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Silicon fertilization for disease management of rice in Florida*

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Although silicon is not considered an essential element; plant development, growth and yield has been increased in many graminaceous and some nongraminaceous crop species. Silicon also is known to reduce plant diseases especially in rice. Silicon fertilization has become a routine practice in Florida rice production. The information within provides an overview on the history of silicon in Florida, application of silicon and disease suppression by silicon and its interaction with fungicides and rice genotypes. Although the focus is on rice and organic soils, this information should be of interest to those working on other grass crops on organic soils as well as rice production on weathered, low-silicon mineral soils. An outlook and future research needs also are presented. © 1997 Elsevier Science Ltd

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Introduction

Silicon (Si) is one of the most abundant elements in the earth's crust and most soils contain considerable quantities of the element (Epstein, 1994). However, repeated cropping can reduce the levels of plant-available Si to the point that supplemental Si fertilization is required for maximum production, and some soils contain little plant-available Si in their native state. Low-Si soils are typically highly weathered, leached, acidic and low in base saturation. Thus, highly weathered soils such as Oxisols and Ultisols can be quite low in soluble Si (Foy, 1992). Highly organic Histosols that contain little mineral matter may contain little Si. Interestingly, soils comprised mainly of quartz sand (SiO_2) such as sandy Entisols also may be very low in plant-available Si. These conditions are found in many crop-producing areas of Africa, Asia, Latin America and the southeastern USA. Much of the crop area of the Everglades Agricultural Area (EAA), south of Lake Okeechobee in Florida, and the surrounding region is of low available Si, since organic and sand soils predominate in this region.

Silicon is considered a plant nutrient 'anomaly' because it is presumably not essential for plant growth and development (Epstein, 1994). However, soluble Si has enhanced the growth and development of several plant species including rice (*Oryza sativa* L.), sugarcane (*Saccharum officinarum* L.), most other cereals and several dicotyledons (Jones and Handreck, 1967; Elawad and Green, 1979; Belanger *et al.*, 1995; Savant *et al.*, 1997). In addition, Si amendments proved effective in controlling several important plant diseases. Recent research has demonstrated that both foliar and soilborne diseases of cucumber and other cucurbits can be suppressed by applying this element (Belanger *et al.*, 1995).

In the 1930s and 1940s, pioneering work by Japanese researchers first indicated that Si was effective in controlling plant diseases, especially in rice (Suzuki, 1935; Kozaka, 1965). These studies demonstrated that applications of various Si sources to Si-deficient paddy soils dramatically reduced the incidence and severity of blast, caused by *Magnaportha grisea* (T. T. Hebert) Yaegashi and Udagawa, and brown spot, caused by *Cochliobolus miyabeanus* (Ito and Kuribayashi in Ito) Drechs. Ex Dastur (Volk *et al.*, 1958; Okuda and Takahashi, 1964; Takahashi, 1967; Ohata *et al.*, 1972). Other rice diseases suppressed by Si fertilization are leaf scald, caused by *Gerlachia oryzae* (Hashioka and Yokogi) W. Gams, sheath blight, caused by *Rhizoctonia solani* (A. B. Frank) Donk, and stem rot, caused by *Magnaporthe salvinii* (Cattaneo) R. Krause and R. K. Webster (Savant *et al.*, 1997).

The mechanism of the Si-induced resistance in rice has been attributed to the formation of a silicated epidermal cell layer (Yoshida, 1975; Ou, 1985; Takahashi, 1995). This layer is believed to prevent physical penetration and makes the plant cell walls less susceptible to enzymatic degradation by fungal pathogens. In addition, Si is known to redistribute around the infection peg and this preferential accumulation of Si at the point of pathogen penetration could also inhibit hyphal growth and haustoria formation (Heath and Stumpf, 1986; Carver *et al.*, 1987; Samuels *et al.*, 1991). Recent research suggests

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that it is not only the insoluble form of the Si that protects the plant from fungal ingression but phenolics, which accumulate at the infection site (Cherif *et al.*, 1992, 1994; Belanger *et al.*, 1995). Rapid deposition of phenolics or lignins at the infection site is a known general defense mechanism of plants to attack by plant pathogens and the presence of soluble Si may facilitate this mechanism of resistance in rice.

