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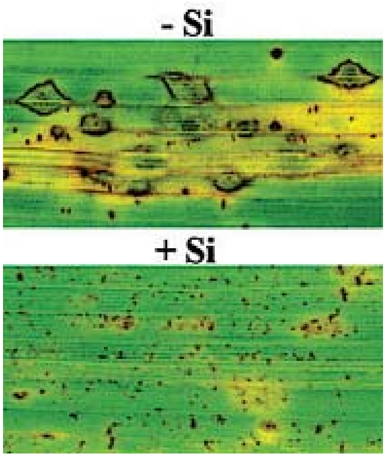

Uberlândia / MG - Brazil

22 - 26 October, 2005

III SILICON IN AGRICULTURE CONFERENCE

Uberlândia, 22 -26 October 2005
Brazil

Welcome to the III Silicon in Agriculture Conference!

First of all, we would like to thank you all for being here! It is a great honor for us to host the III Silicon in Agriculture Conference. We put a lot of time and energy into organizing this scientific meeting, in what you will hopefully consider a very pleasant and comfortable venue. Our Brazilian community of agricultural scientists will warmly receive our colleagues from other parts of world. We hope that during this meeting in Brazil that it will be a time to learn, not only about Silicon in Agriculture, but also about our vast, multi-dimensional, multi-ethnic country.

The Federal University of Uberlândia is a relatively young institution, 30 years old. Many of our MS and PhD graduate programs in Agriculture were recently started and are growing. As a result of this meeting, we believe and hope there will be a significant increase in our teachers and student's enthusiasm and spirit for scientific inquiry. In fact, the entire community of agricultural scientists will gain a lot from this meeting because it offers an array of activities that include: round tables, field day, posters, and speeches with experts in agronomy, entomology, plant breeding, plant nutrition, plant pathology, plant physiology, animal nutrition and soil science. In addition, we will be offering you a multi-cultural program throughout the coffee breaks, oral and poster sessions.

The organizing committee is very appreciative of the financial support we have received to help defray conference expenses. Our sponsors are recognized in this book, and we ask that you join us in thanking them for their contribution. Without their support, programs like this would not be possible.

Lastly, we are extremely happy to receive you in Uberlândia, and you are most welcomed to Minas Gerais! We are considered to be the friendliest state of our nation!

Yours most sincerely,

Gaspar H. Korndorfer & the Organizing Committee

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SCIENTIFIC & CULTURAL PROGRAM

	TITLE	*SPEAKERS/ACTIVITIES*
Saturday, 22		
14:00h-18:00h	Registration	*Local: Center Convention*
19:00h-22:00h	Welcome Reception	*Cocktail ("capoeira" dancing and carnaval music) - Local: Center Convention*
Sunday, 23		
	SECTION 1: General Silicon	
08:00h - 08:30h	Opening Conference	*Deans, Mayor, Directors, etc.*
08:30h - 09:30h	Silicon in Agriculture: a historical review	*E. Epstein, PhD. (USA) - eqepstein@ucdavis.edu*
09:30h - 10:00h	Coffee Brake	
10:00h - 11:00	Silicon and microbiology aspects - overview	*Milton Wainwright, PhD. (England) - M.Wainwright@sheffield.ac.uk*
11:00h - 11:15h	Silicon and microbiology in Brazil	*Siu M.Tsai, PhD. (Brazil) - tsai@cena.usp.br*
11:15h - 11:45h	Biogeochemistry of silica phytoliths in agriculture	*Liovando M. da Costa, PhD. (Brazil) - liovandomc@yahoo.com.br*
11:45h - 13:30h	Lunch	
	SECTION 2: Silicon x Disease and Pest Management	
13:30h - 14:15h	Silicon and disease management	*Lawrence E. Datnoff, PhD. (USA) - ledatnoff@ifas.ufl.edu*
14:15h - 15:00h	Silicon-mediated resistance in monocots: the rice-*magnaporthe grisea* model	*Fabrício de Á.Rodrigues, PhD. (Brazil) - fabricio@ufv.br*
15:00h - 15:45h	The role of silicon in plant-pathogen interactions: toward a universal model	*Richard R. Bélanger, PhD. (Canada) - Richard.Belanger@plg.ulaval.ca & J. Menzies, PhD. (Canada)*
15:45h - 16:15h	Coffee Brake	
16:15h - 16:30h	Silicon and insect management - review	*Mark Laing, PhD. (South Africa) - Laing@ukzn.ac.za*
16:30h - 18:30h	Selected papers - Oral presentation	*Different Authors*
20:00h - 22:00h	Dinner	*State Cookery "Portal" - Rondon Pacheco Avenue*
Monday, 24		
	SECTION 3: Silicon in the Plant	
08:00h - 09:00h	Abiotic stress and silicon	*Yongchao Liang, PhD. (China) - ycliang@njau.edu.cn*
09:00h - 10:00h	Silicon requirement for rice	*Jian F. Ma, PhD. (Japan) - maj@ag.kagawa-u.ac.jp*
10:00h - 10:30h	Coffee Brake	
10:30h - 11:15h	An overview of the impact of silicon in alleviating biotic and abiotic stress in sugarcane	*Jan Meyer, PhD. (South Africa) - meyer@sugar.org.za*
11:15h - 12:00h	Selected papers - Oral presentation	*Different Authors*
12:00h - 14:30h	Lunch and Poster Viewing	*Different Authors*
	SECTION 4: Chemistry of Silicon in Soil and Fertilizer	
14:30h - 14:45h	Silicon in the soil: chemical and mineralogical aspects	*Igo Lepch, PhD. (Brazil)*

14:45h - 15:45h	Organosilicate chemistry: evidence for a cross-linking role in plants	*Stephen D. Kinrade, PhD. (Canada) - skinrade@lakeheadu.ca*
15:45h - 16:15h	Coffee Brake	
16:15h - 16:30h	Available silicon in tropical soils and crop yield	*Gaspar H. Korndorfer, PhD. (Brazil) - ghk@triang.com.br*
16:30h - 20:00h	Poster Presentation	*Different Authors*
20:00h - 22:00h	Dinner	*Brazilian Barbecue "Churrascaria Chima"- Center Convention*
Tuesday, 25		
07:00h - 19:00h	Field trip to the sugar-mill (Guaíra) including lunch (sandwich, fruits and beverage)	*Sugarcane operations: Variable rate application of calcium silicate (precision agriculture), green harvest, fertigation (vinasse) and organic residue application (filter cake)*
---	Dinner	*Free option*
Wednesday, 26		
08:00h - 08:45h	Methods for Si analysis in plant, soil and fertilizers	*Suzanne Berthelsen, PhD. (Australia) - Suzanne.Berthelsen@csiro.au*
08:45h - 09:15h	Slag as Silicon source: application criterion	*Hamilton S. Pereira, Ph.D. (Brazil) - hamiltonseron@uol.com.br*
09:15h - 09:30h	The Brazilian law on the use of silicon as lime and fertilizer	*Erika M. André (Brazil) - emangili@agricultura.gov.br & José Guilherme T. Leal (Brazil) - joseleal@agricultura.gov.br*
09:30h - 10:15h	Round Table - Silicon analysis in soil, plants and fertilizer	*Jan Meyer, PhD. (South Africa); Suzanne Berthelsen, PhD. (Australia); Gaspar H. Korndorfer, PhD. (Brazil); Stephen D. Kinrade, PhD. (Canada);*
10:15h - 10:45h	Coffee Brake	
10:45h - 11:00h	Products to supply Si fertilizer market	*Manah - Bunge*
11:00h - 11:15h	Products to supply Si fertilizer market	*Siligran - Fertion*
11:15h - 11:30h	Products to supply Si fertilizer market	*Ineos Silicas*
11:30h - 11:45h	Products to supply Si fertilizer market	*Recmix - Agrosilício*
11:45h - 12:00h	Products to supply Si fertilizer market	*Excell Minerals*
12:00h - 12:15h	Past and future outlook on Si research	*Lawrence Datnoff, PhD. (USA) - ledatnoff@ifas.ufl.edu*
12:15h - 12:30h	Conference Conclusion	*Decision: local for the next conference*

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- Federal University of Uberlandia

- University of Florida

- Brazilian Soil Science Society

- Brazilian Phytopathology Society

FINANCIAL SUPPORT AND COLLABORATION:

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WELCOME TO UBERLÂNDIA

"GATEWAY TO THE CERRADO"

Author: Roberto Vieira da Silva

There was once a small town called São Pedro de Uberabinha. It was like many towns in the region. Then, with a surge of concentrated effort the town became Uberlândia, an influencial pole of the entire region, where more than 3.5 million people live, work and enjoy their lives. Uberlândia, in the Brazilian Cerrado, is today considered a model city of Latin America , with growth and infrastructure similar to the First World countries. The Cerrado hot weather, predominant during most of the year, is allied to the human warmth of the people who have changed our city into a place which welcomes our visitors and makes them feel at home.

GATEWAY TO THE CERRADO

The Cerrado is the second largest geographical region of Brazil. It is recognized by UNESCO as a "Biosphere Reserve". With an area of close to the two million square kilometers, corresponding to 22% of the national territory. It has very diversified fauna and flora which, because of exploitation and a lack of knowledge are running serious risk of extinction due to economic growth that has not been accompanied by scientific and cultural development. The Cerrado is located in the central region of Brazil, including the states of Bahia, Goiás, Maranhão, Mato Grosso, Mato Grosso do Sul, Minas Gerais, Rondônia and Tocantins. The city of Uberlândia is recognized as "Gateway to the Cerrado", because it is the southern frontier of the region proposes to act as a reference foe the historical, cultural and environmental potential of the Cerrado and the cities that are in its area.

GENERAL FEATURES

Altitude: 863 m above sea level.
Area: 4,040 km^2.
Latitude: 18º55'23"S
Longitude: 48º17'19"W (Greenwich).
Population: ± 500,000

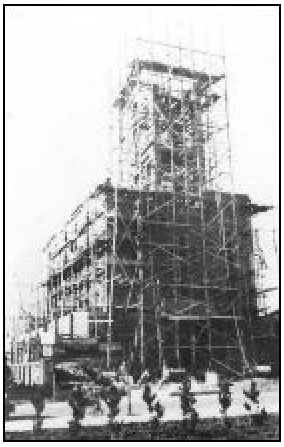
WEATHER

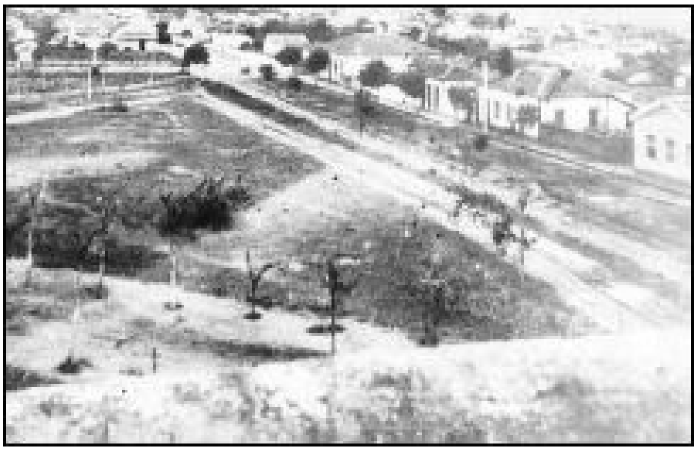
Uberlândia's weather is semitropical, characterized by the alternation of dry Winters and rainy Summers, with an average temperature of 22ºC, the period from October to March is the hottest (24,7ºC). The coldest months are June and July with an average temperature of 18.8ºC. Summer is characterized by a marked instability in the weather, due to the occasional Atlantic polar air masses which precipitate a large amount of rainfall between the months of October and March. The period from December to February receives about 50% of the annual rainfall, which is from 1,500 to 1,600 mm. The winter, June to August is also de dry season.

TOPOGRAPHY, VEGETATION AND SOIL

Uberlândia is situated in the region known as "Domínio dos Planaltos e Chapadas da Bacia Sedimentar do Paraná" (Plateaus of the Paraná Sedimentary Basin). It is a sub-unit known as the "Paraná Basin Septentrional Plateau" (RADAM-Brazil-1983). The region's characteristic vegetation is the Savannah , with acid and not very fertile soils. In the urban areas, the land is gently rolling, with altitudes varying from 700 to 900 m, rivers and smaller streams flowing over basalt, rock formations with many waterfalls, here the soils are fertile.

HISTORY





Following early exploration of the region, João Pereira da Rocha (1818) was one of the first settlers. He cleared an area that became known as the Aldeia de Santana. Today this is the area of the city of Indianópolis . Rocha also cleared other areas, which attracted many families to establish roots in the region, like the Carrejo's. In 1964 Felisberto Carrejo was legally recognized as the founder of Uberlândia. He established, in his home, the first municipal school, which was used as a church on Sundays. With the time the village of São Pedro de Uberabinha became known as Uberlândia, name proposed by João de Deus Faria, meaning fruitful land.

FEDERAL UNIVERSITY OF UBERLANDIA

Created in 1969 by the fusion of three isolated faculties, the resulting university was federalized in 1978. With more than 1,000 professors and nearly 4,000 technical assistants, many performing services in the modern University Hospital , the quality of education is assured for our more than 11,000 students. Complementing the classroom activities are many opportunities for personal development. Students participate with professors in research projects receiving scholarships from the Federal and State Government. Apprenticeships in local agricultural and industrial institutions are available to those finishing their academic programs.

Priority given to research has made it possible to generate resources from government and institutions outside our geographical area and contributes to our productivity and academic excellence. The university also participates in extension programs offering technical, artistic, cultural and academic programs to area groups and residents. These activities are strengthened by the university and local commerce and industry. The University accepts the challenge of constructing a creative and productive institution in a democratic environment. In this way we invest in academic excellence with administrative efficiency to strengthen local resources and guarantee the future of our teaching, research and extension efforts.

General informations

Important things to know about the Conference

- The Conference will take place in the Uberlândia Convention Center – linked to the Center Shopping and Plaza Inn Hotel;

- On October 22 you have to go to the Convention Center and search for us in the general secretary of the meeting to pick up your materials (badge, bag, handbook, declarations and etc). The secretary will be opened from 8:00am to 6:00pm.

- You will need your badge (identification card of the meeting) to get access to all of our activities.

- Posters will be presented in expositors one meter large and two meters tall. Prepare your poster as you wish but we recommend a banner. Nearby Tubal Vilela square, downtown, there are numerous offices that prepare posters and banners.

- Access to e-mail will be provided by the hotels and we also have two lan-houses in the shopping center (2^{nd} and 1^{st} floor). You will pay around R$3.00 per hour, around US$1.25.

Taxi Information:

We made contact with **Radio Taxi 2000** (phones: 0800 342118 or 3214-0077), the best taxi company in Uberlândia, to attend you. They have some drivers that speak English. They will have a small advertisement of our meeting in the car windows.

Itinerary	Day and night ±
Airport to Center Convention	R$15,00
Bus Station	R$10,00
Center Shopping to Portal	R$10,00
Tubal Vilela Square to Center Shopping	R$8,00
UFU (Umuarama) to Center Shopping	R$12,00

Useful Telephone Numbers:

Police	190
Fire Department	193
Center Convention	3239-8300
University of Uberlândia	3218-2225
Hospital (UFU – Civil Service)	3218-2111
Hospital Santa Clara (Private)	3239-6000
UFU (Agronomy Institute)	3218-2225
Dentist (Dr. Carolina Marquez Florim)	3235-9074 or 9971-0107
Radio Taxi 1010 (Taxi) – Official Agency	0800 9407000 or 3214-0077
Tila Turismo (Travel Agency)	3235-0474

Hotel List

1. **EXECUTIVE INN *****
   Address: Av. Rondon Pacheco, 5.000
   (approximately 300 meters from conference)

Room (single): U$ 31.00 - breakfast included
Room (double): U$ 40.00 - breakfast included

2. **VILLALBA *****
   Address: Av. Rondon Pacheco, 4.651
   (approximately 100 meters from conference)

Room (single): U$ 21.00 - breakfast included
Room (double): U$ 25.00 - breakfast included

3. **SAN DIEGO ******
   Address: Av. Rondon Pacheco, 3.500
   (approximately 400 meters from conference)

Room (single): U$ 58.00 - breakfast included
Room (double): U$ 61.00 - breakfast included

4. **CONFORT *****
   Address: Av. Rondon Pacheco, 5.255
   (approximately 500 meters from conference)

Room (single): U$ 37.00 - breakfast included
Room (double): U$ 45.00 - breakfast included

5. **PLAZA SHOPPING ******
   Address: Rua da Bandeira, 400
   (at the conference site)

Room (single): U$ 58.00 - breakfast included
Room (double): U$ 68.00 - breakfast included

Restaurants: a special discount was offered to the Conference attendants by the restaurants bellow located at the Center Convention (Italian Food, Barbecue and Self Service). All you need to do is show your conference badge.

1. Italian Food

2. Barbecue

III SILICON IN AGRICULTURE CONFERENCE SPEAKERS

Emanuel Epstein, PhD
SILICON IN AGRICULTURE: A HISTORICAL REVIEW

Emanuel Epstein. Department of Land, Air and Water Resources. Soils and Biogeochemistry. University of California, Davis. One Shields Ave. Davis, CA 95616-8627. USA - eqepstein@ucdavis.edu

Abstract

The time and place of the beginning of the scientific study of silicon in plants and in agriculture can be stated precisely. The time was the early 1860s and the place was Germany. It was then and there that it was found that plants could be grown to maturity in solution culture. Until then, plants could only be grown in soil, and so it was impossible to withhold any element from plants, because of the impossibility of chemically removing an element from soil without destroying the soil. Nutrient solutions, on the other hand, could be made up with a given element omitted from their formulation. Sachs, prominent plant physiologist, concluded that a nutrient solution with the following constituents was adequate: H_2O, KNO_3, NaCl, $CaSO_4$, $MgSO_4$, CaH_2PO_4, and a little iron salt. His list does not include silicon. He and many authors following him considered it "certain that this substance is superfluous for the chemical processes of nutrition…" Similar sentiments are to be found even in present-day publications, or else silicon may not even be mentioned. Nevertheless, the present Silicon in Agriculture Conference, the third in just a few years, shows that things are changing. What has brought this change about? The renewed interest in silicon is mainly due to scientists who deal with crops in the field rather than with carefully protected plants in greenhouses and controlled environment facilities. In the field, plants are exposed to a multitude of stresses, both biotic and abiotic, and plants are particularly susceptible to stress when deficient in silicon. This recognition of the importance of silicon began in the early 1900s, sporadically at first. By now, that long lag phase in research on silicon in agricultural science is over, and we can look forward to rapid advances.

The earliest considerations and studies

Many of us are puzzled that the element silicon, the focus of this meeting, is to such an extent neglected by plant biologists. But such neglect is not uncommon in our science, or science in general. As late as 1838 a prize was offered in Germany for the best answer to the following questions. "Do the so-called inorganic elements, which are found in the ashes of plants, occur in these plants when exterior sources of these elements are eliminated? Are these inorganic elementary constituents so essential that the vegetable organisms have constant need of them for their complete development?" The prize for the best answer to these questions was awarded in 1840 to A.F. Wiegman and L. Poldstorff (Browne 1944). They germinated seeds of garden cress, *Lepidium sativum*, in an inert medium to which nothing was added but distilled water. After 28 days, the seedlings, which were dying by then, were ashed. It was found that the ash weighed exactly the same as that of an equal number of seeds. Thus these investigators did away, once and for all, with the idea that some vital force generated mineral constituents of plants: "If plants are shut off from all exterior sources of inorganic matter, then the amount of the latter which they contain cannot exceed the quantity originally present in the seeds" (quoted from Browne 1944). Thus ended a lag phase in research on the need of mineral elements by plants, for decades earlier, a pioneering investigator, the Swiss Théodore de Saussure, had provided excellent evidence to the effect that plants absorb mineral elements from soil, and that many of these elements are necessary for their nutrition. Also, the foremost chemist of that time, Justus Liebig of Germany, through his forceful advocacy, had gained acceptance for the "mineral theory of manures" (Liebig 1840).

It was thus recognized by mid-19th century that mineral elements must be absorbed if plants are to thrive, but the methods used could not lead to identification of the specific elements that plants require, among all those present in soil. For that identification a new technique was needed, one that eliminated soil as the mineral medium. A medium was needed from which a given mineral element could be excluded to determine whether plants deprived of it would succumb.

Development of the technique of solution culture provided the means for the identification of the essential mineral elements, or nutrients. It was accomplished by two German investigators, J. Sachs (1860) and W. Knop (1867); see Miller (1938) and Epstein (2000) for brief accounts of this development. The solutions devised by these 19th century investigators differed in the concentrations of various elements but they both had the following constituents: potassium, calcium, magnesium, nitrate, phosphate, sulfate, and a "trace" of iron. That of Sachs also contained sodium chloride. Except for iron, these formulations of nutrient solutions did not contain any micronutrients, but the salts used to make up the solutions, as well as the water and the containers, contributed adequate amounts of them, unbeknownst to the researchers. It would not be till the 1920s that additional micronutrients were identified, more than sixty years after the establishment of the initial list of seven essential mineral elements by Sachs and Knop – a long lag phase.

Silicon was not included in those early nutrients solutions of the 1860s, although it was well known that plants, and particularly grasses, contain it at appreciable concentrations. "Although in such plants half of the total ash often consists of silica, I (and subsequently other observers also) nevertheless succeeded in bringing maize plants to vigorous and complete development with the help of nutrient solutions to which not even a trace of silica was added" (Sachs 1887). Sachs even condemned as "thoughtless" Knop's conclusion that silicon is helpful in keeping cereals from lodging. Sachs thus was quite convinced that silicon "is superfluous for the purposes of nutrition and growth." That, then, was the view of the world's foremost plant scientist of that time, the second half of the 19th century. Similar opinions were expressed in England (Green 1911) and Russia (Palladin 1918). We thus have to realize that from the earliest quantitative studies of plant nutrition, those of de Saussure at the beginning of the 19th century, to those of the beginning of the 20th century, there was a century-long lag phase during which no progress was made in regard to the role of silicon in agriculture and crop science.

Accelerated research

That indifference to silicon on the part of plant biologists changed around the beginning of the 20th century. What caused this change, and why did it occur where it did, viz. in Japan? The answer is twofold. First, the main food staple in Japan is rice, and rice, which absorbs silicon to a greater extent than does any other crop, may be rather low in this element when grown in paddy culture. Second, it was found that rice leaves infected by blast disease had lower silicon contents than did healthy leaves (Onodera 1917) – the first such report (Ma and Takahashi 2002). Since then there have been numerous reports on the mitigation, by silicon, of plant diseases, as amply documented in the volumes resulting from the two Silicon in Agriculture conferences preceding the present one (Datnoff et al. 2001; Silicon in Agriculture Organization Committee 2002), and the volume edited by Ma and Takahashi (2002). A survey of these and other such reports reveals an interesting pattern. To a large extent, advances in our knowledge of the roles of silicon in the performance of plants have not come from laboratory investigations but, initially at least, from experience in the field. In a discussion of a classical review of silicon in agriculture (Jones and Handreck 1967), it was remarked that "its lengthy list of references impresses the reader by the extent to which they come from agricultural and crop science publications rather than from plant physiological ones" (Epstein 1999).

Plants in the field are subject to a large number of stresses. This leads to recognition of yet another pattern. The significance of silicon is most clearly apparent in plants that are under some environmental stress, whether biotic or abiotic. That has been amply documented in the proceedings of the previous Silicon in Agriculture conferences, and in the reviews already referred to. These stressful features include diseases and pests, gravity (the cause of lodging of cereals), and excessively high or low temperatures, metal toxicities, salinity, and still others. These adverse conditions are of the greatest interest to scientists concerned with crops in the field, and that is the reason that it is they who have contributed to such a disproportionately large extent to our knowledge of the roles of silicon in plant life.

Wild plants in nature are subject to the same stressful conditions already mentioned in connection with crops. It is therefore a legitimate criticism to note that to this day the significance of silicon is given short shrift in discussions of plant nutritional aspects of plant ecology. Similar misgivings are in order for purely plant physiological and plant molecular biological investigations of pant stress. For example, surely questions must be raised when experiments on metal toxicity are performed without any attention to silicon, which is known to mitigate such stress. Plants in the real world experience metal toxicity stress in media that do contain silicon. Experiments conducted in its absence therefore impose on the plants an environmental stress that is altogether atypical: the absence of silicon. Experiments conducted under these unrealistic minus-silicon conditions may well give misleading results.

Where do we stand now?

The considerations just mentioned on the inadequate attention paid to silicon in plant ecological and plant physiological contexts drive home the point that we have once again experienced one of those lags in progress that were commented on before. The plant biological community is still not aware that plants grown in media in the formulation of which silicon is not included are experimental artifacts: such minus-silicon plants do not exist in nature or agriculture or forestry (Epstein and Bloom 2005). The situation is exacerbated by the continued reliance on a badly flawed definition of essentiality according to which silicon does not qualify as an essential element. That definition has been criticized, and a new one has been devised (Epstein and Bloom 2005). The significance of silicon to plants being so variable, depending on the genotype and a whole raft of environmental conditions, these authors have assigned to silicon the status of a "quasi-essential" element. (This designation is appropriate for sodium as well, and possibly other elements.)

In any event, this, the Third Silicon in Agriculture Conference, attended by scientists from all over the world, is ample evidence that the "silicon deficiency" in plant science is at an end. Exciting progress is being reported here on all aspects of silicon in plants and microorganisms, in biogeochemistry, and in soils and fertilizers. It is a tribute to the organizers of this and the previous Silicon in Agriculture conferences, and those attending them, that such a large body of evidence is now available about the significance of silicon in agriculture. Another lag phase is over, and rapid progress can confidently be predicted.

Rapid progress is needed. The population of planet Earth is now 6.3 billion and will reach about 8 or 9 billion by 2050. We will have to grow more food. Most good land is already farmed, so that higher yields have to be wrung from existing crop land, and marginal land will have to be pressed into service. Additional challenges will come from global change, pollution, salinization, and still other adversities.

Therefore the plant world, which is our life support system, will increasingly come under stress, and it is plants under stress that respond most markedly to silicon. Thus this historical review ends with a look to the future.

References

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Milton Wainwright, PhD
SILICON AND MICROBIOLOGY ASPECTS - OVERVIEW

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The role of microorganisms in the transformations of silicon has been little studied and, as a result, is little understood; most of the studies having been directed towards the use of silicon by diatoms. The lack of interest in silicon microbiology obviously relates to the fact that there is no evidence that silicon can be oxidised and reduced; as a result, there is no silicon cycle that is comparable to, for example, the sulphur or nitrogen cycles. Similarly, there is little evidence that silicon can be used as an energy source by microorganisms However, as I hope to show in this lecture, microorganisms can influence the availability of silicon in soils, and stimulate the growth of both bacteria and fungi *in vitro*. My aim is to review the available literature on the microbiology of silicon and to show how silicon affects microorganisms in relation to microbial growth in the environment and microbial pathogenesis.

Compounds of silicon are very common, comprising around 28 % of the earth's crust. The element occurs in two forms: silica or the oxides of silicon, which exist in crystalline or amorphous forms as in quartz, flint, sandstone, opal and diatomaceous earths and silicates, of which clay is an example. Silicon, as silicic acid (0.1-0.6 mM) occurs as one of the main constituents of soil solution and it can be regarded as a plant nutrient (Epstein, 1994). Although silicon is close to carbon in the Periodic Table, its chemistry is dominated by stable Si-O bonds, so direct replacement of silicon for carbon in normal biochemistry appears impossible

A wide range of bacteria and fungi can solubilize insoluble silicates by producing mineral and organic acids, and chelating agents (Henderson and Duff, 1965). Most of these silicate solubilizers are common soil micro-organisms, although a specialized silicon solubilizing bacterium, *Bacillus mucilaginosus,* has been described by Russian workers. Silicate-dissolving micro-organisms have been used to remove silicon from low-grade mineral raw materials, like bauxite, and to extract valuable metals from silicate and aluminosilicate ores and minerals (Karavaiko *et al*., 1988).

It has long been known that silicon compounds can stimulate microbial growth; for example, Borrell *et al.* (1922) found that the addition of a small amount of K_2Si0_3 augments the yield of cultures of *Bacille tuberculeux.* Price (1932) also showed that the growth rate of *Amoeba proteus* was greatly increased by the addition of sodium silicate. Similarly, Mast and Pace (1937) found that *Chilomonas paramecium* will not grow in inorganic solutions lacking silicon and also that silicon stimulated starch production, growth and respiration in this organism. Bacteria, such as *Bacillus licheniformis,* can also accumulate silicon from growth media (Mohanty *et al*., 1990).

Much of the early work on the interaction between silicon and bacteria relates to studies on the lung diseases silicosis (a form of pneumoconiosis) and tuberculosis. In the past, silicosis was very common amongst industrial workers (especially coal miners) exposed to dust rich in crystalline silica, but not amorphous silica and silicates. Many silicosis sufferers died from tuberculosis which spread rapidly through the lungs and caused death in a relatively short time. Price (1932) showed that sodium silicate and silicic acid stimulates the growth of *Mycobacterium tuberculosis*, and that even small amounts of silicon compounds, notably the easily soluble forms, produced the stimulatory effect. More recently, Yoshino (1990) found that 100 µg g silicon ml^{-1} has a remarkable stimulatory effect on the growth of *Staphylococcus aureus.* He also showed that a high concentration of silicon present in the mucous membrane acts to enhance the growth of *Pseudomonas aeruginosa*. Sufferers from chronic sinusitis apparently have a high concentration of silicon in their mucous membranes, a fact which led Yoshino to suggest that this stimulatory effect of silicon on bacteria exacerbates the condition.

The stimulatory effect of silicon compounds on microbial growth is not restricted to bacteria and amoebae. For example, silicic acid stimulates the growth of fungi, including *Penicillium* species, when growing in ultra-pure water as well as nutrient-rich media (Wainwright *et al*., 1997). It is not clear why silicon compounds should stimulate the growth of micro-organisms in culture medium as well as purified water, which obviously lacks any added nutrients. Bigger and Nelson (1943) observed that bacterial growth is stimulated by the addition of talc (hydrated magnesium silicate) to distilled water; they suggested that coliform bacteria can use $C0_2$ and ammonia, adsorbed from the atmosphere, a reaction which is in some way promoted by the presence of silicon compounds. Das *et al*. (1992) and Chakrabarty *et al*. (1988) also showed that *Mycobacterium* and *Nocardia* spp. can grow in the absence of carbon provided that silicon compounds were present. They suggested that bacteria grow autotrophically under these conditions, fixing $C0_2$ by using energy gained from silicon metabolism, i.e. by a form of silicon autotrophy. Unfortunately, absolute proof of this was not provided. One problem with attempting to verify silicon autotrophy is that silicon compounds adsorb potential nutrients from the atmosphere. It is possible therefore that, in these studies, bacteria grew oligotrophically, rather than autotrophically, using ammonia and fixed carbon scavenged by the silicon compounds. A similar explanation could also apply when certain fungi were found to grow in ultra-pure water only when silicon compounds were added and on nutrient-free silica gel (Tribe and Mabadaje, 1972; Parkinson *et al*., 1989). However, Mirocha and Devay (1971) have suggested that fungi can grow in the absence of carbon by using energy obtained from the oxidation of ammonium or hydrogen and, under these conditions, silicon might act as a direct energy source or as a catalyst. Although the ability of micro-organisms to grow autotrophically using silicon as an energy source has been suggested, most microbial physiologists would argue that it is theoretically unlikely that microorganisms could gain energy from breaking silicon bonds. Allison (1968), however, has suggested that the reaction of Si-Si-Si with O_2 or oxygen compounds might prove to be an energy yielding process.

The stimulatory effect of silicon compounds, including clays (Stozky and Rem, 1966), on microbial growth might help explain how microorganisms can grow in soil despite the fact that it contains only trace amounts of available carbon. Silicon also plays a role above the ground in protecting plants from predators. The silicon content of plants like cucumber, for example, increases following fungal infection, when it appears to exert a protective effect (Samuels *et al*., 1991).

Al-Wajeeh (1999) found that silicic acid increased the growth of fungi under oligotrophic and nutrient rich conditions. Under the latter conditions, it also stimulated the growth of a *Streptomyces* species, but decreased the growth of bacteria and yeasts as well as reducing the chlorophyll content of the alga, *Dunaniella parva*. Silicic acid also stimulated the production of silicon by *Aspergillus* niger, but decreased nitrification and sulphur oxidation by this fungus. Silicic acid also reduced antibiotic production by a species of *Streptomyces*. Certain fungi such as *Aspergillus, Penicillium*, *Candida, Alternaria*, *Cladosporium* spp. absorb silica when soluble silicates are added to the culture, a fact which may be due mainly to the adsorption of colloidal silica. However, despite the fact that certain micro-organisms accumulate or adsorb silicon (e.g.diatoms, bacteria, fungi), relatively little is known about its role in the metabolic processes. Silicon, in the form of nutrient-free silica gel medium, can also be used to isolate autotrophic bacteria, oligotropically growing fungi and the pathogenic yeast *Candida*, (Wainwright and Al Talhi, 1999), while silica wafers have been used to demonstrate the ability of bacteria to exhibit pleomorphism when growing under starvation conditions (Wainwright *et al,* 1999).

Silicon and Soil Microbiology

A silicon cycle, comparable to say the N and C cycles, does not operate in the environment and the only biological involvement in silicon mobilization-immobilization is represented by the solubilization of insoluble silicon, the release of the element from organic-silicon compounds and the immobilization of silicon by bacteria and fungi. In this respect, silicon is similar to phosphorus. The literature on the potential role of microbial processes in making silicon available to plants is almost non-existent; the exception being silicate solubilization. Soomro (2000) showed that a) bacteria solubilize rock potash, releasing free silicon into the medium, b)the growth of a *Penicillium* sp.*in vitro* increased the solubilization of sodium silicate, but concentrations of free silicon decreased when the fungus was grown in the presence of silicic acid, presumably due to Si-immobilization by the fungus, c) water-extractable silicon increased when silicic acid was added to all soils, under both aerobic and anaerobic conditions,d) liming increased the release of soluble silicon from sodium silicate, silicic acid and rock potash, the effect being seen in all soil types, d) addition of silicic acid generally decreased bacterial numbers in all soils, at least over the first days of the incubation period, e) silicic acid had no effect on nitrification, while the addition of sodium silicate stimulated nitrate production, this effect is assumed to be largely due to the resultant marked increase in soil pH.7.The addition of silicic acid and rock potash also increased sulphur oxidation, f) the addition of silicic acid to the agricultural loam soil led to a decrease in both arysulphatase and dehydrogenase activity, as well as respiration and soil biomass.

The obvious question that rises from this above findings study is-To what extent is silicon addition likely to improve, or adversely affect soil fertility? Firstly, it is clear that water-soluble silicon is released from insoluble silicon compounds following their addition to soil, and that such release is a combination of microbial and chemical-physical processes. The observed decrease in bacterial numbers, arylsulphatase activity, dehydrogenase activity and respiration can be regarded as being detrimental to soil fertility, while increases in sulphur oxidation can be seen as positive responses. The lack of effect of silicon compounds on nitrification can also be seen as being overall desirable; while increased nitrate following the addition of sodium silicate can be regarded a damaging because it leads to the, above-mentioned loss, of N from soils. It may be that many of the observed effects of silicon compounds on soil fertility result more to their alkaline nature, than from any direct effect of silicon itself.

Although silicon is essentially, biological un-reactive, this has not prevented science fiction writers and others (Heron,1989), from suggesting that silicon could act as an alternative to carbon, in the biology on other planets. It has also been occasionally been suggested that silicon may act as an alternative energy source, to carbon for microbial life (Das *et al*., 1992), and more recently Wainwright *et al*.(200??) have suggested that silicon may have helped establish the first bacterium following its development here on Earth or arrival from space (Wainwright *et al*., 2003). Other speculations include the possibility that clays played a role in the origin of life (Cairns Smith, 1985).

Finally, there is increasing interest in the use of silicon-solubilizing bacteria in biotechnology, for example in the bioleaching of silica from low grade, high–SiO_2 bauxites (Niu, *et al.,* 2004). In the future, bacteria and silicon may also find increasing applications in the new science of nanotechology As a result, while the microbiology of silicon has, in the past been somewhat neglected, the interaction between microorganisms and silica is likely to be an increasingly important area of research in the future.

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Liovando Marciano da Costa, PhD
BIOGEOCHEMISTRY OF SILICA PHYTOLITHS IN AGRICULTURE

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Biomineralization is the process by which living organisms control initiation and growth of minerals. Minerals thus formed are different from their abiotic counterparts. They are synthesized by organisms which are influenced by their environment and may provide important information about the interaction organisms *x* environment. Further research on this subject may enhance the understanding of information contained in contemporaneously formed biominerals and in fossilized ones preserved in diverse depositional environments.

Biominerals are formed from precursor organic substances which act as templates that define the final shape of each mineral. Besides shape, biominerals present other specific features such as size, crystallinity, trace element composition, isotopic signature and organic compounds. This kind of information can be compared to the features of minerals formed without participation of living organisms or of those synthesized under laboratory conditions.

There has been only limited research on organic substances contained within biominerals. There is a great diversity of biominerals: carbonates, phosphates, sulfates, sulfides, oxides, and organic crystals such as oxalates. Some biominerals may increase mechanical resistance and protection of organisms against predators, pathogens or abiotic stresses. Crystals formed within living plants may control the activity of some mineral nutrients or toxic chemical elements. Amongst oxides, one of particular importance to a considerable number of species and directly related to this conference is biogenic silica ($SiO_2.nH_2O$). This particular biomineral will be considered separately.

Analyses of the organic fraction of biominerals have focused mainly on total contents of carbon and nitrogen. Other elements associated with organic substances are hydrogen, sulphur and phosphorus, which are also quantified in some research. A number of organic compounds are identified using available techniques.

Proteins are organic polymers of great importance to the formation of biominerals. The amino acids which constitute proteins are the main providers of nitrogen and sulphur contained in biominerals. Another group of macromolecules contributing to the composition of biominerals are the lipids/phospholipids. The phosphorus usually found in chemical analyses of biologic minerals is of phospholipidic origin. Glycoproteins, compounds of carbohydrates and proteins, also contribute to the composition of biominerals. Although most biominerals have low contents of organic carbon, these organic compounds are important as they act as templates to biomineral formation, controlling their variable shapes.

Although a considerable number of species produce silicon biominerals, the emphasis of this work will be on biogenic silica produced by plants. These biominerals are called phytoliths. Chemical composition of biogenic silica comprises an organic fraction and occluded chemical elements. Some data on the chemical composition of biogenic silica will be presented.

In plant tissues, H_4SiO_4 undergoes polycondensation when its concentration exceeds *circa* 2 mM (Perry & Keeling-Tucker, 1998) and biogenic opal or opal-A ($SiO_2.nH_2O$) is formed. Because of the variable angles and distances of Si-O-Si bonds as well as of the variability of the silica hydration state, crystal shape is highly influenced by the organic matrix in which it is deposited (Epstein, 1994; Perry & Keeling-Tucker, 1998). The variously shaped biogenic opals are generally called phytoliths. With the decay and consequent decomposition of plant organic matter, the biogenic silica returns to the soil, where it could be dissolved, and potentially modify Si soil solution chemistry.

Biogenic silica depositions in plants may occur in leaves, seeds, fruits, roots and wood. In plant tissues there are three possible sites for opal deposition: on the cell walls, in the cell lumen, or in intercellular spaces (Sendulski & Labouriau, 1966; Piperno, 1988). The main silicon accumulators and phytolith producers are the Poaceae, but other monocots and some dicots also accumulate considerable amounts of silica in their tissues (Runge, 1999) and some phytolith morphologies seem to be unique enough to allow taxonomic identification of producer species on the family level and sometimes on the genus level (Parry & Smithson, 1964; Sendulski & Labouriau, 1966; Campos & Labouriau, 1969; Silva & Labouriau, 1970). Carnelli et al. (2002) raise the question of whether the use of phytolith morphological types as tracers of plant families or genera is reliable enough because some similar morphotypes occur in genetically unrelated genera.

