions are less conducive to disease development, lower rates might suffice for adequate disease control.

According to Correa-Victoria and Zeigler (7,8), high levels of resistance to blast in cultivars such as Oryzica Llanos 5 and Oryzica Sabana 10 are due to the expression of major blast resistance genes, although cultivars with major genes for resistance to rice blast are known to possess genes for partial resistance. In the case of neck blast, in this study, Si does not appear to exert a strong effect on the expression of resistance by the two blast-resistant cultivars. Based upon the large reductions of leaf and neck blast that can be directly linked to fertilization with Si on partially blast-resistant and blast-susceptible cultivars, it is likely that Si affects one or more components of partial resistance as defined by Parlevliet (22). Partial resistance, which corresponds to van der Plank's "horizontal" resistance (31), results in a reduced epidemic rate (r) and levels of disease that fall between those for completely resistant and susceptible cultivars. The partially blast-resistant cultivars examined in this study showed levels of resistance to leaf

and neck blast that were intermediate in comparison to blast-resistant and blast-susceptible cultivars, and the levels of disease were pushed downward as Si rate was increased. It is plausible that Si could affect some component of complete, or vertical, resistance, which is known to affect the onset of disease (y_0) as well as the epidemic rate (22). In the present study, however, disease onset was observed to occur at nearly the same time for all cultivars (data not shown). While effects on initial infection frequency, which act to reduce y_0 and r , cannot be ruled out, it is unlikely that Si acts to delay onset of disease.

Significant correlations between Si content of leaf or stem tissue and disease were found in this study. Earlier reports have provided evidence that levels of blast, scald, and brown spot are negatively correlated with the amount of Si fertilizer applied to Si-deficient soils; however, only Volk et al. (32) correlated the concentration of Si in *M. grisea*-infected leaf tissue and severity of disease (10,11,20,28,29,33). Winslow (33) compared the incidence of neck blast and severity of scald with Si concentration of flag leaves, but did not

Table 7. Pearson correlation coefficients for rate of Si vs. yield and grain quality of rice

Si ^y	Pearson correlation coefficient				
	Yield ^z	Milling quality ^x		Tissue Si content	
		Head rice (%)	Broken (%)	Leaf	Stem
Santa Rosa	0.34	0.39	-0.37	0.72	0.76
Prob > R	0.02	0.008	0.01	0.0001	0.0001
<i>n</i> = 45					
La Libertad	0.72	0.18	-0.10	0.81	0.89
Prob > R	0.0001	0.23	0.5	0.0001	0.0001
<i>n</i> = 45					

^x Percentage of grains from a 125-g sample sorted into two classes, head rice (whole grains) and broken grains.

^y Applied at 0, 500, and 1,000 kg/ha.

^z Yield of rough rice (kg/ha) from blast-resistant, partially blast-resistant, and susceptible cultivars planted at Santa Rosa and La Libertad.

Table 6. Pearson correlation coefficients for leaf blast, leaf scald, and severity of neck blast of rice vs. tissue Si content, by cultivar at Santa Rosa and La Libertad

Cultivar Variable ^z	Leaf Si content ^y				Stem Si content ^y			
	Santa Rosa		La Libertad		Santa Rosa		La Libertad	
	corr	<i>Pr</i> > R	corr	<i>Pr</i> > R	corr	<i>Pr</i> > R	corr	<i>Pr</i> > R
Resistant								
Leaf blast	-0.47	0.08	-0.61	0.02	...	...	...	...
Leaf scald	-0.91	0.0001	-0.29	0.31	...	...	...	...
Neck blast sev.	...	...	...	...	-0.39	0.15	-0.44	0.09
Part. resistant								
Leaf blast	-0.60	0.02	-0.66	0.008	...	...	...	...
Leaf scald	-0.76	0.001	-0.66	0.007	...	...	...	...
Neck blast sev.	...	...	...	...	-0.49	0.07	-0.64	0.005
Susceptible								
Leaf blast	-0.55	0.03	-0.76	0.01	...	...	...	...
Leaf scald	-0.61	0.01	-0.36	0.18	...	...	...	...
Neck blast sev.	...	...	...	...	-0.81	0.0002	-0.62	0.01

^y Content of Si in leaf tissue and in stem tissue. Foliar diseases (leaf blast, leaf scald) were compared with content of Si in leaf tissue only. Neck blast severity was compared with content of Si in stem tissue only.

^z Variables correlated against Si content of tissue. Leaf blast = severity of leaf blast (% diseased leaf area), leaf scald = severity of leaf scald (% diseased leaf area), Neck blast sev. = severity of neck blast.

always find negative correlations with disease and Si concentration of flag leaf tissue. Because concentration of Si varies by plant part (18), it is possible that Si content of the flag leaf is not representative of the condition of other diseased tissues. In the present study, for all cultivars at both locations, severity of leaf blast was negatively correlated with the concentration of Si in leaf tissue collected at the time of disease evaluation.

Silicon can be used successfully with blast-susceptible and partially blast-resistant cultivars to manage leaf and neck blast, and also leaf scald. Depending upon the rate of Si fertilizer applied to Si-deficient soil, the severity of these diseases on susceptible and partially resistant cultivars can, in some cases, be reduced to the same levels as those observed for blast-resistant cultivars. This could make Si a useful tool for managing rice diseases, possibly in conjunction with reduced rates of fungicide or specific times of application, and may provide alternatives to rice growers in areas where blast-resistant cultivars have become susceptible due to shifts in populations of *M. grisea*. Because breeding for resistance to multiple diseases can be difficult, the ability of Si to reduce diseases such as leaf scald provides an alternative for control of these diseases. The improvements in yield and quality of yield (increased milling quality and reductions of grain discoloration) on all cultivars obtained through fertilization with Si could provide a means for rice growers in upland ecosystems, and in other Si-poor environments, to realize significant economic gains with only a minor increase in input costs. Even where blast-resistant cultivars are deployed, improvements in yield and yield quality alone would justify the application of Si fertilizers. According to McLean (19), demand for rice will increase by more than 60% in the next 30 years as the world's population increases. In areas where plant-available Si is known to be deficient, supplying an adequate level of Si, as shown in this study, could raise yields by up to 60% and help rice growers meet the demand for greater production of rice in the coming years.

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