Japanese growers routinely apply 1.5 to 2.0 Mg ha^{-1} (Mg = megagrams) of basic slag from steel mills as an Si source before planting rice. Since the first reports by the Japanese, many researchers in other countries also have investigated the use of Si for controlling rice diseases (Lian, 1976; Lee *et al.*, 1981; Kim and Lee, 1982; Nanda and Gangopadhyay, 1984; Aleshin *et al.*, 1987; Yamauchi and Winslow, 1987; Datnoff *et al.*, 1991, 1992; Osuna-Canizalez *et al.*, 1991; Correa-Victoria *et al.*, 1994; Savant *et al.*, 1997). In the US, however, Si fertilization has become a routine practice only in Florida.

History of silicon in Florida

Bourne (1934) associated susceptibility of sugarcane to a mosaic disease with the Si content of organic soils in the EAA as early as 1934. He noted that many sugarcane varieties that were completely resistant to the disease on high-Si organic (Torry muck; euic, hyperthermic Typic Medisaprist) soil were susceptible to mosaic when grown on low-Si organic soils in the region. Bair (1966) observed that most soils in the EAA were low in Si and that the leaves of sugarcane grown on these soils also were low in Si. He also related sugarcane yields from good and poor producing areas to variations in soil Si. Gascho and Andries (1974) demonstrated that sugarcane growth and development in the EAA were improved following Si fertilization.

Because Si was shown to be sufficiently low to limit sugarcane production in many EAA soils, and it was known that rice can accumulate large amounts of Si and benefit from Si fertilization (Elawad and Green, 1979), rice Si studies were initiated in 1979 at the Everglades Research and Education Center and in growers' fields (*Figure 1*). Snyder *et al.* (1986) subsequently reported increases in grain yield in excess of 30% for rice that received pre-plant applications of calcium silicate slag that was derived from electric furnace production of phosphorus fertilizer from apatite ore. The fertilized rice accumulated considerably more Si than unfertilized rice, but the tissue concentration of other nutrients (N, P, K, Ca, Mg, Fe, Mn, Zn and Cu) and soil pH remained essentially unchanged. Thus, it was concluded that it was the Si in the calcium silicate slag that caused the yield increases.

Figure 1. Aerial photograph of rice fields in the Everglades Agricultural Area that (A) received no Si amendments and (B) received Si amendments. The darker color of the untreated area is due to rice plants being infected by both *Bipolaris oryzae* and *Pyricularia griesa*

Two of the most obvious visible effects of calcium silicate on rice were reduced floret discoloration and a lower incidence of brown spot (Snyder *et al.*, 1986). These observations generated an interest in evaluating the possible contribution of Si fertilization to disease control of rice in the EAA. Silicon became commercially available in the 1980s and Si fertilization is now practiced routinely for rice production in the EAA.

This paper provides an overview of research related to the use of Si fertilization for suppressing rice diseases in the EAA of south Florida. Although the focus is on rice and organic soils, this information should also be of interest to those working on other grass crops on organic soils as well as rice production on weathered, low-Si mineral soils.

Application of silicon to organic soils in the EAA of south Florida

In commercial rice production, Si is usually broadcast applied to the soil as calcium silicate slag (Calcium Silicate Corporation, Inc., Columbia, TN) at 5 Mg slag ha^{-1} ($\sim$1 Mg Si ha^{-1}). Although additional yield increases have been demonstrated for considerably greater rates, growers generally have been unwilling to spend the additional money required to obtain the maximum agronomic response. Consequently, the best return per dollar spent is obtained at the lower fertilization rate (Snyder *et al.*, 1986). The cost of applying 5 Mg ha^{-1} of the calcium silicate slag as a form of plant-available Si to rice is about $US84.00 ha^{-1}. Rice is normally grown in rotation with sugarcane in the EAA of south Florida. When rice is grown in rotation with sugarcane, only one-third of the cost should be charged to rice while the other two-thirds should be charged to the sugarcane operation, which also benefits from Si (Alvarez, 1992). Research has shown the beneficial increases in yield and disease control of this practice on both crops, and it is more profitable to apply the Si prior to the rice planting when this crop is grown in rotation with sugarcane (Alvarez, 1992).