Until recently, most of the literature on phytoliths dealt almost exclusively on morphology and its potential use as a taxonomic fingerprint (e. g. Parry & Smithson, 1964; Piperno, 1988; Runge, 1999; Thorn, 2004). Brazilian botanist L. G. Labouriau and co-workers published pioneering works on phytolith morphology of grasses from the Cerrado (Sendulski & Labouriau, 1966; Campos & Labouriau, 1969; Silva & Labouriau, 1970). The biological pool of the biogeochemical cycle of silicon has lately received widespread attention, especially because of the growing awareness of the role played by plants in controlling mineral weathering and formation in the soil environment (Lucas et al., 1993; Alexandre et al., 1997; Derry et al., 2005) and also because the weathering of silicate minerals as well as phytoliths themselves represent important sinks for atmospheric CO_2 (Exley, 1998; Parr & Sullivan, 2005).

Table 1 displays the chemical composition of ashes of roots and shoots of wiregrass plants from the state of Georgia, USA, after the use of three different extractants (HCl 0.5 mol L^{-1}, HCl 50% + H_2O_2 30%, and NaOH 2 mol L^{-1}) in a sequential extraction aiming to purify biogenic opal (Costa, 2004). Most of the Si in wiregrass roots and shoots (~ 98%) was extracted by a strong basic solution. These results imply that the element was predominantly in the form of opal-A, which is generally not soluble in acid solutions, except for HF. Some other elements, e.g. Zr, Cu, and Pb were also present in considerable concentrations in the basic extracts, possibly associated with biogenic opal.

The acid-soluble silica is probably an oligomeric, non-opaline, more hydrated form, and its concentration in roots and shoots of wiregrass was very low. Elements extracted by the mild acid solution were mostly contained in ashes. Most of these elements were metals and some of them are generally associated to toxicity problems to plants (Al and Mn). Elements extracted by the HCl+H_2O_2 solution were probably held by resistant organic compounds not completely ashed.

Table 1. Chemical composition of different extracts of roots and shoots of wiregrass (*Aristida stricta*) plants (Costa, 2004).

Plant part	**Element**									
	Mg	**Al**	**Si**	**P**	**Ca**	**Ti**	**V**	**Cr**	**Mn**	**Fe**
	x 10^2 µg dm^{-3}									
Extractant1										
Root	31256	11771	9954	70320	33180	272,24	99,06	35,62	2011,6	7492
Shoot	69352	15055	23004	117980	176140	347,68	88,42	53,72	6666	7008
Extractant2										
Root	3016,2	2364,6	11602	3960	3468	308,54	721,14	60,94	713,6	14408
Shoot	28190	7789,8	40124	33080	57600	66,4	760,92	90,88	11518	21600
Extractant3										
Root	367,5	2097,9	1330560	687,7	546	1153,7	81,4	75,4	21,9	80,3
Shoot	159,9	3645,3	5090400	4925,8	3231	69,8	33,1	75,6	394,9	229,8

Extractant 1: HCl 0.5N ; Extractant 2: HCl 6N + H_2O_2 30% ; Extractant 3: NaOH 2N.

Table 1 (*cont.*). Chemical composition of different extracts of roots and shoots of wiregrass (*Aristida stricta*) plants (Costa, 2004).

Plant part	Element									
	Ni	Cu	Zn	Ge	As	Sr	Zr	Cd	Ba	Pb
	x 10^2 µg dm^{-3}									
Extractant1										
Root	207,02	400	1419,2	9,93	4,74	899,62	2,04	6,74	825,7	123,18
Shoot	164,1	223,4	1453,06	19,7	37,45	3510,8	1,06	6,55	1323,86	31,47
Extractant2										
Root	115,03	95,14	386,62	2,13	198,28	28,59	5,26	0,44	45,78	18,62
Shoot	174,98	177,18	1219,6	11,49	208,42	1110	3,91	3,34	541,94	36,41
Extractant3										
Root	19,5	335,2	220,8	3,31	11,94	32,3	13,32	1,02	47,34	44,41
Shoot	38,81	443	1229,5	13,42	0,17	174,67	9,41	4,49	160,37	83,03

Extractant 1: HCl 0.5N ; Extractant 2: HCl 6N + H_2O_2 30% ; Extractant 3: NaOH 2N.

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Lawrence E. Datnoff, PhD
SILICON EFFECTS ON COMPONENTS OF HOST RESISTANCE: AN OVERVIEW AND IMPLICATIONS FOR INTEGRATED DISEASE MANAGEMENT

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Abstract

Rate-reducing resistance to plant diseases is affected by various components that limit conidial production or secondary inoculum by a plant pathogen. Reductions in the rate of progress of an epidemic in plants with partial resistance to various pathogens have been associated with a lengthened latent period (period between inoculation and sporulation), reduced infection efficiency (the number of sporulating lesions per unit of inoculum), reduced lesion size (length or diameter), retarded rate of lesion expansion, shortened period of sporulation and reduced number of conidia per lesion. In a number of plant-pathosystems, silicon has been shown to slow disease progress by affecting some important components of resistance. As a consequence, silicon can dramatically reduce the epidemic rate (r). There appears to be a strong correlation between the resistance of some plant species against fungal infections and the concentration of accumulated Si in the tissue of those plants. Understanding the role silicon plays in affecting components of host resistance will help in deploying integrated disease management practices that include both fungicide applications and genotypes with varying levels of plant resistance.

Introduction

Although silicon (Si) is not universally recognized as an essential plant nutrient, many plants accumulate Si from 0.1 to 10% of dry matter (Epstein, 1999). Wetland grasses accumulate high levels of Si (more than the accumulated amounts of some macronutrients), upland grasses are intermediate, and numerous other plant species accumulate small amounts of Si. Silicon is beneficial for the growth, development, and yield of some plant species such as rice and sugarcane. It is now recognized that the Si content of rice and other crops is an important contributing factor for resistance to several plant diseases (Datnoff & Rodrigues, 2005; Epstein, 1999). Some examples of plant-pathosystems that are affected by Si are listed in Table 1.

Increased resistance through Si treatment has been associated with the density of silicified buliform, long, and short cells in the leaf epidermis of rice, a model plant used in Si research. Based on this density, silicon is believed to act as a physical barrier, a passive form of resistance, to impede penetration by *Magnaporthe grisea*, the causal agent of rice blast (Datnoff & Rodrigues, 2005). In addition, there are a number of strong correlations between increasing rates of silicon in soil and decreasing plant disease levels in rice and other graminous plants (Datnoff *et al*., 1991; 2005). The higher the level of % dry matter Si in plant tissue the greater the overall reduction in severity of disease. Rodrigues *et al.* (2003a), in an attempt to gain further insight into the role of Si in rice blast resistance, investigated the ultrastructural outcome of the rice-*M. grisea* interaction upon Si application. The authors provided the first cytological evidence that Si-mediated resistance to *M. grisea* in rice was the result of a massive production of phenolic-like compounds that interfered with the development of *M. grisea*. This research suggested that silicon is playing an active role in plant disease resistance because of the production of defensive compounds against the pathogen. In a further study, Rodrigues *et al.* (2004) demonstrated that an alteration in the development of *M. grisea* in leaf tissues of rice plants amended with Si was associated with an enhanced production of phytoalexins. Belanger and his colleagues (2003) demonstrated that *Blumeria graminis* f. sp. *tritici* is capable of penetrating wheat plants supplied with Si, but that its subsequent development is different. Since phenolics accumulate at the fungal infection site, this suggests that a more active form of resistance than merely the formation of a physical barrier might also be playing a role (Dann and Muir, 2002; Bélanger *et al.*, 2003). Samuels *et al.* (1991)

suggested that soluble Si was essential for the beneficial effects against powdery mildew on cucumber, since high levels of accumulated insoluble, polymerized Si in the leaves were not enough to sustain the beneficial effect against powdery mildew when soluble Si was removed from the nutrient solution.

Table 1. Examples of some diseases reduced by silicon.

Crop	**Disease**	**Reference(s)**
rice	sheath blight	Rodrigues *et al.* (2001)
	neck blast	Datnoff *et al.* (1991)
	leaf blast	Seebold *et al*. (2001)
	brown spot	Datnoff *et al*, (1991)
	leaf scald	Seebold *et al*. (2000)
	stem rot	Seebold *et al*. (2000)
cucumber	powdery mildew	Menzies *et al*. (1991)
barley	powdery mildew	Jiang *et al.* (1989)
wheat	powdery mildew	Menzies *et al*. (2002)
sugarcane	sugarcane ring spot	Matichenchov & Calvert (2002)
cowpea	rust	Heath & Stumpf (1986)
bermudagrass	leaf spot	Datnoff *et al*. (1995)
St. Augustinegrass	gray leaf spot	Brecht *et al*. (2004)

Whether the disease defensive mechanism of silicon is active, passive, or both, in several studies (Menzies *et al.*, 1991; Seebold *et al.*, 2001) Si slowed the epidemic rate (*r*), the amount of increase of disease per unit or time in a plant population. However, only recently has more attention been given to the effect of Si on individual components of host resistance. Host resistance is defined as the ability of the host to hinder the growth and/or the development of the pathogen (Parlevliet, 1979). Two major types of resistance are known: vertical and horizontal resistance. Host plants that express vertical resistance towards a particular pathogen possess specific genes that are active against specific pathogenic races only, and are controlled by single genes or major genes. Horizontal resistance also known as partial resistance or rate-reducing resistance is under polygenic control and results in the host having a reduced susceptibility to all races of the pathogen.

Disease severity is often used to assess how much disease is caused by a certain pathogen on a host. To be able to quantify, predict, and study disease progress, it is useful to identify and separate several components of disease. This allows the researcher to investigate which component has a greater effect on disease development than others and can point to integrated disease management strategies. When the individual components and their relative importance are identified, computer models can be developed to predict disease progress in the field. Components of resistance which influence the epidemic rate include infection frequency, latent period, colony and lesion size, conidial production (Parlevliet, 1979) as well as the rate of lesion expansion (Berger *et al.*, 1997). The purpose of this paper is to review some of the research results that specifically address how Si may affect individual components of resistance and its importance in selecting and integrating strategies for disease management.

Latent period

Although the latent period (period between appearance of symptoms and when lesions began to sporulate) can vary greatly depending on the stage of development of the host, a lengthened latent period at a specific host growth stage is an indication of the decreased growth rate of the pathogen on the host (Parlevliet, 1979). The latent period is a very important component of disease resistance. A small increase in the latent period results in a dramatic decrease in the epidemic rate (*r*) as reported by Zadoks (1971). Therefore, a decrease in the final disease severity is also observed. Some researchers measure the incubation period (period between inoculation and appearance of symptoms) rather than the latent period, since both periods presumably vary in similar ways, although there are exceptions to this generalization (Parlevliet, 1979).

Seebold *et al.* (2001) found that although the latent period of the rice blast pathogen did not differ between some rice cultivars with different levels of resistance, the incubation period lengthened with increasing rates of Si. The incubation period of *Rhizoctonia solani* on rice was found to be shorter at 45 days (four leaf stage) and at 65 days (eight leaf stage), but was not clearly affected by Si amendment (Rodrigues *et al*., 2003b) .

From the examples cited above, the effect of Si on the latent and incubation period of fungal plant pathogens may differ for different plant-pathosystems and more research is needed in this area.

Infection efficiency and frequency of infection

Infection efficiency and frequency is defined as the number of sporulating lesions per unit area of the host. A lower infection frequency accumulates over host developmental stages resulting in an overall lower level of disease severity (Parlevliet, 1979).

In an experiment in which the Si accumulation was observed in the contact regions between the epidermal cells of barley and the germ tubes of *Erysiphe graminis*, higher levels of Si accumulation caused the failure of the pathogen to penetrate the epidermal cells (Carver *et al.*, 1987). This could be equated to a decrease in infection efficiency. Volk (1958) showed that increased Si content of rice leaves corresponded to a decrease in the number of sporulating blast lesions per leaf. Seebold and his colleagues (2001) found that the relative infection efficiency, expressed as the number of rice blast sporulating lesions per square millimeter of leaf area, decreased significantly in a linear manner with increasing rates of Si (Figure 1B). An application of 10 tons of calcium silicate ha^{-1} decreased the number of sporulating lesions by 71%. In contrast to the effect of Si on several components of rice resistance to blast (Seebold *et al.*, 2001), Brecht (2002) measured incubation period, latent period, lesion number, lesion area, daily rate of lesion expansion and number of conidia per lesion of gray spot (*M. grisea*) on St. Augustinegrass and, found that only the number of lesions was significantly affected by Si amendment.

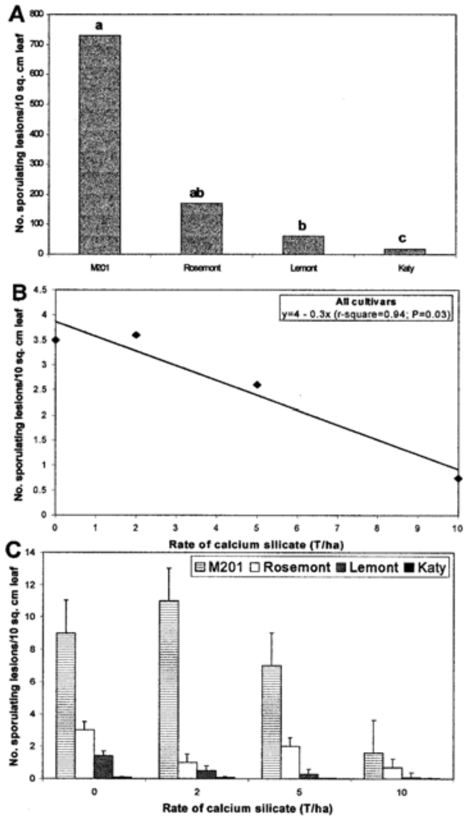

Figure 1. Effects of calcium silicate on the number of sporulating lesions of blast (relative infection efficiency) for rice cvs. M201, Rosemont, Lemont, and Katy. **A,** Mean number of sporulating lesions per square millimeter of leaf for each cultivar averaged across the rate of calcium silicate. Bars with the same letter in **A** do not differ significantly at $P = 0.05$ as determined by Fisher's protected LSD test performed on log-transformed values. **B,** The relationship between the number of sporulating lesions per square millimeter of leaf and rate of calcium silicate, averaged across means for all cultivars. **C,** The number of sporulating lesions per square millimeter of leaf for each cultivar and rate of calcium silicate. Bars represent standard errors of means.

Dann and Muir (2002) showed a decrease in the numbers of lesions caused by *Mycosphaerella pinodes* on pea leaves 7 days after inoculation of plants grown for 5 weeks in a silicon-amended medium in comparison to non-amended medium. This decrease was associated with an increase in concentration of Si in the plants.

The number of colonies of powdery mildew (*Uncinula necator*) per grape leaf was assessed by Bowen *et al.* (1992). They found that 17 mM soluble silicon sprays decreased the number of colonies produced by the fungus. They also showed that hyphae did not develop in areas with thick Si deposits. Potassium silicate was applied to roses via irrigation water and decreased the number of colonies per leaf caused by *Diplocarpon rosae*, the causal agent of black spot. However, at the end of this study, all treatments had high levels of fungal infection (Gillman *et al.*, 2003).

Menzies *et al.* (1991) assessed the number of colonies of *Podosphaera fuliginea* that formed on cucumber leaves in response to increasing amounts of Si that was added to the nutrient solution. They found that increasing Si from 0.5 to 2.3 mM resulted in a 43% reduction in the number of colonies per leaf 10 days after inoculation if the second fully expanded leaf on the plants were inoculated. An 85% reduction was found if the fourth leaf was inoculated. In another experiment in which the fourth fully mature leaf was inoculated, the number of colonies per leaf was reduced by 94% at 14 days after inoculation when the plants were grown in medium containing 4.1 mM Si.

Clearly, there are many examples of Si negatively affecting the infection efficiency of pathogens on their hosts. However, since there is some evidence that Si may also affect the leaf size of the host (Menzies *et al.*, 1991), it is important to determine the number of lesions per leaf area instead of simply the number of lesions per leaf.

Colony and lesion size

Colony and lesion size affect the growth rate of the pathogen in the host and therefore spore production is also affected (Parlevliet, 1979). The size of colonies and lesions determines the effective sporulating area of the pathogen and therefore its ability to reproduce.

In addition to the number of colonies per leaf area, Menzies *et al.* (1991) also assessed the sizes of powdery mildew colonies (*P. fuliginea*) on cucumber in response to increasing amounts of Si added to the nutrient solution. In one of their experiments, Menzies and collaborators found that the individual colony size was reduced by 72% on the fourth fully expanded leaf and 84% on the fifth. The total colony size per leaf was reduced by 55% for leaf 2 at 2.3 mM Si, 94% for leaf 4, and by 99% for leaves 4 and 5 at 4.1 mM Si. Seebold *et al.* (2001) reported that lesion length of rice blast caused by *M. grisea,* was reduced by about 40%, and that the lesion area per leaf for all cultivars tested, except for the most resistant one, was reduced by about 80%, in response to soil amendment equivalent to 10 ton of calcium silicate ha^{-1}.

Silicon seems to affect the colony and lesion size in some studied plant-pathosystems, but many more pathosystems need to be investigated. As mentioned for infection efficiency/frequency, the potential effect of Si on the size of the leaves also needs to be considered.

Conidial production

The ability of the fungus to sporulate effectively is of great importance for polycyclic diseases. Once the pathogen establishes a lasting parasitic relationship with its host, the spread of the disease in the field will reach its maximum. Although Rodgers-Gray & Shaw (2004) found an overall increase in winter wheat resistance to some foliar diseases when plants were fertilized with Si, resistance was associated with a decrease in conidial production and could not be solely explained by Si. Therefore, a further investigation on the effect of Si on other components of resistance of wheat to foliar pathogens is warranted.

In the experiments done by Menzies *et al.* (1991), spore production was not measured, but the germination of conidia of *P. fuliginea* decreased significantly when cucumber plants were grown in increasing concentrations of Si. Viable spore production is a measure of the parasitic fitness of the pathogen on the host. Seebold *et al.* (2001) showed that four different cultivars with various levels of resistance against blast had significantly different numbers of spores per square millimeter of lesion and that these numbers decreased with increased Si levels (Figure 1A).

Not enough research has been done on different pathosystems to come to some general conclusions about how Si may affect conidial production; however, it is obvious that this component of resistance should be measured carefully during the assessments.

Rate of lesion expansion

In many pathosystems, the lesions caused by pathogens on the host continue to expand even after the incubation period has been completed. Berger *et al.* (1997) used a model simulator to assess the effect of the radial rate of lesion expansion to validate a model in two natural epidemics. The authors concluded that lesion expansion is a major component of epidemics. Seebold *et al.* (2001) found that the rate of lesion expansion decreased by 49% as the rate of calcium silicate application increased from 0 to 10 ton ha^{-1}. Rodrigues *et al.* (2001), measured the vertical lesion extension of sheath blight (*Rhizoctonia solani*) on rice cultivars Jasmine and LSRBR-5 (partially resistant), Drew and Kaybonnet (moderately susceptible) and Lemont and Labelle (susceptible) fertilized or not with five Si rates. The data was used to calculate the area under the vertical lesion extension progress curve. This variable decreased significantly on cultivars high in partial resistance, moderately susceptible, and susceptible by 62, 28, and 35%, respectively, amended with Si as compared to those cultivars grown without Si. Rodrigues and collaborators (2003b) also investigated the effect on Si on sheath blight development in Brazil. The predominant commercial rice cultivars BR-Irga 409, Metica-1, EPAGRI-109, Rio Formoso, Javaé, and CICA-8 were grown in pots containing soil from a Si-deficient soil amended with 0, 0.48, 0.96, 1.44, and 1.92 g Si pot^{-1}. The area under the relative lesion extension progress curve decreased by 40% over all cultivars, as the rate of Si increased in the soil. Other than these two studies mentioned above, no reports were found in the literature that measured the rate of lesion expansion for a pathosystem in response to Si amendment. This may be because this resistance component is only recently recognized as a major contributor to host resistance and, generally, only a few scientists are studying the effect of Si on this component of resistance (Berger *et al*., 1997).

Conclusion

Whether the disease defensive mechanism of silicon is active, passive or both, there appears to be a strong correlation between the resistance of some plant species against fungal infection and the concentration of accumulated Si in the tissue of those plants. This element has the potential to affect the level of partial (horizontal) resistance of certain plant species that are capable of accumulating this element in their tissues such as rice by reducing the epidemic rate (*r*). In several plant-pathosystems, different components of resistance were assessed and found to be influenced by Si. However, many more studies are needed before general conclusions can be drawn about the effect Si has on these individual components of host plant resistance. In future studies, research should focus on the components of resistance that have the greatest effect on the final disease severity such as incubation period, lesion expansion over time and the number of sporulating lesions per area of leaf tissue. This information will be vital to select and to integrate other disease management strategies such as rate and scheduling of fungicide applications and choosing commercial plant genotypes with various levels of plant disease resistance.

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SILICON-MEDIATED RESISTANCE IN MONOCOTS: THE RICE-MAGNAPORTHE GRISEA MODEL

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The element silicon (Si) is not considered by many plant scientists as an essential nutrient for plant function. Nevertheless, Si is absorbed from soil in large amounts that are several fold higher than those of other essential macronutrients in certain plant species. Its beneficial effects have been reported in various situations, especially under biotic and abiotic stress conditions. The most significant effect of Si to plants, besides improving their fitness in nature and increasing agricultural productivity, is the restriction of parasitism.

In the rice-*Magnaporthe grisea* pathosystem, increased resistance by Si has been associated with the density of silicified buliform, long, and short cells in the leaf epidermis that act as a physical barrier to impede penetration by *M. grisea*. This physical barrier hypothesis is strengthened by the findings of an existing layer of silica of approximately 2.5 µm thick beneath the cuticle of rice leaves and sheaths. This cuticle-Si double layer may restrict *M. grisea* penetration and, consequently, decrease the number of blast lesions that develop on leaf blades. It is known that Si might form complexes with organic compounds in the cell walls of epidermal cells, therefore increasing their resistance to degradation by enzymes released by *M. grisea*. Indeed, Si can be associated with lignin-carbohydrate complexes in the cell wall of rice epidermal cells. It has been reported that the epidermal cell wall thickness was not significantly affected by Si but the thickness ratios of silica layers to epidermal cell walls were much higher in the resistant cultivar than in the susceptible cultivar. Although the fortification of epidermal cell walls was considered the main cause and reason for the reduced number of leaf blast lesions, no evidence was given to indicate that the narrow penetration peg of *M. grisea* did not overcome the physical impedance offered by the fortified cell wall. The puncture resistance of rice epidermal cells to a needle tip from beneath a torsion balance was studied using leaves collected from rice plants grown under different Si rates. This revealed that the puncture resistance was not explained solely by silicification of the leaf epidermis but was attributed mainly to the nature of the protoplasm of epidermal cells. In another study, rice cultivars resistant to blast were found to have lower lesion numbers and more silicified epidermal cells than susceptible cultivars. The density of silicified cells in rice leaf epidermis is not always proportional to the level of resistance of some rice cultivars to blast. Altogether, these observations suggested that resistance of Si-treated plants to *M. grisea* is much more complex than a physical resistance against penetration due to the silicified cells or to the cuticle-Si double layer.

Considering that the mechanism(s) underlying the increased resistance of rice to blast disease is still poorly understood and inconclusive, studies were initiated to determine if any cytological, biochemical and or molecular changes were associated with fungal restriction in rice tissues upon Si treatment.

An ultrastructural study demonstrated the first cytological evidence that Si-mediated resistance to *M. grisea* in rice was associated with specific leaf cell reaction that interfered with the development of *M. grisea*. Ultrastructural observations of samples collected from plants nonamended with Si revealed that some host cells were devoid of organelles and that some host cell walls were no longer discernible in the massively colonized mesophyll and vascular bundle. A light deposition of osmiophilic material with a granular texture, occasionally interacting with fungal walls, was seen in some epidermal cells. In plants amended with Si, empty fungal hyphae were evenly surrounded by a dense layer of granular osmiophilic material partially occluding the epidermal cells, the vascular bundle, and the mesophyll cells. The possibility that this amorphous material constitutes phenolic compounds appears realistic, considering not only its staining with toluidine blue and its texture and osmiophilic properties, but also the occurrence of marked fungal hyphae alterations. Cytochemical labeling of chitin revealed no difference in the pattern of chitin localization over fungal cell walls of either samples from plants amended or not with Si at 96 h after inoculation with *M. grisea* indicating limited production of chitinases as one mechanism of rice defense response to blast. On the other hand, the occurrence of empty fungal hyphae, surrounded or trapped in amorphous material, in samples from plants amended with Si, suggested that phenolic-like compounds or phytoalexin(s) played a crucial role in rice defense response against infection by *M. grisea*. Therefore, Si could be acting as a modulator to positively amplify rice defense response(s), namely by influencing the synthesis of antifungal compounds after the penetration peg of *M. grisea* enters the epidermal cell.

In a further study, the hypothesis that an alteration in the development of *M. grisea* in leaf tissues of rice plants amended with Si could be associated with an enhanced production of phytoalexin(s) was tested. Two phytoalexins, momilactone A and B, were found present in minute or small quantities in non-inoculated plants amended or not with Si. By contrast, both phytoalexins showed a two to three-fold increase in leaf extract from plants amended with Si and inoculated with *M. grisea* as compared to the lower levels observed in leaf extract from inoculated plants non-amended with Si. Rice plants not amended with Si and inoculated with *M. grisea*, in spite of releasing antifungal compounds including momilactones, were obviously not protected efficiently against fungal colonization. By contrast, rice plants amended with Si and inoculated with *M. grisea* released higher amounts of momilactones probably earlier in the infection process resulting in a lower rice blast severity level.

Cytological and molecular aspects of an incompatible and a compatible rice-*M. grisea* interaction with Si soil amendment were also investigated. Katy, a completely resistant cultivar, responded to an avirulent race of *M. grisea* through the development of a hypersensitive reaction (intense granulation of the cytoplasm and bright autofluorescence of epidermal cells), strong induction of PR-1 and peroxidase transcripts and accumulation of high levels of phenolics and lignin which dramatically reduced hyphal growth within the invaded epidermal cell. These defense responses were similar in both Si- and Si+ treatments. On the other hand, in Si+ plants of the completely susceptible cultivar M201, a differential accumulation of glucanase, peroxidase and PR-1 transcripts and the production of phenolics and lignin restricted hyphal growth in the epidermal cells. Conversely, in Si- plants, *M. grisea* successfully grew and formed an extensive branched mycelium in the first-invaded epidermal cell and colonized many neighboring cells despite strong induction of chitinases, glucanase, chalcone synthase, phenylalanine ammonia-lyase, peroxidase and PR-1 transcripts and high levels of phenolics and lignin. Autofluorescence of epidermal cells became quenched as the lesions expanded when compared to Si+ plants.

In conclusion, the results of these studies strongly suggest that Si plays an active role in rice blast resistance rather than just the formation of a physical barrier to impede penetration by *M. grisea*.

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THE ROLE OF SILICON IN PLANT-PATHOGEN INTERACTIONS: TOWARD A UNIVERSAL MODEL

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Abstract

Silicon (Si) is a bioactive element associated with beneficial effects on mechanical and physiological properties of plants. Silicon alleviates abiotic and biotic stresses, and increases the resistance of plants to pathogenic fungi. Several studies have suggested that Si activates plant defense mechanisms, yet the exact nature of the interaction between the element and biochemical pathways leading to resistance remains unclear. Silicon possesses unique biochemical properties that may explain its bioactivity as a regulator of plant defense mechanisms. It can act as a modulator influencing the timing and extent of plant defense responses in a manner reminiscent of the role of secondary messengers in induced systemic resistance; it can also bind to hydroxyl groups of proteins strategically involved in signal transduction; or it can interfere with cationic co-factors of enzymes influencing pathogenesis-related events. Silicon may therefore interact with several key components of plant stress signaling systems leading to induced resistance.

Introduction

Silicon (Si) has long been known to reduce the incidence of fungal diseases in a number of pathosystems. From the onset, it was proposed that deposition of amorphous silica in the leaf apoplast prevented penetration by pathogenic fungi. Although this mechanism may partly explain the prophylactic effects of Si, monomeric Si is also considered to be biologically active and to trigger a faster and more extensive deployment of plant natural defenses. This hypothesis was first proposed in the dicot system cucumber-powdery mildew [1] but is now believed to be generalized to both monocots and dicots. Consequently, it seems plausible that Si acts on general mechanisms common to most plant species such as those leading to the expression of plant stress genes. In this review, different aspects of Si biochemistry are presented in the context of its possible interaction with plant defense activation. The objective is to bring forth potential alternatives to explore and explain the elusive role of Si in protecting plants against fungal diseases.

Silicon in biological systems

Silicon is the second most abundant element in the lithosphere (27.70 %) and it is as important as phosphorus and magnesium (0.03 %) in the biota [2]. Hydrated silica represents the second most abundant biogenic mineral after carbonate minerals [3]. Silicon is accumulated and metabolized by some prokaryotes [4], and Si compounds can stimulate the growth of a range of fungi [5]. It is well known that Si is essential for diatoms [6]. In mammals, Si is considered an essential trace element, required in bone, cartilage and connective tissue formation, enzymatic activities and other metabolic processes [7-9]. Silicon was suggested to act as a phosphoprotein effector in bone [10]. In mammals, Si is also reported to positively influence the immune system and to be required for lymphocyte proliferation [11]. The aqueous chemistry of Si is dominated by silicic acid at biological pH ranges [12]. Monosilicic acid can form stable complexes with organic hydroxy-containing molecules [13]. Biosilica also has been identified associated with various biomolecules including proteins and carbohydrates [14]. Hypervalent forms of silicon have been found to complex with a range of sugars and sugar derivatives [15,16]. Recently, Kinrade *et al.* [17] reported the first evidence of an organosilicon compound formed *in vivo* in the diatom *Navicula pelliculosa*. In diatoms, Si was suggested to affect phosphorylation of specific proteins required for the synthesis of DNA and specific mRNA [18, 19].

Silicon in higher plants

The potential benefits of Si nutrition in plants have been extensively reviewed [20-22]. These include the enhancement of growth and yield, improvement of mechanical properties (stature, soil penetration by roots, exposure of leaves to light, resistance to lodging), reduction of transpiration and resistance to drought stress, resistance to salinity, resistance to metal toxicities, effects on enzyme activities and increased resistance to pathogens. While some of these properties are likely to derive from the deposition of amorphous silica ($SiO_2.nH_2O$), others should be considered as consequent to the bioactivity of monosilicic acid. Silicon is ubiquitous in monocotyledons and dicotyledons, in amounts equivalent or higher to those of phosphorus and magnesium [23]. Jones and Handreck [24] have divided plants into accumulators (10-15 % dry weight) including wetland grasses, intermediate (1-3 % dry weight) including dryland grasses, and non-accumulators (<1% dry weight) including dicots. Monosilicic acid is absorbed from the soil solution and it follows the transpiration stream. Where silicic acid is concentrated over a critical level (~ 100 ppm at biological pH), it polymerizes as phytoliths ($SiO_2.nH_2O$), which constitutes the bulk of a plant's Si content [24]. Silicon transporters have been characterized in a diatom [25]. The Si uptake system and Si transporters have also been characterized in rice [26]. Neumann and De Figueiredo [27], stating that Si is found in the plant cytoplasm and subcellular structures, proposed a mechanism of Si uptake, aside from that of membrane transporters, in which an endocytotic process allows Si transport inside the cell. In plants, Si tends to polymerize in cell walls, cell lumen, intercellular spaces and in the subcuticular layer [28]. This process of opal formation is not occurring at random. Plant species differ with respect to the size and shape of phytoliths they accumulate. The nucleation and growth of these structures is under the control of specific proteins [29, 30]. Other evidence supports the importance of organosilicon compounds in plants. In a selection of plants containing 0.74 % to 3.59 % Si, more than 50 % of total Si was contained in the organic fraction versus polymerized and soluble forms. The organic Si fraction was found to bind proteins, phenolic compounds (lignin, condensed polyphenols), lipids and polysaccharides (cellulose, pectic substances) [31].

Silicon and disease resistance in plants

i) Mechanical role

The initial theory concerning the mode of action of Si in plant's prophylaxis involved a mechanical barrier against penetration. However, as early as 1965, this theory was put into doubt by Okuda and Takahashi [32], citing Yoshi’s results [33] of non-correlation between Si treatment and leaf toughness as measured by a needle-puncture method: "From this result, it seemed that Si protected the rice plant against blast disease, but the increase in mechanical toughness of the plant tissue resulting from absorbed Si is not sufficient to explain the mechanism of protection". Nevertheless, this theory was maintained over the years. Carver *et al.* [34], upon the observation of Si accumulation in papillae consistent with findings from Kunoh and Ishizaki [35], stated that polymerized Si at attempted sites of penetration may provide an additional mean of resistance against penetration. Recently, Kim *et al.* [36] proposed the reinforcement of cell walls in rice as a mechanism for enhanced resistance provided by Si treatment. Yet, in this work, no evidence linked cell wall reinforcement with penetration failure by the fungus. It should be noted that the logical link proposed between Si deposition and pathogen resistance stems from the fact that Si has been reported in several pathosystems to accumulate at infection sites [37], a process also noted in *Arabidopsis* infected by powdery mildew (Figure 1). This probably derives from a higher transpiration rate at sites where the cuticle is damaged rather than active transport in a defensive way. As a matter of fact, Chérif *et al.* [38] observed the accumulation of Si in needle-punctured leaf holes and showed the absence of such deposits when plants were grown under saturated humidity. Even though Si is effectively deposited at preferential sites of penetration, and is also continuously deposited at higher rates after penetration has occurred, the hypothesis of cell wall reinforcement by Si to explain enhanced resistance of plants against pathogenic fungi has been strongly contested in recent years.

ii) Induced resistance

In the early 90's, the first evidence disputing the role of Si as a mechanical barrier was reported in dicotyledonous models. Samuels *et al.* [39], using the cucumber-powdery mildew pathosystem, showed that within a short period of time after Si feeding was stopped, all prophylactic effects were lost. Thus, the interruption of Si feeding led to a loss of resistance even though opal had irreversibly accumulated and, according to the mechanical barrier hypothesis, should have slowed the pathogen development. Chérif et al. [40] contributed additional data contradicting the passive role of Si against fungi colonization by demonstrating that although Si failed to accumulate at infection sites under conditions of saturated humidity, Si-treated cucumber resisted more efficiently against *Pythium*. Chérif *et al.* [39, 41] went on to propose that soluble Si activated defense mechanisms in cucumber against *Pythium* by showing enhanced activity of chitinases, peroxidases and polyphenoloxydases, and increased accumulation of phenolic compounds. In cucumber infected with powdery mildew, Fawe *et al.* [42] demonstrated the increased production of flavonoid phytoalexins in Si+ treated plants. Largely on the basis of experiments with cucumber, Fawe *et al.* [1] proposed that Si played an active role in reinforcing plant disease resistance by stimulating natural defense reactions.

While this hypothesis became a paradigm in dicotyledons, its extension to monocotyledons, known to accumulate higher amounts of Si, remained invalidated. To address this question, different research groups carried out experiments with Si and monocot-pathogen interactions. In the wheat - *Blumeria graminis* f.sp. *tritici* (Bgt) system, histological and ultrastructural analyses revealed that epidermal cells of Si+ plants reacted to Bgt attack with specific defense reactions including papilla formation, production of callose and release of electron-dense osmiophilic material identified by cytochemical labeling as glycosilated phenolics. These results suggested that Si mediated active localized cell defenses in wheat in the same way as observed in cucumber [43]. Furthermore, Datnoff's group, working with rice blast in Florida, reported cytological evidence that Si-mediated resistance to *Magnaporthe grisea* in rice correlated with specific leaf cell reactions that interfered with the development of the fungus [44]. The same group showed that in rice infected with *M. grisea*, Si was associated with higher accumulation of antimicrobial compounds at infection sites, including diterpenoid phytoalexins [45]. These recent results with Si and monocots bring not only further support to the theory that Si plays an active role in protecting plants against pathogens, but indicate that this role is not specific to dicots but rather generalized to the plant kingdom. However, the exact nature of the interaction of soluble Si with the plant's biochemical pathways leading to disease resistance remains unknown. In order to facilitate and harmonize the approaches to understand the role of Si *in planta*, Ghanmi et al. [46] proposed the use of the *Arabidopsis*-powdery mildew interaction, by showing that this model plant reacted to powdery mildew as other dicots and monocots did under Si treatment (Figure 2).

<u>*How does Si activate plant defense reactions*</u>

i) Silicon mediated resistance

On the basis of their observations with cucumber, Fawe *et al.* [1] suggested a model to explain how Si would play a role in induced resistance. According to their model, Si bioactivity was compared to that of known activators/secondary messengers of systemic acquired resistance (SAR) whereby it would act as a modulator influencing the timing and extent of plant defense responses. Like secondary messengers, the effects of Si on secondary metabolism are significant only after elicitation; both Si and known activators are characterized by a saturable effect. A difference between known SAR activators and Si is the loss of activity when Si feeding is interrupted, because polymerization of Si leads to its inactivation as an inducer of resistance. These points of comparison prompted the authors to propose that Si acted as a signal in inducing defense responses.

ii) Modulation of primary signal transduction

Silicic acid may modulate the activity of post-elicitation intracellular signaling systems. Hutcheson [47] has distinguished three classes of active defense mechanisms. The primary response occurs in cells infected by the pathogen, the secondary response is induced by elicitors and limited to cells adjacent to the initial infection site, and the systemic acquired response is transmitted hormonally to all tissues of the plant. Silicon is perhaps acting in the primary response, and the integration of enhanced signal transduction at the single cell level should result in increased levels of induced systemic resistance. Post-elicitation intracellular signaling leads to the expression of defense genes directing hypersensitive response, structural modifications of cell walls, stress hormones synthesis, antimicrobial compounds synthesis and PR proteins. As mentioned earlier, Si is involved in the processes leading, among other responses, to the accumulation of phytoalexins. The target of plant signaling upon pathogen elicitation is the cell nucleus, which receives information for *de* *novo* protein and antimicrobial compounds synthesis. Gene expression control through the phosphorylation of transcription factors and their inhibitors is a major plant stress response. Signals leading to the expression of plant defense responses are transmitted to the nucleus through the activation of specific kinases/phosphatases cascades. This can be generalized to both endogenous [48–53] and exogenous [54] signaling events. Responses to biotic stresses are largely dependent on mitogen activated protein (MAP) kinases [55-58].

Protein kinases transmit information to the nucleus by the phosphorylation of hydroxyl group on amino acid residues. Silicon is known to bind to hydroxyl groups and may thus affect protein activity or conformation. The mode of action of Si in signal transduction may also derive from interactions with phosphorus. As early as 1906, Hall and Morrison [59] reported interactions between Si and phosphorus in barley. It is now considered that the internal improvement of P utilization and the broadening of P fertilization range provided by Si fertilization [60] derives from interactions with cationic metals such as Mn and Fe [61]. Metals play a structural role for many enzymes. Enzymatic dysfunctions may derive from the excess of essential metal species or the presence of toxic metal species [62]. Whether Si improves plant defenses indirectly by sequestering cationic metals, or directly by modulating protein activity involved in signal transduction remains to be investigated.

iii) Silicon and induced systemic resistance

Silicon-fed plants will naturally translocate silicic acid throughout all tissues. Upon pathogen attack, the infected tissue will synthesize, among other defense reactions, antimicrobial compounds together with systemic stress signals such as salicylic acid, jasmonic acid and ethylene. In a given cell, if Si indeed modulates the signaling events leading to the synthesis of antimicrobial compounds, it should also modulate the generation of systemic signals given that both processes depend on primary elicitation. Accordingly, silicic acid, without being itself a secondary messenger, could play a positive role in both local and systemic resistance.

