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RESPONSE OF CITRUS TO SILICON SOIL AMENDMENTS

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Abstract. **Silicon (Si) is a basic mineral forming element and a beneficial nutrient for higher plants. Fertilization with soil amendments containing chemically activated Si has an effect on physical and chemical soil properties, including increased soil exchange capacity, improved water and air regimes, reduced Al, heavy metal and organic pollutant toxicities, optimized pH level of soil, and maintenance of nutrients in plant-available form. Improving plant Si nutrition has been shown to reinforce plant protection properties against diseases, insects, and other unfavorable conditions. Improving Si nutrition also aids in the initiation of root and fruit formation in higher plants. The object of this investigation was to determine the response of citrus growing in South Florida to a Si soil amendment consisting of Ca-Mg slag. Both field and greenhouse experiments were conducted. A comparative study was made of Si compounds in the soil and of the Si status of citrus leaves. The resulting data showed that sandy soils are low in biogeochemically active Si. A relationship was determined between the soil Si status and the leaf Si content and also tree vigor of 'Valencia' orange [*Citrus sinensis* (L.) *Osbeck*]. Optimization of Si nutrition was responsible for a significant increase in the mass of roots and green mass of germinated 'Marsh' grapefruit (*Citrus paradisi* Macf.) seedlings.**

The content of Si in plant tissue ranges from 0.1 to 10% (Epstein, 1999). Beginning in 1840, numerous laboratory, greenhouse, and field experiments have shown the benefits of Si soil amendments for rice, corn, wheat, barley, sugar cane, and other crops (Epstein, 1999; Hodson and Sangster, 1989; Mann and Ozin, 1996; Menzies et al., 1991). In Russia and the USA as well as in some southeastern Asian countries, Si soil amendments are successfully used for commercial crop production. Si soil amendments influence plant growth in at least two ways. First, the role of improved Si nutrition in plant growth must be considered. Second, soil treatment with biogeochemically-active Si substances optimizes soil fertility through improved water, physical, and chemical soil properties while maintaining nutrients in plant-available form (Matichenkov et al., 1995).

Si is absorbed by plants as monosilicic acids or its anion forms (Youshida, 1975). Si is accumulated primarily in epidermal tissue both in roots and shoots (leaves) as polymerized silica-gel and is associated with pectin and calcium ions (Waterkeyn et al., 1982). The thickening epidermal silicon-cellulose layer supports mechanical stability of plants and can increase plant resistance against insects, diseases, salt and drought stresses (Epstein, 1999; Yoshida, 1975).

Optimization of Si nutrition results in a series of positive effects on plants. Si fertilizers increase the weight and volume of roots (Bocharnikova, 1996). Si nutrition reinforces plant protection properties against disease, insects and unfavorable climatic conditions (Epstein, 1999). The sugar content in sugar beets and sugarcane increased under improved Si nutrition (Ayres, 1966; Klechkovsky and Vladimirov, 1934). Probably, the function of Si as a protective agent is one of the most important for plants. The mechanisms responsible for Si effects on plant tolerance have scarcely been investigated. In addition, improved Si nutrition has been shown to increase plant tolerances to abiotic stresses such as Al, Mn, heavy metal toxicities, salinity, frost, and drought (Epstein, 1999; Matichenkov, 1990; Maton et al., 1986)

In citrus leaves, the content of Si ranged from 0.04-0.2% of the dry weight (Weber and Batchelor, 1948). The content of Si in the ash of citrus fruit, leaves, wood, and roots ranges 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).

Grove studies conducted in Russia on citrus responses to Si fertilizers showed 30 to 80% accelerated growth, 2-4 week earlier maturation of fruit, and increased fruit yield (Taranovskaia, 1939). Also silicon fertilizer was found to increase the frost tolerance of lemons (Taranovskaia, 1940).

In 1989, Wutscher demonstrated in a laboratory experiment that optimization of Si nutrition for 1-year-old and 2-year-old orange trees increased fresh weight of shoots by 30-40% during a 6-month period. The trees treated with Si absorbed more nutrients than the untreated trees (Wutscher, 1989). However, he concluded that citrus is apparently not a Si-accumulating plant and that the results indicated only a limited role of this element in citrus nutrition.