It is estimated that a rice crop producing a total grain yield of 5 Mg ha^{-1} will remove from 0.23 to 0.47 Mg Si ha^{-1} from the soil (Savant *et al.*, 1997). Therefore, applications of 5 Mg slag ha^{-1} (1 Mg Si ha^{-1}) appear to be sufficient for supplying enough Si to the plant so that the tissue content will be 3% or greater (Snyder *et al.*, 1986). This concentration is believed to be the minimum tissue level needed for optimizing yields in the EAA. Others have reported an Si tissue content of 5% or greater for optimizing yields, but this was on mineral soils (Savant *et al.*, 1997). These concentrations, between 3 and 5%, may be the minimum tissue levels needed for disease control. More recently in Florida a preliminary soil test has been developed to determine if Si applications would be beneficial (Snyder, 1991). When 0.5 M HOAc-extractable Si is near 25 mg Si L^{-1} in soil then the rice straw Si content will be 3% or greater and Si applications are not needed. However, if extractable Si is 10 mg Si L^{-1} in soil or less, Si applications are deemed necessary.

Disease suppression with broadcast silicon

How Si enhances rice yield is not thoroughly understood, but one of the most obvious effects is disease suppression. In 1987, trials in commercial rice fields in the EAA of south Florida were conducted to evaluate Si rates and their residual effect on suppressing disease development in rice. Silicon was applied as calcium silicate slag at 0, 5 Mg slag ha^{-1} ($\sim$1 Mg Si ha^{-1}), 10 Mg slag ha^{-1} ($\sim$2 Mg Si ha^{-1}) and 15 Mg slag ha^{-1} ($\sim$3 Mg Si ha^{-1}) and the trial was duplicated on new plots in 1988 (Datnoff *et al.*, 1991; Datnoff, 1994). In addition, specific plots receiving Si in 1987 were fertilized again in 1988 with 1 Mg Si ha^{-1} while others received no additional fertilizer. Thus evaluations of disease development in 1988 could be made on the plots containing only residual Si from 1987, plots containing residual Si from 1987 plus an additional 1 Mg Si ha^{-1} and also newly fertilized 1988 plots.

Both brown spot severity and neck blast incidence (*Figures 2* and *3*) decreased significantly with increasing Si rates. At the greatest Si rate, brown spot severity was 15% less than the control and neck blast incidence was reduced by 30%. In 1988, brown spot was reduced by 14% in the plots with residual Si, compared to an 18% reduction for plots newly fertilized in 1988. Plots with residual Si plus the additional 1 Mg Si ha^{-1} application had 16% less brown spot than the control. Neck blast incidence at the 3 Mg Si ha^{-1} rate was 29% less in the residual plots in comparison to the control. In the amended residual treatment, blast was reduced by 32%, similar to the 27% in the newly applied treatment. It is clear that the residual Si in the soil can be very effective in control of diseases of rice crop planted the following year. This has obvious economic ramifications for growers. Rice yields increased significantly with increasing Si rates, ranging from 56 to 88% over the control. However, the greatest yield increases were realized on plots receiving new applications of Si. The Si content in the plant tissue increased with increasing rates of Si, while the Ca did not change (*Figure 4*). The Si content increased from 1.8% in the control to 4.4% at the highest rate. This represented a 64 to 152% increase in Si.

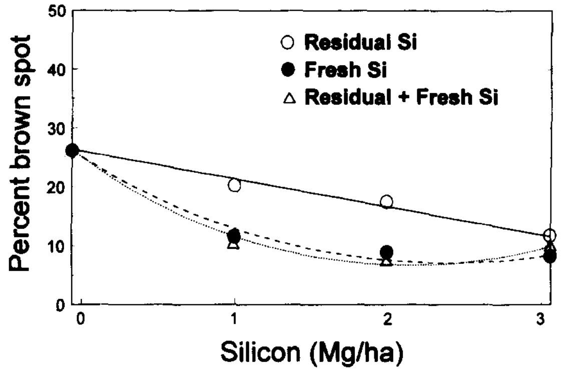

Figure 2. Relationship between brown spot and rate of applied silicon. Residual Si applied only in 1987, Y = 25.9 − 1.2x; fresh Si applied only in 1988, Y = 25.7 − 2.9x; and residual and fresh Si applied in 1987 and in 1988, Y = 25.6 − 3.1x + 0.1x^2. The percent mean leaf area affected for each numerical rating for each replication was used for calculating regression equations (n = 5)

