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SILICON FERTILIZERS FOR CITRUS IN FLORIDA

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Abstract. **Most soils used for citrus in Florida are sandy with low cation-exchange capacity. Numerous laboratory, greenhouse and field experiments have shown the benefits of silicon fertilizers for agricultural crops and the importance of silicon fertilizers as a component in sustainable agriculture. Two different effects on plants from silicon fertilizers have been distinguished: i) an indirect influence through soil fertility and ii) a direct effect on plant tolerance to stress. Fertilization with silicon-rich materials not only reduced leaching of nutrients, but remained in plant-available forms in sandy soils. Silicon-rich substances applied to the soil enhanced the initial growth of grapefruit seedlings. The Si content in orange and grapefruit leaves increased with leaf age and appeared to be related to the silicon status of the soil. Acid-extractable silicon from Spodosols was usually higher under healthy-appearing trees than under unhealthy-appearing trees. Although more work needs to be done, it appears that citrus in Florida could benefit from improved silicon nutrition.**

Introduction

Despite the fact that the element silicon is, next to oxygen, the most abundant element known, comparatively little attention has been paid to its distribution and properties in plants and animals. Effects of silicon fertilizers have only been thoroughly investigated on rice (Savant et al., 1997; Takahashi, 1995; Yoshida, 1975). The role of silicon in other plant species has been sporadically investigated and has only touched on various aspects of plant pathology, physiology and biochemistry (Hodson and Sangster, 1989; Mann and Ozin, 1996; Menzies et al., 1991).

The investigation of Si role in plants was initiated about two hundreds years ago. The scientist Sir Humphey Davy (1778-1829) wrote: "The siliceous epidermis of plants serves as a support, protects the bark from the action of insects and seems to perform a part in the economy of these feeble vegetable tribes (Grasses and Equisetales) similar to that performed in the animal kingdom by the shell of crustaceous insects" (1814).

Silicon is an integral part of plants. The content of Si in plant tissue ranges from 0.1 to 10% (Epstein, 1999). In leaves of citrus, the content of Si was only 0.04-0.2% of the dry weight. The content of Si in ash of citrus fruit, leaves, wood and roots ranged from 0.30 to 0.50%, from 1.19 to 1.49%, from 0.61 to 1.45% and from 0.84 to 3.17%, respectively (Chapman, 1968; Wutscher, 1989).

Silicon is absorbed by plants as monosilicic acids or its anion (Youshida, 1975). Silicon is accumulated primarily in epidermal tissues of both roots and shoots (leaves) as polymerized forming silica-gel and is associated with pectin and calcium ions (Waterkeyn et al., 1982). The thickening epidemical silicon-cellulose layer supports mechanical stability of plants and can increase plant resistance against biotic and abiotic stress (Epstein, 1999).

Optimization of silicon nutrition can result in positive effects on plants. Silicon fertilizers increased weight and volume of roots (Bocharnikova, 1996). The increase in sugar content of sugar beets and sugar cane under silicon fertilization may be attributed to a biochemical influence of silicon (Ayres, 1966; Klechkovsky, Vladimirov, 1934). The bulk of silicon fertilization studies have described increasing plant tolerance to biotic stress (insects and infection). The function of Si as a protective agent is probably one of the most important for plants. The mechanism of the affect of silicon on plant tolerance to stress has scarcely been investigated. In addition, silicon fertilization increased the plants tolerance to abiotic stresses like toxicity of Al, Mn, heavy metal, salinity, frost and drought (Epstein, 1999; Matichenkov, 1990; Maton et al., 1986).

Field investigations of the effect of silicon fertilizers on citrus were conducted in Russia more than 50 years ago. Silicon fertilization accelerated growth of citrus by 30 to 80%, fruit maturation by 2 to 4 weeks and increased amount of fruit (Taranovskaia, 1939). Silicon fertilizer also increased the frost tolerance of lemon (Taranovskaia, 1940). In greenhouse experiments, optimization of silicon nutrition for 1-year-old and 2-year-old orange trees increased fresh weight during a 6 months period. However, he concluded that citrus is not a Si-accumulating plant, and that the results indicated only a limited role of this element in citrus nutrition (Wutscher, 1989).