Our preliminary investigations demonstrated that relationships exist between the soil Si status (content of plant-available Si in the soil), the content of Si in leaves, and the health of citrus trees (Matichenkov et al., 1999; Matichenkov et al. 2000). Insect damage and infection from plant diseases resulted in increased Si content in citrus leaves. This possibly means that citrus may actively transport monosilicic acid as a means of increasing resistance against outside stresses (Matichenkov et al., 2000). Grapefruit germination under various levels of Si nutrition demonstrated that monosilicic acid may help control root development (Matichenkov et al., 1999).

The general aim of the project reported here was to determine experimentally the possible responses to improved Si nutrition of citrus grown under various stresses in the greenhouse and of young citrus trees in field locations.

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Materials and Methods

Pro-Sil (a finely processed Ca-Mg silica slag provided by the Pro-Chem Chemical Co., West Palm Beach, Fla.) was used as the Si source in this project for both greenhouse and field experiments because previous investigations demonstrated a favorable effect of this product on soil and plants (Matichenkov et al., 1999; Matichenkov et al., 2000). Selected properties of Pro-Sil are presented in Table 1, according to the Pro-Chem Chemical Co.

Grapefruit germination. 'Marsh' grapefruit seeds were germinated in $5 \times 5 \times 5$-cm plastic pots containing soil taken from a cultivated Spodosol grove soil. Eight treatments replicated 16 times were used in the grapefruit germination experiment (Table 2). Pro-Sil was applied at the rates of 0, 2, 4 and 8 t ha^{-1}. Half of the seeds were irrigated with distilled water and the other half were irrigated with a NPK-bearing (macronutrient) solution. The concentration of macronutrients in solution was 200 mg L^{-1} of elemental N, P, and K.

Germinated grapefruit seedlings receiving each of the eight Pro-Sil rate treatments were subjected to four stress situations as follows: a) without stress, b) salt stress, c) high soluble Al concentration and d) low temperature stress. During the first 2 months all grapefruit were grown without stress. At the beginning of the third month 0.2% NaCl and 300 µM Al were added each second day during 1 month to the appropriate pots to simulate high salt and Al toxicity conditions, respectively.

The influence of low temperature on germinated grapefruit seedlings was studied in a climatic chamber maintained at 0°C. Approximately 75-d-old plants were placed in the chamber twice for 2 h during a 2-d period and then the plants were grown under normal conditions for a 2-week period.

After the 3-month growth period for the germinated grapefruit, all plants were carefully removed from their plots, washed in distilled water and water was removed by wipers. Fresh weight of shoots and roots and of roots only was measured for each individual plant.

Field experiment with young citrus. In Nov. 2000 an experiment was initiated in the Indian River Research and Education Center grove near Ft. Pierce to determine possible beneficial effects of Pro-Sil on the growth of young 'Valencia' orange trees. These 1.5-year-old trees were planted on a Spodosol (Ankona series, sandy, siliceous, hyperthermic, orsten Arenic Alaquods) that had received standard mineral fertilization applications (Tucker et al., 1995). The Ca-Mg silica slag was applied in doses equivalent to 0, 2, 4 and 8 ton ha^{-1}. Each treatment was replicated eight times and each plot contained three trees. In Nov. 2000 and again in May 2001 growth measurements were taken consisting of total height of each tree and the length of each tree's main branches.

All data were subjected to a statistical analysis based on comparative methods using Duncan's multiple range test for mean separation at the 5% level of significance (Duncan, 1955).

Table 1. Selected properties of Pro-Sil.

Material	pH (H_2O)	CaO	MgO	Fe_2O_3	Al_2O_3	SiO_2
	- % (by wt.) -					
Pro-Sil	10-11.5	41-46	10.1-12.7	1.72-7.47	3.32-5.00	22.1-32.0

*These data were provided by Pro-Chem Chemical Co. (West Palm Beach, Fla.).

Table 2. The scheme of the grapefruit germination study.

Treatment	Rate of Si soil amendment applied, t ha^{-1}	Irrigation with NPK-bearing solution, mg L^{-1}
1	0	—
2	2	—
3	4	—
4	8	—
5	0	200
6	2	200
7	4	200
8	8	200

Results

Greenhouse study

Increasing rates of Pro-Sil silica slag either alone or applied with the macronutrient solution generally increased both mean root and mean total plant weights over mean weights measured on the check plants (Tables 3 and 4). Considering the first four treatments shown in Table 3 in column one, the fresh weight of plants receiving the 4 or 8 t ha^{-1} silica slag rates was significantly greater than plants receiving the 2 t ha^{-1} rate. However, plants treated at all rates weighed significantly more than the control treatment. Similarly, considering the next four treatments (treatments 5-8) fresh weight of plants treated at these rates was significantly greater than plants receiving the corresponding control treatments. The maximum increase in germinated plant weight was observed for Pro-Sil silica slag applied at 4 t ha^{-1} with macronutrients. The maximum increase in root weight was observed with the macronutrient application combined with the 2 t ha^{-1} Pro-Sil silica slag treatments (Table 4).