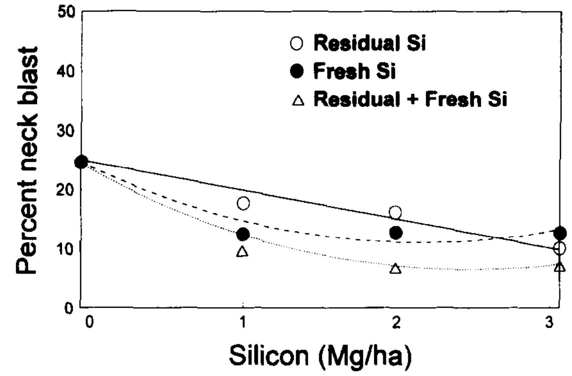

Figure 3. Relationship between neck blast incidence and rate of applied silicon. Residual Si applied only in 1987, Y = 36.0 − 1.7x; fresh Si applied only in 1988, Y = 35.5 − 3.9x; and residual and fresh Si applied in 1987 and in 1988, Y = 35.1 − 4.5x + 0.2x^2. The mean percent blast incidence for each replication was used for calculating regression equations (n = 5)

Fertilizer grades of silicon

Various compounds can be used as silicon fertilizers; however, the quality and grades may vary within compounds. In a test of the efficacy of calcium silicate grades on disease control, three materials were applied: fine (100% ≤ 0.15 mm), standard (90% < 2.4 mm) and pellets made from the fine material (100% > 1 mm and < 3.4 mm) (Datnoff *et al.*, 1992; Datnoff, 1994). Brown spot severity was reduced 21, 19 and 5% for the fine, standard and pelletized forms relative to the control, respectively (*Table 1*). Blast severities also were reduced in relation to the control by 21, 19 and 11% for the fine, standard and pelleted forms, respectively (*Table 1*). Although blast severities decreased with different

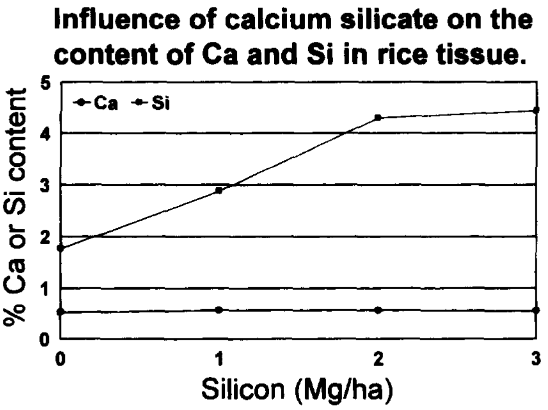

Figure 4. Influence of silicon fertility on the cation content of Ca and Si in tissue from rice grown in organic soil (Histosol)

Table 1. Influence of silicon grades on brown spot and blast severities

Grade[a]	% brown spot[b]	% blast[b]
Fine	5	21
Standard	11	32
Pellet	24	40
Control	26	41
FLSD (P = 0.05)[c]	12	36

[a] Fine = 100% ≤0.15 mm, standard = 90% <2.4 mm and pellet = 100% > 1 mm and <3.4 mm made from the fine material. [b] Brown spot severity was determined using a standardized rating scale of 0 to 9, where 0 = no disease and 9 = more than 76% of affected leaf area, and blast severity was determined using a similar rating scale of 0 to 9, where 0 = no disease and 9 = more than 51% of panicle area infected. The percent mean affected area of leaf or panicle for each numerical rating was used for estimating differences between treatments. [c] Fisher's least significant difference value.

forms of applied Si, they were not significantly different from the untreated control. Nevertheless, these results were consistent with earlier observations on the relationship of Si applied to the organic soils in the EAA and to brown spot and blast development (Datnoff *et al.*, 1991).

Grain yields exceeded the control by 26% for the fine, 18% for the standard and 4% for the pelletized forms. Evidently, particle size of the silicon fertilizer is important in increasing Si content of the rice plant for subsequent disease control and improved yields (Datnoff *et al.*, 1992). Particle size is associated with increased surface area, which should increase Si dissolution in the soil. In addition, the distribution of smaller Si particles mixed in the soil is most likely enhanced and the probability of root particle contact is increased. Consequently, these results suggest that reduced rates of a fine grade Si might enhance disease management and improve yields at a lower production cost than coarse grades.