Conclusion

Silicon is a bioactive element in various biological systems, but its mode of action in plants remains a matter of speculation. It has been shown to enhance the expression of natural defense mechanisms and the accumulation of phytoalexins in monocots and dicots. Because phytoalexins are highly specific in each plant species, it is more likely that Si acts on mechanisms shared by all plant species, such as those leading to the expression of plant stress genes (signaling cascades). Silicon, in the form of silicic acid, would act locally by inducing defense reactions in elicited cells and would also contribute to systemic resistance by enhancing the production of stress hormones. However, the exact mechanism by which Si modulates plant signaling remains unclear. From the gathered evidence, Si could act as a potentiator of plant defense responses or as an activator of strategic signaling proteins. Silicon may therefore interact with several key components of plant stress signaling systems ultimately leading to induced resistance against pathogenic fungi.

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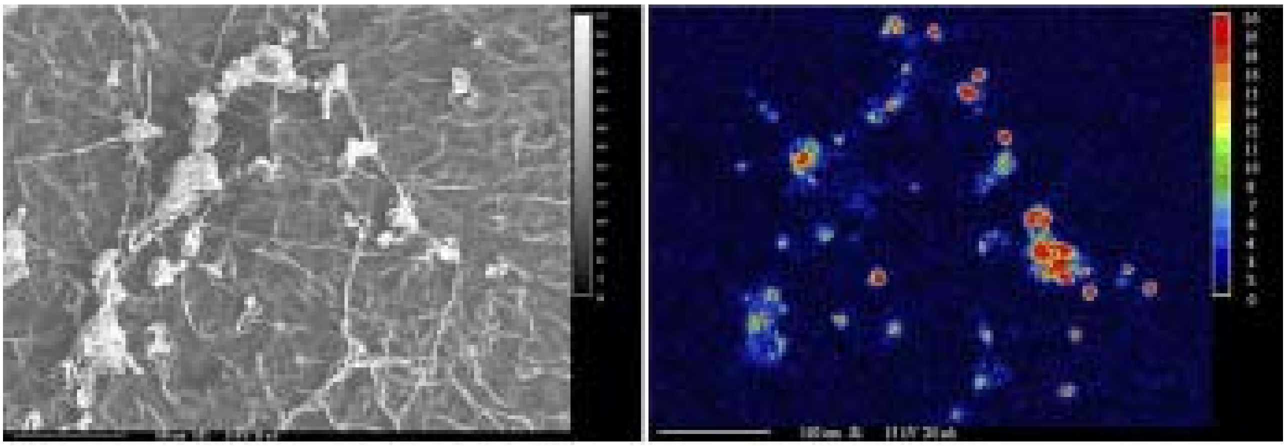

Figure 1. Scanning electron (left) and X-ray (right) microanalysis showing that the accumulation of Si is coincident with *E. cichoracearum* presence on Si-treated *A. thaliana* leaves. The concentration of Si is indicated by color (see inset), where red represents the highest concentration of Si and black indicates no Si.

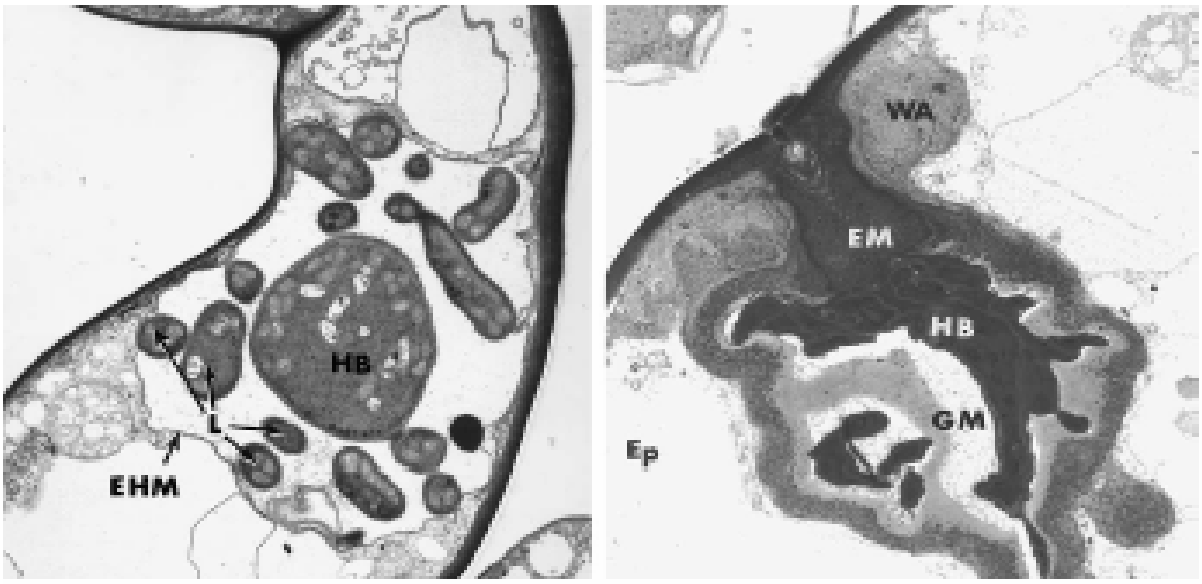

Figure 2.Transmission electron micrographs of ultra-thin sections of *A. thaliana* leaves infected by *E. cichoracearum.* Silicon treatment (right) led to more efficient defense compared to control plants (left). EHM, extrahaustorial membrane, HB, haustorial body, Ep, epidermis, GM, granular material, WA, wall apposition, EM, electron-dense material, L, lobes. Adapted from Ghanmi *et al.* (2004) [46].

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SILICON AND INSECT MANAGEMENT - REVIEW

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Abstract

Silicon (Si) deficiency in crops has been relatively unknown, and the element has been regarded as non-essential for plant growth. However, recent research show that Si is a "functional" plant nutrient, and that silicon application can significantly enhance insect pest resistance in plants, with consequent yield increases. Most reports show that responses to Si application in reducing pest populations and plant damage was more obvious in susceptible than in resistant varieties. Recent evidence suggests that silicon deposition in the plant may reinforce plant insect resistance by providing a mechanical barrier against insect pests, though this passive role of Si is contested in the relation Si-treated plant and resistance to diseases. Silicon is widely considered as activator by stimulating the expression of natural defense reaction through the production of, among other chemicals, phenolic compounds. The application of Si in crops provides a viable component of integrated management of insect pests and diseases because it leaves no insecticide residues in food or the environment, and it can be easily integrated with other pest management practices, including biological control.

Index terms: silicon, insect control, pest resistance, defense reaction, IPM

Article Outline

1. Introduction
2. Silicon application and sugarcane resistance to insect pest
3. Silicon application and wheat resistance to insect pest
4. Silicon application and rice resistance to insect pest
5. Silicon application and maize resistance to insect pest
6. Silicon application and other crops resistance to insect pest
7. Discussion
8. Conclusion and future research
9. Acknowledgements
10. References

1. Introduction

Insect pests are one of the major biological constraints that limit crop production throughout the world (Ukwungwu, 1990). For example, in South Africa sugarcane (*Saccharum offinarum* L.) regularly suffers from stalkborer (*Eldana saccharina* Walker (Lepidoptera: Pyralidae)) damage, costing the industry approximately R60 million during 2003-04 (Meyer and Keeping, 2005). Among all insect control methods, the planting of pest resistant varieties is one of the most effective (Ukwungwu, 1990) because it leaves no insecticide residues in food or the environment, and is constantly effective. However, pest damage may also be reduced through careful management of the nutrient requirements of the crop or amendments with mineral nutrients, such as silicon (Si), that reduce crop susceptibility to pests (Meyer and Keeping, 2005). This is because the development of phytophagous insects often depends on the physiological condition of host plants, and particularly their nutrient and stress status (Sétamou *et al*., 1993).

For many years, Si deficiency in crops went unrecognized, and this element was widely regarded as non-essential for plant growth, although often present in the highest concentration amongst inorganic constituents (Jones and Handreck, 1967). However, there is now a greater consensus amongst scientists in the role of Si as a "functional" plant nutrient (Bhavnagary *et al*., 1988; Epstein, 1999). Silica content in the plant is reported to play an important role in strengthening the cell walls of the plants (Painter, 1951; Table 1) and enhances resistance to both pests and diseases in the field (Qin and Tian, 2004) and in storage (Korunic, 1997). It has been reported that silicon suppresses insect pests such as the stemborer, brown planthopper, green leafhopper, whitebacked planthopper, and non-insect pests such as spider mites (Ma and Takahashi, 2002). The objective of this paper is to review past and present research in application of silicon and insect control in crops as summarized (Table 2).

2. Silicon application and sugarcane resistance to pest damage

One of the earliest reports linking Si nutrient levels with stalkborer damage in cane is credited to Indian research (Rao, 1967). The author found that sugarcane varieties tolerant to the shootborer *Chilo infuscatelus* Snellen showed the highest density of Si per unit area in the leaf sheath.

In Florida, Elawad *et al*. (1982), found that by applying 20 t/ha of TVA slag to a muck soil, there was a significant decrease in leaf freckling in sugarcane. Furthermore, that with improved Si nutrition, there was an increase in the sugarcane resistance to the stem borer *Diatraea saccharalis* F. (Elawad *et al.,* 1985). Subsequent studies have confirmed the positive effect of silicon in increasing the resistance of sugarcane to this stalkborer (Anderson and Sosa, 2001).

In Taiwan, Pan *et al.* (1979) conducted an experiment where different forms of Si including bagasse furnace ash and silica slag were applied. The results showed that the incidence of borer damage in Si-treated sugarcane was less than in untreated control sugarcane.

In South Africa, recent studies have focused on the association between silicon assimilation and host-plant resistance to *Eldana saccharina* (Keeping and Meyer, 2003; Meyer and Keeping, 2005). Greenhouse and field trials have been conducted to compare the efficacy of four silicon sources (Keeping and Meyer, 2003). In the greenhouse, sugarcane varieties were artificially inoculated with *E. saccharina* and treated with three doses (0, 2.5 and 5 t/ha) of calcium silicate. At 5 t/ha calcium silicate, there was a reduction of 30% in borer damage and 20% in borer mass. The most susceptible varieties showed the highest silicon uptake and the greatest response. Of the four carriers tested, stalkborer incidence declined as follows: local Namibian calcium silicate > imported USA calcium silicate > local Slagment > flyash. In the field experiment, similar results were recorded.

3. Silicon application and wheat resistance to pest damage

Miller *et al.* (1960) found that wheat (*Triticum aestivum* L.) stems containing high levels of Si were not injured severely by larvae of Hessian fly, *Phytophaga destructor* (Say). They indicated that several susceptible varieties developed marked resistance when they were grown in a solution containing sodium silicate. Moreover, in a greenhouse experiment, they showed that most of the resistant wheat varieties had dark shapes of Si depositions ranging from round to oblong and a relatively dense and grainy covering of Si over the entire surface of the leaf sheath. More extensive deposition of Si was found as the age of the plant increased. In all susceptible varieties, the Si was deposited in rod-shaped masses arranged in rows with spaces between the rows. Recent reports showed that application of Si to susceptible wheat increased crop resistance and reduced pest infestation, both in the field (Weryszko-Chmielewska and Soczyński, 1994; Basagli *et al*., 2003; Moraes *et al*., 2004, Kordan *et al*., 2005) and in storage (Korunic, 1997).

4. Silicon application and rice resistance to pest damage

Ukwungwu and Odebiyi (1985) recorded a negative correlation between percentages of Si content in different rice (*Oryza sativa* L.) varieties and the percentage of bored stems by the African striped borer *Chilo zacconius* Bleszynski (Lepidoptera: Pyralidae), and the number of living larvae per plant.

Panda *et al*. (1975) reported that the larvae of the yellow rice borer, *Scirpophaga incertulas* (Walker) (Lepidoptera: Pyralidae) were unable to attack resistant rice plants because of the high silica content of their stems. Similarly, Sasamoto (1961) found an increase in the Si content of rice plants when grown in Si supplied soils and a parallel decrease in their susceptibility to the stem borer *Chillo suppressalis* Walker. In

Petri dish trials using rice stem pieces with various Si contents, Ma and Takahashi, (2002) showed that the number of larvae which bored into the stems, and the amount of faeces, was negatively correlated with the Si content of the stems (Table 1).

Other experiments in Asia showed that, on rice, silicic acid at concentrations as low as 0.01 mg Si/ml was an active sucking inhibitor against the brown planthopper (*Nilaparvata lugens* (Stal) (Yoshihara *et al*., 1979). Furthermore, Salim and Saxena (1992) found that at high levels of Si, fewer planthopper nymphs became adults and there was a decreased in adult longevity and female fecundity.

5. Silicon application and maize resistance to pest damage

Sharma and Chatterji (1972) found that a high Si content contributed to maize (*Zea mays* L.) resistance to stalkborer (*Chilo zonellus* Swinhoe) damage. Similarly, in Benin Sétamou *et al.* (1993) evaluated the effects of silica application to maize on the borer, *Sesamia calamistis* Hampson (Lepidoptera: Noctuidae). They applied sodium metasilicate ($Na_2SiO_3.5H_2O$) at a rate of 0, 0.56 and 0.84 g Si/plant. They recorded that an increasing silica supply reduced larval survival from 26.0% (control) to 4.0% at 0.56 g Si/plant. Rojanaridpiched *et al*. (1984) showed that maize resistance to the second generation of *Ostrinia nubilalis* Hübner (Lepidoptera: Pyralidae) was significantly correlated with the silica content in the sheath and collar tissue.

6. Silicon application in other crops for resistance to pest damage

The contribution of Si content to pest resistance has also been recorded in other crops such as vegetables (Chelliah, 1972; Puzyrkov *et al*., 1996), citrus (Matichenkov *et al*., 2000) and turf (Korndorfer *et al*., 2004). Furthermore, Si deposits occurring in plant organs were reported in most crops, including both Mono- and Dicotyledonous families (Jones and Handreck, 1967; Nishimura *et al*., 1989). This suggests that Si plays a role in pest resistance in most, if not all, cultivated crops.

7. Discussion

Many experiments have been conducted since 1960 on the potential agronomic benefits of Si in agriculture. The use of silicon (replacing carbon) with its high natural abundance, and non-toxic nature, has received most attention. Examples of silicon-for-carbon exchange can be found for all major classes of insecticides, including carbamates, organophosphates, pyrethroids, as well as di-ethyl di-chloroethane (DDT) and juvenile hormone analogues and generally, the silicon analogues retain insecticidal activity (Sieburth *et al*., 1990a). Recent research has focused on the beneficial effects of Si in increasing crop resistance to pests and diseases (Sétamou *et al*., 1993; Keeping and Meyer, 2003; Kordan *et al*., 2005). According to Bernays and Barbehenn (1987) several features of Gramineae make them relatively difficult to chew and Si content in the plant is one of these factors. The authors reported that most of the plant Si occurs in the epidermis which might dislodge young borer larvae before they can establish in the stem. Silicon increases hardness of plant tissue, interferes with insect larval boring and feeding activity, and constitutes a strong factor in resistance to rice striped borer (Ukwungwu and Odebiyi, 1985). Painter (1951), Takahashi (1996) and Epstein (1999) suggested that Si deposited in the epidermal tissue may have several functions including support and protection as a mechanical barrier against pathogen and predator invasions. It has been demonstrated that the mandibles of larvae of the rice stem borer are damaged when the Si content of rice plants is high (Jones and Handreck, 1967). However, in some varieties of wheat, resistance to Hessian fly was not found to be related to high silica content in the plant, and Miller *et al.* (1960) suggested that the physical arrangement of silica along the abaxial portion of the leaf sheath might also be another important factor in the resistance of the varieties to the insect.

In plant diseases, the hypothesis of cell wall reinforcement by Si to explain enhanced resistance of plants against pathogenic fungi has been strongly contested in recent years in dicots, particularly in cucumber plants (Samuels *et al*., 1991; Chérif *et al*., 1994). These authors proposed that soluble Si activated defense mechanisms in cucumber against *Pythium* by showing enhanced activity of chitinases, peroxidases and polyphenoloxydases, and increased accumulation of phenolic compounds. This is supported by recent evidence suggesting that silicon may reinforce plant disease resistance by stimulating the expression of natural defense reaction through the production of flavonoid phytoalexins (Belanger *et al*., 1995). In the expression of pest resistance, a parallel mechanism is also possible, such as the resistance to *E. saccharina* in sugar cane (Meyer and Keeping, 2005), and in other pest resistant crops (Schoonhoven *et al*., 1998). Significant positive correlations were found between the concentration of silicon dioxide in the needles and the total phenols in *Thaumetopoea pityocampa*-infected *Pinus* species plants (Schopf and Avtzis, 1987). Furthermore, the mode of action of silicon compounds against insects, such as the noctuid *Trichoplusia ni*, the coccinellid *Epilachna varivestis*, the aphid *Acyrthosiphon pisum*, and the cockroach *Periplaneta americana* was reported to be repetitive firing in the cercal sensory nerves (Sieburth *et al*., 1990b). This could lead to a lower incidence of insect pests observed in crops with high silicon levels.

8. Conclusion and future research

Research has shown clearly that Si applications can contribute significantly to reducing damage due to pests and diseases (Belanger *et al*., 1995; Ma and Takahashi, 2002; Meyer and Keeping, 2005). Furthermore, they may alleviate aluminum (Al) and manganese (Mn) toxicity (Meyer and Keeping, 2005), reduce excess nitrogen (N) uptake leading to enhanced insect damage (Sétamou *et al*., 1993, Savant *et al*., 1999), and enhance biological control (Qin and Tian, 2004). They reduce pest populations, leave no insecticide residues in food or the environment, are relatively cheap, and could easily be integrated with other pest management practices including biological, chemical, and cultural practices (Ukwungwu, 1990).

Future research into pest management with Si applications could include:

1. Validation of Si application for pes control
2. Identification of good Si sources, and their optimal dosages for effective pest control in different crops
3. Clarification of the mode of action of Si in plant resistance to pests
4. Integration of Si applications with biological control for ecologically sustainable pest (and disease) management.

Table 1: Effect of silica supply on the resistance of rice to *Chilo suppressalis*

Parameters	Amounts of silica gel supplied (g/pot)			
	0	1.5	4.5	6.0
SiO_2% in the stem	1.35	1.71	2.02	2.11
NLB	22	7	4	2
Amounts of feces (mg)	139	29	11	9

*Forty fourth instar larvae were incubated in each Petri dish containing 5 cut stems of various SiO_2 contents. Number of the larvae which bored into the rice stems (NLB) were counted 24h after inoculation (Ma and Takahashi, 2002).

Table 2: Silicon and insect management (1985-2005)

Crops and countries	**Insects**	**Silicon forms and dosages**	**Authors**	**Results**
Barley and wheat	*Oulema melanopus*		Guslits, 1990	The main role in resistance in spring barley and wheat was played by silicon deposits

Barley	*Oscinella pusilla*		Sinel\'nikov and Shapiro, 1990	The resistant cultivar had a greater density of crystals
Cereals In Japan, Philippines and other countries in eastern Asia	Environmental pests, including termites (*Coptotermes* spp.) and wood-boring beetle	Silafluofen (or silaneophane) HOE 084498, silicon-containing insecticide	Knauf *et al*., 1990; Schubert *et al*., 1990; Roomi, 1990; Adams *et al*., 1995;	Effective against the most important rice pests in the Lepidoptera, Homoptera and Coleoptera. As a termiticide, Silafluofen, applied as a dust toxicant, may suppress or even eliminate Coptotermes spp.
Citrus In Florida			Matichenkov *et al*., 2000	Si-rich fertilizers may be useful for plant protection against external stresses such as diseases and insect attack
Grains in store	*Rhyzopertha dominica*	Silicon dioxide, a sorptive dust, and diamond dust, an abrasive	Lord, 2001	Synergistic interaction with entomopathogenic fungus Beauveria. bassiana on adult R. dominica
Maize	*Chilo zonellus*		Sharma and Chatterji, 1972	Increase resistance
Maize	*Ostrinia nubilalis*		Rojanaridpiched *et al*., 1984;	Increase resistance to second generation
Maize	*Ostrinia nubilalis*		Coors, 1987	Increase resistance to second generation
Maize (Corn)	Asian corn borer, *Ostrinia furnacalis*	Increase rate of silica in artificial diets	Horng and Chu, 1990	Pupal weights, fecundity, net reproductive rate and intrinsic rate of increase were negatively correlated with silica content
Maize In Benin	*Sesamia calamistis*	Sodium metasilicate ($Na_2SiO_3.5H_2O$) Applied at 0, 0.56 and 0.84 g Si/plant	Sétamou *et al*., 1993	Increase silica reduced larva survival
Maize (corn)	Fall armyworm Spodoptera frugiperda	Sodium silicate solution (25-28% SiO_2) Rate: 3.2 ml for 96.8 ml water	Goussain *et al*., 2002	Fall armyworm feeding difficult, causing higher mortality and cannibalism, thus increasing plant resistance
Rice	*Chillo suppressalis*	Silica gel Applied at 0, 1.5, 4.5, 6 g/pot	Sasamoto, 1961	High Si and decrease of number of larvae bored and feces
Rice In India	Yellow rice borer,, *Scirpophaga incertulas*		Panda *et al*., 1975	Increase resistance
Rice In India	First-instar larvae of *Tryporyza incertulas*	Potassium silicate at sowing Applied at 5 g per pot	Subbarao and Perraju, 1976	Silica content was an important component of resistance. High silica content resulted in higher insect mortality, lower larval

				weight and lower incidence of dead hearts
Rice In Asia	Brown planthopper, (*Nilaparvata lugens*	Silicic acid Applied at 0.01 mg Si/ml	Yoshihara *et al*., 1979	Active sucking inhibitor
Rice In Nigeria	Striped borer, *Chilo zacconius*		Ukwungwu and Odebiyi, 1985	Crude silica increases with bored stems and number of living larvae per plant decreased
Rice	*Cnaphalocrocis medinalis*		Dan and Chen, 1990	Larvae growth rates negatively correlated with Si
Rice In India	yellow rice borer,, *Scirpophaga incertulas*		Mishra *et al*., 1990	Increase resistance
Rice	Whitebacked planthopper	Silicic acid	Salim and Saxena, 1992	High level of Si, and fewer nymphs to adults, decreased in adult longevity and female fecundity
Rice In India	Stem borer (Pyralidae)	Calcium silicate slag with prilled urea and single superphosphate (PU + SSP) or urea briquettes containing diammonium phosphate (UB-DAP)	Talashilkar *et al*., 2000	Application of Si in combination with PU + SSP as well as UB-DAP resulted in a significant reduction in number of hills affected by stem borer [Pyralidae]
Rice	Stem borer	Complete silicon fertilizers	Meiqing, 2005	Reduce rate of borer incidence by 1.27%
Sorghum In Brazil	Greenbug *Schizaphis graminum*		Carvalho *et al*., 1999	Silicon reduced the feeding preference and reproduction of S. graminum.
Sugarcane In Indiana	*Chilo infuscatelus*		Rao, 1967	High density of silicon/unit leaf with increase resistance
Sugarcane In Taiwan	Stem borers	Bagasse furnace ash (60.44% silica), and silica slag (42.95% silica)	Pan *et al*., 1979	Increase resistance
Sugarcane In Florida	*Diatraea saccharalis*	TVA slag Applied at 20 t/ha	Elawad *et al*., 1982	Decrease in leaf freckling with increase resistance
Sugarcane	*Diatraea saccharalis*		Anderson and Sosa, 2001	Increase resistance
Sugarcane (greenhouse and field)	*Eldana saccharina*	Calcium silicate (NCS, USAS, LS and	Keeping and Meyer, 2003; Meyer and	Reductions of 30% borer damage and 20% borer mass NCS>USAS>LS>F

In South Africa		F) Applied at 0, 2.5 and 5 t/ha	Keeping, 2005	
Turf	Tropical sod webworm (TSW), *Herpetogramma phaeopteralis*	Calcium silicate slag Applied at 10 MT/ha	Korndorfer *et al.*, 2004	Increased silicon in plant tissue from calcium silicate applications did not affect growth and development of TSW
Vegetables			Chelliah, 1972	Increase resistance
Wheat	Hessian fly, *Phytophaga destructor*	Sodium silicate	Miller *et al.*, 1960	Marked resistance with round-oblong-shape silica deposition for resistance Varieties and rod-shape for susceptible ones
Wheat In the Labo.	dermestid *Trogoderma granarium*	Tricopper silicophosphate (0.3-1.5%), tricalcium silicophosphate (1-1.5%) and trizinc silicophosphate (1.5%)	Bhavnagary *et al.*, 1988	Reduced infestation
Wheat	cereal leaf beetles, *Oulema* spp.		Weryszko-Chmielewska and Soczyński, 1994	High number of silicon cells in 1 mm^2 in resistant cultivar.
Wheat in storage in sealed jars	*Sitophilus oryzae* and *Tribolium castaneum*	Diatomaceous earth (DE) from USA, Mexico, Canada, Australia, Japan, China and Macedonia	Korunic, 1997	Effective against insects but depends on different properties of the diatom particles (adherence, particle size distribution, shape and pH)
Wheat	green-aphid *Schizaphis graminum*	sodium silicate solution at 0.4% SiO_2 Applied at 50 ml/pot	Basagli *et al.*, 2003	Affected feeding, longevity, and production of nymphs of *S. graminum*, thus, conferring resistance to wheat against the aphid
Wheat	greenbug, *Schizaphis graminum*	silicon application via the leaves and in the soil	Moraes *et al.*, 2004	Silicon application increased the degree of resistance in wheat plants, decreasing greenbug preference
Wheat	stored grain product weevil, *Sitophilus granarius*	Sulsil (highly dispersed sulfur and sodium thiosulfate in silicon matrix)	Kordan *et al.*, 2005	Powder formulation had a stronger inhibitory effect on the development of grain weevil, and increase of grain resistance

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Yong C. Liang, PhD
ABIOTIC STRESS AND SILICON

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Abstract

Although Silicon (Si) is the second most abundant element both on the surface of the earth crust and in the soils, it has not yet been listed among the essential elements for higher plants partly because direct evidence is still lacking that Si is part of the molecule of an essential plant constituent or metabolite. However, the beneficial role Si plays in stimulating the growth and development of many plant species has been generally recognized. More recently, Epstein and Bloom (2003) have proposed a new definition of essentiality. Based on this new definition, the essentiality of Si for higher plants will be finally established.

Over last two or three decades, the striking and unique role of Si in conferring plants against various abiotic and biotic stresses has received increasing interest. Silicon is known to effectively mitigate various abiotic (environmental) stresses including manganese, aluminium, and heavy metal toxicity, and salinity, drought, chilling or freezing stresses etc. However, mechanisms for such Si-mediated alleviation of various abiotic stresses remain poorly understood. This paper reviewed the current knowledge on beneficial effect of Si with focuses being on the possible mechanisms involved in Si-mediated alleviation of such abiotic stresses as manganese, aluminium, cadmium, and salinity toxicity. The key mechanisms of Si-mediated alleviation of abiotic stresses in higher plants include: 1) stimulation of antioxidant systems in plants, 2) complexation or co-precipitation of toxic metal ions with Si, 3) immobilization of toxic metal ions in growth media, 4) uptake processes, and 5) compartmentation of metal ions within plants. Future directions of research on Si-mediated alleviation of abiotic stresses in higher plants are also discussed.

Key words: Abiotic stress, biotic stress, heavy metals, silicon, salinity

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SILICON REQUIREMENT FOR RICE

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Abstract

Although silicon (Si) has not been recognized as an essential element for plant growth, the beneficial effects of Si have been observed in a wide variety of plant species. The beneficial effects of Si are usually expressed more clearly in Si-accumulating plants under various abiotic and biotic stress conditions. Silicon is effective in controlling various pests and diseases caused by both fungi and bacteria in different plant species. Silicon also exerts alleviative effects on various abiotic stresses including salt stress, metal toxicity, drought stress, radiation damage, nutrient imbalance, high temperature, freezing and so on. These beneficial effects are mainly attributed to the high accumulation of silica on the tissue surface although other mechanisms have also been proposed. To obtain plants resistant to multiple stresses, genetic modification of the root ability to take up Si has been proposed. In this review, the role of Si in conferring resistance to mutiple stresses and recent progress on silicon uptake system are described.

Silicon (Si) is the second most abundant element in soil. In soil solution, Si occurs mainly as monosilicic acid (H_4SiO_4) at concentrations ranging from 0.1 to 0.6 mM and is taken up by plants in this form (Epstein 1994; Ma and Takahashi 2002). After the uptake, Si accumulates on the epidermis of various tissues mainly as a polymer of hydrated amorphous silica. All terrestrial plants contain Si in their tissues although the content of Si varies considerably with the species, ranging from 0.1% to 10% Si on a dry weight basis (Ma and Takahashi 2002). However, Si has not been recognized as an essential element for plant growth. The major reason is that there is no evidence to show that Si is involved in the metabolism of plant, which is one of the three criteria required for essentiality established by Arnon and Stout (1939). However, recently, Epstein and Bloom (2003) have reconsidered this definition of essentiality and proposed a new definition of elements that are essential for plant growth: An element is essential if it fulfills either one or both of two criteria, viz. (1) the element is part of a molecule which is an intrinsic component of the structure or metabolism of the plant, and (2) the plant can be so severely deficient in the element that it exhibits abnormalities in growth, development, or reproduction, i.e. "performance", compared to plants with a lower deficiency. According to this new definition, Si is an essential element for higher plants because Si deficiency causes various abnormalities in the plant, as reported in a number of papers (for a review, see Ma and Takahashi 2002).

Despite these arguments on the essentiality of Si, it has been known for almost one century that Si exerts beneficial effects on the growth of plants. Several beneficial effects of Si have been reported, including increased photosynthetic activity, increased insect and disease resistance, reduced mineral toxicity, improvement of nutrient imbalance, and enhanced drought and frost tolerance. Overall, the beneficial effects of Si show two characteristics. One is that the beneficial effects vary with the plant species. Beneficial effects are usually obvious in plants that accumulate high levels of Si in their shoots (Ma et al. 2001a). One typical example is rice, which accumulates Si up to 10% Si on a dry weight basis in the shoot. High accumulation of Si in rice has been demonstrated to be necessary for healthy growth and high and stable production. For this reason, Si has been recognized as an "agronomically essential element" in Japan and silicate fertilizers have been applied to paddy soils. The other characteristic is that the beneficial effects of Si are usually expressed more clearly when plants are subjected to various abiotic and biotic stresses. Silicon is probably the only element which is able to enhance the resistance to multiple stresses. In this review, the role of Si in enhancing the resistance of plants to various stresses was emphasized.

1. Silicon Enhances the Resistance to Biotic Stresses

Several studies have shown that Si is effective in enhancing the resistance to diseases and pests.

(1) Silicon and rice blast disease

The suppressive effect of Si on rice blast was reported as early as 1917 by Onodera (1917). Rice blast, caused by *Magnaporthe grisea* (Hebert) Barr, is the most destructive fungal disease of rice, particularly in temperate, irrigated rice and tropical upland rice. The pathogen can infect all the above-ground parts of the rice plant, but occurs most commonly on leaves causing leaf blast during the vegetative stage of growth or on neck nodes and panicle branches during the reproductive stage, causing neck blast (Bonman et al. 1989). Silicon reduces the epidemics of both leaf and panicle blast at different growth stages. In Florida, where soil is deficient in Si, application of silicate fertilizer is as effective as fungicide application in controlling rice blast (Datnoff et al. 1997). Rice seedling blast is significantly suppressed by the application of Si fertilizers in the nursery (Maekawa et al. 2001).

Recently, Seebold et al. (2001) have tested the effects of Si on several components of resistance to blast using susceptible, partially resistant, and completely resistant rice cultivars. They found that, regardless of the cultivar resistance, incubation period was lengthened, and the number of sporulating lesions, lesion size, rate of lesion expansion, and the number of spores per lesion were significantly reduced by Si application. Maekawa et al. (2002) reported that Si accumulated near the blast appressorium on inoculated rice leaves by using VP-SEM and EDX.

(2) Silicon and powdery mildew disease

Silicon has been reported to prevent the incidence of powdery mildew disease, which is caused by *Sphaerotheca fuliginea*, in a number of plant species. Miyake and Takahashi (1983) reported that by increasing the Si concentration in the culture solution, the Si content in the cucumber shoot increased, resulting in a reduced incidence of powdery mildew disease. In strawberry, when the Si content of leaves increased proportionally to the increase of the Si concentration in the culture solution, the incidence of powdery mildew decreased (Kanto 2002). Silicon deficiency in barley and wheat leads to a poor growth habit and increased powdery mildew susceptibility (Zeyen 2002). Menzies et al. (1991) found that infection efficiency, colony size, and germination of conidia were reduced when cucumbers were grown in nutrient solutions with high concentrations of Si.

Foliar application of Si has been reported to be effective in inhibiting powdery mildew development on cucumber, muskmelon, and grape leaves (Menzies et al. 1992; Bowen et al. 1992). Si applied to leaves may deposit on the surface of leaves and play a similar role to that of Si taken up from the roots.

(3) Silicon and other diseases

In addition to blast and powdery mildew, the occurrence of brown spot, stem rot, sheath brown rot on rice, fusarium wilt and corynespora leaf spot on cucumber decreased by increasing the Si supply. In turfgrass, several diseases were also suppressed by Si application (Datnoff et al. 2002).

Rice bacterial blight caused by *Xanthomonas oryzae* pv. oryzae (Xoo) is a serious disease worldwide. Chang et al. (2002) reported that in the cultivar TN1 which is susceptible to this disease the Si content in leaves was lower than that of the resistant breeding line, TSWY7 under the nutrient cultural system adopted. The degree of resistance to this disease increased in parallel with the increased amount of applied silicon. Si-induced decrease of soluble sugar content in the leaves seems to contribute to the field resistance of the disease.

Silicon is also effective in increasing the resistance to the fungal diseases caused by *Pythium ultimum* and *P. aphanidermatum* in cucumber roots (Cherif et al. 1994).

(4) Silicon and pests

Silicon suppresses insect pests such as stem borer, brown planthopper, rice green leafhopper, and whitebacked planthopper, and noninsect pests such as leaf spider and mites (Savant et al. 1997). Stems attacked by the rice stem borer were found to contain a lower amount of Si (Sasamoto 1961). In a field study, a positive relationship between the Si content of rice and resistance to the brown planthopper has been observed (Sujatha et al. 1987).

(5) Possible mechanisms involved

Two hypotheses for the Si-enhanced resistance to diseases and pests have been proposed. One is that Si deposited on the tissue surface acts as a physical barrier. It prevents physical penetration and/or makes the plant cells less susceptible to enzymatic degradation by fungal pathogens. This mechanism is supported by the positive correlation between the Si content and the degree of suppression of diseases and pests. The other one is that Si functions as a signal to induce the production of phytoalexin (Cherif et al. 1994). Si application to cucumber resulted in the stimulation of the chitinase activity and rapid activation of peroxidases and polyphenoloxidases after infection with *Pythium* spp. Glycosidically bound phenolics extracted from Si-treated plants when subjected to acid or beta-glucosidase hydrolysis displayed a strong fungistatic activity. However, in oat attacked by *Blumeria graminis*, Si deficiency promoted the synthesis of henolic compounds (Carver et al. 1998). The phenylalanine ammonia-lyase activity was enhanced by Si deficiency. The reason why Si deficiency exerts opposite effects on the synthesis of phenolic compounds, as a disease response in different plant species, has not been elucidated.

Recently, Kauss et al. (2003) have reported that during the induction of systemic all acquired resistance (SAR) in cucumber, the expression of a gene encoding a novel proline-rich protein was enhanced. This protein has C-terminal repetitive sequences containing an unusually high amount of lysine and arginine. The synthetic peptide derived from the repetitive sequences was able to polymerize orthosilicic acid to insoluble silica, which is known to be involved in cell wall reinforcement, at the site of the attempted penetration of fungi into epidermal cells. This study provided a biochemical and molecular basis of Si-enhanced resistance to diseases.

2. Silicon Increases the Resistance to Abiotic Stresses

(1) Silicon and physical stresses

A number of studies have showed that Si alleviates physical stresses, including radiation, low and high temperature, wind, drought and waterlogging, low and high light and so on.

a. Silicon and radiation damage

Radiation injures plants. Silicon seems to protect plants from radiation injury. When rice seedlings (30-d-old) were irradiated with different doses of γ-rays, the decrease in the dry weight was less appreciable in the Si-supplied plants than in the Si plants that had not been treated with Si, suggesting that Si increases the resistance of rice to radiation stress (Takahashi 1966). Furthermore, when the plant was supplied with Si after radiation treatment, the growth recovery was faster compared to that of the plants without Si supply.

b. Silicon and water stress

Water deficiency (drought stress) leads to the closure of stomata and subsequent decrease in the photosynthetic rate. Silicon can alleviate water stress by decreasing transpiration. Transpiration from the leaves occurs mainly through the stomata and partly through the cuticle. As Si is deposited beneath the cuticle of the leaves forming a Si-cuticle double layer, the transpiration through the cuticle may decrease by Si deposition. Silicon can reduce the transpiration rate by 30% in rice, which has a thin cuticle (Ma et al. 2001a). Under water-stressed conditions (low humidity), the effect of Si on rice growth was more pronounced than on rice that cultivated under non-stressed conditions (high humidity) (Ma et al. 2001a).

When rice leaves were exposed to a solution containing polyethylene glycol (PEG), electrolyte leakage (EI) (an indicator of membrane lesion) from the leaf tissues decreased with the increase in the level of Si in the leaves (Agarie et al. 1998). The level of polysaccharides in the cell wall was higher in the leaves containing Si than in those lacking Si. These results suggest that Si in rice leaves is involved in the water relations of cells, such as mechanical properties and water permeability.

Among the yield components, the percentage of ripened grains is most affected by Si in both rice and barley (Ma and Takahashi 2002). This function of Si may be attributed to the alleviative effect of Si on water stress. One important factor for the normal development of the spikelets is to keep a high moisture condition within the hull (Seo and Ohta 1982). The Si content in the hull of the rice grain becomes as high as 7% Si and that of the barley grain is 1.5%. Silicon in the hull is also deposited between the epidermal cell wall and the cuticle, forming a cuticle-Si double layer as in the leaf blades. However, in contrast to the leaves, transpiration occurs only through the cuticle because the hull does not have a stoma. Silicon is effective in decreasing the transpiration from the hull. The rate of water loss from Si-free spikelets was about 20% higher than that from spikelets containing Si (7% Si) at both the milky and maturity stages (Ma et al. 2001a). Therefore, Si plays an important role in keeping a high moisture condition within the hull by decreasing the transpiration rate from the hull. This is especially important under water deficiency stress and stress associated with climatic conditions.

c. Silicon and stress associated with climatic conditions

Silicon application in rice is effective in alleviating the damage caused by climatic stress such as typhoons, low temperature and insufficient sunshine during the summer season (Ma et al. 2001a). A typhoon attack usually causes lodging and sterility in rice, resulting in a considerable reduction of the rice yield. Deposition of Si in rice enhances the strength of the stem by increasing the thickness of the culm wall and the size of the vascular bundles (Shimoyama 1958), thereby preventing lodging. Strong winds also cause excess water loss from the spikelets, resulting in sterility. Silicon deposited on the hull is effective in preventing excess water loss. In addition, the effect of Si on the rice yield is also obvious under stress due to low temperatures and insufficient sunshine (for a review, see Ma and Takahashi 2002).

d. Silicon and heat stress

Silicon also increases the tolerance to heat stress in rice plants. Agarie et al. (1998) observed that electrolyte leakage caused by high temperature (42.5^{o}C) was less pronounced in the leaves grown with Si than in those grown without Si. These results suggest that Si may be involved in the thermal stability of lipids in cell membranes although the mechanism has not been elucidated.

(2) Silicon and chemical stress

There has been a considerable amount of work on the effects of Si under chemical stresses including nutrient imbalance, metal toxicity, salinity and so on.

a. Silicon and deficiency in or excess of P

Deficiency in P in soil is a worldwide problem. The beneficial effects of Si under P-deficiency stress have been observed in many plants including rice and barley. Early observations from a long-term field experiment conducted at Rothamsted Experimental Station, showed that barley yield was higher in a field amended with Si than in a field without Si application when P fertilizers were not applied. In an experiment using a nutrient solution, Si supply resulted in a larger increase of the dry weight of rice shoot at a low P level (14 μM P) than at a medium level (210 μM) (Ma and Takahashi 1990a).