The object of this investigation was to determine the direct effect of silicon-containing compounds on citrus grown on sandy soils. This work was intended as a first step towards understanding the potential role of Si in stress tolerance of citrus.

Materials and Methods

Leaf Sampling and Analysis

In May 1999, citrus leaves were sampled from orange and grapefruit trees planted on soils classified as cultivated Alfisols, Entisols and Spodosols at the Indian River Research and Education Center grove and also from a commercial citrus grove in St. Lucie County. Healthy-appearing young and old leaves as well as leaves visibly stressed from insect injury and *Sooty Mold*, were sampled from each tree. Soil from below three healthy-appearing trees and also from three nearby unhealthy-appearing trees, was sampled from each type of soil. Unhealthy trees were of comparable size but with smaller leaves and thinner canopies. All trees had received the same horticultural care. Sampled leaves were washed in distilled water, dried at 70°C for 72 h and ground in a Wiley mill. Silicon content was analyzed using a spectrophotometric method at a wavelength of 660 nm (Elliot and Snyder, 1991; Iler, 1979).

Soil Sampling and Analysis

Soil samples were collected under each tree at depths of 0-20 cm and 20-40 cm. Each soil sample was divided into two subsamples. One subsample was air-dried and ground to pass through a 1 mm sieve. The content of biogeochemically active silica was deter-

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mined in these subsamples by acid extraction (Barsukova and Rochev, 1979). The second subsample was passed through a 2 mm sieve and soluble monosilicic acids (plant-available silicon) were determined after water extraction from fresh soil (Matichenkov and Snyder, 1996; Matichenkov et al., 1999). Silicon analysis was by the Mallen-Raily method with the spectrophotometer at a wavelength of 660 nm (Iler, 1979).

Grapefruit Germination

Grapefruit seeds were germinated in washed quartz sand (particles size from 0.5 to 1 mm) in plastic pots which were $5 \times 5 \times 5$cm. Fine amorphous silica, Calcium silicate slag (product of PRO-CHEM Co., Florida), and silicon-bearing irrigation solutions of 5, 10 and 20 ppm of Si as monosilicic acids, were established as silicon sources. The Si-bearing solutions were prepared by dissolving of amorphous silica (Wessalon 50-S) in distilled water. The solid materials were applied at the rate of 10t/ha. The zero Si control pots and those with solid Si-rich materials were irrigated as needed with distilled water. The pots treated with soluble silicon sources were irrigated as needed with Si-bearing solutions during a 1 month period.

All treatments were replicated four times with three plants per replicate. One month after germination, all plants were sampled. The weight of shoots and roots were measured separately. Plant tissue was washed in distilled water, dried and ground. Tissue silicon was analyzed as above (Elliot and Snyder, 1991; Iler, 1979). All data were tested for significant differences using an analysis of variance and Fisher's LSD.

Table 1. Content of silicon-rich substances in cultivated Alfisols, Entisols and Spodosols under healthy-appearing and unhealthy citrus trees.

	Soil		
Tree appearance	Depth (cm)	Plant-available silicon (Si mg kg^{-1})	Acid- extractable silicon (Si mg kg^{-1})
		Alfisol (Grapefruit)	
Healthy	0-20	8.6	51.0
	20-40	8.0	36.9
Unhealthy	0-20	6.3	43.9
	20-40	3.0	39.3
LSD$_{.05}$		0.3	24.0
		Entisol (Grapefruit)	
Healthy	0-20	9.8	46.0
	20-40	6.8	29.0
Unhealthy	0-20	8.9	48.0
	20-40	5.8	31.0
LSD$_{.05}$		0.3	23.0
		Spodosol (Grapefruit)	
Healthy	0-20	8.5	78.9
	20-40	5.4	54.0
Unhealthy	0-20	3.6	37.0
	20-40	3.8	29.0
LSD$_{.05}$		0.3	25.0
		Spodosol (Orange)	
Healthy	0-20	13.0	112.5
	20-40	5.4	86.8
Unhealthy	0-20	3.3	68.7
	20-40	4.1	37.9
LSD$_{.05}$		0.3	25.0