Interaction of fungicides and silicon

Integrated disease management systems are needed for rice growers in the EAA. Consequently, an evaluation of Si fertilization in combination with fungicides was undertaken for managing both blast and brown spot (Datnoff, 1994; Datnoff and Snyder, 1994a,b). A rice crop was treated with Si at 0 and 2 Mg Si ha^{-1}, benomyl (Benlate DF50) at 0 and 1.68 kg ha^{-1} and propiconazole (Tilt^R) at 0 and 0.44 L ha^{-1}. Fungicide sprays were applied at 2.1×10^5 Pa with a CO_2 backpack sprayer equipped with three Cone-Jet (Weed Systems Equipment, Inc., Keystone Heights, FL) nozzle tips (HC-5) on a hand-held boom at panicle differentiation, boot, heading and heading+14 days. During these experiments, environmental conditions (frequent rainfall and high relative humidity) were favorable for both rice blast and brown spot development. Blast incidence was 73% in the non-Si, non-fungicide control plots and 27% in the benomyl-treated plots (*Figure 5*). Where Si was applied blast incidence was 36% in the non-fungicide plots and 13% in the benomyl-treated plots. The same degree of disease control was generally obtained when either the benomyl or Si were applied individually. Brown spot responses were similar to those observed with blast (*Table 2*, *Figure 6*). Lesion number, AUDPC and brown spot severity were dramatically reduced, however, silicon alone was more effective than propaconizole. For both diseases, the greatest disease control was obtained by using both treatments together. Thus, Si amendments provide control for two economically important diseases while currently available fungicides used in the US do not have the same broad spectrum of activity.

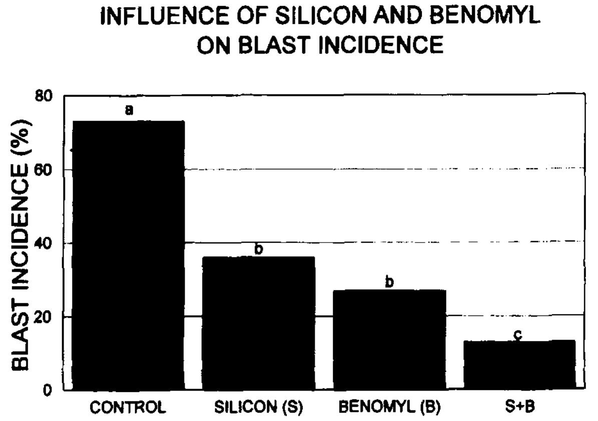

Figure 5. Influence of silicon fertilization and benomyl foliar spray on blast incidence. Values with the same letter are not significantly different based on Fisher's LSD (P = 0.05)

The Florida rice growers now know that soil amended with a plant-available Si source not only will increase their yields by as much as 30% but can substitute for fungicides. The cost of a fungicide such as benomyl plus two aerial applications is about $US79 ha. If a fungicide were applied twice per season on about 80% of the 8900 ha of rice planted and amended with Si, the cost would be about $US563,200. So, theoretically, the growers have saved themselves over half a million dollars annually. Because Si can control diseases to the same general degree as a fungicide, it is possible that Si might help reduce the number of fungicide applications (Seebold *et al.*, 1995) or even the rate of application if Si amendments are used.

Genotype and silicon interactions

Effective disease-control strategies for agronomic crops, in particular, include the incorporation of genetically controlled resistance into cultivars. Since genotypes vary in disease resistance, the relationship between Si content among genotypes and disease

Table 2. Effect of propiconizole and silicon on brown spot development

Treatment	Lesion number (cm^2)	AUDPC[a]	Brown spot severity[b]
Control	2.5 a[c]	2772 a	87 a
Propiconizole (P)	2.0 b	1124 b	61 b
Silicon (S)	1.6 c	583 c	37 c
S+P	0.6 d	284 d	14 d

[a] AUDPC = area under disease progress curve. [b] Brown spot severity based on a 0–9 scale, where 0 = no disease and 9 = 76% or more of leaf area affected. The percent mean affected area of leaf for each numerical rating was used for estimating differences between treatments. [c] Means followed by a different letter are significantly different based on FLSD (P = 0.05).