Such beneficial effects of Si were previously attributed to a partial substitution of Si for P or to the enhancement of P availability in soil. However, subsequent experiments showed that Si was unable to affect P availability in soil. In a P-deficient soil, previous addition of silicic acid at various concentrations did not affect the P fixation capacity of soil (Ma and Takahashi 1990b). Phosphorus fixed was not desorbed by various concentrations of silicic acid (Ma and Takahashi 1991). Silicon is present in the form of silicic acid in the soil solution, which does not undergo dissociation at a pH below 9. Therefore, it is unlikely that interaction between silicic acid and phosphate (anionic form) occurs in soil.

The uptake of P was also not affected by the Si supply at a low P level in both soil and solution culture (Ma and Takahashi 1990a; 1990b; 1991). However, the uptake of Fe and Mn significantly decreased in the Si-treated plants. Phosphorus is translocated and redistributed in plants in an inorganic form. Since P shows a high affinity with metals such as Fe and Mn, internal availability of P could be controlled by the level of Mn, Fe and other metals when the P concentration is low. Therefore, the larger beneficial effect of Si on plant growth under P-deficiency stress may be attributed to the enhanced availability of internal P through the decrease of excess Fe and Mn uptake. This is supported by the fact that Si supply increased the rate of P translocation to the panicles in rice (Nagaoka 1998).

Excess P stress hardly occurs in natural soils, but was observed in some green house soils where P fertilizers had been heavily applied or in nutrient solution culture where a high P concentration is supplied. Excess P causes chlorosis or necrosis in leaves, probably due to the decreased availability of essential metals such as Fe and Zn. Silicon can alleviate the damage caused by P excess by decreasing the excessive uptake of P, resulting in a decrease in the internal inorganic P concentration. Silicon deposited on the roots and/or Si-induced decrease of transpiration may be responsible for the decreased uptake of P when the P concentration in the medium is high. Si has been found to be deposited in the endodermal cells of roots in many plant species (e.g. Lux et al. 1999, 2003), which may form apoplastic barriers against the radial movement of P across the root. The Si-induced decrease of P uptake has also been observed in some Si non-accumulating plants, including tomato, soybean, strawberry and cucumber (for a review, see Ma et al. 2001a), in which roots Si is also deposited.

b. Silicon and N excess

Application of nitrogen fertilizers is an important practice for increasing yield. However, excess N causes lodging, mutual shading, susceptibility to diseases and so on. Silicon deposited on the stems and leaf blades prevents lodging and mutual shading, as stated above. The occurrence of blast disease is significantly inhibited by Si application in the field, especially when N application is heavy (Ohyama 1985). These functions of Si are especially important in the cultivation systems with dense planting and high N application.

Excessive application of nitrogen fertilizers also causes a high protein content in brown rice, which affects its quality. Sufficient supply of Si to rice is effective in producing low protein rice (Morimiya 1996).

c. Silicon and heavy metal toxicity

An alleviative function of Si on Mn toxicity has been observed in hydroponically cultured rice (Okuda and Takahashi 1962), barley (Williams and Vlamis 1957; Horiguchi and Morita 1987), bean (Horst and Marschner 1978), and pumpkin (Iwasaki and Matsumura 1999). Three different mechanisms seem to be involved depending on the plant species. In rice, Si reduced Mn uptake by promoting the Mn oxidizing power of the roots (Okuda and Takahashi 1962). In bean (Horst and Marschner 1978) and barley (Williams and Vlamis 1957), Si did not reduce the Mn uptake, but led to a homogeneous distribution of Mn in the leaf blade. Although the mechanism for this homogeneous distribution has not been elucidated, Horst et al. (1999) found that Si led to a lower apoplasmic Mn concentration in cowpea and suggested that Si modifies the cation binding properties of the cell wall. However, recently, further studies by the same group have indicated that the maintenance of a reduced state of the apoplast by soluble Si was also involved in the Si-enhanced Mn tolerance in cowpea (Iwasaki et al. 2002a, b). This is supported by the evidence that there was no correlation between the apoplastic Mn concentration and the expression of Mn toxicity, but that there was a negative correlation between the apoplastic Si concentration and the expression of Mn toxicity. A negative correlation was observed between the apoplastic guaiacol peroxidase (POD) activity and the Si concentrations in apoplastic washing fluid (AWF). Silicon seems to affect the oxidation process of excess Mn mediated by POD through the interaction with phenolic substances in the solution phase of the apoplast (Iwasaki et al. 2002a).

By contrast, Si caused a localized accumulation of Mn around the base of trichomes in pumpkin (Iwasaki and Matsushima 1999). The uptake of Mn was also not affected by Si in this plant.

Silicon was also effective in alleviating Fe excess toxicity in rice (Okuda and Takahashi 1962). Silicon enhanced the oxidative power of rice roots, resulting in enhanced oxidation of Fe from ferrous iron to insoluble ferric iron. Therefore, excess Fe uptake was indirectly prevented by Si application. For upland plants, excess Fe stress is not a problem.

In heavy metal-tolerant *Cardaminopsis halleri*, grown on Zn- and Cu-polluted soil, Zn was coexisted with Si in the cytoplasm (Neumann and Nieden 2001). It was observed that Zn-silicate is a transient storage compound for the metal and undergoes a slow degree of degradation to SiO_2. Zn is then translocated into the vacuoles and accumulated in an unknown form. It was suggested that the formation of Zn-silicate is part of the mechanism of heavy metal tolerance and may be responsible for the alleviation of Zn toxicity in *Cardaminopsis*.

d. Silicon and salinity

The beneficial effect of Si under salt stress has been observed in rice (Matoh et al.1986; Yeo et al. 1999), wheat (Ahmad et al. 1992) and barley (Liang et al. 1996). In rice, shoot and root growth of rice was inhibited by 60% in the presence of 100 mM NaCl for three weeks, but Si addition significantly alleviated salt-induced injury (Matoh et al. 1986). The Na concentration in the shoot decreased to about half by Si addition. This function of Si may be ascribed to the Si-induced decrease of transpiration (Matoh et al. 1986) and to the partial blockage of the transpirational bypass flow, the pathway by which a large proportion of the uptake of Na in rice occurs (Yeo et al. 1999). In barley, Si increased the leaf superoxide dismutase activity and suppressed the lipid peroxidation caused by salt stress and stimulated root H^+-ATPase in the membranes, suggesting that Si may affect the structure, integrity and functions of plasma membranes by influencing the stress-dependent peroxidation of membrane lipids, although these effects may be indirect (Liang et al. 2002).

e. Silicon and Al toxicity

Al toxicity is a major factor limiting crop production in acid soils. Ionic Al inhibits root growth and nutrient uptake (Ma et al. 2001b). Alleviative effect of Si on Al toxicity has been observed in sorghum, barley, teosinte, maize, rice, and soybean (for a review, see Cocker et al. 1998). In an experiment with maize, Si addition as silicic acid significantly alleviated Al-induced inhibition of root elongation (Ma et al. 1997). The alleviative effect was more apparent with increasing Si concentration. Concentration of toxic Al^{3+} was found to decrease by the addition of silicic acid. These results suggest that interaction between Si and Al occurs in the solution, presumably by the formation of Al-Si complexes, a non-toxic form. However, other mechanisms for the alleviative effect of Si have also been proposed, including codeposition of Al with Si within the plant, action in the cytoplasm, effect on enzyme activity and indirect effects (Cocker et al. 1998). The alleviative effect of Si on Al toxicity varies with plant species, probably due to difference in Al tolerance and/or differences in the mechanisms involved.

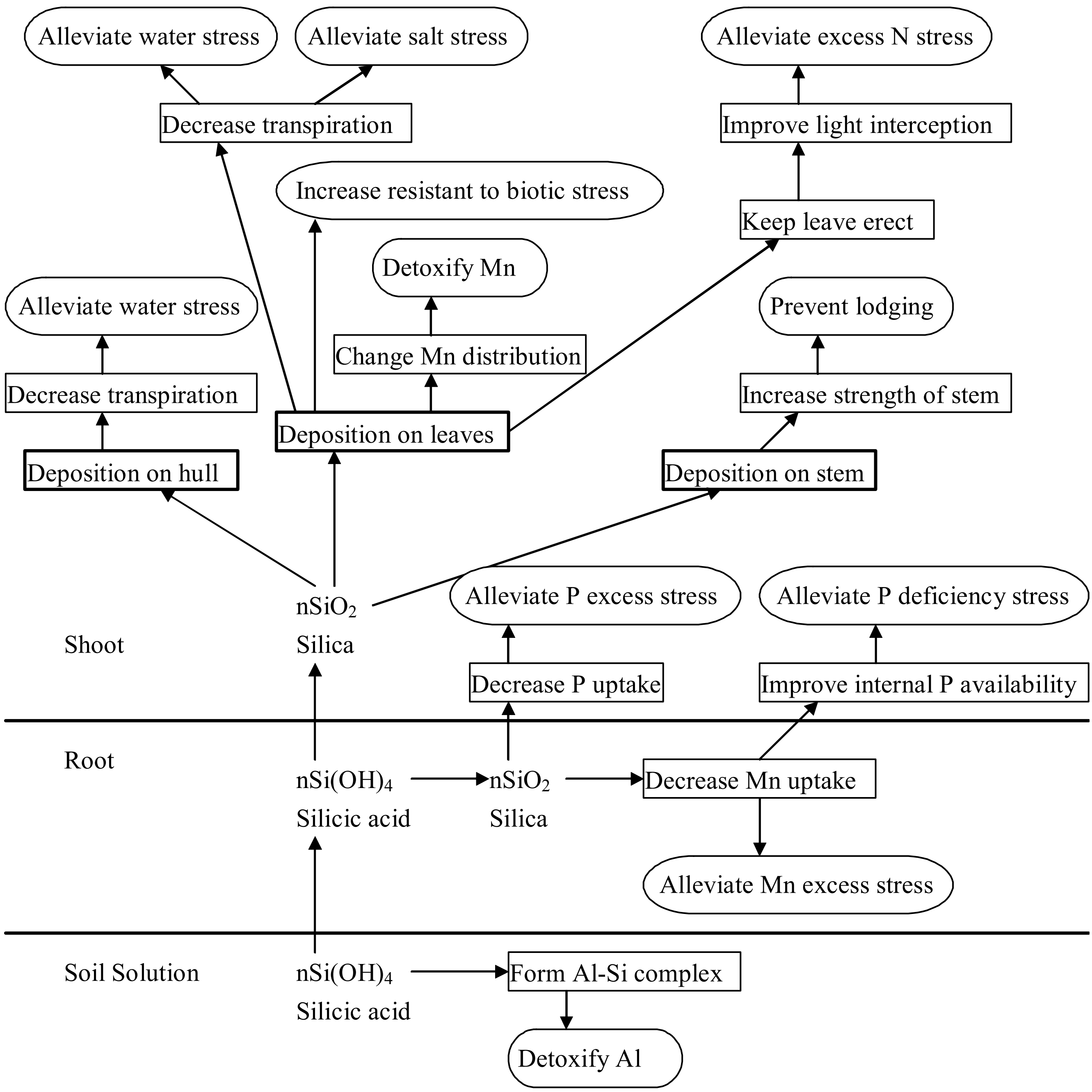
3. Recent progress of silicon uptake system

The beneficial effects of Si under stress conditions are summarized in Fig. 1 (Ma et al. 2001a; Ma and Takahashi 2002). It is obvious that most of the effects of Si were expressed through Si deposition on the leaves, stems, and hulls. The more Si accumulated in the shoots, the larger the effect. However, Si accumulation in the shoot varies considerably with the plant species and most plants are unable to accumulate high levels Si in the shoots. The difference in Si accumulation was attributed to the ability of the roots to take up Si. Recently, the uptake system of Si was investigated in terms of radial transport from external solution to root cortical cells and release of Si from cortical cells to xylem in rice, cucumber and tomato, which differ greatly in the shoot Si concentration (Mitani and Ma, 2005). The concentrations of Si in the root-cell symplast in all species were higher than that in the external solution, although the concentration in rice was 3- and 5-fold higher than that in cucumber and tomato, respectively. A kinetic study showed that the radial transport of Si was mediated by a transporter with a K_m value of 0.15 mM in all species, but with different V_{max} values in the order of rice> cucumber >tomato. In the presence of the metabolic inhibitor 2,4-dinitrophenol and at low temperature, the Si concentration in the root-cell symplast decreased to the similar level of apoplasmic solution. These results suggest that both transporter-mediated transport and passive diffusion of Si are involved in the radial transport of Si and that the transporter-mediated transport is an energy-dependent process. The Si concentration of xylem sap in rice was 20- and 100-fold higher than that in cucumber and tomato, respectively. In contrast to rice, the Si concentration in the xylem sap was lower than that in the external solution in cucumber and tomato. A kinetic study showed that xylem loading of Si was also mediated by a kind of transporter in rice, but by passive diffusion in cucumber and tomato. These results indicate that a higher density of transporter for radial transport and the presence of a transporter for xylem loading are responsible for high Si accumulation in rice.

To identify the genes encoding Si transporter in rice, a rice mutant (*lsi1*) defective in Si uptake has been isolated, by using Ge tolerance as an index (Ma et al., 2002). This mutant had a plant type similar to the wild type except that the leaf blade of *lsi1* remained droopy when Si was supplied. The Si concentration of the tops was much lower in the mutant than in the wild type, while that of the roots was similar. A short-term uptake experiment showed that the Si uptake by the mutant was significantly lower than that by the wild type, while there was no difference in the uptake of other nutrients such as P and K. Further, Si uptake by the wild-type rice was inhibited by metabolic inhibitors including NaCN and 2, 4-dinitrophenol and by low temperature, whereas Si uptake by *lsi1* was not inhibited by these agents. The Si concentration in the xylem sap of the wild-type rice was also much higher than that of *lsi1*. These results suggest that an active transport system for Si uptake is disrupted in the mutant (Ma et al., 2002). By using this mutant, the responsible gene has been mapped to chromosome 2, flanked by microsatellite marker RM5303 and EST-based PCR marker E60168 (Ma et al., 2004).

Silicon is abundant in soil, however, since most plants especially dicots are unable to take up a large amount of Si from soil, they do not benefit from Si. One approach to enhance the resistance of plants to multiple stresses, is to genetically modify the Si uptake ability. Further identification of genes controlling Si uptake in rice will provide new tools for this approach.

Figure 1 Beneficial effects of Si under various stresses.


Alleviate water stress
Alleviate salt stress
Alleviate excess N stress
Decrease transpiration
Improve light interception
Increase resistant to biotic stress
Keep leave erect
Detoxify Mn
Alleviate water stress
Prevent lodging
Change Mn distribution
Decrease transpiration
Increase strength of stem
Deposition on leaves
Deposition on hull
Deposition on stem
Alleviate P excess stress
Alleviate P deficiency stress
$nSiO_2$
Shoot
Silica
Decrease P uptake
Improve internal P availability
Root
$nSi(OH)_4$
$nSiO_2$
Decrease Mn uptake
Silicic acid
Silica
Alleviate Mn excess stress
Soil Solution
$nSi(OH)_4$
Form Al-Si complex
Silicic acid
Detoxify Al

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Jan Meyer, PhD
AN OVERVIEW OF THE IMPACT OF SILICON IN ALLEVIATING BIOTIC AND ABIOTIC STRESS IN SUGARCANE

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Abstract

For many years silicon (Si) deficiency in crops was relatively unknown and this element was widely regarded as non-essential for plant growth. Ever since the discovery by D'Hotman De Villiers, in 1937, that sugarcane growing on highly weathered soils in Mauritius could be rejuvenated, by applying finely crushed siliceous basalt, silicon has emerged as an important nutrient for sugarcane. With the exception of potassium, sugarcane is known to take up more Si than any other mineral nutrient, with the potential to accumulate up to 400 kg ha^{-1} in a 12-month old irrigated crop. This paper documents some of the more important studies and outcomes of research into the Si requirement of sugarcane in countries such as Brazil, Florida, Hawaii, Puerto Rico, Australia, Mauritius and South Africa. Early studies have tended to emphasize the role of Si in alleviating abiotic stress caused by factors such Al and Mn toxicity in soils. Results of field studies conducted in South Africa have shown that four out of five field trials produced significant responses to the application of calcium silicate and these varied from 9 to 24 tc/ha. More recent research has focused on the beneficial role of Si in alleviating biotic stress from factors such as pests and disease.
Keywords: Silicon, silicic acid, calcium silicate, sugarcane, soil acidity, genotypic differences, stalk borer.

INTRODUCTION

Despite silicon being regarded as a non-essential element for plant growth, a considerable amount of research has been conducted worldwide since 1960, on the potential agronomic benefits of Si in sugar cane (Savant et al 1999). Members of the grass family such as sugar cane (*Saccharum officinarum* L.) and rice (*Oryza sativa* L.), accumulate large amounts of Si in the form of silica gel ($SiO_2.nH_2O$) that is localized in specific cell types. It is has been reported that under certain conditions sugarcane may absorb more silicon than any other nutrient from the soil. In Puerto Rico, the above ground parts of a 12-month crop contained 379 kg ha^{-1} of Si, compared with 362 kg ha^{-1} of K and 140 kg ha^{-1} of N (Samuels 1969).

For plant growth the important soluble forms of soil Si are monosilicic acid ($(Si(OH)_4)_n$, various polymers and silica gels, Si adsorbed onto sesquioxidic colloidal surfaces, and slowly available forms released from both crystalline and amorphous minerals. The availability of Si in the soil is governed not only by Si polymorphs but also by a number of factors (Epstein 1994) which include soil moisture, temperature, soil pH, organic matter complexes, redox potential, particle size distribution, sesqui-oxide colloids, the presence of aluminium, iron and phosphate ions, as well as various exchangeable/dissolution reactions (Beckwith and Reeve, 1964; Jones and Handreck, 1963, 1965, Drees 1989). Organic complexes such as alginic acid, ATP, and amino acids may also improve the dissolution of soil Si (Evans, 1959).

Significant responses to silicon treatment in both cane and sugar yields, varying from 10 to 38% have been reported in several countries including Hawaii, Mauritius, South Africa, Puerto Rico, Florida and Australia (Fox *et al*., 1967; Wong You Cheong and Halais, 1970; Du Preez, 1970; Samuels and Alexander, 1969; Elawad *et al*., 1982, Haysom and Chapman, 1975). There have also been a few reports dealing with the agronomic benefits of silicate applications from other countries such as Malaysia (Pan, et al 1979), Taiwan (Shiue, 1964 and 1973), and Indonesia (Allorerung,1989)

Early studies emphasized the role of Si in alleviating abiotic stress caused by factors such Al and Mn toxicity, while more recent research has focused on the beneficial role of Si in alleviating biotic stress from factors such as pests and disease (Rao 1967 and Raid et al 1992). Savant et al (1999) have recently reviewed the literature concerning the silicon nutrition of sugarcane but only scant reference was made to important studies conducted in South Africa, Mauritius and Australia. The objective of this paper is to highlight some of the more important past research outcomes into the Si requirement of sugarcane in other cane producing countries and to highlight some recent outcomes of research conducted in the South African Sugar Industry.

KEY OUTCOMES OF PAST INTERNATIONAL RESEARCH

Mauritius

The discovery that applications of silica may benefit cane growth was indirectly made in 1947 in Mauritius, by a young researcher named D'Hotman De Villiers. He found that highly weathered sugarcane soils could be rejuvenated , by applying finely crushed basalt. In carefully conducted trials, cumulative yield responses of between 30 to 60 tc/ha were obtained over five crops to crushed basalt applied at rates varying from 200 to 400 t/ha. (D'Hotman De Villiers, 1947) Subsequent studies based on soil and leaf analysis confirmed that it was the soluble silica in the basalt that caused the favorable yield increases (D'Hotman De Villiers, 1961). Vlamis and Williams (1957) first suggested the possible role of silicon controlling Mn toxicity, while Halais and Parish (1963) concluded that cane yield was inversely related to the Mn/SiO2 ratio in the cane sheath. Controlled solution culture investigations by Wong You Cheong et al (1973), showed that maximum cane and sucrose yields occurred between 50 and 75 ppm Si. Leaf freckling symptoms only occurred in the zero Si control plots and once they appeared, they increased in intensity particularly in the older leaves, covering as much as 5% of the total leaf area.

Ross et al. (1974) observed marked residual effects on sugarcane yield over a 6-year cycle crop cycle from applications of calcium silicate, applied at a rate of 7 t ha^{-1} to Si deficient soils (less than 77 mg dm^{-3} Si extractable with modified Truog's extractant). The application of calcium silicate was profitable when the total Si level in the third leaf lamina was below 0.67 % of Si or if the acid-soluble soil Si was below 77 mg dm^{-3} Si

USA (Hawaii)

The first direct use of silicon in the USA for improving sugar cane growth took place in Hawaii (Clements 1965a). A disorder called leaf freckling, comprising small rust-colored or brownish spots on the leaves of cane was linked to a suspected deficiency of silicon..In a series of field experiments the leaf freckling was corrected with applications of TVA calcium silicate slag as well as obtaining significant increases in cane and sucrose tonnage (Clements 1965b).

In searching for reasons for the yield increases, Clements analyzed sugar cane leaves and roots from the various treatments. His findings indicated that yield increases were obtained from silica when the soluble silica supply of the soil was low or when an increasing intake of soluble manganese depressed the silicon levels in the plant He also observed a drastic reduction in the ratio of manganese expressed as ppm to silica% in the TVD leaf. In addition to serving as a source of calcium when needed, applications of calcium silicate suppressed the uptake of aluminum and boron, when they were present in toxic levels, by raising the pH of the soil.

Further investigations showed that the soils used for sugar cane of the humic and hydrol humic latosol types, where calcium silicates gave responses, were, by their very nature, soils with a low pH in which toxic levels of soluble aluminum, boron, iron and manganese accumulated and resulted in damage to the roots and tops of the cane plant. This injury was further compounded by the use of acid-forming fertilizers. Clements concluded that calcium silicate eliminated, through precipitation, toxic levels of Al and Mn that were injurious to the roots and tops of cane. Calcium carbonate helped to improve soil conditions, but calcium silicate appeared to be more suitable for a more permanent correction (Clements et al, 1974).

Ayres (1966), obtained responses ranging from 9 to 18% in cane yield and 11 to 22% in sucrose yield for plant cane, following the application of 6.2 t ha^{-1} of electric furnace slag to aluminous humic ferruginous latosols in Hawaii. The beneficial effect of the slag lasted on low Si soils for four years, and the first ratoon crop produced about 20 % more cane and sugar. In investigating the reasons why calcium silicate increased cane and sugar yields, Ayres acknowledged Clement's reason for depressing aluminum and manganese toxicity but he pointed out that in his experiments, these elements were not toxic. Instead, soluble silicon was found to be low in both the soil and the plant. Because of this, he expressed the view that there was a level of extractable or available soil silicon below which there would not be satisfactory growth of sugar cane regardless of the supply of other available nutrients (Ayres 1966).

Puerto Rico

Samuels and Alexander (1969) performed an interesting nutrient culture pot trial with quartz sand as the inert medium and showed that manganese uptake of the cane plant was suppressd as its silicon supply was increased. As the Mn content of the plant dropped, the Si content increased However, the converse did not apply as when the cane plant was faced with an excessive supply of Mn, it attempted to compensate by increasing its Si uptake. Fox et al (1967) obtained highly significant correlations between several soil extractants for silicon and soluble silicon extracted from sugar cane leaf sheaths [R ranging from 0,92 to 0,97] From these data tentative calibration ranges were proposed for classifying sugarcane into probable, questionable and unlikely silicon deficiency (See Table 1).

Table 1 Critical soil and leaf sheath Si values for sugar cane [After Fox et al 1967]

Silicon status	Water ppm	Soil extracts $Ca[H_2PO_4]_2$	HOAc	H_2SO_4	Sheath Si TCA soluble ppm fresh	Total %Ovendry
Deficiency probable	< 0.9	<50	<20	<40	<30	<0.5
Deficiency questionable	0.9 to 2.0	50 to 150	20 to 40	40 to 100	30 to 40	0.5 to 0.7
Deficiency unlikely	Over 2.0	Over 150	Over 40	Over 100	Over 40	Over 0.7

A far reaching research outcome by Alexander et al (1969) concerned identifying the dual role of Si in the synthesis,storage and retention of sucrose in the sugar cane plant. Firstly it was found that sucrose inversion in sugarcane juice samples could be delayed for several days by adding sodium metasilicate immediately after milling.Silicate forms a physical complex with sucrose which prevents invertase combining with its substrate. Secondly, Alexander hypothesized that the fructose-silicate configuration is retained even after sucrose is inverted, thereby preventing fructose from being metabolized by microorganisms. In general fructose appears to be the preferred carbon source for microbial growth. Greater cognicance needs to be taken in sucrose synthesis models of the role of the dual role of Si in preserving fructose due to repressing bacteria as well as its ability to inhibiting invertase.

Alexander also showed a relationship between silicon and photosynthesis in investigating enzyme-silicon reactions with gibberellic-acid-treated sugar cane during the post-growth-stimulatory phase (Alexander et al 1969). In another study, Lau et a (1978), proposed that under normal light, that silica deposited in silica cells and stomatal guard cells could serve as 'windows' allowing more light to pass through the epidermal to the photosynthetic mesophyll tissue, thus enabling higher rates of photosynthesis and more tillers per plant. However, no attempt was made to link these hypotheses with the phenomenon of leaf freckling. Freckled plants are considered to be less efficient in photosynthesis because freckling reduces the active leaf area for photosynthesis.

USA (Florida)

In the late seventies the focus of silicon research in sugar cane shifted back to the USA but this time to Florida. Gascho and Andreis (1974) and Gascho (1976), concluded from a series of studies that Si is beneficial and probably essential for sugarcane grown on organic and quartz sand soils in Florida. The authors obtained significant positive responses to slag treatments ranging from 13 to 32% on the muck trial sites and two out of four sand sites In follow up investigations, yields of five varieties of sugarcane were increased on average by 17 % and 21 % during 1989 and 1990 respectively following the addition of 6.7 t ha^{-1} calcium silicate slag (Raid et al. 1992). Florida is well known for its rice-sugarcane rotation, which has been shown to be both economically and agronomically beneficial (Alvarez and Snyder, 1984). Subsequently Anderson and his co-workers observed that an application of 20 t ha^{-1} of slag increased cumulative cane yield by as much as 39 % and sugar yield as much as 50 % over three crop years (Anderson et al, 1991). In all the studies conducted in Florida, no evidence could be found for any mineral toxicity causing the response to Si, nor an improvement in P uptake Available evidence based on leaf analysis and a soil survey conducted by Gascho, indicated that the benefits from Si treatment were linked to a direct silicon deficiency (Gascho, 1976 and 1979).

There have been some interesting developments in researching the role of silicon in disease and pest management. Elawad et al (1982) observed significant decrease leaf freckling in sugarcane following the application of 20 t ha^{-1} of TVA slag to muck soil. Recently, Ulloa et al 1991, Raid et al. (1992) assessed the effect of cultivar and calcium silicate slag treatment on foliar disease development, in a number of sugar cane hybrids. They observed a significant average reduction of 67% in the severity of ringspot, with the addition of the slag (*Leptosphaeria sacchari* Breda de Hann) across the five cultivars studied. However, the severity of sugarcane rust (*Puccinia melanocephala* H. Syd. and P. Syd) was not affected by application of silicate slag. Elawad et al. (1985) also observed that with improved Si nutrition there was a marked increase in the resistance of sugarcane to stem borer (*Diatraea saccharalis* F.). Freshly hatched *D. saccharalis* larvae, feed on epidermal tissue of the sheath, leaves and new internodes in the immature top of the plants. Increased Si uptake from Na_2SiO_3 treated plants apparently acted as a deterrent to the borers. An interesting outcome from their trial was that leaf Si contents were negatively related to shoot borer incidence

Under field conditions at least 1% Si in the TVD leaf is required for optimal cane yields while a Si content as low as 0,25% will result a yield decline of a least 50% of the yield potential (Anderson et al, 1991) Very recent studies have focussed on genotypic differences between cane varieties as better Si acccumulating varieties may have the advantage of needing less frequent Si fertilization (Deren et al 1993 and Korndorfer 1998)

Brazil

Despite that sugarcane is grown extensively on oxisols that are prone to Si deficiency there has surprisingly been very few studies conducted during the early years on the Si requirement of sugarcane in Brazil. In a laboratory investigation of six soils from different regions of Brazil, Lopes (1977) concluded that an increase in pH increased Si adsorption and that the adsorption of Si by the soils decreased P adsorption, especially around pH 7. Casagrande (1981) observed little effect on yield or sucrose content when 4 t ha –1 of cement was applied to sugar cane growing in an oxisol. An investigation to compare the efficacy of several Si sources (Wollastonite, thermal-phosphate, calcium silicate and basic slag) applied to four different soils groups showed that thermal-phosphate was the most effective source to supply both Si and P to rice and sugar cane (Gascho and Korndörfer 1998). In more recent trials conducted at the Sao Martinho and other mills, yield response of between 15 to 20% were obtained to applications of cement, ranging between 4 to 6 t/ha (Korndörfer 2003). A number of new silicon related projects are currently under investigation at various institutes in Brazil.

Australia

Studies conducted in Australia have highlighted that fact that silicon is an important component of the production system and should not be ignored when attempting to attribute causes for below optimum production There are several reports of increases in yield and sugar attributed to silicate based materials and mill wastes (Hurney1973, Haysom and Chapman, 1975, Rudd and Berthelsen, 1998). During the eighties, in some areas cement was used commercially as a source of silicon and applied to cane where the soil Si content was below the critical value of 20ppm(using 0.02N $CaCl_2$) 100 ppm (using 0.01N H_2 SO_4) based on the Truog method of extraction In recent years cement has become uneconomical to use and cheaper sources such as fly ash and filter cake from the mill are increasingly being applied as a substitute (Kingston, 1999) Recently the Yield Decline Joint Venture also focussed some of its activities on studies of soil Si (Berthelsen 1997). The construction of a soil Si map for the Tully/Innisfail area, comprising 34 000 ha., clearly demonstrated that substantial sugar cane areas of the wet coast were inherently low in soil Si (67%). Of interest is that the occurrence of the condition known as Northern Poor Root Syndrome (NPRS) as outlined by Egan *et al*. (1984) and more recently referred to as 'yield decline', appeared in part to be related to sub-optimal levels of soil Si found in many north Queensland sugarcane soils. The areas where NPRS was first recorded as a major problem co-incided with areas that were rated as low in soil silicon (Berthelsen and Noble 2001).

It was concluded that continual sugarcane production has undoubtedly lowered the levels to the extent where cane yields are being substantially affected. Paired site analysis of virgin and associated cultivated soils have also shown that many more soils are becoming deficient under long term sugarcane monoculture Conversely, analysis of rotation sites has shown that breaking the monoculture with a cover crop can increase the availability of silicon (Garside *et al.* 1999. It has also been suggested that observed genotypic differences in the Si status of varieties in more recent selections have been made under declining levels of soil silicon and that "the effects of degraded soil conditions may conceivably be masked by genetic manipulation". (Berthelsen and Noble 2001).

Asia and the Far East

One of the earliest reports linking silicon nutrition with borer damage in cane may be credited to an Indian researcher (Rao 1967). Sugarcane varieties that were tolerant to a shoot borer showed the highest number of Si cells per unit area in the leaf sheath. In Taiwan, Pan and his co-workers showed that the incidence of borer damage in silicon treated cane was less than in untreated sugarcane (Pan et al. 1979). Silicon deposited in the epidermal tissue may have several functions including support and protection in the form of a mechanical barrier against pathogen and predator invasions. (Takahashi and Miyake , 1990). An earlier hypothesis proposes that the polymerized Si acids fill up apertures of cellulose micelle constituting cell walls and make up a Si cellulose membrane. This membrane is supposed to be mainly responsible for protecting the plant from some diseases and insects (Yoshida et al., 1969)

When Si becomes deficient in soils, there is evidence from a number of studies that the rate of transpiration increases and may become excessive. Solution culture studies in Japan with rice have shown that Si strongly influences water loss in plants by reducing cuticular transpiration. In one particular study, an application of 45ppm Si in the nutrient solution decreased the transpiration rate from 5.1 to 3.6ml/g biomass/24 hour period (Okuda and Takahashi 1964). According to Wong You Cheong et al.(1972), improved Si nutrition may reduce excessive leaf transpiration in sugarcane. Jayabad and Chockalingam (1990) observed increased yields of sugarcane (var. CO. 6304) that was subjected to moisture stress after spraying with 2.5 % sodium metasilicate. The effect was attributed to a reduced rate of transpiration.

These findings suggest a role for Si in the water economy of the plant The rate of transpiration is controlled by the amount of silica gel associated with the cellulose in the cell walls of epidermal cells This mechanism could explain why wilting may occur under conditions of low humidity. A thickened layer of silica gel will help to reduce water loss, while epidermal cell wall with less silica gel will allow water to escape at an accelerated rate. By increasing the Si content of plants, it may be possible to reduce their internal water stress and in this way increase their tolerance to salt stress Yoshida (1965) showed that rice plants without a Si supply could not grow in a culture solution which contained salt equivalent to an osmotic pressure of 5 atm, whereas plants with a Si supply grew well in the same nutrient solution.

South Africa

For many years, silicon deficiency was relatively unknown in the South African sugar industry but in 1967, aluminium toxicity together with silicon deficiency, were first identified as potential growth limiting factors in the highly weathered oxisol soils of the newly developed cane areas of the Natal Midlands (Bishop1967).

Further evidence that silicon was potentially a growth limiting factor in these soils was one of the outcomes from the wattle brush ash investigation that were initiated in 1969 (Meyer 1970). The superior growth of cane along these lines was associated with the windrows of wattle brushwood, which were burnt prior to land preparation. Analyses of soils containing wattle ash showed highly significant reductions in acidity and labile Al, and increases in the amounts of plant available Si,Ca, Mg, P, and K.

A second pot trial with sugarcane to compare various sources of Si showed that the highest yields were obtained with cement at 9 metric tons per hectare and Blast furnace slag at 18 metric tons per hectare (see Fig 1). Both these yields were significantly better than the highest yield obtained from the addition of calcium carbonate (Du Preez, 1970). The author concluded that the main factors probably responsible for the yield increases were decreased levels of aluminium and manganese, and increased levels of silicon in the soil.

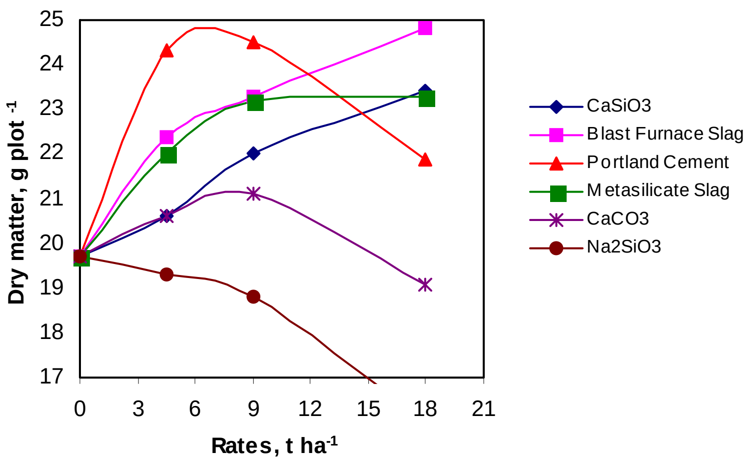

Figure 1. Effect of different Si sources on sugarcane dry matter production

A series of follow up field trials covering a total of 14 crops from six trials to compare the relative efficacy of Si carriers such as Slagsil [SiO_2 35%], Hulsar lime [SiO_2 <2%], Amcor slag [SiO_2 37%] and Hawaiian calcium metasilicate [SiO_2 49%], conclusively showed that the silicon carriers were superior to lime treatments with nine significant responses to Si and six for the lime treatment (Moberly and Meyer 1975). Residual treatment effects were also marked and in one of the trials at Seven Oaks, the Slagsil treatment increased yield significantly in the plant crop and significant residual treatment effects were also obtained in the following three ratoon crops.

ROLE OF SILICON IN ALLEVIATING BIOTIC STRESS

Apart from the beneficial effect of Si in alleviating abiotic stress factors, there is a growing body of evidence, largely from rice, that Si can reduce the effects of biotic stress by directly enhancing plant resistance to pests and fungal-based diseases. Sasamoto (1953) was among the early workers to report the beneficial effect of applied silicate and available soil silicon on resistance of rice to the rice stem borer *Chilo suppressalis* (Walker). In sugar cane one of the earliest reports linking silicon nutrition with borer damage may be credited to an Indian researcher (Rao 1967). He found that varieties tolerant to the shoot borer *Chilo infuscatelus* Snellen, exhibited the highest density of silica cells in the leaf sheath. Pan *et al.* (1979) reported that sugarcane treated with bagasse furnace ash (composed of 60.44% silica) and silica slag (42.95% silica) suffered less damage by stem borers than check plots. Similarly, treatments with potassium silicate significantly decreased the third and fourth brood population of the pyralid borer *Scirpophaga excerptalis* and increased cane yield and sugar (Gupta et al. 1992). Elawad *et al.* (1985) found that plants growing inside a greenhouse suffered progressively lower infestation by the sugarcane borer, *Diatraea saccharalis* F., with higher treatments of calcium silicate in the potting soil. Subsequent studies confirmed the positive effect of silicon in increasing the resistance of sugar cane to this stalk borer (Anderson and Sosa 2001). Savant e*t al.* (1999), drew attention to the observation that increased incidence of stalk borers (*Eldana saccharina* and

Chilo auricilius) in sugarcane with high N application alone, could probably have been prevented by application of silica together with N fertilizers.

Apart from the ringspot study conducted by Raid and others (1992) in sugar cane, very few studies have been conducted by plant pathologists to assess the potential role of Si in integrated disease management for reducing fungicide use. In contrast with rice, there have been numerous reports of Si treatments controlling diseases including blast, brownspot, sheath blight, leaf scald and grain discoloration as reviewed by Datnoff et al (2001)

Recent research outcomes from the South African Sugar Industry

In South Africa, the eldana stalk borer is still endemic and recent studies have focused on the association between silicon assimilation and host-plant resistance to the stalk borer *Eldana saccharina* Walker (Lepidoptera: Pyralidae), (Meyer and Keeping 2000). Both pot and field trials are in progress to compare the efficacy of locally available Si sources such as fly and boiler ash from the mills, Slagment, and a local calcium silicate slag with two high quality imported calcium silicate slags used in the Florida sugar industry.

Evidence from a large scale pot trial in which sugarcane was treated with calcium silicate at two levels (2.5 t/ha and 5 t/ha) and artificially infested with *E. saccharina* at 9.5 months, showed a significant response in average stalk yield to the Si treatments, as well as significant reductions of 30% in borer damage and 20% in borer mass to the 5t/ha calcium silicate treatment. Values for the 2.5t/ha treatment were intermediate between controls and the higher treatment (Meyer and Keeping 2001). An assessment of the six varieties tested showed a positive response in silicon uptake with silicon treatment. On average the intermediate silicon treatment doubled the stalk silicon content from 0.16 to 0.33. %. In general the more susceptible varieties showed the highest silicon uptake. The length of stalk damage was inversely correlated with the silicon content of the cane stalk. The most susceptible variety (N11) showed the greatest benefit in terms of reduced stalk damage from silicon treatment and this coincided with the largest percentage increase in silicon content in the stalk. In contrast, the more resistant varieties such as N21 showed the lowest rate of increase in silicon content in the stalk (Meyer and Keeping 2001).

The results of a second pot trial confirmed that soil Si amendments can significantly reduce stalk damage and yield loss due to the eldana borer. The most encouraging aspect of the results was that the resistance to eldana was markedly improved even in our more tolerant varieties such as N21 and N33 (Keeping and Meyer 2002). Another valuable outcome from this trial was that the untreated resistant varieties were characterized by markedly higher average stalk silicon contents (N33 0.19% and N21 0.14%) than the susceptible varieties (N26 0.08% and N30 0.11%). Stalk borer damage was inversely correlated with the silicon content of the stalk (R^2 = -0.78*).