Salt stress, Al toxicity and low temperature had independent significant negative effects on total mean weights of the germinated grapefruit seedlings used as controls (Table 3). However, salt and Al stresses did not have independent significant effects on the biomass of roots of the seedlings used as controls (Table 4). Mean root weights were significantly higher from control plants stressed by low temperature. The reason for this is not readily apparent, except perhaps this was a root protection response against low soil temperatures.

The application of macronutrients and salt stress resulted in a significant decrease in plant and root weights of the control plants (Tables 3 and 4). High Al concentration and low temperature stresses had no influence on weight of the control seedlings receiving the macronutrient applications (Tables 3 and 4).

Applying Pro-Sil silica slag to grapefruit seedlings with or without macronutrients had positive effects on the mean weights of both plants and roots when grown under stress from the $AlCl_3$ application (Tables 3 and 4). It should be noted that the highest application rate of Pro-Sil combined with the Al stress factor was responsible for the maximum weight of grapefruit seedlings.

Silica slag applied at the 2, 4 and 8 t ha^{-1} rates, with and without macronutrients and receiving a salt application as a stress factor also gave significant increases in the mean weight of both plants and roots (Tables 3 and 4). The maximum weight of germinated seedlings receiving the salt stress factor was obtained at the 2 and 4 t ha^{-1} Pro-Sil rate without macronutrients.

Low temperature is one of the most important factors affecting citrus production (Jackson, 1991). The largest statistically significant positive response shown in Tables 3 and 4 for 3-month-old grapefruit seedlings for mean weights of both roots and plants was for low temperature stress and 8 t of silica slag ha^{-1} without macronutrients.

Table 3. Effect of Si soil amendment on the total weight of germinated grapefruit grown under various stresses.

Treatment		Fresh weight (g)			
		Without stress	Salt stress	Al toxicity	Low temperature
1	Control	0.238 Da	0.207 Eb	0.206 Db	0.208 Eb
2	2 t ha^{-1}	0.261 Cd	0.297 Ac	0.302 Bb	0.329 Ba
3	4 t ha^{-1}	0.280 Bc	0.293 Ab	0.317 Ba	0.308 Cab
4	8 t ha^{-1}	0.283 Bc	0.279 Bc	0.311 Bb	0.346 Aa
5	Control + NPK	0.265 Ca	0.183 Fb	0.254 Ca	0.247 Da
6	2 t ha^{-1}+ NPK	0.308 Aa	0.227 Db	0.300 Ba	0.303 Ca
7	4 t ha^{-1} + NPK	0.317 Aa	0.220 Db	0.306 Ba	0.305 Ca
8	8 t ha^{-1} + NPK	0.303 Ab	0.250 Cc	0.327 Aa	0.306 Cb

Using Duncan's multiple range tests, column value (Si soil amendment effect) followed by the same capital letter and row value (stress effects) followed by the same lower case letter are not statistically different ($P < 0.05$).

Table 4. Effect of Si soil amendment on root weight of germinated grapefruit grown under various stresses.

Treatment		Fresh weight (g)			
		Without stress	Salt stress	Al toxicity	Low temperature
1	Control	0.059 Db	0.057 Bb	0.052 Cb	0.081 Ca
2	2 t ha^{-1}	0.073 Cc	0.112 Aa	0.081 Bb	0.121 Ba
3	4 t ha^{-1}	0.078 Cc	0.107 Aa	0.093 Ab	0.111 Ba
4	8 t ha^{-1}	0.082 Cc	0.104 Ab	0.096 Ac	0.129 Aa
5	Control + NPK	0.092 Ba	0.041 Cb	0.094 Aa	0.084 Ca
6	2 t ha^{-1} + NPK	0.109 Aa	0.064 Bb	0.104 Aa	0.114 Ba
7	4 t ha^{-1} + NPK	0.101 ABa	0.054 Cb	0.105 Aa	0.117 Ba
8	8 t ha^{-1} + NPK	0.103A Bb	0.066 Bc	0.104 Aa	0.131 Aa

Using Duncan's multiple range tests, column value (Si soil amendment effect) followed by the same capital letter and row value (stress effects) followed by the same lower case letter are not statistically different ($P < 0.05$).