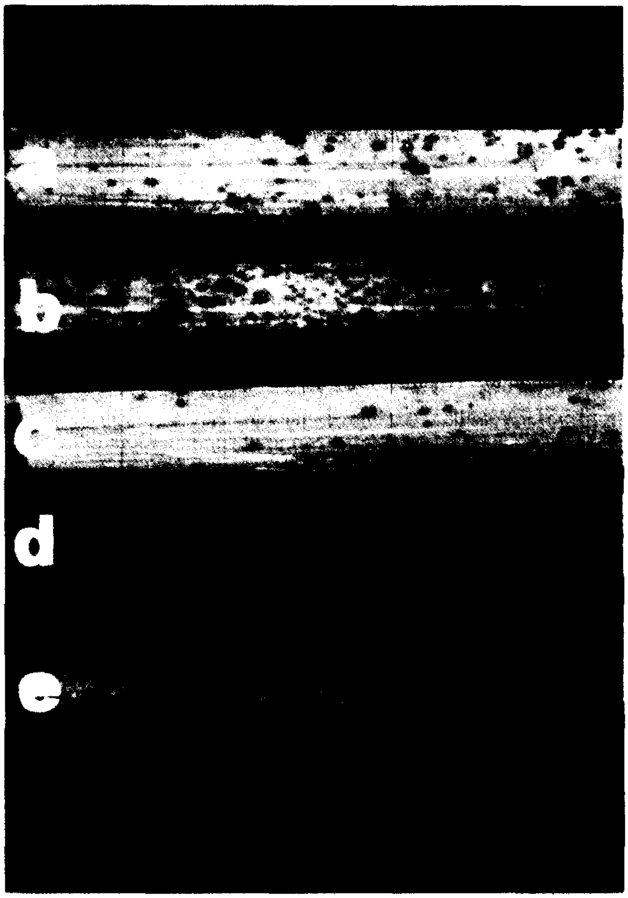

Figure 6. Brown spot symptoms as influenced by applications of silicon alone (a and e), propiconizole alone (b), the combination of both treatments (c), and the nontreated control (d)

Table 3. Mean percent silicon concentration and percent brown spot severity of 10 rice genotypes grown in the Everglades Agricultural Area

Genotype	Si concentration (%) Control	Si concentration (%) Si amended	Brown spot severity (%)[a] Control	Brown spot severity (%)[a] Si amended
Rico 1	2.2	4.6	86	83
Della X2	2.2	4.9	88	51
Exp. Line 1	2.1	4.5	61	33
Exp. Line 2	2.1	4.5	81	44
Jasmine 85	2.0	3.9	66	42
Lemont	2.0	4.5	88	48
A 301	1.9	3.4	84	54
Katy	1.7	4.2	54	32
Gulfmont	1.8	4.3	65	34
Lebonnet	1.8	4.4	66	34
FLSD (P = 0.05)[b]	0.4	0.7	10	9

[a] Brown spot severity based on a 0–9 scale, where 0 = no disease and 9 = 76% or more of leaf area affected. The percent mean affected area of leaf for each numerical rating was used for estimating differences between treatments.
[b] Fisher's least significant difference.

resistance was investigated. In a test of 18 rice cultivars grown at three locations representing high (116 mg Si L^{-1} soil), typical (40 mg Si L^{-1} soil) and low (6 mg Si L^{-1} soil) soil Si status, cultivars varied significantly for tissue Si concentration (Deren *et al.*, 1992). Certain genotypes consistently ranked high or low in Si concentration across all locations. This suggested that the acquisition of Si may be an inherited trait. Similar variations in Si concentration have been reported for African japonicas (Winslow, 1992).

Genotypes were further evaluated for Si accumulation and brown spot development on a low-Si soil fertilized with 0 and 2 Mg Si ha^{-1} (*Table 3*) (Deren *et al.*, 1994). Genotypes varied significantly for Si concentration in plant tissue. However, the range among genotypes was very narrow. Rico 1 and Della X2 tended to have the greatest Si concentrations in both Si-deficient and Si-amended soils.