In a follow up third pot trial, the efficacy of the four silicon carriers in increasing the silicon content of the cane stalk and reducing damage from eldana declined in the order: Local Namibian calcium silicate > Imported USA slag>Local Slagment>Flyash. On average the highest silicon treatment (1200 kg/ha Si) reduced borer numbers by 31% across all Si sources in the two susceptible varieties (N26 and N30) and by 13% in the two resistant varieties (N21 and N33) (Keeping and Meyer 2003). The largest significant increase in plant-Si% (especially stalk-Si%) resulted from treatment with local calcium silicate, followed by that from USA calcium silicate; plant-Si% from Slagment and flyash treatments was somewhat less and more variable. Although varieties differed in Si uptake from each source, there was no evidence that it was higher in susceptible varieties than resistant ones. However, there were indications (from the untreated controls) that the resistant varieties had an inherently higher stalk Si content than their susceptible counterparts (Si% mean, range: N21: 0.14, 0.11 – 0.21; N33: 0.19, 0.16 – 0.22; N26: 0.08, 0.06 – 0.09; N30: 0.11, 0.09 – 0.14). Significant differences between cultivars in leaf Si content (Deren et al., 1993) and in Si accumulation capacity (Savant et al., 1999) have been demonstrated for sugarcane.

Of the four field trials with silicon treatments that have been harvested three have shown positive results in reducing damage from the eldana borer. The first trial established in 1998 to assess the potential of a local Si source, applied at a rate of 3t/ha to a grey Cartref soil (13% clay), showed reductions of 31% in borer numbers and 23% in length of stalk damaged. In a second trial with flyash, containing about 10% Si, borer numbers were reduced from an average of 45 per 100 stalks where no fly ash was used to 18 per 100 stalks where the soils had been treated with a broadcast application of 80t/ha fly ash. The plant crop results of a recently established silicon x eldana field trial with two susceptible and one resistant cane variety, showed maximum reductions in percent stalk length damaged (depending on Si carrier and treatment level) of 24%, 30% and 35% in varieties N27, N29 and N35% respectively. On average, the most susceptible variety N35, also gave the greatest yield response to silicon treatment (+23%), followed by N27 (+9%) and N29 (+4%).

Silicon-nitrogen interaction effects on resistance to pests

According to Setamou et al (1993), the development of phytophagous insects often depends on the physiological condition of the plant, particularly its nutrient status which is also a source of food for herbivores.The use of fertilizers to enhance plant nutrition often influences the longevity, fecundity and damage caused by insects and mites. Studies conducted in Nigeria on the maize borer Sesamia calamistis have shown that increasing N doses significantly increased larval survival from 18 to 37% and larval weight from 49mg to 99mg, while increasing silica supply reduced larval survival from 26 to 4% (Setamou et al 1993). Similar results were reported by Atkinson and Nuss (1987) for sugar cane with increasing N supply under conditions of moisture stress.

The results from a preliminary glasshouse trial to study the interaction between nitrogen and silicon nutrition on eldana infestation showed that applied N significantly increased the relative percentage yield response in sucrose (see Table 2). In the absence of Si the response to the 120 and 180 kg/ha N treatments tended to be curvilinear while in the presence of Si the response was linear up to the highest N level. On average the applied Si treatment increased relative yield response by 16% across all three N treatments and varieties Meyer and Keeping 2005).

Table 2. Impact of nitrogen and silicon treatment on relative sucrose yield and eldana damage (average across five varieties)

N level	Si level	Relative Sucrose Yield (%)	%stalk damaged	% internodes damaged	Weighted average
N1 60kg/ha	Si0	44	79	14	68
N2 120kh/ha	Si0	68	74	11	90
N3 180kg/ha	Si0	79	87	17	208
N1 60kg/ha	Si1	49	42	5	19
N2 120kh/ha	Si1	74	55	7	61
N3 180kg/ha	Si1	100	76	11	155
LSD(0.05)		19	14	3	25

Highly significant differences in eldana susceptibility were obtained to nitrogen and silicon treatment. Nitrogen treatment in the absence of Si increased the weighted eldana susceptibility rating from an average of 68 at the low level of N (60kg/ha N) to 208 at the high level of N (180kg/ha N) across all varieties. NCo376 and N35 showed the greatest change in susceptibility to eldana and increasing N levels, with ratings increasing from resistant (<weighted average <50) at the low level of N, to highly susceptible (>175) at the high level of N (see Fig2). Variety N31 was the least affected by N, but the weighted average rating was already high (144) at the low level of N. Of interest was that the most eldana resistant variety in this trial, N37, while resistant at the low and intermediate levels of N (37 and 34 respectively), became susceptible to eldana at the high level of N (166).

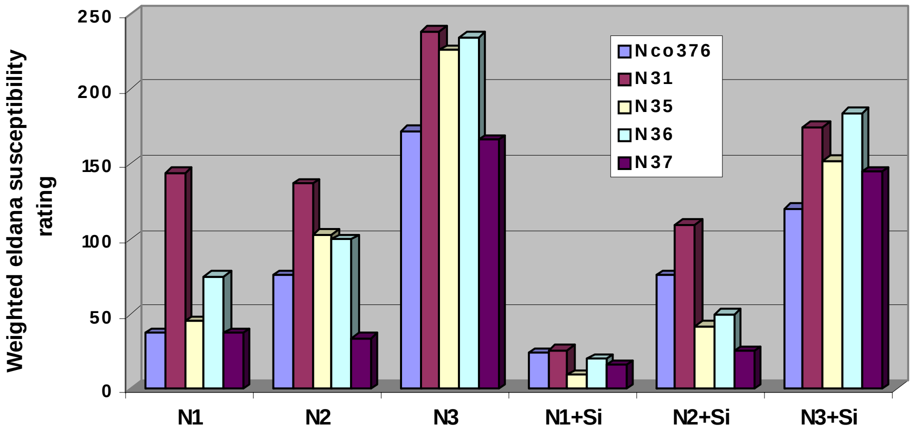

Figure 2 Effect of nitrogen treatment in the absence and presence of silicon on susceptibility to eldana borer in five cane varieties (after Meyer and Keeping 2005)

Overall treatment with Si had a significant impact in reducing the damaging effects of N treatment on eldana levels. The percent stalk damaged was reduced by an average of 47% across all five susceptible varieties that were included in the trial. Maximum reductions in percent stalk damaged from silicon treatment, ranged from a 70% average at the lowest N level, to 39% at the intermediate N level down to 35% at the highest N treatment. The beneficial effect of Si in reducing borer damage at the high N level was also evident in the reduced stalk length bored, lower number of internodes damaged, lower borer numbers and borer mass. This may be seen from the weighted eldana susceptibility rating, which declined from an average of 208 in the absence of Si to 155 where Si had been applied. N35 showed the greatest reduction from Si treatment, the weighted average declining from 226 to 152. Si treatment also produced benefits at the low level of N with the weighted average declining on average from 68 to 19. The susceptible variety N31 showed the greatest benefit to Si treatment at the lowest level of N, declining from a weighted average of 144 to 26.

It was evident from leaf and stalk tissue analysis that increased nitrogen application increased nitrogen and reduced silicon uptake, and this condition in turn favored increased survival of larvae and borer infestation. Overall, the relatively poor performance of varieties N31 and N35 compared with N37 may be ascribed to the greater susceptibility of these two varieties to eldana infestation, resulting in a severe loss in cane yield as well as sucrose content. However, the addition of Si at the high rate of N tended to militate against the borer damage resulting in an improvement in sucrose yield (not significant).

A further important outcome from the trial was the finding that the leaf and stalk N/Si ratio's were better correlated with resistance to stalk borer than either N% or Si% expressed separately. Leaf N/Si ratios above 2:1 were associated with cane showing increasing risk from eldana damage. High resistance to eldana (weighted eldana resistance (ER) ratings below 50) was associated with N/Si leaf ratios below 2 whereas moderate resistance (ER ratings from 50 to 100) was associated with N/Si ratios varying from 2 to 4. Moderate to low resistance (ER ratings of 100 and higher) tended to be associated with and leaf N/Si ratios in excess of 4.

Possible mechanisms for Si in alleviating biotic stress

Silica deposits, commonly called phytoliths, occur in cell walls, cell lumens or in intercellular spaces and external layers (Parry and Smithson 1964). Silicification also occurs in roots and the shoot including leaves, culms and, in grasses, most heavily in the inflorescence. Deposits occur in epidermal, strengthening, storage and vascular tissues (Sangster 1999). Silicification is reported in the Pteridophyta and the Spermatophyta, including gymnosperms and angiosperms. Among the monocotyledons, the Cyperaceae and Poaceae (Gramineae) are pre-eminent accumulators of Si although recent evidence indicates that certain Dicotyledon families such as Fabaceae, Cucurbitaceae and Asteraceae also containing significant amounts of silicon (Richmond and Sussman 2003). Biogenic silica structure is affected by ambient physico-chemical conditions mediated by tissue maturation, pH, ionic concentrations and cell wall structure. Polymerized Si acids fill up apertures of cellulose micelle constituting cell walls that make up a Si cellulose membrane forming a mechanical barrier against pathogen and predator invasions (Yoshida et al., 1969, Takahashi and Miyake 1977). The increase of the borer's incidence may also be partly due to the formation of stronger stalks (Jones 1965, Jones and Handreck, 1967; Lewin and Reimann, 1969). Plants like sugarcane and rice, with high Si contents, seem to interfere in the feeding of larvae, damaging their mandibles. The presence of Si crystals in these tissues hinders the feeding of the insect, which in the early stage has rather fragile mandibles. Studies in the South African sugar industry have shown decreased mandibular wear among larvae recovered from bioassays using electron microscopy from Si treated sugar cane (Kvedaras et al 2005).

The interaction of Si in the water economy of the plant in terms of reducing moisture stress and the form of nitrogen could also be part of the mechanism in conferring resistance to hyphae and pest attack. The Japanese studies have suggested that Si deficiency increases the effects of moisture stress on the plant. Studies in the South African sugar industry have shown that excessive N usage under conditions of moisture stress greatly increased survival of larvae and infestation of sugar cane by the Eldana borer presumably because of a lower uptake of silicon under these conditions. Other evidence has indicated that Si physiologically promotes ammonium assimilation and restrains the increase in soluble nitrogen compounds, including amino acids and amide, which are instrumental for the propagation of hyphae (Takahashi and Miyake, 1990). It seems likely therefore that not only does Si deficiency increase moisture stress but that the form of nitrogen changes to predominantly amino acid which are conducive to borer infestation.

Other recent evidence suggests that silicon may also reinforce plant disease resistance by stimulating the expression of natural defense reactions through the production of low-molecular weight metabolites which include flavonoid phytoalexins (Belanger et al 1999). Previous research at SASRI has emphasized the role of stalk bud scale flavonoids in *Eldana saccharina* resistance (Rutherford et al 1993 and 1998) and it is possible that silicon similarly stimulates the expression of these flavonoids. These mechanisms could compliment the physical barrier effect and explain the significant reductions in borer damage and in borer mass obtained from Si treatments in recent SASRI trials.

CONCLUSIONS AND FUTURE RESEARCH

This review has highlighted silicon as an important component of the sugarcane production system. A considerable amount of research has been conducted worldwide into the silicon requirement of sugarcane and the evidence suggests that a multi functional role may be assigned to silicon in alleviating stress in sugarcane Sugar cane yield responses to Si may be associated with alleviating abiotic stresses such as Al and Mn toxicity, moisture stress during drought, reduced lodging, increased resistance to freezing as well as the potential for relieving biotic stresses caused by certain diseases and pests In the South Sugar Industry, several studies have shown that silicate slags are more effective than limestone in overcoming Al toxicity problems in highly weathered oxisols that occur in the Kwa ZuluNatal midlands Current research has focussed on the association between silicon assimilation and host-plant resistance to the stalk borer *Eldana saccharina* Walker (Lepidoptera: Pyralidae). Research outcomes have shown that an application of calcium silicate at a rate of 5t/ha can improve the resistance of sugar cane to the eldana borer and reduce the risk of damage in susceptible varieties by as much as 40%. The use of silicon will also enable many growers who have severely cut back on their nitrogen applications to reduce the risk of eldana damage, and to resume applying the normal recommended rates of nitrogen ensuring that nitrogen will not be limiting crop yield. Results have also confirmed that the efficacy of local sources of calcium silicate, are as good as imported sources from the USA. Foliar diagnosis confirms that the silicon content of top visible dewlap leaf (TVD) is a good guide to the silicon requirement of sugar cane with Si levels below 0.75% indicating a need for Si. However, our studies indicate that the N/Si ratio is better correlated with potential eldana damage than Si alone and that sugar cane with TVD values in excess of 4 are associated with increasing risk from borer damage. The silicon status of the stalk is also closely related to borer damage and silicon levels below 0.2% are associated with increasing risk from damage by the eldana borer. As this pest is still endemic and responsible for major annual losses in sugar production.in the South African sugar industry, further research on silicon assimilation and host-plant resistance to the stalk borer *Eldana saccharina* Walker (Lepidoptera: Pyralidae) is warranted and needs to be accelerated.

Other aspects of silicon nutrition of cane that appears to be warranted includes:

- the interaction between nitrogen, silicon and water stess needs further investigation particularly with regard to confirming the forms of nitrogen when the crop is deficient in nitrogen. Does a silicon layer exert a proportionately greater effect in enhancing resistance in water stressed Si-treated plants than in unstressed Si-treated plants?
- comparing the efficacy of locally available silicon sources such as filter cake, fly ash, siliceous slags and liming materials
- determining whether silicon has a role in increasing resistance to other fungal derived diseases such as smut and mosaic as well as pests such as white grub and nematodes
- calibrating a suitable soil test extractant for measuring plant available silicon
- conducting periodic surveys of the silicon status of sugarcane through the analysis of soil and leaf samples in the main extension areas of the sugar industry
- investigating genotypic differences between cane varieties Better Si-accumulating varieties may have the advantage of requiring lower rates of Si fertilizer or less frequent applications.
- researching the role that Si plays in the synthesis, storage and retention of sucrose in the sugarcane plant. Since the pioneering work by Alexander, very little follow up research has been carried
- there are opportunities for the biotechnologists to clarify the mechanisms for Si uptake, transport and deposition in the plant and to identify those genes that are involved in silicon biology (Richmond and Sussman 2003).The identification of putative silicon transporters and the control of their expression will help to promote research into the role of silicon in the physiology of sugar cane.

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Stephen D. Kinrade, PhD
ORGANOSILICATE CHEMISTRY: EVIDENCE FOR A CROSS-LINKING ROLE IN PLANTS

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Despite growing awareness of silicon's importance in plants, knowledge of its physiological and biochemical activity remains poor. The only organic molecules known to interact with silicon under physiological conditions are those containing certain sugar derivatives, such as ribose and threitol. The molecular mechanism underlying silicon's bio-essentiality is a mystery. Nevertheless, very recent work suggests that the benefits plants derive from silicon may be due to its ability to cross-link key molecules in the sugar-rich environment of plant cell walls, as described below.

In-vitro experiments reveal that silicon binds to the apiose residues of rhamnogalacturonan II (RG-II), a pectic polysaccharide found in the primary cell walls of angiosperms, gymnosperms, lycophytes and pteridophytes. It has been long established that boron binds at these sites, cross-linking pairs of RG-II molecules and thus strengthening the pectic network. Plant-stem cells of wheat (*Triticum aestivum*) grown to maturity in hydroponic medium containing either nil or 0.02 mM Si exhibited significantly smaller wall thicknesses in the case of the +Si plants, an effect not unlike that induced by boron. The cells affected were those lacking a secondary cell wall, such as the outer parenchyma cells which, in the +Si plants, exhibited a 75% decrease in wall thickness. In a follow-up experiment, wheat grown in peat (containing traces of soluble silicon) and watered with solution that was Si-free or contained 100 ppm Si showed a similar effect, although it was less pronounced. The average wall thickness of leaf parenchyma cells in the +Si plants was 14% less than that of the –Si plants, even though the total Si content of the leaves was nearly the same for both sets.

These preliminary findings support the hypothesis that silicon does indeed play a cross-linking role in the cell walls of plants. A *constant* supply of dissolved Si is critical, however, to maintain a significant concentration of these labile cross-links.

Gaspar H. Korndörfer, PhD
AVAILABLE SILICON IN TROPICAL SOILS AND CROP YIELD

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1. INTRODUCTION

Increases in Si availability in the soil are usually accompanied by increased Si content in the plant, which may result in increased growth and productivity in several grasses, especially rice, sugarcane, sorghum, millet, brachiaria, oat, wheat, and corn, and in some non-grass species such as soybean, bean, tomato, strawberry, and cucumber.

In the plant, the absorbed Si has beneficial effects related mainly to an increased resistance against the attack of pests (insects), nematodes, diseases, and a decrease in transpiration rate. All these benefits suggest that Si should be included in the micronutrient list. Thus, starting with Decree-Law number 4,954, which regulates law number 6,894 of 01/16/1980, passed on 14 January 2004 (Brasil, 2004), and provides for the production and sale of fertilizers, Si has been included in the list of micronutrients.

2. SILICON IN THE SOIL

Several soil classes in the central region of Brazil, especially in areas under cerrado vegetation, are poor in soluble Si (available to plants) (Raij & Camargo, 1973). Under these conditions, positive responses can be expected from Si application in the form of fertilizers and/or silicate-based corrective amendments, especially when they are applied in Si-accumulating plants, such as most grasses.

With regard to soil soluble Si, soil texture (clay content) has been considered one of the most important parameters in predicting Si requirements to plants.

Defining the best soil extractor method is another essential aspect to be considered when recommending fertilizers that contain Si. Several extractors can be used, such as water, calcium chloride (0.01M), common in Australia and Brazil, and acetic acid (0.5M), used in the United States.

2.2. RELATION BETWEEN pH AND AVAILABLE SILICON

In acid and weathered soil (desilicated or "old" soils) the silica contained in minerals has been strongly leached. The remaining soluble Si can be linked by the soil constituent depending on soil pH, reaching maximum values at acid pH levels. Increases in pH promote the release of colloid-adsorbed Si to the soil solution. On the other hand, the higher the soil pH, the higher the transformation of polysilicic acid (insoluble) into monosilicic acid (soluble). This pH effect on the soluble Si was showed by Oliveira (2004) in a sandy soil cultivated with dryland rice (Figure 1).

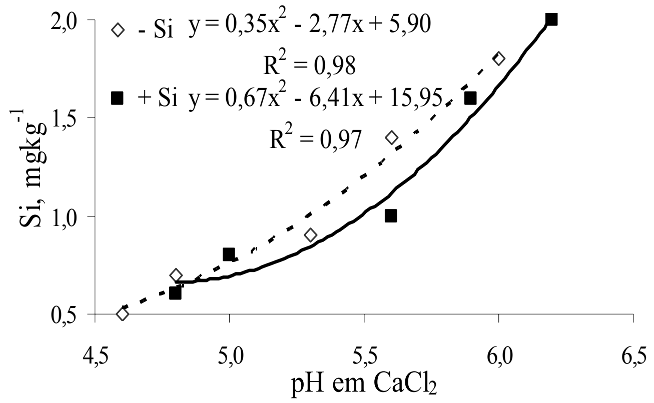

Figure 1 – Si content extracted with $CaCl_2$ in a Typic Quartzipsamment (sandy soil) as a function of pH changes (Source: Oliveira, 2004).

Mckeague & Cline (1963) verified that the degree of ionization in the soil solution increases as pH increases, i.e., at alkaline pH levels there is greater formation of silicate ions ($H_3SiO_4^-$). At the normal pH range (5.5 to 6.5), H_4SiO_4 is the main Si form (chemical species) present in the soil solution. At high concentrations, around 28 mg dm^{-3} Si in the solution, the monomer becomes polymerized to form amorphous silica precipitated.

A 90 days incubation experiment was carried out to determine soluble silicon using different extractors in 13 important soils cropped in the Triangulo Mineiro region in Brazil under 0, 2, 4 and 6 t ha^{-1} of $_{CaCO3}$ (Vidal, 2005). The acetic acid was able to extracted more silicon from the soils than either $CaCl_2$ or water extractor. The available silicon increased according to the soil pH increase, i. e., the greater pH, the higher was the extraction of the silicon in the acetic acid. The application of phosphorus fertilizer to the soils increased the soluble silicon (Figure 2). The solubility of silicon in the soils was also affected by pH when the $CaCl_2$ extractor was used, however, in some soils the solubility of Si increased and in others it decreased. This is different from what was observed with acetic acid extractor. Comparing silicon and phosphorus sorption in the same soils it was showed that P sorption capacity range was much higher compared to silicon sorption capacity for the same soils. Silicon was much less affected by sorption reactions compared to those of P (Figure 2 and 3).

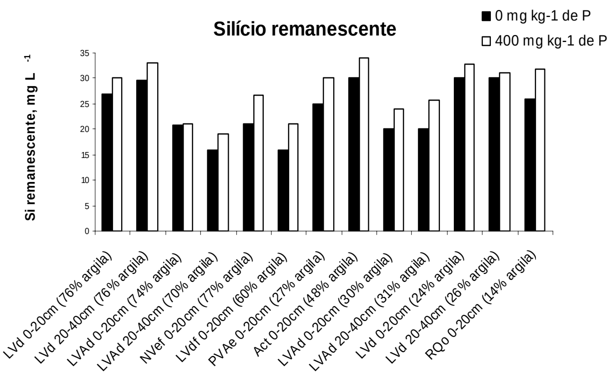

FIGURE 2. Residual silicon in solution after the addition of 60 mg L^{-1} of Si with the soil.

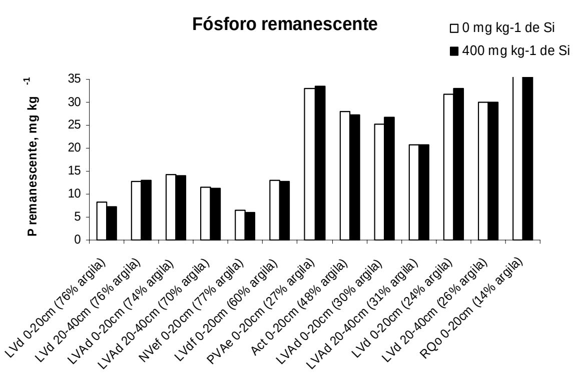

FIGURE 3. Residual phosphorus in solution after the addition of 60 mg L^{-1} of P with the soil.

2.3. SOIL TEXTURE AND SOLUBLE SILICON

Extractable Si values increase with soil clay contents (Meyer, 2001). Gontijo (2000) studied soils from different locations and with different textures, and observed that soil silicon values decreased as sand values increased (Figure 4).

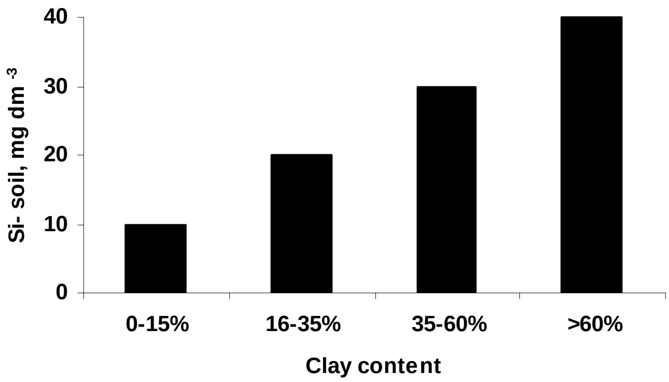

Figure 4 – Extractable (acetic acid) Si contents in soils with different textural classes (Source: Gontijo, 2000).

Soils with high percentages of sand tend to show low Si contents due to their little capacity to supply Si to plants. Sand consists basically of quartz minerals and, in spite of having a high SiO_2 content in its composition, has a low Si release potential in the short and medium term. Thus, the sand fraction of a soil is practically inert. Sandy soils normally also show good drainage, which prevents Si accumulation and the resulting polymerization of these compounds.

3. SOIL AVAILABLE SILICON AND CROP YIELD

Silicon is a chemical element involved in transpiration-related functions, capable of concentrating in the epidermis of leaves, forming a mechanical barrier against the invasion of fungi within the cells, and also making it more difficult for sucking and chewing insects to attack (Epstein, 1999). The mechanical protection effect of Si in plants is mostly attributed to the fact that it is deposited in the cell wall in the form of amorphous silica ($SiO_2.nH_2O$). The accumulation of silica in transpiration organs, in turn, causes the formation of a double layer of cuticle silica which decreases water requirements in plants by reducing transpiration.

Sugarcane responds favorably to Si fertilization, particularly in sandy soils with low concentrations of this element (Si < 18 mg kg^{-1} extracted with 0.5M acetic acid). Field works have demonstrated that the application of non-conventional Si sources (cement), may result in benefits for the crop. An average increase of 14 t ha^{-1} of sugarcane was observed with the application of 4 t ha^{-1} of cement at sugarcane planting, at Nova União sugar mill (Figure 5). Cement, however, presents several inconveniences, such as price and the risk that the soil will become concreted.

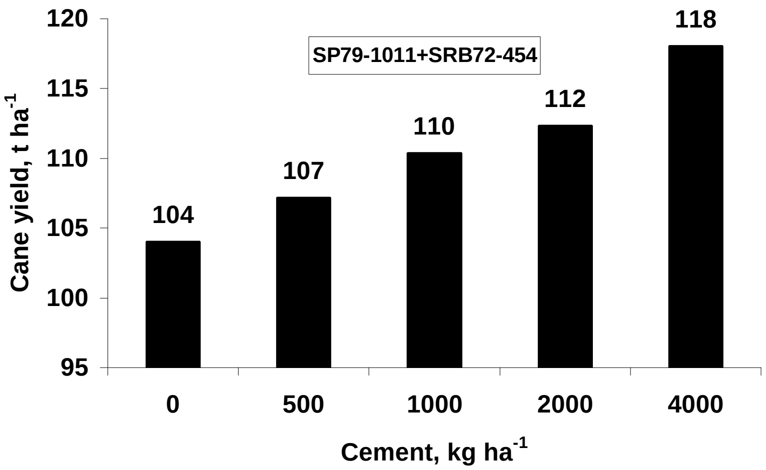

FIGURE 5. Effect of cement application as Si source in plant cane (Us.Nova União/SP, cultivars SP79-1011 and RB72-454)

Bittencourt et al. (2003), studying the effects of calcium silicate, showed increases of 7% in the sugarcane stalks yield and of 11% in the production of sugar per hectare (Table 1). Silveira Jr. et al. (2003) also obtained stalk yield increases in plant cane (Figure 6) and ratoon cane (Figure 7) with the use of silicate; these were higher than the effects of limestone. The authors of both papers concluded that there is no effect of calcium silicate on the technological characteristics of the sugarcane. The effects of silicon on sugarcane yield could be associated with the pest control or even because of an increased tolerance to water stress provided by the accumulation of silicon in the leaves, and by an increase in photosynthesis rate due to plant architecture changes (Faria, 2000).

TABLE 1. Technological analysis, stalk and sugar yield of plant cane (RB85-5536) in the 16th month after planting in the Amoreira Farm, EQUIPAV sugar-mill (Source: Bittencourt et al, 2003).

Silicate	**Juice Brix**	**Cane Fiber**	**Sugar WBW**	**Si Leaf**	**Stalk Yield**	**Sugar Yield**
kg ha^{-1}	%	%	kg t^{-1}	%	t ha^{-1}	t ha^{-1}
0	21.5	14.1	148	0.41	128	19.6
700	20.2	12.7	138	0.43	134	19.4
1400	20.9	12.5	136	0.41	136	20.8
2800	20.9	11.8	132	0.47	137	21.7
5600	21.9	12.2	136	0.51	135	21.1
Prob.	3.7	1.7	2.3	5.5	10.8	30.3
CV%	3.1	6.7	4.1	8.7	4.0	8.2

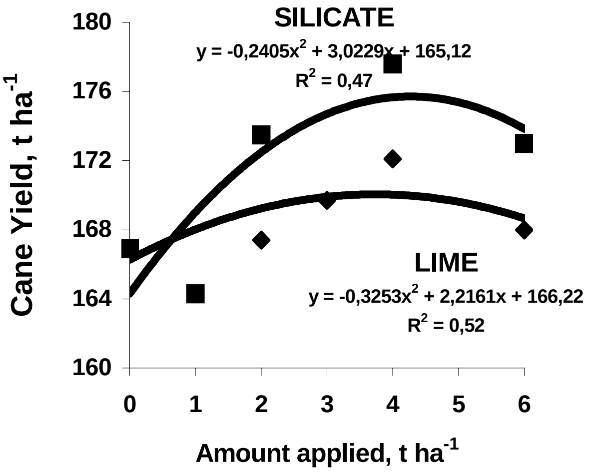

FIGURE 6. Effect of calcium silicate and limestone application on stalk yield of plant cane.

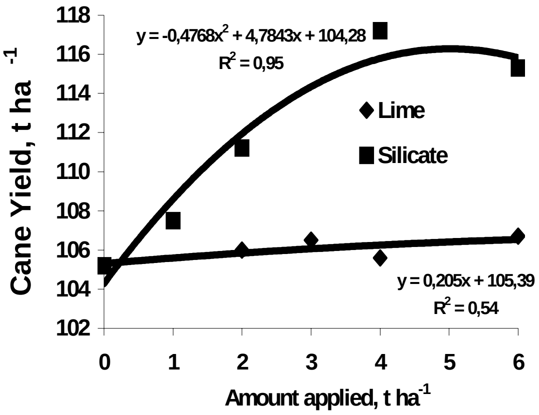

FIGURE 7. Effect of calcium silicate and lime application on stalk yield of plant cane.

Increases in rice grain yield as a consequence of Si application have been verified in several papers. Korndörfer et al. (2001), working with paddy rice during the 1992-1996 period, concluded that there was an average increase of 1,007 kg ha^{-1} in grain yield for plots that received Si in the form of silicate (mean of 23 field experiments).

Faria (2000) also verified an increase in rice yield as a function of Si rates applied. Regardless of soil type used, there was a linear increase in grain yield going from 38.6 to 54.3 g pot^{-1} in a sandy soil and from 60.6 to 79.0 g pot^{-1} in a clay soil, for doses of 0 and 600 kg ha^{-1} Si, respectively (Figures 8 and 9). This linear behavior suggests that rice grain yield could have been even higher if Si rates higher than 600 kg ha^{-1} would have been used in the test. According to Marschner (1995) and Takahashi, (1996), Si accumulated in the rice plant reduces the transpiration rate, thus decreasing water intake necessity by the crop.

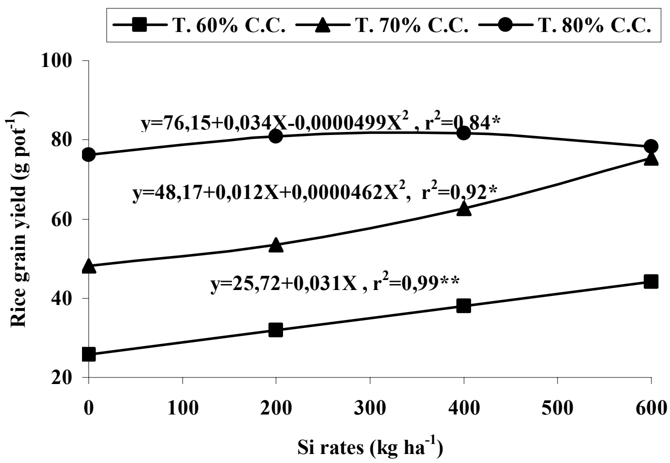

FIGURE 8. Rice grain yield as a function of Si application in soils submitted to different moisture content, C.C.= field capacity (Source: Faria, 2000).

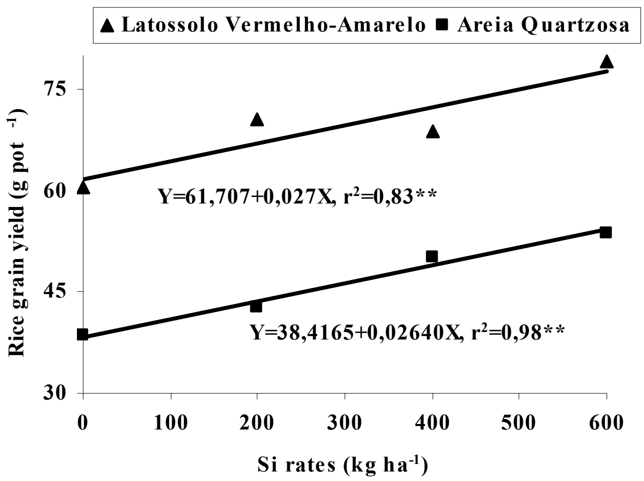

FIGURE 9. Rice grain yield as a function of Si application in two different soil type (Source: Faria, 2000)

Korndörfer & Gascho (1999), studying changes in the chemical characteristics of a soil cultivated with rice, observed that both soil and plant parameters were significantly affected by the Si sources and rates used (Table 2). During the initial stages (3 weeks), differences in rice growth habit (more erect plants), plant height, green matter yield, and leaf coloration were more favorable in treatments containing Ca silicate, Wollastonite, and thermophosphate, when compared with other sources. All available Si sources increased soil pH.

TABLE 2. Changes in soil chemical characteristics and in Si concentration in rice plants as a function of silicate sources (Adapted from Korndorfer & Gascho (1999).

SOURCES	Doses	Si	Soil			
	Si	Plant	pH	Si	P	Ca
	mg kg^{-1}	g. kg-1	(H_2O)	mg kg^{-1}		cm_c dm^{-3}
Control	0	11c	4.6c	5c	20d	1.8b
Tennesse Slag	500	14b	5.4b	53b	46b	4.4a
Wollastonite	500	22a	5.7ab	58b	34c	4.4a
Minas Alloy	500	15b	5.8ab	8c	37c	2.1b
Serpentinite	500	7d	4.8c	9c	37c	1.9b
Thermophosphate	500	20a	6.2a	107a	345a	4.5a

In Brazil, several studies have been conducted with the objective of linking plant Si accumulation with plant diseases and crop yield. Rodrigues (2000) showed that an increase in Si contents in rice plants with the application of Ca and Mg silicate in the soil could explain the reduction in the appearance of lesions caused by "sheath blight" *(Rhizoctonia solani)* and in the relative length of those lesions.

Santos et al., (2003) studying the occurrence of rice blast disease, observed that silicate application resulted in the control of its severity, producing a 47% increase in paddy rice yield (Table 3). Fonseca et al. (2003) showed that the use of 4 t ha^{-1} of Ca silicate did not influence sheath blight but reduced the incidence of rice blast disease (Table 4). The Si effect on the incidence of diseases in rice is even more striking when high nitrogen rates are applied (Datnoff et al., 1990). This occurs because nitrogen fertilization leaves the rice plants more sensitive to diseases, particularly to the attack of *P. grisea* (rice blast disease).

TABLE 3. Effect of silicate rates and occurrence of leaf and panicle diseases and irrigated rice yield, in the Formoso Project, Tocantins, 1999-2000 cropping season (Source: Santos et al., 2003)

Silicate Doses	Severity		Incidence Rice Blast Disease in panicles**	Grain spot		Grain yield
	Brown Spot*	Rice blast disease leaves*		Incidence**	Severity*	
(kg ha^{-1})	(degree)	ratings from 0 to 9	% panicles	% grain with spots	ratings from 0 to 4	(kg ha^{-1})
Control	47.6 a	5.0 a	4.6 a	25.2 a	2.0 a	2240 b
1000	58.4 a	3.8 ab	4.2 a	23.6 a	2.0 a	2490 b
2000	67.8 a	3.7 ab	4.6 a	24.8 a	1.8 a	2510 b
4000	38.6 a	3.6 ab	4.8 a	23.2 a	1.8 a	3090 a
6000	30.0 a	3.0 b	4.0 a	23.6 a	1.4 a	3290 a
C.V.(%)	29	8	11	15	8	3

*degree of lesions – flag leaf

TABLE 4. Mean incidence values of sheath blight and rice blast disease in panicles, obtained in relation to treatments containing silicon, nitrogen, and treated seeds, in the Formoso Project, 2000/2001 cropping season\1.

FACTOR	Treatments	Incidence	
		Sheath blight\2	Rice Blast Disease in Panicles
Silicon	S_1 - Without Si	4.5 a	4.4 a
	S_2 - 4 t ha^{-1} silicate	4.1 a	3.7 b
Nitrogen\3	N_1 – N application splitted	4.2 a	3.6 b
	N_2 - N single application	4.4a	4.8 a
Seed	C_1 – Treated seed	4.5 a	4.2 a
	C_2 – Non-treated seed	4.1 a	4.2 a

\1Data transformed to arc sin sqrtr (x + 0.5).
\2Means followed by a common lower-case letter in rows and lower-case letters in the columns do not differ among themselves by Tukey test at 5% .
\3N_1 = 70 kg ha^{-1} urea applied 45 days after planting + 70 kg ha^{-1} urea applied 70 days after planting; N_2 = 100 kg ha^{-1} urea applied 45 days after planting.

Calcium carbonate or calcium silicate was applied in the top soil in amounts equivalent to 0, 1500, 3000, 6000 or 12000 kg ha^{-1} (Figure 10). Soybean leaf silicon concentration (Figure 10) and incidence of *Cercospora sojina* (Figure 11) were evaluated. Lime did not reduce disease incidence; however, calcium silicate was effective in the reduction of downy mildew 47 and 66 days after soybean seeding. Calcium silicate surface application before seeding was effective in reducing incidence of *Cercospora sojina* at all dates evaluated (Nolla et al. not published).

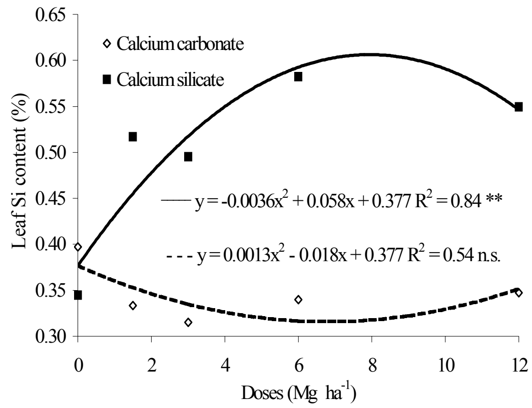

Figure 10. Leaf silicon content (%) in soybean cultivar BRS/MG-68, as a function of the application of calcium carbonate or silicate rates.