Field study. The application of Pro-Sil silica slag to young 'Valencia' orange trees significantly increased both the total tree height and the length of tree branches (Table 5). The silica slag application increased tree height from 14 to 41% and accelerated the growth of the tree branches from 31 to 48% over a 6-month period (Table 5). The growth rate increases were consistent with those obtained by Wutscher (1989) in Si rate studies with young citrus trees.

Pro-Sil is a complex product containing Ca, Mg, Si and several micronutrients (Table 1). Therefore, it is possible that application of this product influenced not only Si nutrition of the citrus trees, but also optimized other plant micronutrient nutrition aspects. However, our previous studies suggest that chemically activated Si compounds may have played a more dominant role and were responsible for the main plant responses obtained from Ca-Mg silica slag (Diakov et al., 1990; Matichenkov 1999; Matichenkov et al., 2000).

The results obtained thus far demonstrate promising responses from the application of the Ca-Mg silica slag to citrus. Similar responses would be expected from other crops grown in areas with soils characterized by a low content of plant-available Si. More research is needed with plant-available Si on various soils with other citrus cultivars.

Table 5. Effect of Si soil amendment on the young orange trees.

	Total height				Branch length				Increase of total height		Increase of branch length	
	October 2000		May 2001		October 2000		May 2001					
	cm	% of control	(cm)	% of control	cm	% of control	(cm)	% of control	cm	% of control	(cm)	% of control
Control	72.0 a		82.4 a		50.3 b		115.8 a		10.4		65.6	
2 t ha^{-1}	73.3 a	101.7	87.9 a	106.7	65.2 a	129.7	156.5 a	135.1	14.7	140.9	91.2	139.2
4 t ha^{-1}	72.8 a	101.2	84.7 a	102.8	57.0 b	113.4	142.7 a	123.2	11.9	114.1	85.7	130.8
8 t ha^{-1}	70.1 a	97.3	84.3 a	102.2	57.6 b	114.7	154.8 a	133.7	14.2	136.2	97.1	148.1

Using Duncan's multiple range test, values within a column followed by the same letter are not statistically different ($P < 0.05$).

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WASTEWATER AND RECLAIMED WATER—DISPOSAL PROBLEM OR POTENTIAL RESOURCE?

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Abstract. **Before 1980, many communities in Florida considered sewage wastewater to be a disposal problem. When it was proposed to convert wastewater to reclaimed water for crop irrigation, citrus growers were reluctant to accept the water because of fears of heavy metals, flooding, or disease problems. For various reasons, several reclaimed water projects were started, and Water Conserv II has become one of the largest agricultural irrigation projects of its type designed for the use of reclaimed water. The project distribution center is located west of Orlando and provides irrigation for over 4300 acres of agricultural crops. Reclaimed water is also provided for irrigation of the Orange County National Golf Center and West Orange Country Club. The water is chlorinated, is odorless and colorless, and has been used successfully for crop irrigation for 15years. Excess reclaimed water is discharged to areas of rapid percolation called rapid infiltration basins (RIBs). Water quality standards were established, and continued intensive sampling insures water of excellent quality for irrigation. The reclaimed water meets drinking water standards for a number of compounds including NO_3, SO_4, Na, Cl, Cu, Zn, Se, and Ag. Initial fears that reclaimed water would cause flooding, disease, or heavy metal problems proved to be unfounded. In the sandy, well-drained soil, high irrigation rates with reclaimed water (100 inches/year) promoted excellent tree growth and caused no major problems. This reclaimed water cannot provide complete nutrition, but does supply all the Ca, P, and B required by trees under Florida conditions. Because of a recent severe drought in Florida, attitudes toward reclaimed water have changed. Once believed to be a disposal problem, reclaimed water is now considered to be a viable resource that can meet irrigation demands. Average statewide reuse flow rates have increased by 116% in 10 years.**

Disposal of wastewater is a problem for many urban areas. In the 1980s, disposal of effluent was considered to be a growing problem, primarily because of environmental concerns about degradation of surface waters. Urban-area wastewater disposal had commonly been handled by treating the wastewater to a certain level and then disposing of it in the most convenient or cheapest manner. Usually, this meant discharging the water into a nearby river or lake, spraying it onto a field, or loading it into a percolation pond. Disposal was the primary consideration since the amounts of wastewater continued to increase as an unavoidable consequence of population growth. As the wastewater volume increased, con-

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