There was a significant, negative correlation between plant Si concentration and brown spot development among genotypes observed ($r = -0.33$, $P \leq 0.05$). Winslow (1992) reported similar findings for husk discoloration. Most genotypes had a 30 to 40% relative decrease in brown spot severity when Si was added (*Table 3*). Rico 1, which is known to be brown spot susceptible, was the most severely diseased whereas Katy and Exp. Line 1 were the least affected. The increased Si concentration of a genotype resulting from Si fertilization is strongly associated with reduced intensities for blast and brown spot (Kozaka, 1965; Datnoff *et al.*, 1991, 1992). However, a correlation between these traits among genotypes is less demonstrable. In Japanese germplasm, Kozaka (Kozaka, 1965) concluded that a genotype with a greater silicon concentration is not necessarily more disease resistant than a genotype that has a lower Si concentration when both are grown under the same Si fertility level, suggesting that other genetic resistance factors also are very important. In this study, there was a general trend across genotypes for decreasing brown spot development with increasing tissue Si concentration; however, there was one exception, Rico 1. This exception has also been observed for blast. Some cultivars with low Si concentration were resistant whereas others with high Si concentration were susceptible (Ou, 1985). This variation in cultivar susceptibly with either high or low Si content simply may reflect variability within the pathogen. However, resistance may be controlled by other factors inherent within a genotype as well as by plant accumulation of Si. In this case, the role of soluble Si, as previously mentioned, could be very important because genetic factors might control the redistribution of Si at the point of pathogen penetration as well as the mobilization of phenolics or lignins at the infection site. This merits further investigation especially in rice.

Implications for regions outside the EAA

Silicon fertilization is now a common practice for rice production in the EAA. Growers realize the benefits of this element for controlling several important rice diseases and for improving yields. In fact, Si can control several economically important diseases at the same time, whereas no single fungicide is currently available in the US with this broad spectrum of activity. This situation may or may not be true in other countries where the fungicides used are potentially more efficacious and more broad spectrum. Nevertheless, our research suggests that this practice could be of benefit in other parts of the world where rice is produced on low-Si soils or where continuous rice mono-cropping leads to soil-Si depletion. The benefits of Si applications in these situations were confirmed by recent research in upland rice on highly weathered savanna soils at the Centro International Agricultura Tropical (CIAT) in Colombia (Correa-Victoria *et al.*, 1994). For example, leaf scald severity and neck blast incidence were reduced from 26 and 53% in non-amended plots, respectively, to 15% in Si-amended plots. More recently in Asia, Kumbhar *et al.* (1995) demonstrated that leaf blast was controlled up to 45 days after sowing to seedbeds that received black–gray ash from rice hulls. Fertilizer application strategies involving Si as a nutrient input offer improved control over several important diseases, thus reducing the reliance on frequent fungicide use (Seebold *et al.*, 1995). Also, Si also has been reported to control certain insect pests and improve plant utilization of other nutrients such as phosphorus (Savant *et al.*, 1997). This implies that insecticides and fertilizers (macro- and/or micronutrients) might be better managed if Si soil amendments are used.

Outlook and future research needs

Silicon fertilization of rice and related crops, especially where natural soil levels of Si are deemed less than optimum, offers promising results with respect to disease control and improved yields. Silicon reduces susceptibility in rice to fungal diseases. Silicon can control disease to the same general degree as a fungicide and reduce the amount of fungicides needed. Consequently, Si sources and their management practices should be developed and practiced in integrated pest management programs.

Silicon sources have residual activity that persists over time, raising the possibility that applications need not be applied annually. Also, after the first initial Si amendment, subsequent application rate requirements might be considerably lower due to these residual effects. However, silicate slags are considered to be expensive Si sources so there is a need to find or develop cheaper and more efficient Si sources (Savant *et al.*, 1997). Recycling of rice hulls and/or straw may be one possible alternative.

Since genotypes differ in their Si content, responding differently to applied Si, genetics definitely play an important role in Si accumulation. This factor merits further consideration while selecting genotypes for other important traits. The strategic combination of fine-grade Si formulation with 'Si-accumulator' cultivars/genotypes would also reduce application rate requirements, thereby minimizing the cost of the Si amendment program.

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