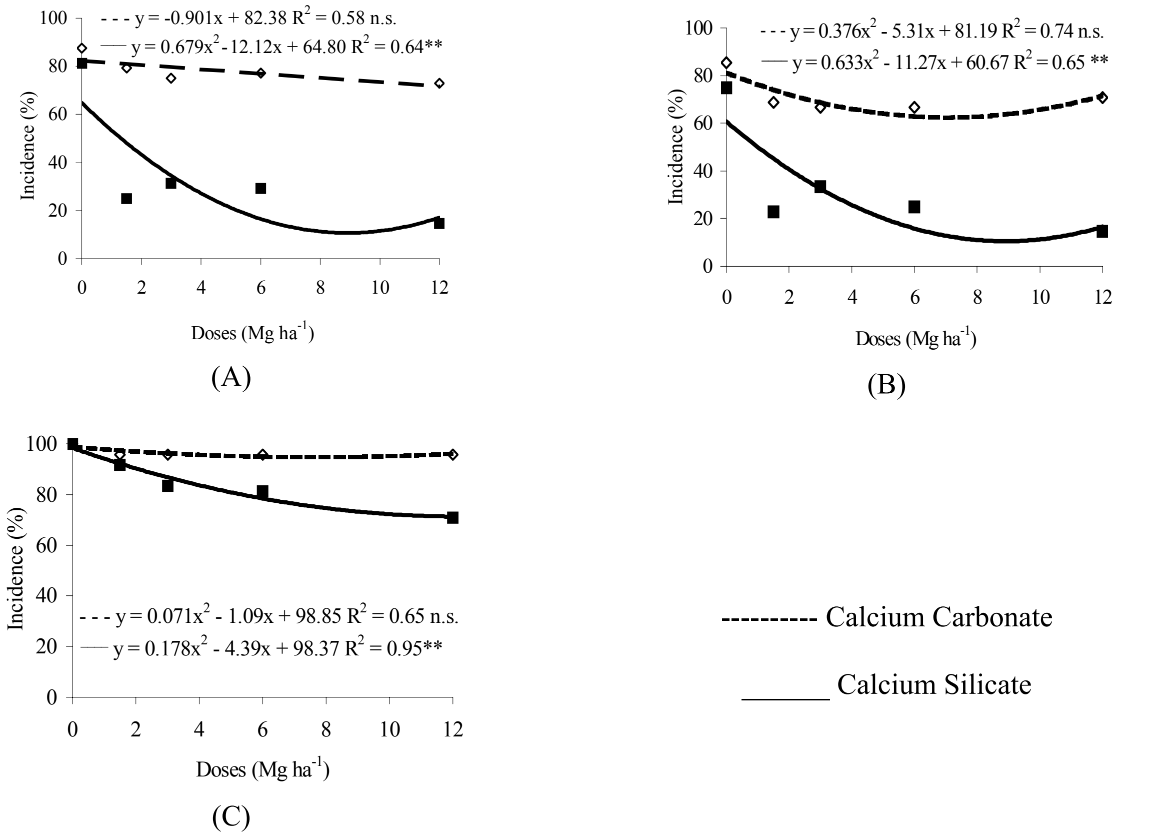

Figure 11. Leaf incidence (%) of *Cercospora sojina* in soybean cultivar BRS/MG-68 at 47 (a), 66 (b) and 79 (c) days after seeding, as a function of the application of increasing doses of calcium carbonate or silicate (Source: Nolla et al, not published).

4. ACKNOWLEDGEMENTS

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Suzanne Berthelsen, PhD
METHODS FOR SI ANALYSIS IN PLANT, SOIL AND FERTILIZERS

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Abstract

To develop recommendations for field applications of silicate materials, knowledge of the soil Si status and the availability of Si in the amendment are essential. To determine a crops response to application of Si requires calibration of soil Si status and plant uptake. While a method for determining plant Si levels using the auto-clave induced digestion procedure (Elliott and Snyder, 1991) is well established, the challenge for routine testing of soils and amendment materials is the development of simple, dependable and robust methods that correlate well with changes in soil Si status and corresponding plant tissue levels. The total Si content of soils can have little relationship to the concentration of soluble Si in soils, which is the component important for plant growth. The concentration of soluble Si is dynamic, and although leaching of Si from the soil and plant uptake are important processes determining Si concentrations, the equilibrium concentration is largely controlled by adsorption/desorption reactions. A number of chemical extraction procedures have been developed to determine the 'plant available' soil Si status, and a range of these are compared when used on different soil types. However, a complication occurs when Si is added to soil, as it reacts rapidly with amorphous surfaces, and amount and rate of Si adsorption is dependant on the sesquioxide content of the soil, soil pH, and the presence of other anions. Although many soil tests are effective in predicting 'sub-optimality', there may be a need to refine soil-testing techniques that enables an assessment of 'responsiveness' to silicate additions. These soil reactions also influence the solubility of, and hence availability of Si in various amendments, causing poor correlation with laboratory chemical extraction procedures for determining available Si in a material and plant uptake once that material is added to the soil. Various methods to determine the potential for a material to supply 'plant available' Si are compared.

Index terms: Chemical analysis, silicon, soil, plant, amendment

Total silicon content of soils, plants and fertilizers

Silicon (Si) is abundant in nature, and as such, the total silicon content of soils, plants and materials suitable for use as soil amendments for agricultural purposes, can be high.

In soil, Si exists in a wide variety of forms and stabilities. It is estimated to represent about 28 percent of the earth's crust, and as alumino-silicates and quartz can be as much as 75 - 95 percent of the inorganic fraction of soil (Jackson *et al.*, 1948). Silica (SiO_2) can occur in different crystalline forms, of which quartz is the most common, or as amorphous Si-containing substances. Also present in soils are amorphous forms of Si, including allophane, a non-crystalline Si-containing colloidal mineral substance, and the hydrated forms of silica ($SiO_2.nH_2O$), commonly known as phytoliths, resulting from plant decomposition. Phytoliths can be relatively stable and usually concentrate in the surface horizon of soils. Amounts of opal phytoliths commonly range from <1 to 30 g/kg on a total soil basis (McKeague and Cline, 1963a).

Silicon represents a major mineral constituent of plants, and is present in plants in concentrations similar to that of the other macronutrients. At 0.1 percent, Si is equivalent to the levels of macronutrients, Ca, Mg, P and S; while the upper levels of 10 percent exceed the concentrations of the mineral nutrients like K and N (Epstein, 1994 and 1999). However, the Si content of different plants, and of various plant parts, is extremely variable. Different plant species differ in both their concentrations of Si, and their accumulation of Si from the soil solution. Jones and Handreck (1967) divided plants into three major groups according to the SiO_2 percent of the leaf tissue on a dry weight basis. "Wetland" grasses (e.g. paddy-grown rice) have the highest levels at 5 - 15%; "dryland" grasses having intermediate levels of 1 - 3%; and the dicotyledons generally having the lowest levels of less than 1%.

There are many types of silicated materials suitable for use as soil amendments/fertilizers, however, their effectiveness is more dependent on their reactivity rather than total Si content. An excellent review of sources suitable for agriculture is provided by Gascho (2001). As mentioned plant material can have high concentrations of Si, and crop residues (e.g. rice hulls and sugar mill wastes) are commonly used, although high rates are usually necessary. There are a few naturally occurring mineral materials, such as wollastonite ($CaSiO_3$), olivine ($MgSiO_3$) and diatomaceous earth, which can have total silicon contents of approximately 55%, 30% and >70% SiO_2 respectively, but often availability limits their potential use. By far the most common forms of silicated materials used as soil amendments are various industrial by-products, for example, calcium silicate slag, a by-product from the production of elemental phosphorus.

The total Si content of soils, plants and fertilizers can be easily determined using X-ray fluorescence spectroscopy (XRF). This is a non-destructive analysis requiring the preparation of dry-powder pellets made from finely ground material. There are a range of other techniques used for total Si analysis, generally requiring pre-solubilization of the Si using various digestion methods. Snyder (2001) has provided a comprehensive review of the various gravimetric, digestion and non-destructive methods that can be used, so more detail will not be provided here, except to make mention of the ease of using the autoclave-digestion procedure for determining plant Si content (Elliott and Snyder, 1991). This procedure produces consistently reliable results, and the only special equipment required is an autoclave and spectrophotometer. This allows the analysis of large sample batches to be carried out using the equipment available in most standard laboratories.

Measurement of plant available silicon in soils

While Si compounds such as quartz, various crystalline silicate minerals, silicate clays and amorphous silica compounds dominate the solid phase of all soils, the soluble forms in the soil solution consist of monosilicic acid ($Si(OH)_4$) and polysilicic acids, and complexes with organic and inorganic compounds. The total Si content of soils can have little relationship to the concentration of soluble Si in soils, which is the component important for plant growth. The concentration of soluble Si in soils is dynamic. Monosilicic acid will remain in solution in the monomeric state in neutral and weakly acid solutions. However, rapid polymerization occurs at high solution concentrations, with increasing soil pH and in the presence of oxides and hydroxides of aluminium and iron.

Table 1 illustrates the diversity of some of the methods that have been used world wide to determine the amount of Si available for plant growth. The quantity of Si varies depending on the extracting solution used to solubilize the soil Si. In general, the most successful extractants are acid rather than neutral solutions, and dissolution is further increased by chelating agents (due to decreased Si sorption resulting from the lower concentration of Al and Fe in solution). Other factors such as the method of equilibration, soil:solution ratio, temperature, and pH of extractant solution are also important. Once in solution, $Si(OH)_4$ can be measured by the silicomolybdate blue colour method (Iler, 1979).

Although water extracts have often been used to estimate readily soluble Si this is generally not a suitable method since the low ionic strength of the solution will cause dispersion (Lindsay, 1979). As most of the soluble Si below pH 8 is uncharged monosilicic acid, changes in ionic strength should not significantly alter extractable levels in most soils. In this respect, Elgawhary and Lindsay (1972) recommend the use of 0.02 M $CaCl_2$ as the reactive media to equalize ionic strengths and facilitate ready flocculation of colloidal Si. Soils extracted with dilute $CaCl_2$, measure Si in the soil solution, and corresponds more closely to the levels of $Si(OH)_4$ expected from solubility predictions (Lindsay, 1979).

A study comparing a number of extractant methods over a wide range of soil types from north Queensland in Australia resulted in Si values, which although differing by scales of magnitude, still demonstrated a general relationship between each other (Berthelsen, 2000). This relationship between extractants was supported by the relativity between the 'critical levels' established for the different extractants despite the fact that they were established in independent studies. The different extractants tended to target Si held within different components of the soil matrix, as the Si solubilized was related to other soil properties specific to the soil type. Dilute salt solutions (e.g. 0.01M $CaCl_2$) provided a measure of the readily available Si present in the soil solution, while results obtained using NH_4OAc and acetic acid indicated that the Si solubilized was likely to be the more simple polymers affected by changes in pH, CEC and the ratio of soluble Si:Al in the soil solution. However, clay content and relationships between extractable Si and Fe and Al were more prominent factors in Si extracted by phosphate acetate, citric acid and 0.005M H_2SO_4, suggesting that the Si solubilized was more strongly sorbed onto the Al and hydroxides, and possibly to some extent, also some of the crystalline and noncrystalline soil minerals.

Work done in different cropping systems demonstrate that many of the extractants listed in Table 1 can correlate well with plant uptake and may provide excellent crop response curves, allowing an estimation of the required soil Si concentration necessary to achieve maximum crop growth under various rates of Si fertilization, (Korndorfer *et al, 2001*; Ma and Takahashi, 2002; Kingston et al., this conference). However, as reported by Ma and Takahashi (2002), after a long history of silicate slag additions, extractants such as the acetate buffer method can over-estimate the plant-available Si. Many silicate fertilizers have inherently low solubility, and stronger extractants may dissolve non-available Si from the silicate amendment previously added to the soil (Savant *et al*., 1997).

This highlights the problem of choosing a soil extractant that will best predict sub-optimality. A study carried out in north Queensland, Australia (Berthelsen *et al.,* 2003), illustrated the challenge of choosing the appropriate extractant. Soil and plant 'top visible dewlap' (TVD) samples were collected from approximately 200 sites, representing all the major soil types from all the sugarcane growing areas of north Queensland, Australia. Plant available soil Si was determined following extraction with 0.01M $CaCl_2$, and also a stronger extractant, 0.005M H_2SO_4. Determination of Si in the TVD leaf samples used the "Auto-clave digestion" procedure described by Elliott and Snyder (1991). It was notable that plant Si levels were significantly related to readily soluble soil Si levels (0.01M $CaCl_2$) but showed no relationship to soil levels obtained using the stronger acid extractant (0.005M H_2SO_4). The variability observed between all the soils sampled in this survey suggested that interpreting soil Si status using strong extractants should be done with caution, particularly on soils with poor drainage or high Si sorption ability and high organic matter content. Similar observations have been reported by Fox *et al*. (1967) and Medina-Gonzales *et al*. (1988), who observed highly significant relationships between plant Si and water extractable Si, but not with any other soil extractant.

Table 1. Methods used to determine soluble and extractable soil Si

Extractant	Soil : Solution Ratio (or recommended weights and volumes)	Method	Suggested critical level	Reference
H_2O	pre-wet air-dry soil at a matric suction of 0.1 bar	incubate at 25°C for 1 day and centifuge at 900g (RCF) for 1 hr.		Gillman and Bell, 1978; Menzies and Bell, 1988
H_2O	saturated paste		2 mg/kg	Fox and Silva, 1978
H_2O	1g :1 mL	allow to stand 2 weeks with repeated shaking, filter and centrifuge		Clements *et al* ., 1967
H_2O	10 g : 100 mls	continuous shaking for 4 hrs. and centrifuge at 24,000g (RCF)	< 0.9 mg/kg (deficient) < 2.0 mg/kg (marginal) 8.0 mg/kg	Fox *et al* ., 1967; Elawad et al., 1982
H_2O	10 g : 60 mls	'incubation method' - shake, degass, seal bottle, incubate at 40°C for 1 week without shaking.		Takahashi and Nonaka, 1986
H_2O	1:4	'supernatant method' - shake, degass, fill to replace all air space, seal bottle, incubate at 30°C for 4 weeks		Sumida *et al* ., 1998
Phosphate acetate (pH 3.5) [500ppm P as $Ca(H_2PO_4)_2$ and 0.1 M (H,NH4)OAc]	10 g : 100 mls	continuous shaking for 4 hrs. and centrifuge	< 50 mg/kg (deficient) 50-150 mg/kg (marginal - adequate)	Fox *et al* ., 1967
0.04 M sodium phosphate buffer (pH 6.2)	1 g : 10 mls	continuous shaking for 24 hrs at 40°C		Kato and Sumida, 2000
Modified Truog - [0.01 M H_2SO_4 containing 3 gms $(NH_4)_2SO_4$/liter]	1 g : 100 mls	continuous shaking for 30 minutes	< 40 mg/kg (deficient) 40-100 mg/kg (marginal - adequate)	Fox *et al* ., 1967
0.5 M NH_4OAc (pH 4.5-4.8)	5 gms : 100 mls	continuous shaking for 1 hr.	< 20 mg/kg (deficient) 20-40 mg/kg (marginal - adequate) < 50 mg/kg (deficient)	Fox *et al* ., 1967 Wong You Cheong and Halais, 1970; Ayres, 1966
0.5 M NH_4OAc (pH 4.5-4.8)	2.5 gms : 50 mls	2.5 gm soil leached with 10 * 5 ml aliquots of extractant		Bishop, 1967
acetate buffer, pH 4.0	10 g : 100 mls	intermittant shaking over 5 hours at 40°C		Imaizumi and Yoshidai, 1958
0.01 M $CaCl_2$	1:10	continuous shaking for 16 hrs and centrifuged	< 20 mg/kg (deficient - marginal)	Haysom and Chapman, 1975
0.01 M CaCl2	1:25	shake for 7 days, with a few drops of chloroform on a reciripicol shaker at 250 C		Wickramasinghe, 1994
0.005 M H_2SO_4	1 : 200	continuous shaking for 16 hrs and centrifuged	< 100 mg/kg (deficient-marginal)	Hurney, 1973
0.5 M Acetic acid	1:10	1 hr shake, rest 15 minutes, decant and filter, rest 12 hrs before analysis	< 15 mg/kg (deficient)	Snyder, 1991; Korndorfer, G. (per. comm.)
0.1 M Citric acid	1:50	2 hr shake, rest O/N, 1 hr shake, centrifuge		Acquaye and Tinsley, 1964

The 'capacity' of the soil to supply Si to the soil solution depends on solid phases that are less soluble than amorphous Si but are more soluble than quartz (Elgawhary and Lindsay, 1972). If the concentration of soluble Si in the soil solution is controlled by the most soluble silicate mineral, regardless of the amount present in the soil (Herbillon *et al.*, 1977), then factors controlling solubility become important in ensuring that adequate amounts are available for plant growth. Important factors include soil mineralogy (including the Si:sesquioxide ratio), soil pH, organic carbon content, clay content, concentration and solubility of plant phytoliths in the silt fraction and soluble Al. Many of these factors are inherent soil characteristics, but can be greatly affected by the cultural practices involved with crop production. Therefore, to adequately predict a response to silicate additions, knowledge of past fertilizer history is important. Previous fertilizer history with silicate fertilizers should be taken into account, as discussed by Ma and Takahashi (2002). In addition, the history of other agronomic practices such as liming should be considered. The increase in soil pH following liming promotes polmerization of Si and the formation of alumino-silicate compounds, which can have a marked influence on the solubility and availability of Si. In this respect, the stronger extractant again may overestimate the Si available for plant growth, by dissolving these compounds of lower solubility.

Plant available soil Si levels need to be considered from three aspects: 'intensity' (concentration of Si in the soil solution available for immediate plant use); 'capacity' (the reserve supply of Si present as solid phases in the soil); and 'buffer capacity' the factors that affect the sorption/desorption reaction in the soil (ability of the solid phase to replenish the soil solution following depletion through leaching or plant use). The difference in Si obtained using different extractants has led many researchers to suggest using two methods of extraction. The first in water or a dilute salt solution to provide a solution concentration near equilibrium with the soil system (an 'intensity' factor), and the second, using a stronger extractant such as phosphate acetate, citric acid and 0.005M H_2SO_4, to provide an index of the adsorbed soil Si (a 'capacity' factor) (Khalid *et al.*,1978; Berthelsen *et al.,* 2003).

It is also generally agreed that most of the rapidly soluble Si is derived from sorption sites and not from any specific compound of Si (McKeague and Cline, 1963a, 1963b, 1963c; Beckwith and Reeve, 1964; Jones and Handreck, 1967). Therefore the importance of the role of Al and Fe compounds in the dissolution kinetics of soil Si has led many to propose that concurrent examination of the Si:Fe and Si:Al ratios should be considered in conjunction with extractable Si levels. Acquaye and Tinsley (1964) recommended the use of citrate solutions and citric acid for the simultaneous extraction of Si, Al and Fe, and Beckwith and Reeve (1963) suggested that the determination of Si and Al following extraction with 0.005M H_2SO_4 was effective in differentiating soils with respect to supplying Si providing an assessment of both 'intensity' and 'capacity' factors of the 'reactive' Si status. The differing ability to adsorb added Si can also be determined using an Index of Silica Reactivity (ISR), which may prove to be a useful research tool in understanding and developing application rates of silicate amendments (Gallez *et al.*, 1977). An Index of Silica Saturation (ISS), which takes into account both the solubility and the sorption characteristics of the soil with respect to Si, can be calculated using the ISR %, and the concentration of readily available soil Si as determined following extraction with 0.01*M* $CaCl_2$ (Herbillon *et al.*, 1977). Sumida (1991) reported that a method measuring the simultaneous dissolution and adsorption of Si of various soils with different histories of fertilizer management provided better correlation with Si content of rice straw than other standard methods, and was a valuable method for diagnosing the Si supply capacity of paddy soils.

It is possible that no single measure is adequate to determine plant available Si. However, if a single measure is required, extraction with a dilute salt such as 0.01M $CaCl_2$ may be preferable. As 'intensity' and 'quantity' are linked, it is unlikely that readily available Si will be high unless there is sufficient 'capacity'. As 0.01M $CaCl_2$ extractable Si represents the Si available in the soil solution, it also reflects the net effects of the sorption/desorption reactions that control solubility, thus giving a true measure of current availability. To assist in developing recommendations for the amelioration of sub-optimal levels of plant available soil Si, useful additional information could include, the 'capacity' of the soil Si reserves and the sesquioxide content and a measure of the buffer capacity of the soil to sorb Si (as determined by the 'index of silica reactivity' and the 'index of silica saturation').

However, it is clear a number of extractants can be successfully used to estimate soil Si. The choice of extractant will often be based on its ease of adoption for a particular laboratory and its suitability for specific soil characteristics, which will in turn be reflected in its ability to correlate with plant uptake of Si. In this respect, it must be remembered that plant levels vary with variety, plant part, age, ratoon age (as with sugarcane), so consistency in plant sampling is critical. It is also very important that when trial work is reported, that the extractant methodology used to obtain the results (including information regarding suggested 'critical levels') is provided to allow comparisons.

Measurement of plant available silicon in fertilizers

Unfortunately selecting a suitable silicate materials and assessing it efficacy is difficult. While a number of chemical extractant methods have been used to estimate both total and soluble Si in silicate materials, often the results obtained do not correlate well with plant uptake of Si, once the material is applied to the soil. In addition to the effect on particle size on solubility, other chemical characteristics of the material such as pH, molar ratio of $CaO:SiO_2$ have been shown to influence Si availability (Ma and Takahashi, 2002). Once a product is added to the soil, soil chemical reactions, for example, the increase in soil pH due to the dissolution of Ca and Mg from the material can further influence the solubility and hence availability of Si (Ma and Takahashi, 2002). Consequently, it is possible that there is not a universal extractant that is suitable for determining available Si that will cover all types of materials, and for all soils and soil conditions (Gascho, 2001).

However there is a need for a rapid laboratory test to provide an initial assessment of different silicate sources. This would be useful to screen materials, allowing further glasshouse and field testing to concentrate on materials with the most potential. A number of different chemical extractants for estimating available Si in silicate materials have been used to varying success. Extraction with 0.5M NH_4OAc or 0.5M HCl are two of the earliest methods recorded, and at various stages were standard methods in Japan. However, these, plus many other acidic extractants commonly used, including citric acid and acetic acid have lost favour as they have generally shown poor correlation with crop uptake of Si. Simple water extractions of calcium silicate slags have also been used, however, as it was found that dissolution of the calcium silicate resulted in increases in pH and Ca in solution, both of which repressed further dissolution of the product, this method was modified to include a weakly acidic cation exchange resin in the water to both moderate pH and adsorb Ca (Kato and Owa, 1997). Based on the dissolution principles of Kato and Owa (1997), Snyder (2001) developed a 'column' technique which maintains neutral solution pH, low Ca concentration near the Si source and low dissolved Si concentration to minimize polymerization. More recently, Pereira *et al.* (2003) proposed an extraction method that they stated would quantify the Si potentially available to plants by using an alkaline extractor (using different extraction ratios and extraction/resting times) of $Na_2CO_3 + NH_4NO_3$.

Berthelsen *et al.* (2003) compared the effectiveness of a number of chemical extraction methods described in the literature on a diverse selection of silicated materials (including calcium silicate slag, cement, wollastonite, olivine, diatomaceous earth, flyash and filtercake scrubber waste). These same materials were then compared through indirect chemical extraction after soil incubation, and then an assessment of plant Si uptake and changes in soil Si status was undertaken following glasshouse pot studies. This series of experiments indicated that the extraction method developed by Kato and Owa (1997), using the addition of a weakly acidic cation exchange resin in the H+ form (Amberlite IRC-50) to the extraction medium, provided the best indicator of plant-available Si, which correlated well with both the indirect chemical extraction results and also soil and plant Si and yield when the materials were used in the glasshouse pot studies. These results are supported by recent work by Pereira *et al*. (2003) who compared a similar range of extraction methods and tested them against 12 different sources of Si material and also found a high correlation with Si content and Si uptake in rice using this 'resin' method.

As various forms of calcium silicate materials are the most widely used Si fertilizer, most proposed methods are based on estimating available Si from this source. Other silicate materials may possibly behave quite differently. Whatever method is used, it is important to keep a wide product to solution ratio, to keep the concentration of monosilicic acid low and prevent polmerization from occurring. In addition, as generally Si availability increases with decreasing particle size, it is important to define and standardize particle size when attempting to determine their reactivity and Si availability.

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SLAG AS SILICON SOURCE: APPLICATION CRITERION

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Introduction

Slag is the name given to the silicon-bearing residue that is formed together with the fusion of metals; it can be acid when a high silica content is present, or alkaline when it has a high content of basic oxides. Iron ore processing originates metallurgy slags, which are byproducts basically consisting of calcium and magnesium silicates, plus impurities. The slag results from the reaction between lime and silica (SiO_2), the main impurity present in iron ore:

$$SiO_2 + CaCO_3 \equiv CaSiO_3 + CO_2$$

In average, 1 ton of blast furnace slag is generated per each 4 tons of pig iron produced.

In its original state, slag is a material with quite variable chemical and granulometric composition, depending on the type of processing, iron ore, and fluxing agent (lime) used. Metallurgy slags can be either blast furnace slags generated during pig iron production, or steel metallurgy slags originated during the transformation of pig iron into steel, where the different types of steel and furnaces used are also sources of slag variability.

Alkaline metallurgy slags are used as soil amendments, as a source of nutrients, and also as a source of silicon. These Si-rich slags are apparently the most indicated sources to meet the increasing demand for this element. The high temperatures used in iron metallurgy processes frequently release Si from more crystalline states to more reactive and consequently more soluble forms.

The characteristics considered ideal for a Si source to be effective for agricultural use are: high soluble Si content available for plants, good physical properties, easily accomplished mechanized application, good availability in the market, balanced ratios and amounts of calcium (Ca) and magnesium (Mg), no soil contamination potential by heavy metals, and low cost. Once ground and processed for the removal of residual metals, almost all of these characteristics are well matched by slags, with variations depending on the type of slag, silicon solubility, and contents of Ca, Mg, and contaminants. Usually, slags are low-cost products, since they are sold as a way of reducing the environmental liability of steel metallurgy plants; however, the distance from the metallurgy plant to the application site often renders their use impracticable.

In order to meet this increasing demand for Si utilization, it is necessary to investigate and identify the most promising or potentially available slags with the ability to supply Si to plants.

Solubility

Si is applied with the purpose of providing the element to plants in soluble form, which can be absorbed. Thus, a good source must provide this truly "available" Si to the soil solution in sufficient amount. This is highlighted as the most important Si trait, and one of the most difficult to be obtained. For this reason, the identification of slags with good Si solubility through chemical analyses has not been easily accomplished; it can be seen that the plant is still the best way to identify which sources can best supply Si.

Weak or diluted acids frequently fail to correctly estimate the amount of “available” Si in slags (Takahashi, 1981; Kato & Owa, 1997, Pereira et al, 2003), especially in blast furnace slags. Recently, other extraction methods have been suggested, such as cation exchange resin (Kato & Owa, 1997) and sodium carbonate in association with ammonium nitrate (Pereira et al, 2003). So far these methods show the best correlations between the amount of Si extracted and the amount recovered by the plant (Figure 1) (Pereira et al, 2003). A method that is showing good correlations between silicates solubility assessment and the amount of Si recovered by crops is the "leaching" method (Snyder, 2001); however, it is a very labor-intensive method and does not quantify soluble Si, only estimating the source with the highest "available" Si potential.

A second alternative to evaluate the effectiveness of Si sources is the incubation method, which consists in mixing the sources with the soil and measuring the amount of available Si in the soil after a certain period of time; however, care should also be taken in selecting an extractor of Si from the soil when using this method. The extractor is essential to determine Si available to plants in the soil; Medina-Gonzales et al. (1988) used the same test to evaluate two sources in the Hawaiian region. After incubation, Si was analyzed using water, 0.5 mol L^{-1} ammonium acetate, and saturated paste as extractors. The authors found that Si absorption by roots was best correlated with water extraction, followed by saturated paste, and finally by ammonium acetate. In a similar work involving fifteen sources incubated in four Brazilian cerrado soils, Queiroz (2003) analyzed Si using 0.5 mol L^{-1} acetic acid and water as extractors. The work demonstrated that the use of a weak acid as soil extractor not only extracts Si from the soil but also from some sources where Si is unavailable to plants. In a research carried out at UFG with the incubation of 25 slags in a sandy soil, we observed that extraction with $CaCl_2$ 0.01 mol L^{-1} showed the highest correlation with extraction by plants, followed by ammonium acetate 0.5 mol L^{-1} (Figure 2).

Si availability variations in slags have been observed; Takahashi (1981) determined that the Ca:Si ratio affects Si availability: ratios higher than 1.0 favor Si absorption by the plant. Slags vary considerably in their Si contents. Among slags, those originated from steel in general contain less Si (5-10%); therefore, they contain Si in a more soluble form than in blast furnace slags (15-20%), which result from pig iron making. Slags yielded during phosphorus production by electrical processes, although possessing approximately 20% Si (only slightly less than minerals from calcium silicate deposits, such as Wollastonite), present good Si solubility. Similar results were observed by Vidal (2003), working with 12 Brazilian metallurgy slags.

Many variations occur in Si contents and solubility from steel production slags. Stainless steel production slags present Si in its most soluble form (Table 1), but other processes must still be evaluated in seeking more soluble sources.

Physical properties

Under an agronomical point of view, physical characteristics (granulometry) are determinative of performance in fertilizers, corrective amendments, and soil conditioners in general, especially when they present low solubility; the same consideration can be made about slags.

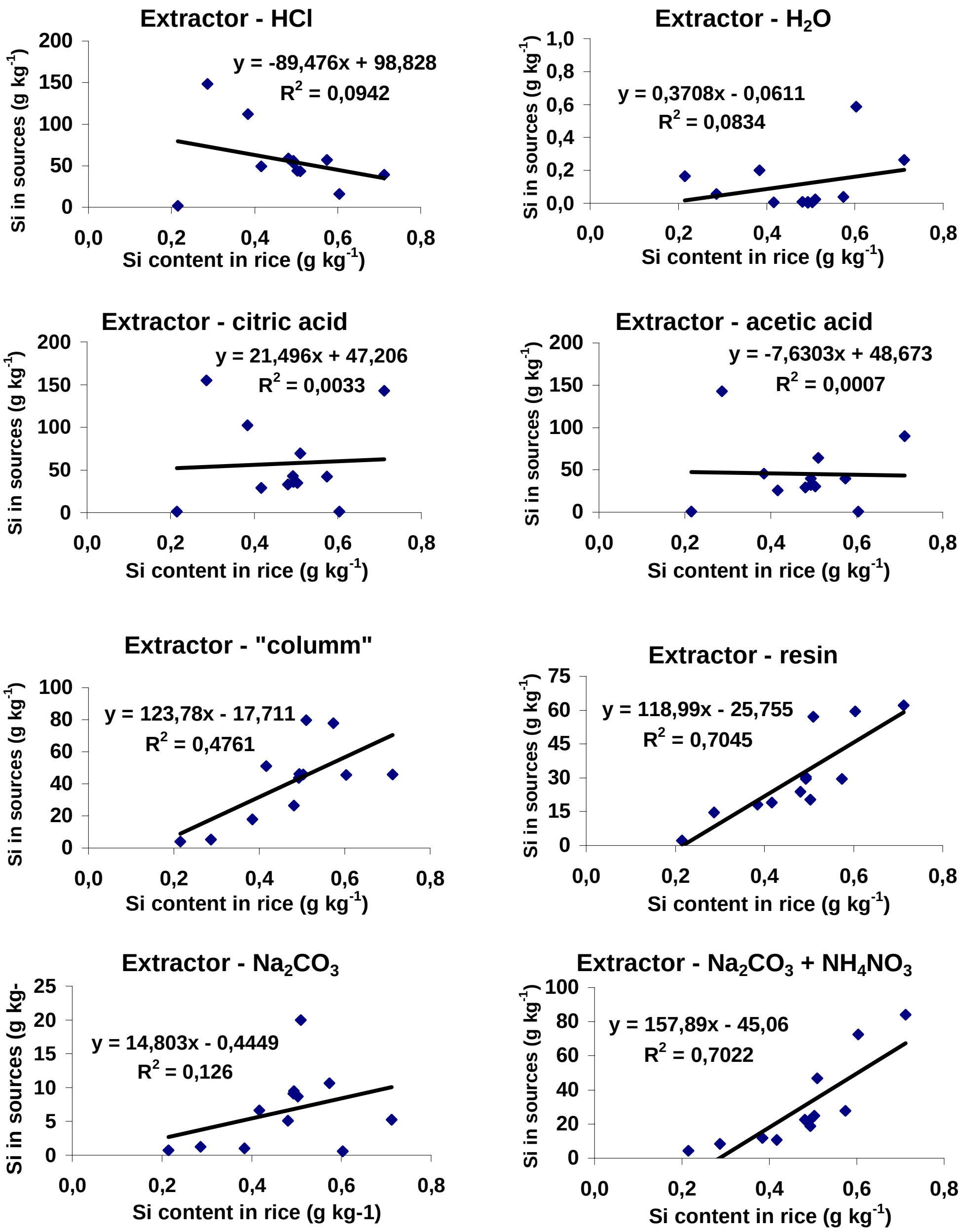

Figure 1. Correlations between silicon extracted by rice and different extractors of silicon from sources

Table 1. Soluble, leached and total SiO_2, CaO and MgO contents, and neutralizing power (NP) of some silicon sources.

Materials/Slags	Origin	SiO_2			CaO	MgO	NP Eq.$CaCO_3$
		Total	Soluble*	Soluble leac.24h**			
		%	%	mg	%	%	%
Wollastonite	Vansil	52	30	45	42	0,2	76
blast furnace slag	Mannesman	38	7	18	30	7,5	73
LD furnace steel slag	Mannesman	12	33	46	41	7,3	91
Phosphorus solub. slag	Rhodia	46	39	46	43	0,7	80
Silicate clay MB-4	Mibasa	48	2	4	2	19,1	52
blast furnace slag	CSN	33	5	5	43	5,2	89
LD furnace steel slag	CSN	11	5	26	28	7,6	69
LD furnace steel slag	Belgo	17	27	44	40	9,6	94
Electric furnace steel slag	Siderme	16	41	78	26	12,6	77
Stainless steel slag	Recmix	23	43	80	41	11,0	101
LD furnace steel slag	Açominas	11	21	51	28	2,9	57

* Percentage of total soluble Si in Na_2CO_3+NH_4NO_3

** 3g of Si source + 5g low density polyethylene. This mixture is placed on a leaching column and washed with Tris Buffer (pH 7.0) using a peristaltic pump. SiO2 determination is made in the leachate after 24 and 48 hours.

Slags must be applied in the form of dust (finely ground), because when coarsely ground, the product is less effective and has not proved successful. The finer the product, the broader the contact surface of particles with the soil; consequently, the distribution and dissolution of particles in the soil are increased, and the probability of contact with the root also increases.

Papers have shown that blast furnace slags with particles smaller than 0.3 mm were more effective in supplying Ca and Mg to the soil, while coarser slags (particles > 2 mm) were less effective (Oliveira et al., 1994). For example, larger amounts of blast furnace slag with a 2.0 mm granulometry were required in relation to a 0.3 mm granulometry for *Eucalyptus urophyll*a seedlings to produce the same amount of dry matter (Novais et al.,1993).

ACESITA slag samples (Iron-Nickel slags, blast furnace slag, and EAF, LD, and AOD steel manufacturing slags) were tested (3.0 t ha^{-1} dose) in order to identify the importance of granulometry (<0.4. <1.0; <2.0; >4,0 mm) on *Eucalyptus saligna* plant growth (Rocha and Fuinhas, 1989). The smaller-than-0.2mm granulometry provided the greatest growth in eucalyptus plants (Table 2).

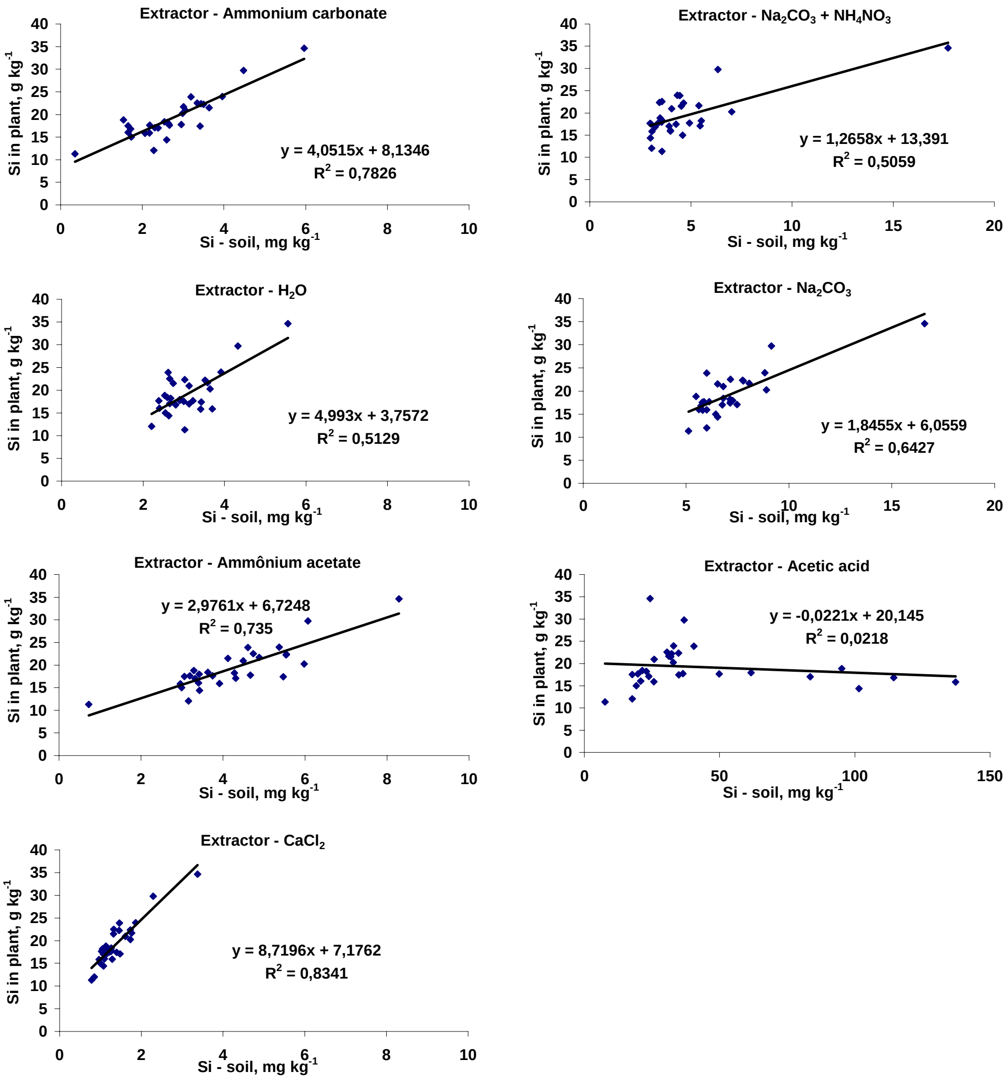

Figure 2. Correlations between silicon extracted by rice and different soil silicon extractors.

Table 2. Influence of ACESITA steel metallurgy slags (LD) at different granulometries on *Eucalyptus saligna* solid volume growth in the Cerrado Region in Northeastern Minas Gerais (Source: Rocha and Fuinhas, 1989).

Granulometries (mm)	Solid volume (m^3/ha)	Relative growth (%)
2,0 < gran. < 5,0	93,82	84
1,0 < gran. < 2,0	97,51	87
0,4 < gran. < 1,0	109,47	98
< 0,4	112,13	100

Gama et al. (2002) worked with 6 sources at 6 different granulometries, between 2 and 1.41mm, 1.41 and 0.85 mm, 0.85 and 0.50 mm, 0.50 and 0.30 mm, and < 0.30 mm, and demonstrated that the capacity to correct soil pH decreased as granule size increased when compared with pure calcium carbonate (Figure 3).

Slag granulometry is a very important factor, especially when mechanical broadcasting equipment is used. Normally, the granulometry of amendments classifies them either as dusts (limes and silicates) or coarser-textured materials (gypsum), since they are generally not very soluble. Owing to the action strategy in the release of nutrients and soil correction, they have to come into contact with a large volume of soil in order to react with it. When applied, a product with great granulometric variation will be subject to segregation. Thus, the more uniform the granulometry, the less subject the product will be to this type of effect. Another important property is product moisture; this physical trait causes the most problems during application in the field. Excess moisture may give products a tendency to stick to the distribution mechanisms, changing the flow and impairing fluidity.
It must also be pointed out that the specific surface of a lime particle is smaller than the specific surface of a slag particle for the same granulometric fraction. This is due to the fact that lime is ground from a compact and uniform rock, while slags are obtained from a fusion and cooling process in furnaces, generating irregular and porous particles.