Results

The content of plant-available silicon in all the soil samples examined was relatively low and ranged from 8.3 to 13.0 mg kg^{-1} in surface horizons and from 3.0 to 8.9 mg kg^{-1} in subsurface soil horizons (Table 1). All soil horizons sampled under the healthy-appearing trees had more plant available silicon than soil sampled under unhealthy-appearing trees. There were significant differences between the content of plant-available monosilicic acids in soil under healthy and unhealthy trees. The content of acid-extractable silicon from soil sampled from the Spodosol was usually higher under healthy trees than under unhealthy trees. This was not true for the soil sampled from the Alfisols and Entisols areas.

Si content in citrus leaves from both oranges and grapefruit increased with age of the leaves (Table 2). Young leaves (less than 1-2 months old) had 0.13-0.28% of Si. Leaves, 1-2 years old, had 0.17-36% and 0.31-0.46% Si for grapefruit and orange, respectively (Table 2). In general, the leaves from healthy trees contained more Si than leaves from unhealthy trees.

Trees may have been more resistant to disease and insect attack because they had a high level of Si in their leaves. In healthy orange trees on Spodosols, the Si content increased in leaves suffering from insect injury or *Sooty Mold* infection (Table 2). The trends for unhealthy trees were not as consistent perhaps because the content of plant-available silicon in the soil under unhealthy trees tended to be lower than that under healthy trees. The unhealthy trees may have had inadequate silicon nutrition.

Both the solid and soluble compounds of silicon used in this study had a positive effect on the initial growth of grapefruit seedlings (Table 3). The average shoot weight increased from 0.196 g to 0.289 g when treated with a solution of 10 ppm of soluble Si. The root weight increased from 0.162 to 0.272 g when treated with

Table 2. Silicon content (% in dry weight) in citrus leaves.

	Leaves		
Tree appearance	Young	Old	Old with insect injury or *Sooty Mold*
		Alfisol (Grapefruit)	
Healthy	0.28	0.31	0.34
Unhealthy	0.18	0.32	0.30
LSD$_{.05}$	0.05	0.05	0.05
		Entisol (Grapefruit)	
Healthy	0.22	0.33	0.35
Unhealthy	0.12	0.21	0.11
LSD$_{.05}$	0.06	0.05	0.05
		Spodosol (Grapefruit)	
Healthy	0.13	0.31	0.36
Unhealthy	0.13	0.17	0.21
LSD$_{.05}$	0.05	0.06	0.05
		Spodosol (Orange)	
Healthy	0.18	0.35	0.46
Unhealthy	0.19	0.31	0.40
LSD$_{.05}$	0.06	0.06	0.06

Table 3. The effect of silicon compounds on initial growth of citrus seedlings.

Treatments	Weight of shoots (g)	Weight of shoots % of control	Weight of root (g)	Weight of root % of control
Control	0.196		0.162	
Amorphous SiO_2	0.256	130.6	0.214	132.1
Calcium silicate slag (Pro-Chem)	0.194	98.9	0.197	121.6
Si Solutions: 5 ppm Si	0.182	92.8	0.189	116.7
10 ppm Si	0.289	147.4	0.271	167.3
20 ppm Si	0.236	120.4	0.272	167.9
$LSD_{.05}$	0.024	—	0.021	

a solution of 20 ppm of soluble Si (Table 3). Soluble silicon compounds in solution were more effective than soil-applied Si materials. It should be noted that the application of silicon solutions also changed the branching morphology of the root system (Fig. 1). The control plant had a very simple tap root system. Increasing silicon resulted in the formation of a more branched root system.