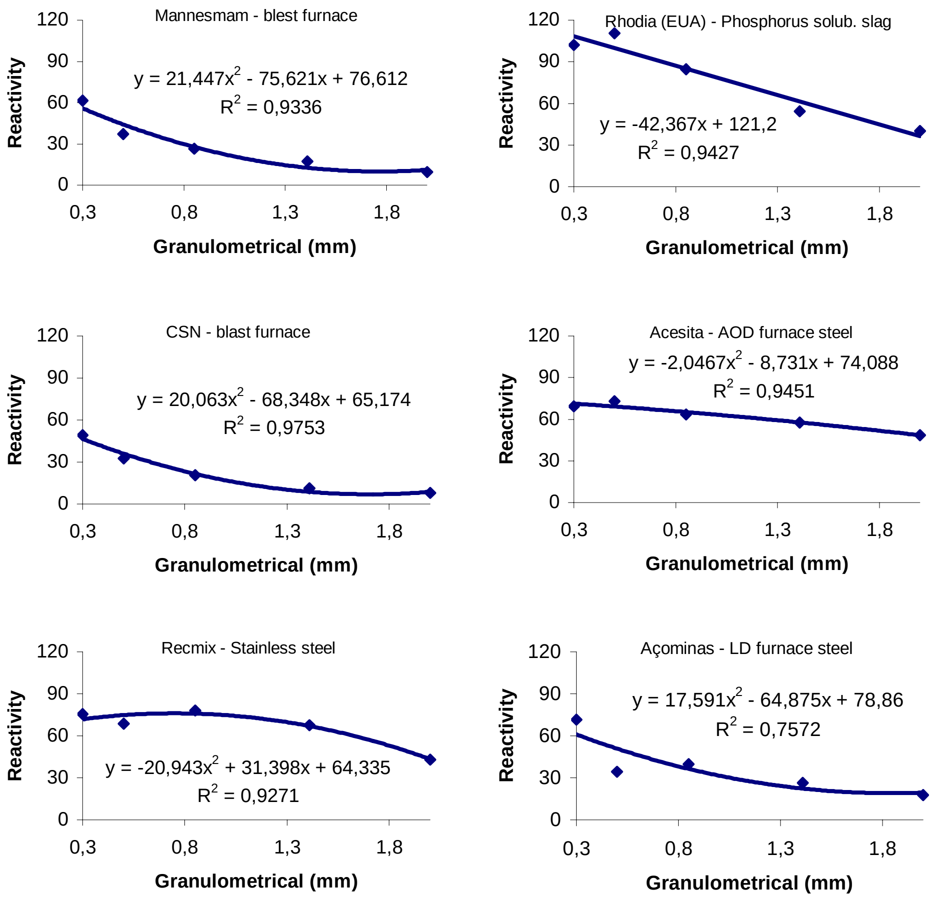

Figure 3. Relative pH efficiency in connection with calcium carbonate as a function of amendment granulometry.

Residual effect of applied Si

Figure 4 presents Si release curves for different slags, showing slags with high, medium and low solubility. Another behavior that has also been observed refers to Si release velocity; thus, there are slags where Si is readily available, and is quickly released into the soil solution, while others may present slower release, increasing with time. The behavior of different sources may correspond to a variation of these Si release forms (fast, slow, or gradual), so that a source with slower release may have longer residual effect.

In sugarcane, for example, Si applied at planting not only affects plant cane, but also ratoon cane productivity. Anderson et al. (1991) verified a decrease in ratoon cane productivity of up to 45% in relation to plant cane when plant cane was not fertilized with Si, and only 28% when plant cane received calcium silicate fertilization at planting. This result confirms the significant residual effect of Si even 2 years after application.

Anderson et al. (1992) mentioned that silicate slags present low solubility at high pH values, but have neutralizing power in acid soils, and that slags must be used as long-term acidity correction amendments.

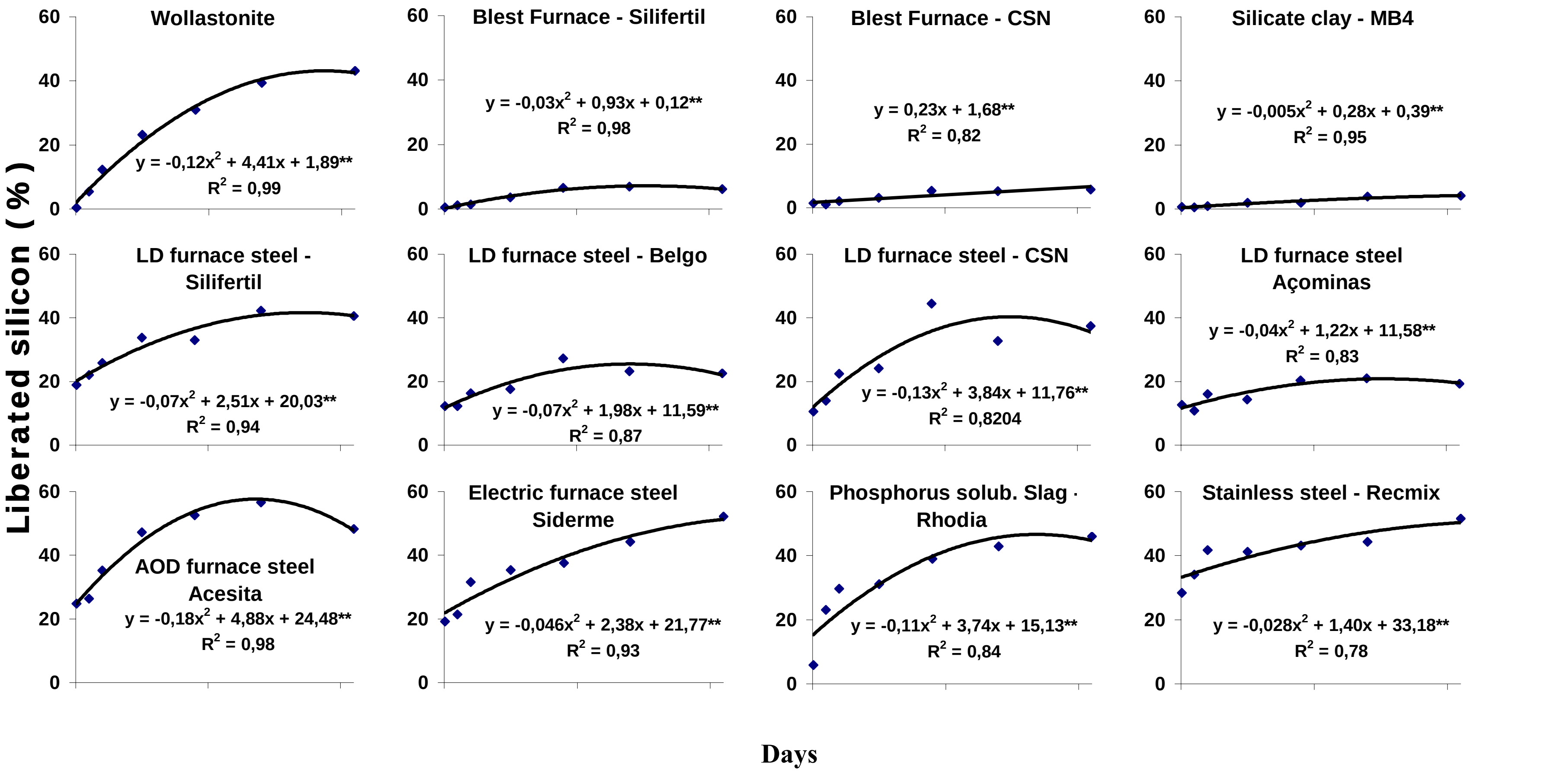

Figure 4. Percentage solubility in relation to total Si from some sources as a function of rest time; extraction made with $Na_2CO_3 + NH_4NO_3$ (10 + 16 g L^{-1}). ** significant at 1%.

Contaminants

Slags may present high heavy metals contents in their composition; in this case, their use in agriculture is not recommended, in order to prevent soil contamination. However, there are some materials derived from the steel metallurgy industry which show low metal contents and can sometimes present lower levels than commercial limestones. This is possible mainly due to the recovery of the metallic part that contaminates slags and constitutes raw material for the steel metallurgy industry. Many steel metallurgy plants are already demonstrating their concern by installing, in their industrial units, equipment for the recovery of steel, which comes along with the slag during the separation process when exiting the furnace. Most heavy metals that contaminate slags are found in steel.

With regard to soil contamination by heavy metals, estimates performed by Amaral Sobrinho et al. (1995) suggested that annual slag applications of up to 25 ton ha^{-1}, made during a 10-year period, did not result in contamination.

Availability and low cost

To become a candidate for use in agriculture, a slag must be obtained within a reasonable distance from the application site under low cost conditions and have great beneficial potential. Under such circumstances, there are limited conditions in agriculture for the selection of soluble sources.

From February 2003 to January 2004, 60,843.9 thousand tons of steel and 33,048.9 thousand tons of pig iron were produced in Brazil. If about 300 kg of slag is generated for each ton of steel and iron produced, it can be estimated that during that period 9,914.7 thousand tons of blast furnace slag and 18,253.2 thousand tons of steel metallurgy slag were produced in Brazil. The State of Minas Gerais is the country's largest producing state, followed by the states of São Paulo, Rio de Janeiro, and Espírito Santo.

Blast furnace (BF) slags are not very interesting for agriculture due to their low Si solubility (Figure 4), but are largely consumed by cement factories and also as thermal insulators. Steel manufacture (LD) slags, however, are more interesting for agriculture, due to their high soil correcting potential and higher Si solubility. Thus, increasing interest exists in selling steel-manufacturing slags for agricultural purposes; meanwhile, large quantities of slag are piled up in steel metallurgy plant waste yards.

When considerations are made about the cost of a product, its cost:benefit ratio, not its actual price, should be analyzed; the sum of its effects on crops should be taken into consideration, such as: fertilizing effect of Si on the crop; corrective effect in the soil, since many silicates have the ability to correct acidity, such as carbonate; other nutrients supplied; reduction in the use of fungicides and insecticides; and even reduction in expenses with irrigation.

Soil acidity-correcting effect

Slag effectiveness as an acidity-correcting material has already been demonstrated in several studies. Silicates behave in a manner similar to carbonates in the soil. They can increase pH, neutralizing exchangeable Al and other toxic elements. According to Alcarde (1992), the reactions involving silicate materials that occur in the soil are:

$$\begin{matrix} CaSiO_3 \\ MgSiO_3 \end{matrix} + H_2O \rightarrow \begin{matrix} \nearrow Ca^{2+} \\ \searrow Mg^{2+} \end{matrix} + SiO_3^{2-}$$

$$SiO_3^{2-} + H^+ \rightarrow HSiO_3^-$$

$$HSiO_3^- + H^+ + H_2O \rightarrow H_4SiO_4$$

Ribeiro et al. (1986) corrected soil acidity in a clay-textured, non-cultivated Rhodic Hapludox (pH = 4.1, Al^{3+} = 1.3 $cmol_c\ L^{-1}$) in the city of Viçosa, Minas Gerais, and concluded that the slag used was equivalent to good-quality lime (Table 4). The relatively high CaO and MgO contents in the slag gave it a total neutralizing power of 83%, making its use viable as an acidity-correcting material.

Table 4. pH and soil cation exchangeable contents at different slag rates (Mg ha^{-1}) and incubation times (days).

Dose ton ha^{-1}	Time (Days)	pH (H_2O 1:2,5)	Al^{3+}	Ca^{2+}	Mg^{2+}
			(Extraction: KCl mol L^{-1})		
			------------------- $cmol_c$ L^{-1} -------------------		
0	-	4,1	1,3	0,3	0,2
3,72	0	4,7	0,6	1,1	1,0
	15	5,0	0,2	1,4	1,3
	30	5,2	0,1	1,5	1,3
7,44	0	5,1	0,1	1,7	1,5
	15	5,4	0,0	2,2	1,7
	30	5,6	0,0	2,4	1,8
14,88	0	5,6	0,0	2,5	1,8
	15	6,0	0,0	2,5	2,0
	30	6,3	0,0	3,1	2,1

Source: Ribeiro et al. (1986)

Slags as sources of nutrients

Slags are rich in Ca and Mg, and also present some of the most important macro- and micronutrients required by plants in their composition, such as P, Fe, and Mn (Kluger, 1989). Steel metallurgy slags in Brazil have low phosphorus contents due to the low quantities of this element in iron ore (Firme, 1986). This low phosphorus content is a limitation to their use as a source of this nutrient (Ribeiro et al., 1986). However, the authors highlight the fact that 5 ton ha^{-1} of slag correspond to the incorporation of 315 kg ha^{-1} of single superphosphate. High Fe and Mn contents did not cause toxicity problems in sorghum plants grown in the soil that received slag.

Use and application recommendations

The recommendation for the use of slags in agriculture as a soil corrective amendment and/or as Si source depends on soil Si availability, the crop in question, and slag solubility/reactivity. Studies indicate that rates ranging from 1.5 to 2.0 ton ha^{-1} calcium silicate were adequate for a good rice yield in Japan, Korea, and Taiwan (DeDatta, 1981). In Japan, rates varying from 0.5 to 1.0 ton ha^{-1} are applied in the area cultivated with rice that annually receives calcium silicate fertilizations, even though the recommended amount ranges from 1.5 to 2.0 ton ha^{-1}.

Soil and/or plant analyses are essential tools for a diagnostic to determine whether silicates should be applied or not; the smaller the Si content in the soil, the higher the rate to be applied. According to Korndörfer et al. (1999 and 2001), soil Si values lower than 20 mg kg^{-1} when extracted with 0.5 mol acetic acid, and sandy soils in general, are those most frequently responsive to the application of silicates. Also, soil Si values < 6 - 8 mg kg^{-1} when extracted with $CaCl_2$ 0.01 mol L^{-1} indicate a high probability of response to the application of fertilizers containing Si in sugarcane. It is important to point out that the soil analysis calibration data for Si are still insufficient and require many more studies.

So far, there is no information on record indicating whether Si could cause a phytotoxic effect in plants; therefore, there are no limits for the use of this element. A limit will be observed when the corrective effect of silicates and the cost:benefit ratio are taken into account, i.e., excessive silicate rates, especially in soils that already received liming may cause pH increases above the desired values for the crops and thus cause an imbalance of other elements, such as micronutrients (Cu, Fe, Zn, and Mn) and P, due to insolubilization reactions.

The use of Ca and Mg silicates as acidity-correcting amendments is not different from the use of lime, i.e., the amount of silicate required for a certain soil type is the same as that of lime. Therefore, the recommendation criteria for the use of lime are also valid for silicates. In already amended soils, that is, where the pH and/or base saturation values are at desirable or adequate levels, the amount of Si supplied by silicates should not be higher than 800 kg ha^{-1} in order to avoid nutritional imbalances. The season, form of application (broadcasting or incorporation), and criteria for reapplication follow the same orientation as for lime. Just like lime, silicates also present a long residual effect (3 - 5 years).

Recent researches point toward the use of silicates not only in the entire area (broadcasting), but also for application in the row, together with the seeds. This type of application allows the use of silicates at smaller rates, favoring the root environment, decreasing the acidity generated by acidulated fertilizers, with reflexes on productivity.

Conclusion

- In the slags the total content of Si is not the most important and yes the amount of Si that can be liberated the plants;
- Slags must be finely ground to provide good reactivity and make a higher amount of silicon available;
- Although having smaller Si contents, iron metallurgy slags show the highest availability of this element;
- Treatment for the removal of metals in slags is recommended, not only to facilitate the grinding process but also to remove metals, especially heavy metals that might cause some sort of soil contamination.

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BRAZILIAN LEGISLATION FOR THE USE OF FERTILIZERS AND LIMES WITH SI

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In Brazil, the inspection and supervision of fertilizers production and trade are realized based on the Brazilian Federal Legislation (Decreto 4.954, published on 14/01/2004). The Ministry of Agriculture (MAPA) is responsible for the inspection and supervision of the fertilizers production, importation, exportation and trade. According with this Federal Norm, Decreto 4.954/04, mineral fertilizer is a fundamentally mineral product, natural or synthetic, obtained by a physic, chemical or physic-chemical process, that provides one or more plant nutrients. According with the same Federal Norm, Decreto 4.954/04, nutrient is an element that is essential or beneficial for the vegetable growth and production. Silicon is considered a beneficial element for the plants growth and production.

The producers of mineral fertilizers, as those fertilizers containing silicon, must to be registered at the Ministry of Agriculture (MAPA); the production of these establishments is supervised, to guarantee good quality products for the customers. To obtain the registry as a fertilizer producer, the establishment has to inform MAPA about the complete production process, to present the list of materials used for the fertilizers fabrication, to have the environmental permission by the government, etc. These establishments must to have a quality control of their products, to guarantee the nutrients quantities informed for each type of product, and to control the heavy metals contamination, specially for the fertilizers that contain micronutrients.

To be registered as a mineral fertilizer, silicon products must to follow another Federal Norm (Instrução Normativa 10, published on 28/10/2004), that give the definitions and rules about specifications, guarantees, tolerances, registry, packing and label of mineral fertilizers used in agriculture.

The simple mineral fertilizers included at this Federal Norm are: calcium silicate, calcium and manganese silicate, Cu, Mn, Fe, Mo, Co and B silicate. These products can be obtained from the natural silicates (silicon rock), by the thermal treatment (1000ºC) of silicate composts and Ca and Mg composts or by the grinding of residues from the steel production. Potassium silicate solution is obtained by the reaction of silicate minerals with potassium hydroxide.

The establishments that produce Si fertilizers, obtained from the residues of steel production, must to have a Ministry of Agriculture authorization to trade their products.

Mineral fertilizers containing silicon must have at least the guarantees showed at Table 1.

SIMPLE MINERAL FERTILIZER	GUARANTEES
Calcium Silicate	20% Si; 29% Ca
Calcium and Magnesium Silicate	10% Si; 7% Ca; 1,8% Mg
Copper Silicate	5% Si; 1% Cu
Manganese Silicate	5% Si; 2% Mn
Iron Silicate	5% Si; 2% Fe
Zinc Silicate	5% Si; 3% Zn
Mo Silicate	5% Si; 0,1% Mo
Cobalt Silicate	5% Si; 0,1% Co
Boron Silicate	5% Si; 1% B
Potassium Silicate Solution	10% Si; 15% K_2O

Mineral fertilizers for soil application must to declare the total quantity of silicon; mineral fertilizers for application on leaves, hydroponic cultives and other fluids must to declare the water soluble silicon quantity.

Some of the fertilizers containing silicon, as calcium silicate and magnesium silicate, are considered as lime products. However, to be registered as limes, calcium silicate and calcium and magnesium silicate must present, at least: 67% of Neutralization Power (PN); 38% of CaO+MgO and 45% of Total Neutralization Relative Power (PRNT). These and other values used to register limes and soil conditioners are present at another Federal Norm (Instrução Normativa 4, published on 02/08/2004). Beside these characteristics listed above, mineral fertilizers and limes must to attend many other requisites present at the Brazilian Legislation, as granulometry, for exemple.

The Ministry of Agriculture (MAPA) is searching and studying methods to evaluate silicon, in order to have an official method to analyze this element in fertilizers.

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III Silicon in Agriculture Conference
ORAL PRESENTATIONS - PROGRAM

Sunday, 23 - Oral Presentation		
Time	**Title**	**Author**
16:30h-16:45h	**OP-002**-Influence of silicon and potassium sources on the incidence of major pests of rice (*Oriza sativa*)	Balasubramaniam*, P.; Subramanian, S.; Chandramani, P.
16:50h-17:05h	**OP-007**- Impact of calcium silicate amendments on sugarcane yield and soil properties in Queensland – Australia	Kingston*, G., Berthelsen, S.; Hurney, A.P.; Rudd, A.; Noble. A.D.
17:10h-17:25h	**OP-008**-Immunodetection of silica-binding proteins in rice and other graminaceous plants	Wang, H.*; Xin-Hui, S.; Chuang-Deng, O.; Fu-Suo, Z.
17:30h -17:45h	**OP-012**- Does silicon increase resistance of water stressed sugarcane to larval feeding by the african stalk borer, *Eldana accharina walker* (Lepidoptera: Pyralidae)?	Kvedaras*, O.L.; Keeping M.G.; Goebel R.; Byrne M.
17:50h -18:05h	**OP-013**- Silicon uptake and transport is an active process in *Cucumis sativus l.*	Liang*, Y.; Si, J.; Römheld, V.

Monday, 24 - Oral Presentation		
Time	**Title**	**Author**
11:30h -11:45h	**OP-044**-Importance of rhizosphere ph for silicon availability and plant uptake	Zhang, C.; Zhang, F.; Römheld*, V.
11:45h-12:00h	**OP-073**-Thermogravimetric analysis to evaluate rice hull and rice hull ash as a source of bioavailable silicon in rice	Prakash, N.B.; Moriizumi, M.; Itoh, S.
12:00h–12:15h	**OP–087-** Effect of foliar application of potassium silicate on angular leaf spot development on beans	Rodrigues*, F.Á.; Duarte, H.S.S.; Korndörfer, G.H.; Wordell Filho, J.A.; Zambolim, L.
12:15h-12:30h	**OP-088-** Effect of foliar application of potassium silicate on Asian soybean rust development on soybean	Rodrigues*, F.Á.; Duarte, H.S.S.; Korndörfer, G.H.; Zambolim, L.

THERMOGRAVIMETRIC ANALYSIS TO EVALUATE RICE HULL AND RICE HULL ASH AS A SOURCE OF BIOAVAILABLE SILICON IN RICE

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Rice hull is a valuable and sustainable bio-resource material accumulated without any cost by rice producing countries. The estimated worldwide rice hull production is about 120 million tons, of which about 90% is generated in developing countries and can be a significant source of energy. Rice Hull Ash (RHA), obtained as by product, is an important source of silicon (Si) and can be an economically viable raw material for many industries. It is being commonly used as Si source in rice farming of many developing countries. The thermogravimetric analysis of rice hull and RHA obtained at different temperatures revealed that the carbonaceous materials can be seen only in the RHA 300 and RHA-400 samples and such materials are absent in RHA-500 and other RHA obtained at higher temperatures. The greenhouse study indicated that the soil solution Si was higher in RHA-300 and RHA-400 treatments followed by RHA-500 and RHA-600 treatments. Average soil solution Si content from planting till harvest was higher in RHA-400 treatment compared to other treatments. The average soil solution Si content and Si concentration of soil solution at different growth stages of RHA-700, RHA-800 and RHA-900 treated pots were on par with that of control treatment indicating less release of Si from RHA obtained at higher temperatures. The soil solution Si, content of Si in rice straw and rice hull was higher in the RHA-400 treated plants and a good relationship was found between the burning temperature of the rice hull and plant available Si.

Index terms: rice hull ash, thermogravimetry, silicon.

INFLUENCE OF SILICON AND POTASSIUM SOURCES ON THE INCIDENCE OF MAJOR RICE PESTS

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An experiment was conducted with the supply of Rice Straw (RS), Silicate Solubilizing Bacteria (SSB), RS + SSB and Sodium Meta Silicate (SMS) with graded levels of soil test based K on the incidence of major rice pests: white backed plant hopper (WBPH), brown plant hopper (BPH), gall midge, leaf folder and stem borer. The application of different sources of silicon and potassium increased the content of these two elements in rice plant which decreased pest incidence. The plot with SMS showed the lowest incidence of 1.8% WPBH per tiller, 1.7% for PBH per tiller, 7.6 % for gall midge, 6.3 % for leaf folder and 2.6% for stem borer followed by RS + SSB. The highest incidence was observed in the control. Similarly, as the rate of K increased from 0 to 100 % soil test based K resulted in a decreased incidence of these pests. In addition, the incidence of different pests were negatively correlated with Si and K content.

Index terms: sodium meta silicate, pests, rice straw, silicate solubilizing bacteria

EFFECT OF FOLIAR APPLICATION OF POTASSIUM SILICATE ON ANGULAR LEAF SPOT DEVELOPMENT ON BEANS

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The most significant effect of silicon to some agronomic crops, besides improving their fitness in nature and increasing agricultural productivity, is the control of many diseases. The purpose of this study was to determine the effect of foliar application of potassium silicate (INEOS Silicas Brazil) on the control of angular leaf spot, caused by the fungus *Phaeoisariopsis griseola*, on beans. A 5 x 2 factorial experiment, consisting of five potassium silicate rates (0, 8, 20, 40 and 60 g/L) with (pH = 5.5) and without (pH 10.5) pH change was arranged in a randomized complete block design, under field conditions, with three replications. An additional treatment consisted of plants sprayed with the fungicide Tebuconazole (0.5 L/ha). Plants of beans (cultivar "Carioquinha Talismã") were artificially inoculated with spores of the fungus (1.6×10^4 spores/ml) at 30 days after seed germination (DASG). Plants from each treatment and replication were sprayed at 45, 60 and 75 DASG. Disease severity (DS) was evaluated at 85 DASG using a scale with values ranging from 0.2 to 30.4. The response of DS to potassium silicate rates was significantly quadratic and linear, respectively, to pH 10.5 ($DS = 29.63 - 0.47x + 0.0057x^2$, $R^2 = 0.93$) and 5.5 ($DS = 26.41 - 0.17x$, $R^2 = 0.69$). Plants from plots receiving the application of potassium silicate rates at pH 10.5 were visually less affected by the disease as compared to plants from plots receiving the application of potassium silicate rates at pH 5.5. The treatment corresponding to the application of fungicide (DS = 1.1) was significantly different all treatments.

Index terms: potassium silicate, angular leaf spot, beans, *Phaeoisariopsis griseola*.

EFFECT OF FOLIAR APPLICATION OF POTASSIUM SILICATE ON ASIAN SOYBEAN RUST DEVELOPMENT ON SOYBEAN

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Asian soybean rust, caused by the fungus *Phakopsora pachyrhizi*, is the most important disease of soybean in Brazil. This fungus attacks the foliage of soybean plants causing early drop of the leaves and, as a consequence, pod setting and yield are negatively affected. The spray of fungicide is the only method of control available to the growers. The purpose of this study was to determine the effect of foliar application of potassium silicate (PS) (INEOS Silicas Brazil) on the control of this disease. The experiment was arranged in a randomized complete block design, under field conditions, with seven treatments and three replications. Plants of soybean (cultivar "Sambaiba") were artificially inoculated with uredospores of the fungus (2×10^4 uredospores/ml) at 25 days after seed germination (DASG). The treatments were as following: 1- control; 2- PS (8 g/L); 3- PS (20 g/L); 4- PS (40 g/L); 5- PS (60 g/L); 6 - KOH (pH 5.5) and 7 - Epoxiconazole + Pyraclostrobin (0.5 L/ha). The pH of the PS was adjusted to 5.5. The treatment with KOH (pH 5.5) was included to equilibrate the amount of potassium with treatment 4. Plants from each treatment and replication were sprayed at 50, 60 and 85 DASG. Disease severity (DS) was evaluated at 95 DASG using a scale from 0 to 5 where: 0 = no disease symptoms, 2 = 11 to 25%; 3 = 26 to 50%; 4 = 51 to 75% and 5 = more than 75% of the leaf area with pustules. The response of DS to potassium silicate rates was significantly quadratic ($DS = 58.89 - 2.13x + 0.026x^2$, $R^2 = 0.72$). There was statistical difference between the treatments potassium silicate (40 g/L) and KOH for DS (25 and 46%, respectively). The treatment 7 (DS = 0.7) was significantly different from all treatments. Silicon negatively affected the development of Asian soybean rust as compared to potassium.

Index terms: potassium silicate, Asian soybean rust, soybean, *Phakopsora pachyrhizi*.

IMMUNODETECTION OF SILICA-BINDING PROTEINS IN RICE AND OTHER GRAMINACEOUS PLANTS

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Although the accumulation of silica in grasses is a well-known phenomenon, the mechanism controlling silica deposition in these plants is not clear. Recently, we found a silica-binding protein, namely SBP117, which is tightly bound to silica bodies in rice leaves and can induce silica precipitation *in vitro*. In order to detect the distribution of SBP117 in rice and similar proteins in other graminaceous plants, specific polyclonal antibodies against SBP117 were successfully raised by synthesized peptides that were conjugated with Keyhole Limpet Hemocyanin and used as antigens to immunize rabbits. Western blot and dot blot results indicate that the antibodies not only can react with silicon-binding protein of rice, but also cross react with the proteins of other silicon-accumulated graminaceous plants, while it does not react with other proteins such as BAS and from non-silicon accumulated dicotyledonous plants such as tomato. These findings suggest that the homologous proteins of SBP117 exist widely in the graminaceous plants. Furthermore, tissue-printing study showed that SBP117 is mainly located at the epidermal and sclerenchymatous cells of leaves. The distribution of SBP117 in rice plants coincided with the sites of Si accumulation, which had been reported previously by other authors. Therefore, it is concluded that the silicon-binding protein (SBP117) may be involved in the control of silicon deposition in rice plants.

Index terms: silicon-binding protein, polyclonal antibodies, silicon deposition.

SILICON UPTAKE AND TRANSPORT IS AN ACTIVE PROCESS IN CUCUMBER

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Silicon (Si) content vary greatly in plant tissues depending much upon plant species, which is attributed mainly to the differences in the mechanisms for Si uptake and transport. In general, graminaceous plants accumulate much more Si in their tissues than other species, while most dicotyledonous plants take up Si passively, and some dicots such as legumes exclude Si from uptake. Cucumber (*Cucumis sativus*) is a species known to accumulate high levels of Si in the shoots, though the mechanism for its high Si uptake is little understood. In a series of hydroponic experiments, we examined uptake and xylem loading of Si in cucumber along with beans (*Vicia faba*) at three levels of Si (0.085, 0.17 and 1.7 mM). The results showed that measured Si uptake in cucumber was more than twice as high as calculated from the rate of transpiration assuming no discrimination between silicic acid and water in uptake. Measured Si uptake in beans, however, was significantly lower than the calculated uptake. Concentration of Si in xylem exudates was several folds higher in cucumber, but was significantly lower in bean compared to the Si concentration in external solutions, regardless of Si levels. Si uptake was strongly inhibited by low temperature and 2, 4-dinitrophenol, a metabolic inhibitor, in cucumber but not in beans. It can be concluded that Si uptake and transport in cucumber is active and independent of external Si concentrations in contrast to the process in beans.

Index terms: beans, cucumber, dicotyledon, silicon, transpiration, uptake, xylem loading

IMPORTANCE OF RHIZOSPHERE pH FOR SILICON AVAILABILITY AND PLANT UPTAKE

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Besides Mn and Zn, particularly silicon is of importance for plant health, e.g. in rice against blast disease. There is a general understanding that solubility and plant uptake of silicon is lower at a higher soil acidity. Thus, soil incubation experiments were conducted at different pH values (3.5-7.5) for measurement of silicon extractability by water and $MgSO_4$ as well as a pot growth experiment with manipulated rhizosphere pH by supply of different N forms (NO_3^- versus NH_4^+) to rice (*Oryza sativa*. L.) and cucumber (*Cucumis sativus*. L.). Contrary to what was expected, silicon extractability by water and $MgSO_4$, as well as Si uptake by both plant species were increased at lower pH when both soils were supplied with NH_4-N stabilized by a nitrification inhibitor (DMPP). The effect of pH was more expressed in the soil supplemented with fly ash or silicate lime. As a consequence of the unexpected pH effect on silicon solubility and plant uptake achieved with both soils used, an incubation experiment with further defined soils has been set up. The importance of an adapted fertilization management via rhizosphere pH for an enhanced silicon acquisition and plant health will be discussed.

Index terms: rice, pH, rhizosphere.

IMPACT OF CALCIUM SILICATE AMENDMENTS ON SUGARCANE YIELD AND SOIL PROPERTIES IN QUEENSLAND AUSTRALIA.

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Deficiency in plant available silicon is a significant constraint to productivity of sugarcane in Queensland, Australia. Cane yield and ccs response to Si application was measured, and diagnostic threshold values in soil and leaf tissue validated in three major replicated field trials that received six rates of calcium silicate slag between 0 and 12 ton/ha. There was a 32% increase in total cane yield at a rate of 9 ton/ha Ca-silicate, over two years at the Innisfail site. At Mossman, a rate of 12 ton/ha gave a 35% total yield increase compared to the control over the same time period. At Bundaberg, over a crop cycle of 4 years, 12 ton/ha Ca-silicate resulted in a 45% increase in yield compared to the control. The results clearly indicate that silicon should be treated as an integral part of any fertilizer strategy associated with cane production. Silicon uptake by biomass increased with rate of applied slag. On average, untreated controls acquired 77 kg Si/ha while cane treated with 6 ton slag/ha acquired 166 kg Si/ha. Soil data from the Mossman and Innisfail sites demonstrated significant increases in CEC in all treatments receiving Ca-silicate additions suggesting, that in part, the observed yield responses where associated with improvements in the chemical properties of these degraded soils. A strong and significant relationship existed between relative cane yield and index leaf Si status (r^2= 0.73). An asymptotic function showed 95% of Y_{max} was achieved with a leaf Si of 0.55%. Current soil agronomic tests used to determine the Si status of soil were effective, particularly for the light textured soils. The experimental data supported current recommendations of 10mg Si/kg soil in 0.01 M $CaCl_2$ extract and 100mg Si/kg in 0.005 M H_2SO_4 extract. Further research is required for interpretation of soil and plant data for soils with higher clay content, high sorptive ability due to levels of Al and Fe oxides and hydroxides and possibly poorly drained soils with high levels of organic matter and alkaline or sodic soils.

Index terms: silicon, calcium silicate, sugarcane, soil analysis, cation exchange capacity, critical levels.

DOES SILICON INCREASE RESISTANCE OF WATER STRESSED SUGARCANE TO LARVAL FEEDING BY THE AFRICAN STALK BORER, *ELDANA SACCHARINA* WALKER (LEPIDOPTERA: PYRALIDAE)?

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The mechanical barrier hypothesis of silicon-mediated plant resistance to insect herbivores and fungal diseases argues that Si deposition in plant tissues increases mechanical resistance to penetration and or feeding by the insect or fungal agent involved. We designed a study to test whether this hypothesis explained, at least in part, the enhanced resistance of water stressed, Si-fertilized sugarcane to stalk borer, *Eldana saccharina*. Four sugarcane varieties, two resistant (N21, N33) and two susceptible (N26, N11) to *E. saccharina* were grown in a pot trial in Si deficient river sand with and without calcium silicate as a source of Si. A split-plot design with six replicates was used. At eight months, drip irrigation to half the trial was reduced in a staged manner to induce water stress. At nine months, the plants were artificially infested with *E. saccharina* eggs and pre-assigned pots were subsequently harvested at 14, 21 days and 400 day-degrees (≈ 30 days) after inoculation. The 14 day harvest allowed determination of Si effects on larval survival before or at stalk penetration (external Si barrier), while at 21 and 400 day-degree allowed assessment of its effects on larval survival and growth at two stages after stalk penetration (internal deposits of Si). Consistent with the Si barrier hypothesis, the 14 day harvest results indicated that young larvae attempting stalk penetration suffered greater mortality on Si+ plants than on Si- plants and that Si+ plants show less damage due to larval feeding. Later larval stages also showed increased mortality and slower growth in Si+ plants, indicating an internal effect of Si as well. Although final harvest results are not yet available, we anticipate that they will demonstrate a role for Si in reducing water stress, hence affording greater protection against *E. saccharina* attack in water stressed plants.

Index terms: Eldana saccharina, calcium silicate, host plant resistance, mechanical barrier hypothesis, silicon, sugarcane, water stress.

III Silicon in Agriculture Conference
POSTERS CONTRIBUTIONS

SECTION 1: Silicon in General

CUMULATIVE RELEASE OF SILICON IN POST HARVEST RICE SOIL INCORPORATED WITH RICE STRAW

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An experiment was conducted with rice under submerged conditions with sources of Si and K. Rice Straw (RS), Silicate Solubilizing Bacteria (SSB), RS + SSB and Sodium Meta Silicate (SMS) were the treatments. After harvest, the soil samples were sequentially extracted for Si. The amount of Si released during first extraction was higher for all treatments in comparison to the control. In the succeeding extract, the amount of Si released decreased successively until reaching a constant rate. This indicated that a considerable reserve of Si was present even after the last extraction. The rate release of Si became constant after the 6th and 8th extraction in the control and RS + SSB, respectively. The cumulative release of Si was greater due to SMS followed by RS + SSB. The cumulative release of Si exhibited a good fit with the Cobb–Douglas exponential functional relationship of $y = a x^b$.

Index terms: rice straw, silicate solubilizing bacteria, constant rate, cumulative release

A SURVEY FOR SI CONTENT IN THE AMAZONIAN DARK EARTH SOILS

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Archeological Black Earth or Amazonian Dark Earth (ADE) soils occur widely in the Brazilian Amazonian region, showing a high fertility level in comparison to those surroundings soils. This superior degree of fertility of ADE soils is, possibly, related to the anthropogenic activities during the period of 500 to 2500 B.C. These sites, usually not larger than 2 to 3 ha, are found within areas with different soil formation, but all them have high organic matter contents that correspond to high soil fertilities. Analyses of silicon content were performed in order to evaluate its availability to plants as well determined the chemical and physical properties of the soils. Preliminary data showed a large variability in Si content among the 17 sites of ADE sampled. The Hatahara site and its surrounding soil showed a clear ADE gradient (Terra Mulata) was present and the greatest amount of Si extracted was around 60 mg Si/kg soil in $CaCl_2$ 0,01 mol L^{-1}.

Index terms: Amazonian Dark Earth, anthropogenic soil, silicon

EFFECT OF WATER STRESS ON LEAF SILICIFICATION OF THREE TROPICAL FODDER GRASS SPECIES (*PENNISETUM PURPUREUM* SCHUMACH, *PANICUM MAXIMUM* CULTIVAR C1 AND *P. MAXIMUM* JACQ.) IN BENIN

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We created water stress in three tropical fodder grass species by watering pots every three days (droughted treatment) and every day in the control, from 4 January until 15 march in 2002. Aerial biomass of all species decreased in response to drought stress. Visual symptoms of plant drought-stressed such as leaf discoloration and winding were also observed. The much lower leaves biomass associated to the higher specific leaf area was accompanied by a significant decrease of silica concentration in *Pennisetum purpureum*. Silica concentration ranged from 2.03% to 6.19% in blades and from 1.95% to 4.04% in sheaths, depending on treatments and species, with a highly significant species effect. *Panicum maximum C1* had lower values whereas *P. purpureum* showed higher values.There were few significant effects of stress on leaf traits. In *Pennisetum purpureum*, drought stress decreased silica concentration in blades and increased RWC and SLA. Increased silica deposition in well watered plants may result from higher transpiration rates. Silica was highly correlated with soluble ashes in both species.

Index terms: water stress, grass, silica, specific leaf area, relative water content, carbon, soluble ashes.

THE EFFECT OF SILICON ON NODULATION AND NITROGEN FIXATION OF SOYBEAN AND BEAN UNDER HYDROPONIC CONDITIONS

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The role of silicon on nodule and plant development was evaluated in soybean and bean under hydroponic conditions. In soybean, nodulated soybean plants with B*radyrhizobium japonicum*, strain CB 1809, were submitted to Si at rates of 0; 0.36; 1.07 and 3.57 mM of $Na_2SiO_3.5H_2O$, kept under pH 6.0. Nodulation was determined at 39 and 44 days after emergence, respectively, in two subsequent studies. In both studies, the addition of Si in nutrient solution increased the nodule number and mass as well as nodule nitrogenase activity with maximum values observed at the rate of 1,07 mM. In the first study, an increase of 20% in the shoot nitrogen content was obtained, although no significant variation was observed in the plant biomass. In bean, nodulated bean plants with *Rhizobium tropici*, strain CIAT 1899, were submitted to Si concentrations of 0; 0.36; 0.89; 1.78; 2.7 and 3.57 mM supplied as $Na_2SiO_3.5H_2O$ and kept under pH 6.0. Increases of nitrogenase activity and in shoot nitrogen content were obtained at Si concentrations up to 1.78 mM. However, decreases in the plant biomass were observed with higher rates of Si. These results confirm the beneficial role of Si on the biological nitrogen fixation but care should be taken if a balanced equilibrium between plant growth and biological nitrogen fixation processes is expected to occur under an adequate level of silicon.

Index terms: nodulation, soybean, bean, nitrogenase activity, silicon.