Si content of grapefruit seedlings treated with amorphous silica increased from 0.066 to 0.156% in shoots and from 0.160 to 0.434% in roots (Table 4). The Si enhancement effect was greater with amorphous silica than with the other Si sources.

Discussion

Our investigation showed that cultivated Alfisols, Entisols and Spodosols of Florida can be characterized by extremely low contents of plant-available and biogeochemically active silicon compounds (Matichenkov and Snyder, 1996; Matichenkov et al., 1999). Quartz (SiO_2) is the main mineral component in these soils. However, this inert form of silicon has a poor adsorption capacity, low water holding capacity and very low solubility. Since silicon fertilizers usually possess a very large surface area, application of silicon fertilizers increased the water holding capacity of sandy soils and raised the soils adsorption capacity (Matichenkov, 1990; Savant et al., 1997). Silicon fertilizers also can reduce leaching of P and K from surface soil horizons (Matichenkov et al., 1997; Taranovskaia, 1940).

Multiple laboratory and field experiments have shown that use of silicon fertilizers is more effective than liming for reducing aluminum toxicity (Myhr and Erstad, 1996; Haak and Siman, 1992). Five different mechanisms of Al toxicity reduction involve Si-rich compounds. 1) Monosilicic acids can increase the pH level of the acid soils (Lindsay, 1979). 2) Monosilicic acids can be adsorbed on aluminum hydroxides impairing their mobility (Panov et al., 1982). 3) Soluble monosilicic acid can form with ions of aluminum to form slightly soluble substances (Lumsdon and Farmer, 1995). 4) Silicon-rich compounds have a strong adsorption capacity of mobile aluminum on silica surfaces. (Schulthess and Tokunda, 1996). 5) According to Rahman, et al. (1998), mobile silicon compounds can increase plant tolerance to Al. All these mechanisms can work simultaneously, but usually one mechanism will be the most prevalent.

Data from this study showed an apparent association between the content of Si in the soil and leaves of citrus. Apparently healthy trees most often had a higher amount of silicon in leaves than unhealthy trees. Consequently, there may be a relationship between health of citrus and silicon nutrition. More work will need to be done to determine if Si can increase the tolerance of citrus to biotic and abiotic stresses as has been shown with other plant species (Belanger et al., 1995; Savant, et al., 1997; Yoshida, 1975).

Figure 1. One-month-old grapefruit seedlings after treatment with various concentrations of plant-available silicon. a) Control, b, c, d—treatment with 5 ppm, 10 ppm and 20 ppm of Si- bearing solutions.

Our data demonstrated that a Si percentage in leaves increased with leaf age and the level may be related to biotic stress (Table 2). Citrus has a mechanism for transport of silicon, because the concentration of Si increased in response to Si fertilization. The weight of roots was increased more than shoots (Table 3). This may be related to the fact that citrus roots contain the higher concentration of Si than shoots (Chapman, 1968; Table 4). In addition, improving silicon nutrition changed the branching patterns of the root system (Fig. 1).

Conclusion

Data from this study implies that silicon may play a very important role in citrus tree growth and development. There appears to be a relationship between silicon nutrition and health of citrus trees. The Si in citrus leaves increased with age and with biotic stress. The monosilicic acids increased the weight of shoots and roots of grapefruit seedlings from 20 to 60% and improved root system branching. Thus, it appears that silicon can have a direct effect on citrus growth. Certainly, these results indicate that more study of Si fertilization for citrus is needed.

Table 4. The effect of silicon compounds on the content of Si in young citrus seedlings.

Treatments	Si in green shoot (%)	Si in root (%)
Control	0.066	0.160
Amorphous SiO_2	0.156	0.434
Calcium silicate slag (Pro-Chem)	0.098	0.198
Si Solution: 5 ppm Si	0.105	0.195
10 ppm Si	0.076	0.180
20 ppm Si	0.094	0.224
$LSD_{.05}$	0.025	0.020

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