STABILIZED ORTHOSILICIC AND MONOSILICIC ACID SOLUTION KEEP THE VIABILITY OF STIMULATED MACROFAGES WTHOUT INTERFERE IN NITRIC OXIDE PRODUCTION

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Water is the principal medium for the chemical and biochemical processes that support plant metabolism. Under pressure within plant cells, water provides physical support for plants. The `default condition` for solute transport across cell membranes is that the solute crosses the membrane by diffusion across the lipid component of the membrane. The most significant interactions of silicic acid with organisms involve the entry of silicic acid into cells and, for multicellular organisms, into the aqueous intercellular spaces of the organism. The present work took into consideration the fact that the major events responsible to modulate the inflammatory response remain unknown, and aimed to investigate cellular viability of stimulated and unstimulated murine macrophages (J774) in contact with the ionic products from the dissolution of a stabilized orthosilicic acid (BioSil) or monosilicic acid (H_4SIO_4). Cell culture was performed with suspensions of 2.5 x 10^5 cells/ ml cultured in RPMI plus 10% of calf serum in humidified chamber at 37^o C and 5% CO_2. Kinetic experiments were carried out with observations every 6 hs from 6 to 48 hs of cell culture for silicon preparations at various concentrations, ranging from 10 ng to 10 µg. It was observed that none of the silicon concentrations impared or increased nitric oxide from both unstimulated or IFN-y and LPS-stimulated macrophages. We also found that under, under silicon treatment, macrophages exhibited a significant increase in their proliferation ratios, particularly after 30 and 48 hs, maintaining the cell viability at those time points. Together, our results indicate that silicon treatment is able to maintain macrophage viability, even when these cells are submitted to strong stimulation, without interfering in the nitric oxide production.

Index terms: membrane, silicon, macrophage

THE SILICON EFFECT ON CELLULAR VIABIILITY AND CYTOTOXICITY

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Water is essential in the plant environment and it transports minerals through the soil to the roots where they are absorbed by the plant. The soil system is composed of three major components: solid particles (minerals and organic matter), water with various dissolved chemicals, and air. An active root system requires a delicate balance between the three soil components; but the balance between the liquid and gas phases is most critical, since it regulates root activity and plant growth process. Considering that the effects of silicon on critical cellular events leading to the modulation of the inflammatory response remain unknown, in the current work we investigated cellular viability, proliferation, morphology changes of stimulated and unstimulated murine macrophages (J774) in contact with the ionic products from the dissolution of a stabilized orthosilicic acid (BioSil®) or monosilicic acid (H_4SiO_4). Cell culture was performed with suspensions of 2.5 x 10^5 cells/ ml cultured in RPMI plus 10% of calf serum in humidified chamber at 37 ^{o}C and 5% CO_2. Kinetic experiments were done with observations at each 6 hs from 6 to 48 hs. Of cell culture in preparations submitted or not to treatment of silicon preparations in various concentrations, ranging from 10 ng to 10 µg. Macrophages were also submitted to stimulation with IFN-γ or LPS (10 ug/ml).When treated by BioSil® or H_4SiO, we observed that macrophages did not present any apparent morphological alterations, even at the highest silicon concentration and after 48 hours of cell cultures.

Index terms: macrophages, silicon, root activity

MOVEMENT OF SILICON IN AVOCADO (Persea americana Mill.)

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During the past three years, a mineral rich in silicon was applied to avocado trees (*Persea americana* Mill., cultivar HASS) and other fruit crops (mango, strawberry, guava). This silicon material was broadcast spread on the root zone twice a year at the beginning and at the end of the raining season, starting on February 2002. The chemical composition of the mineral is: CaO_2, SiO_2, MgO_2, Fe_2O_3, ZnO, Al_2O_3, K_2O, Na_2O and SO_3, in a proportion of 25, 15, 13, 5, 3, 3, 1, 0.5, and 0.2%, respectively. Improvements were observed in: vegetative development (canopy and roots), times of flowering a year, average yield and crop and harvest health. No agrochemicals were applied during the course of this study, and insects and fungal diseases were low to limiting. The movement of silicon was sequenced using SEM-EDS techniques in the avocado crop. The results showed that silicon was solubilized by weathering process or to some enzyme complex coming from the avocado roots or to the action of soil microflora. Afterwards, it is transported from roots to shoots in different soluble forms which include polymeric, finally forming crystals on the leaf surface. Differences were observed in the anatomy of tissue and cells of trees during the crop development due to the silicon mineral treatments.

Index terms: avocado, *Persea americana* Mill, silicon.

SECTION 2: Silicon X Pest and Disease Management

EFFECTS OF POTASSIUM SILICATE AND "CALDA VIÇOSA" MIXED OR NOT WITH SILICATE ON THE CONTROL OF COFFEE LEAF RUST.

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The most significant effect of silicon to some agronomic crops, besides improving their fitness in nature and increasing agricultural productivity, is the control of many diseases. There is no information in the literature regarding its foliar application on the control of coffee rust, caused by the fungus *Hemileia vastatrix*, under field conditions. The objective of this study was to test the effect of foliar application of potassium silicate (INEOS Silicas, Brazil) and "Calda Viçosa - Viça Café" alone or in combination with potassium silicate ("Café Brazil, Alfenas, MG, Brazil) to control coffee leaf rust. The trial was arranged in a completely randomized design with four replications at Piranga county, MG on December of 2004. The coffee plants were from the cultivar "Catuaí" with four years old. The following treatments were used: 1- Control; 2- "Viça Café" 5 kg/ha + sodium metassilicate 2.2 kg/ha, pH 6.0; 3- "Viça Café" 5 kg/ha + potassium silicate 1.5 kg/ha, pH 5.0; 4- "Viça Café" 5 kg/ha + sodium silicate 1.2 kg/ha, pH 5.0; 5- potassium silicate 40g/L, pH 5.5; 6 - "Viça Café" 5 kg/ha, pH 5.8 and 7 - Epoxiconazole 0.8 l/ha. Plants from each treatment were sprayed every 30 days from December 2004 through March 2005 in a total of four applications except for the treatment 7 which was done twice. The incidence of leaves with rust was evaluated every 30 days from December 2004 through June 2005 and the data obtained was used to calculate the area under the disease progress curve (AUDPC). There were not statistical difference among the treatments 2, 3, 4, 6 and 7 (759; 865.25; 766; 1026.75 and 106.75, respectively) but they were statistically different from treatments 1 and 5 (5121.75 and 4298.50, respectively). Treatments 1 and 5 were not statistically different. The application of potassium silicate alone did not seem to have any positive effect on the control of coffee rust when sprayed every 30 days. The use of potassium silicate mixed with "Viça Café" did not improve the control of coffe rust.

Index terms: potassium silicate, *Coffea arabica* L., *Hemileia vastatrix*, nutrient mixture.

SERPENTINITE AS A SILICON SOURCE TO CONTROL LEAF BLAST IN IRRIGATED RICE

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Rice blast, caused by *Pyricularia grisea*, is one of the major yield constraints and ranks first among the diseases of irrigated rice in the State of Tocantins. The role of silicon in increasing rice resistance to diverse pathogens has been demonstrated in experiments conducted in different parts of the world including Brazil. However, a paucity of information exists on the efficiency of the available Brazilian sources of silicon in controlling rice blast. A by-product of asbestos mining industry, serpentinite, with high silicon content is available in large quantities in Minaçu, GO. A field experiment was conducted using the irrigated rice cultivar BRS Formoso to assess the efficiency of calcinated serpentinite containing 45.5% of SiO_2 on rice blast development under natural field conditions. The experimental design was a split-plot with four replications. The main plots consisted of five rates of calcinated serpentinite (0, 2, 4, 6, 8 ton ha^{-1}) and the subplots were foliar fungicide treatments (non-treated and treated) to control panicle blast. The leaf blast severity was reduced at the rate of 1.48% per ton of calcinated serpentinite. The total tissue sugar content decreased significantly with the increased rates of serpentinite. The relationship between the tissue sugar content and leaf blast severity was linear and positive (r^2= 0.74; $P \leq 0.01$). The decrease in leaf blast severity with increased rates of calcinated serpentinite appears to be associated with a decrease in sugar levels. Plant dry weight increase was quadratic and the estimated maximum was 851 g m^{-2} for serpentinite applied at the rate of 4.2 ton ha^{-1}. Rice blast is a high sugar disease and the application of calcinated serpentinite has been shown to decrease sugar levels in rice tissue while increasing rice blast resistance.

Index terms: silicon sources, rice blast, calcinated serpentinite.

EFFECTS OF SILICON ON CORN RESISTANCE TO FALL ARMYWORM (*Spodoptera frugiperda* (J.E. Smith) (Lepidoptera: Noctuidae)) AND ITS INTERACTION WITH INSECT GROWTH REGULATOR

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Corn (*Zea mays* L.) is one of the most important cultivated cereals in the world. In Brazil, the fall armyworm is the major crop pest, and synthetic insecticides are widely used for its control. However, there is a problem with pest resistance development. Silicon might increase the natural resistance level of the plant and, consequently, decrease the infestation and yield losses. Laboratory and greenhouse experiments were performed with the aim to test the silicon effect, applied to soil and leaves and its interaction with the insect growth regulator lufenuron. Nine treatments were evaluated in a 3 x 3 factorial with five replications. Treated and untreated leaves were offered to the insect caterpillars in a choice test. No-preference was found for any of the treatments after 24 hours. Lufenuron + silicon decreased consumption, increased larval mortality and produced less injury in comparison with the other treatments in both laboratory and greenhouse conditions.

Index terms: silicon, lufenuron, corn, resistance.

EFFECT OF SILICON DOSES AND SOURCES ON THE INTENSITY OF THE BROWN EYE SPOT OF COFFEE SEEDLINGS.

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A better understanding of nutrient dynamics in coffee plants is been required as a function a greater nutritional requirement by more productive coffee cultivars and the expansion of these crops in low natural fertility soils. Silicon is considered to be beneficial for reducing disease intensity, as the brown eye spot in coffee plants, even so it does not have specific physiologic and nutritional function in plants. Brown eye spot of coffee is an important nursery disease. The objective of this work was to evaluate the effect of calcium and sodium silicate on the intensity brown eye spot (*Cercospora coffeicola* Berk. & Cooke) in coffee seedlings (Catuai IAC 99) by using doses (0; 0.32; 0.63 and 1.26 g of $SiO_2.kg^{-1}$ of substrate). Five evaluations were done by counting the number of diseased plants, number of leaf with lesions, number of lesions per leaf and total number of lesions per plant. The concentration of macro, micronutrients, silicon and lignin in the leaves were determined at the end of the experiment. The lowest area under the disease progress curve of the total number of lesions was observed with 0.84 $g.kg^{-1}$ of sodium silicate. A linear decrease for area under the disease progress curve of the plants diseased and increase in the concentration of lignin up to the dose of 0.52 $g.kg^{-1}$ of sodium silicate was found. The increase of sodium silicate and dose application into the soil up to 0,53 $g.kg^{-1}$ decreased the concentration de SiO_2 on the stem.

Index terms: relationship nutrition disease, *Cercospora coffeicola*, *Coffea arabica*

USE OF SILICON AND ACIBENZOLAR-S-METHYL AGAINST THE GREEN APHID *Schizaphis graminum* (Rond.)(Hemiptera: Aphididae) ON WHEAT PLANTS

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The green aphid *Schizaphis graminum* (Hemiptera: Aphididae) is a wheat crop pest. This work is intended to evaluate the preference of the green aphid on wheat plants in a number of treatments. Wheat seeds of the cv Embrapa 22 were sown in pots with 1 Kg of substrate. 0.5% silicic acid and 0.05% ASM was sprayed in two applications 1^0 = 18 days and 2^0 = 28 days after sowing. Treatments: 1= control; 2= Silicon in two applications; 3= Silicon at the second application, 4= ASM at the first application; 5= ASM in two applications; 6= ASM at the second application; 7= Silicon at the first and ASM at the second application; 8= ASM at the first application and Silicon at the second; 9= Silicon + ASM at the first application; 10= Silicon + ASM at the first and second applications; 11= Silicon + ASM at the second application; 12= Silicon at the first application. The free choice test was undertaken 44 days after sowing, by collecting a leaf from each corresponding to each treatment and replicate. In the Laboratory, the leaves were cut into 7-cm long sections and put into Petri dishes with 1% Agar, where 48 aphids/dish were released. Counts of aphids present in each leaf section at 24, 48 and 72 hours from release were performed. In the remaining plants 10 aphids were released of each pot and after 10 days, the count of insects was done. The design was completely randomized, with 12 treatments and 6 replicates. The data were submitted to the analysis of variance and means compared with Scott-Knott ($P<0,05$). It was found that application of silicon and/or ASM showed reduction of the colonization of the plants by aphids.

Index terms: wheat, silicon, ASM, induced resistance.

EFFECTS OF SILICON ON DEVELOPMENT OF GRAY LEAF SPOT IN PERENNIAL RYEGRASS TURF.

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The effects of silicon on development of gray leaf spot in perennial ryegrass (*Lolium perenne* L.) turf was evaluated in two golf courses in Pennsylvania. The soil types of the sites were described as Ultisols with a soil silicon level and pH of 15 ppm and 5.3 (site 1) and Alfisols with a soil silicon level and pH of 38 ppm and 6.8 (site 2). The experiments were designed as a split-plot with source of silicon (wollastonite and calcium silicate slag) as main-plot factor and rate of silicon amendments (0, 0.5, 1, 2, 5 and 10 metric ton/ha) as sub-plot factor. Silicon was incorporated into soil by core-aerification. Nine weeks after application of silicon, the grass was inoculated with a monoconidial suspension of *Magnaporthe grisea* (60 x10^3 conidia/ml of water). Disease assessments were made weekly as visual estimates where 0= no blighting and 100 = entire plot area blighted. Disease progress over time was evaluated using the parameter estimates (rate r, Y_{max} and AUDPC) to determine the treatment effects. There were significant differences ($P \leq 0.05$) between sources for AUDPC and final disease severity at site 2. However, such differences were not found at site 1. The rate of disease progress did not significantly differ between sources at any of the sites. There were significant differences ($P \leq 0.05$) between the rate of silicon amendments for AUDPC and final disease severity at both sites. Rate parameter r significantly differed ($P \leq 0.05$) between the rates of silicon amendments only at site 1. Gray leaf spot severity was significantly reduced at both sites on several individual assessment dates. Results of this study suggest that application of silicon has great potential for use as integral part of a gray leaf spot management strategy.

Index terms: gray leaf spot, perennial ryegrass, silicon, turf.

COMBINING SILICON WITH MICROBIAL AGENTS FOR THE BIOCONTROL OF POSTHARVEST FRUIT DISEASE AND DETERMINATION OF POSSIBLE INVOLVED MECHANISM (S)

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Application of silicon (Si) combining with antagonistic yeasts was significantly effective in controlling postharvest diseases in different fruits. Silicon in combination with *Cryptococcus laurentii* provided synergistic effects against blue mold and brown rot of sweet cherry fruit caused by *Penicillium expansum* and *Monilinia fructicola*, respectively, at 20°C. In addition, combining 2% Si with *C. laurentii* and *R. glutinis* at a concentration of 5×10^7 cells/ml provided the best effectiveness in controlling the diseases caused by *A. alternata* and *P. expansum* of jujube fruit stored at 20ºC. When fruit were stored 0ºC, combining Si with the antagonistic yeasts showed the same level of control against these pathogens. There was a positive relationship between concentration of Si application and fruit decay inhibition. Results of scanning electron microscopy showed that Si significantly inhibited spore germination and growth of the pathogens in the wounds of fruit. Compared with wounded water control, Si treatment induced a significant increase in the activities of phenylalanine ammonia-lyase, polyphenoloxidase, and peroxidase in fruit, but did not improve the level of lignin. These findings suggest that the improvement of biocontrol efficacy of antagonistic yeasts may be associated with Si, since direct fungitoxicity property to the pathogens were observed as well as the elicitation of biochemical defense responses in fruit. However, Si did not influence the growth of the antagonists.

Index terms: antagonistic yeasts, silicon, postharvest diseases, fruit.

SILICON RESEARCH COMBINED WITH BIOLOGICAL CONTROL

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There is a considerable body of research suggesting that increased silicon levels in plants can enhance disease and insect resistance. A research team at the University of KwaZulu-Natal, Pietermaritzburg, South Africa is undertaking research in this field, funded by Ineos Silicas. Target diseases include *Pythium* and *Rhizoctonia* of hydroponic lettuce, cucumber, wheat and cabbages, *Fusarium* of wheat and bananas, take-all of wheat, Asian rust of soybeans, Cercospora leafspot of beet, powdery mildew of several crops, postharvest diseases of citrus and litchi, damping off of maize and nematodes. Target insects include red spider mite, thrips, diamond backed moth, American bollworm, weevils, white grubs. Colleagues at the SA Sugar Research Institute are tackling Eldana moth damage of sugar. An added element of our research is that we are looking for synergistic interactions between biological control agents and silicon in terms of disease and insect control. Application of Eco-T® (*Trichoderma harzianum*), a commercial biocontrol agent, results in substantial enhancement of rooting and production of root hairs by treated plants. It is our hypothesis that the combination of both Eco-T® and silicon will result in enhanced levels of silicon in plants and therefore, result in enhanced levels of disease and pest resistance. One challenge we face is to develop a compatible formulation of readily soluble silicon with good spray characteristics, compatibility with other products and optimal uptake into plants. A further question is whether the application of foliar applications of silicon results in direct uptake or whether the silicon washes off and is accumulated by surface roots of target plants, as is the case with many water-soluble fungicides which cannot penetrate the waxy cuticle of leaves.

Index terms: silicon, biological control, plant diseases, *Trichoderma harzianum*.

NITROGEN AND SILICON IMPACT ON THE RESISTANCE OF SUGARCANE TO *ELDANA SACCHARINA* STALK BORER (LEPIDOPTERA: PYRALIDAE)

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There is ample evidence from the literature that nutrients such as nitrogen and silicon play important roles in the susceptibility and resistance of a range of crops to stalk borer damage. The use of nitrogenous fertilizers to enhance plant nutrition often influences the longevity, fecundity and damage caused by insects and mites as it acts as an important source of food for herbivores. Crop and sucrose loss from damage by *Eldana saccharina* Walker (Lepidoptera: Pyralidae) still ranks as being the most important factor limiting productivity in the South African sugar industry.Recent studies have emphasized the important role of applied silicon in improving the resistance of sugarcane to *E. saccharina* infestation. Because the effects of nitrogen and silicon on *E. saccharina* behaviour have previously been studied independently, a preliminary glasshouse trial was conducted to study the combined influence of these nutrients on *E. saccharina* infestation on a range of cane varieties, to determine whether applied silicon can offset the negative effects of applied N on *E. saccharina* build-up. Highly significant differences in susceptibility to *E. saccharina* were obtained in response to the nitrogen and silicon treatments. Nitrogen treatment in the absence of Si increased overall susceptibility from an average of 68% at the low level of N to 208% at the high level of N across all varieties. Overall, treatment with the equivalent of 200kg/ha Si had a significant impact in reducing the promotional effects of N treatment on *E. saccharina* survival and damage. Percentage stalks damaged was reduced by an average of 47% across all five susceptible varieties that were included in the trial. Maximum reductions in percent stalks damaged from silicon treatment, ranged from a 70% average at the lowest N level, to 39% at the intermediate N level down to 35% at the highest N treatment. The use of silicon will enable many growers who have severely cut back on their nitrogen applications to reduce the risk of *E. saccharina* damage, and to resume applying the normal recommended rates of nitrogen, thereby ensuring that nitrogen will not limit crop yield.

Index terms: sugarcane, nitrogen, silicon, calcium silicate, soil nutrients, *Eldana saccharina*, stalk borer, insect pest.

EFFECT OF SILICON ON THE DEVELOPMENT OF COFFEE SEEDLINGS AND ON THE INTENSITY OF COFFEE LEAF RUST.

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Orange rust, caused by the fungus *Hemileia vastatrix*, is considered the most serious disease of coffee. The objective of this research was to verify the effect of potassium silicate and calcium/magnesium silicate on the development of the coffee seedlings, cultivar "Mundo Novo" as well as to evaluate the incidence of the coffee leaf rust development under greenhouse conditions. The experiment was done in São Paulo at the Phytopathology Biochemistry Laboratory at the "Instituto Biológico." The experiment was a completely randomized design with 12 treatments with ten plants per treatment. The treatments were 0, 10, 50, 75, 100 and 150 ppm for each source of silicon incorporated into the soil. Leaf area, plant height, and total number of leaves were recorded 6 months after planting. The seedlings were inoculated with urediniospores suspension of *Hemileia vastatrix* (2mg.mL^{-1}) 7 months after planting (six pairs of leaves). A statistical analysis of the growth parameters revealed a significant effect of the different sources of silicon on the coffee plant development. Potassium silicate reduced the leaf area, plant height and the total number of leaves when compared to calcium/magnesium silicate. The inoculation was done recently, therefore, the symptoms could not be observed yet because there was not sufficient time for rust development.

Index terms: silicate, coffee seedlings, coffee leaf rust.

POTASSIUM SILICATE ENHANCES RESISTANCE/TOLERANCE OF ORNAMENTAL PLANTS TO INSECT ATTACK

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There is a growing body of scientific evidence that demonstrates that silicon is an important and beneficial plant nutrient. Increasing the silicon level in plants may enhance growth, quality and yield. Moreover, it has been shown to increase plant resistance to a biotic stress and reduce damage done by plant pathogens and arthropods. Most of this work done has focused on plant pathogens, with relatively little data documenting the impact of silicon on arthropod pests. We hypothesize that the addition of silicon to ornamental plants will increase their ability to resist insect attack. The objective of this work was to evaluate the increased levels of silicon in chrysanthemum plants on their resistance/tolerance to the serpentine leafminer (*Liriomyza trifolii*. Chrysanthemum (var. 'Miramar') plants were watered with different levels of commerically available calcium silicate (100 ppm, 200 ppm, 300 ppm, 500 ppm, and 1000 ppm of silicon) for four weeks. Plants were then individually caged and infested with three mated pairs of leafminers per cage. Three weeks later, the number of leafminer offspring per plant was recorded. Results clearly demonstrated that the addition of potassium silicate at the rate of 200 ppm or higher significantly reduced leafminers compared to the untreated control. These results suggest that the addition of potassium silicate may be an important component in IPM programs for *Liriomyza* leafminers and other pests.

Index terms: potassium silicate, insect, ornamental plants.

EFFECT OF FOLIAR APPLICATION OF POTASSIUM SILICATE ON COFFEE RUST DEVELOPMENT

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The most significant effect of silicon to some agronomic crops, besides improving their fitness in nature and increasing agricultural productivity, is the control of many diseases. The purpose of this study was to determine the effect of foliar application of potassium silicate (INEOS Silicas Brazil) on the control of coffee rust. A 5 x 2 factorial experiment, consisting of five potassium silicate rates (0, 8, 20, 40 and 60 g/L) with (pH = 5.5) and without (pH 10.5) pH changes was arranged in a completely randomized design with six replications. Twenty-four hours after application of the treatments, two leaves per plant (cultivar "Catuai Vermelho") were inoculated with uredospores of *Hemileia vastatrix* (1.5 mg/mL). Leaves sprayed with sterile water or with the fungicide Epoxiconazole (1 mL/L) were the controls. Inoculated plants were transferred to a mist chamber (RU ≈ 95%, 21 22°C) 47in the dark for 48 hours. Thirty days after inoculation, the total number of pustules (TNP) and rust severity (RS) were evaluated. The TNP response to the potassium silicate rates was negatively quadratic and linear, respectively, to pH 10.5 (TNP= 47.3 2.98x + $0.038x^2$, $R^2 = 0.70$) and pH 5.5 (TNP =.60 - 0.80x, $R^2 = 0.83$). A negative second order regression curve best described the effect of potassium silicate rates on the SEV ($SEV_{pH10.5} = 38.10 - 2.51x + 0.033x^2$, $R^2 = 0.67$; $SEV_{pH5.5} = 40.15\ 2.18x + 0.026x^2$, $R^2 = 0.72$). The application of potassium silicate rates at pH 10.5 was more efficient in controlling rust than at pH 5.5. There was no statistical difference among the treatments: fungicide, potassium silicate (60 g/L) at pH 10.5 and potassium silicate (60 g/L) at pH 5.5 for both TNP and SEV variables (0/0; 0.4/0.2 and 1.4/0.5, respectively).

Index terms: potassium silicate, *Coffea arabica* L., *Hemileia vastatrix*.

SILICON INFLUENCES CYTOLOGICAL AND MOLECULAR EVENTS IN COMPATIBLE AND INCOMPATIBLE RICE-*MAGNAPORTHE GRISEA* INTERACTIONS

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Cytological and molecular aspects of an incompatible and a compatible rice-*Magnaporthe grisea* interaction with a silicon (Si) soil amendment were investigated. Katy, a completely resistant cultivar, responded to an avirulent race of *M. grisea* through the development of a hypersensitive reaction (intense granulation of the cytoplasm and bright autofluorescence of epidermal cells), strong induction of PR-1 and peroxidase transcripts and accumulation of high levels of phenolics and lignin which dramatically reduced hyphal growth within the invaded epidermal cell. These defense responses were similar in both Si- and Si+ treatments. On the other hand, in Si+ plants of the completely susceptible cultivar M201, a differential accumulation of glucanase, peroxidase and PR-1 transcripts and the production of phenolics and lignin restricted hyphal growth in the epidermal cells. Conversely, in Si- plants, *M. grisea* successfully grew and formed an extensive branched mycelium in the first-invaded epidermal cell and colonized many neighboring cells despite strong induction of chitinases, glucanase, chalcone synthase, phenylalanine ammonia-lyase, peroxidase and PR-1 transcripts and high levels of phenolics and lignin. Autofluorescence of epidermal cells became quenched as the lesions expanded when compared to Si+ plants. The results of this study strongly suggest that Si plays an active role in rice blast resistance rather than just the formation of a physical barrier to impede penetration by *M. grisea*.

Index terms: silicon, rice, *Oryzae sativa* L., mechanisms of resistance, PR-genes.

CAN FOLIAR SPRAY OF POTASSIUM SILICATE INDUCE SYSTEMIC PROTECTION AGAINST COFFEE RUST?

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The most significant effect of silicon to some agronomic crops, besides improving their fitness in nature and increasing agricultural productivity, is the control of many diseases. The main objective of this study was to determine if potassium silicate (PS) (INEOS Silicas Brazil) could translocate from sprayed to non-sprayed leaves and control coffee rust development. A 5 x 2 factorial experiment, consisting of five treatments (PS 20g/L pH 5.5 (T1); PS 20 g/L pH 10.5 (T2); benzothiadiazole (1 g/L) (T3), Epoxiconazole (systemic fungicide) (1 mL/L) (T4) and the control (leaves sprayed with sterile water) (T5)) and two leaf spray application methods, was arranged in a completely randomized design with five replications. The two lower leaves were sprayed with the treatments and the two upper leaves were inoculated (method 1) or the two lateral leaves (right side) were sprayed and the other two lateral leaves (left side) were inoculated (method 2). Leaves were inoculated with uredospores of *Hemileia vastatrix* (1.5 mg/mL) 24 hours after spraying the treatments. Inoculated plants were transferred to a mist chamber (RU ≈ 95%, 21-22^{o}C) in the dark for 48 hours. At 30 days after inoculation, the number of pustules (NP) per leaf and rust severity (RS) were evaluated. Regardless of the leaf application method tested, there was no statistical difference for NP and RS among T1, T2, T3 and T5 but all these treatments were significantly different ($P \leq 0.05$) from T4. The lowest values for NP and RS were observed on T1, T2 and T3 (method 1: 20/8.5%; 34.6/19.3% and 36/21.1%, respectively; method 2: 42.1/17.3%; 39.7/24.5% and 42.2/23.9%, respectively) even though there was no statistical difference ($P > 0.05$) between these treatments and T5 (method 1: 57.2/59.8%, respectively; method 2: 51.7/45%, respectively). Based on these results, potassium silicate and benzothiadiazole apparently did not translocate in coffee leaves and, as a consequence, were unable to reduce NP and RS as compared to the systemic fungicide.

Index terms: potassium silicate, *Hemileia vastatrix*, components of resistance, translocation.

EFFECT OF POTASSIUM SILICATE ON THE CONTROL OF COFFEE LEAF RUST UNDER FIELD CONDITIONS

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The most significant effect of silicon to some agronomic crops, besides improving their fitness in nature and increasing agricultural productivity, is the control of many diseases. There is no information in the literature regarding the foliar application of potassium silicate on the control of coffee leaf rust, caused by the fungus *Hemileia vastatrix*, under field conditions. The objective of this study was to test the effect of foliar application of potassium silicate (INEOS Silicas, Brazil) to control this disease. The trial was arranged in a randomized complete block design with four replications at Piranga county, Minas Gerais State on December of 2004. The coffee plants were from the cultivar "Catuaí" with four years old. The treatments were five potassium silicate (PS) rates (0, 8, 20, 40 and 60 g/l) with pH adjusted to 5.5 and an additional treatment corresponding to the application of the fungicide Epoxiconazole (0.8 l/ha). Plants from each treatment were sprayed four times (from December 2004 through March 2005) except for the treatment with fungicide which was used twice. The incidence of leaves with rust was evaluated every 30 days from January 2005 through June 2005 and the data was used to calculate the area under the disease progress curve (AUDPC). It was not possible to adjust any model to the AUDPC data obtained from the potassium silicate rates treatments. However, there was statistical difference among the treatments PS (60 g/l), fungicide and control (1263.5; 106.8 and 1840.5, respectively). The application of potassium silicate did not seem to have any positive effect on the control of coffee rust when sprayed in a 30 days interval.

Index terms: potassium silicate, *Coffea arabica* L., *Hemileia vastatrix*.

EFFECT OF POTASSIUM SILICATE COMBINED OR NOT WITH SYSTEMIC OR PROTECTOR FUNGICIDES ON THE CONTROL OF ASIAN SOYBEAN RUST

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Asian soybean rust, caused by the fungus *Phakopsora pachyrhizi*, is the most important disease of soybean in Brazil. This fungus attacks the foliage of soybean plants causing early drop of the leaves and, as a consequence, pod setting and yield are negatively affected. The spray of fungicide is the only method of control available to the growers. The main objective of this study was to evaluate the foliar application of potassium silicate (INEOS Silicas Brazil) mixed or not with systemic or protector fungicides on the control of Asian soybean rust. The experiment was arranged in a randomized complete block design, under field conditions, with eight treatments and three replications. Plants of soybean (cultivar "Sambaiba") were artificially inoculated with uredospores of the fungus (2×10^4 uredospores/ml) at 25 days after seed germination (DASG). The treatments were as following: 1- control; 2- mancozeb (3 kg/ha); 3- mancozeb (3 kg ha^{-1}) mixed with Epoxiconazole + Pyraclostrobin (0.5 l/ha); 4- Epoxiconazole + Pyraclostrobin (0.5 l/ha); 5- potassium silicate (40 g/l; pH 10.5); 6 - potassium silicate (60 g/l; pH 10.5); 7 - mancozeb (3 kg ha^{-1}) + potassium silicate (40 g/l; pH 10.5); 8 - Epoxiconazole + Pyraclostrobin (0.5 l/ha) + potassium silicate (40 g/l; pH 10.5). Plants from each treatment and replication were sprayed at 60 and 75 DASG. Disease severity (DS) was evaluated at 105 DASG using a scale from 0 to 5 where: 0 = no disease symptoms, 2 = 11 to 25%; 3 = 26 to 50%; 4 = 51 to 75% and 5 = more than 75% of leaf area with pustules. All treatments were significantly different from treatment 1 ($P \leq 0.05$). The treatments 5 (DS = 9.4%), 6 (DS = 11.5%) and 2 (DS = 6.4%), although were less efficient on the control of the disease, reduced disease severity by 21, 34 and 55%, respectively, compared to the control (DS = 14.4%). The treatments 8, 4, 7 and 3 were the most efficient on the control of soybean rust with disease severity values of 2.4, 2.9, 3.4 and 3.5%, respectively.

Index terms: potassium silicate, Asian soybean rust, soybean, *Phakopsora pachyrhizi*, systemic fungicide, protector fungicide.

EFFECT OF FOLIAR APPLICATION OF POTASSIUM SILICATE AND FUNGICIDES ON THE CONTROL OF BROWN EYE SPOT ON COFFEE.

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The most significant effect of silicon to some agronomic crops, besides improving their fitness in nature and increasing agricultural productivity, is the control of many diseases. There is no information in the literature regarding the foliar application of potassium silicate on the control of brown eye spot, caused by the fungus *Cercospora coffeicola* Berk. & Cooke), under field conditions. The objective of this study was to test the effect of foliar application of potassium silicate as well as fungicides on the control of brown eye spot. The trial was arranged in a completely randomized design with five treatments and four replications at Piranga county, Minas Gerais State on December of 2004. The following treatments were used: 1 - Control; 2 - Thiophanate methyl 1 kg ha^{-1}; 3 - "Viça café" 5 kg ha^{-1} + potassium silicate 1.5 kg ha^{-1}, pH 5; 4 - potassium silicate 1.5 kg ha^{-1}, pH 5 and 5 - Cooper Oxychloride 3 kg ha^{-1}. Plants from each treatment were sprayed every 30 days from December 2004 through March 2005 in a total of four applications. The incidence of leaves with brown eye spot was evaluated every 15 days from December 2004 through June 2005 and the data obtained was used to calculate the area under the disease progress curve (AUDPC). There was not statistical difference between the treatments 1 and 4 (11279.50 and 11835.25, respectively) but these treatments were statistically different from treatments 2, 3 and 5 (10143.25; 9587.75 and 8434, respectively). The application of potassium silicate alone did not seem to have any positive effect on the control of brown eye spot when sprayed every 30 days. However, the mixture of potassium silicate with cooper fungicides may help to improve the control of brown eye spot under field conditions.
Index terms: potassium silicate, *Coffea arabica* L., *Cercospora coffeicola*, brown eye spot.

EVALUATION OF SILICON AND PHOSPHORUS FOR CONTROL OF POWDERY MILDEW IN POTTED MINIATURE ROSES

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Due to environmental concerns restrictions on the use of pesticides have been introduced in Denmark in the recent years. New, more environmentally friendly production methods for disease suppression in plants need to be developed. With an annual production of 50 million plants, potted miniature roses are one of the most important crops in the horticultural industry in Denmark. Powdery mildew caused by *Sphaeroheca pannosa* often occurs in this crop resulting in poor quality and production losses. In a newly started research project on miniature potted roses, the effects of silicon, either alone or combined with reduced phosphorus availability, are evaluated with respect to plant growth and induced resistance against powdery mildew. Soluble silicon is either applied as a foliar spray ($0.9\ 10^{-3}$ mmol Si from Actisil™ (0.6% Si as Si(OH)4, and 2% Ca) on a weekly basis, or in the nutrient solution at 0.7, 1.4, 2.1, 3.6 mmol Si from SiCal™ (9.1% Si, 25.5% K) mixed into a full nutrient feed solution and provided whenever irrigation is needed. A P buffering technique (Compalox®-P) is used to maintain a predetermined and stable P concentration in the growth substrate.

Index terms: powdery mildew, miniature roses, silicon, phosphorus

EFFECT OF CALCIUM SILICATE AND CALCIUM CARBONATE ON *CERCOSPORA SOJINA* INCIDENCE IN SOYBEAN

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Silicon application has promoted several benefits in different crops such as resistance to pests and diseases. In soybean, resistance against diseases can be boosted by toxin (phytoalexin) synthesis, resulting in a faster and more extensive activation of plant defense mechanisms. The efficiency of calcium carbonate and calcium silicate on control of *Cercospora sojina* was studied by planting soybean in Ustoxic Quartzipsamment soil. Previously fertilized soil was added to 200 - kg pots, and the equivalent to 0, 1500, 3000, 6000 and 12000 kg ha^{-1} $CaCO_3$ or $CaSiO_3$ were added over the soil surface. Soybean was cultivated for 120 days. It was evaluated soybean leaf silicon concentration and *Cercospora sojina* incidence on soybean at 47, 66 and 79 days after emergence. Calcium silicate increased silicon content in soybean leaves up to 1.7 times compared with check plot ranging from 0.34 to 0.55%. Soybean cultivated under $CaCO_3$, accumulated little silicon. Calcium silicate added to the soil significantly reduced *Cercospora sojina* incidence in soybean at all dates evaluated. Calcium carbonate was less effective than calcium silicate on *Cercospora sojina* control, indicating a good potential for plant biochemical defense against pest and disease attack.

Index terms: phytoalexins, diseases, non-accumulating plants, biochemical mechanism, silicon

SECTION 3: Silicon in Plants

SILICON IMPROVES WATER USE EFFICIENCY IN MAIZE PLANTS (*Zea mays* L.,cv. Nongda108)

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The influence of silicon (Si) on water use efficiency (WUE) in maize plants (*Zea mays* L., cv. Nongda108) was investigated. The results showed that plants treated with 2 mmol L^{-1} silicic acid (Si) had 20% higher WUE than that of plants without Si application. The WUE was increased up to 35% when the plants were exposed to water stress and this was accounted for by reductions in leaf transpiration and water flow rate in xylem vessels. To examine the effect of silicon on transpiration, changes in stomata opening were compared between Si-treated and non-treated leaves by measuring transpiration rate and leaf resistance. The results showed that the reduction in transpiration following the application of silicon was largely due to a reduction in transpiration rate through stomata indicating that Si affected stomata movement. In xylem sap of plants treated with 2 mmol L^{-1} silicic acid, the Si concentration was 200-fold higher while the Ca concentration, which is mainly determined by the transpiration rate, was 2.5-fold lower than that of plants grown without Si. Furthermore, the water flow rate in xylem vessels in plants with and without Si was compared. Flow rate in plants with 2 mmol L^{-1} Si was 20% lower than that without Si, which was accounted for by the increased affinity for water in xylem vessels induced by silica deposits. The results of this study suggest that Si plays a role in improving WUE in maize plants.

Index terms: maize; silicon; water use efficiency.

EFFECTS OF SILICON ON GROWTH, PHYSIOLOGICAL DEVELOPMENT, MINERAL NUTRITION AND THEIR RELATION TO NaCl TOLERANCE IN TWO LEGUME SPECIES

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Two legume plant species, cowpea and kidney bean, were grown in a glasshouse in hydroponics system and the effect of silicon (calcium silicate) supplied to the nutrient solution to alleviate salt stress was investigated. The plants were subjected to four different treatments: 1 nutrient solution alone (C), 2 nutrient solution + 1 mM $CaSO_4$ + 40 mM L^{-1} NaCl (NaCl + $CaSO_4$), 3 nutrient solution + 40 mM L^{-1} of NaCl + 0.5 mM L^{-1} of $CaSiO_3$ (NaCl + $CaSiO_3$), and [4] nutrient solution + 1 mM L^{-1} of $CaSiO_3$ + 40 mM L^{-1} NaCl (NaCl + $CaSiO_2$). The results showed that for both species, salinity reduced all growth variables but the silicon amendment partly overcame the reduction in growth. Addition of silicon in NaCl stressed plants maintained membrane permeability. Net photosynthesis, chlorophyll contents, stomatal conductance, and transpiration was higher in plants under non-salinized solution and the inclusion of silicon in the nutrient solution resulted in a slight increase in plant. Intercellular CO_2 was higher in plants under silicon treatments than in plants under non-salinized solution or CaSO treatment. Calcium concentration was higher in roots and shoots in the treatments where silicon or CaSO was added. Potassium concentration was reduced in all salt treatments, but increased in both species in salt treated plants in the presence of silicon. Sodium and chloride concentration in both shoots and roots in both species were markedly higher in the presence of NaCl and were reduced in the plants under silicon treatments. In conclusion, the results from this study suggest that in hydroponically grown cowpea and kidney bean crops, the inclusion of silicon in the nutrient solution is beneficial because of it improves the growth, the physiological characteristics and may contribute to a more balanced nutrition by enhancing the nutrients uptake under NaCl stressed conditions.

Index terms: salinity tolerance, *Vigna unguiculata*, *Phaseolus vulgaris*, calcium silicate.

NUTRITIONAL EFFICIENCY OF COFFEE CULTIVARS FERTILIZED WITH SILICON

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Although silicon (Si) is not considered an essential nutrient, this element is classified as being useful and may alter the nutritional dynamics so plants are more efficient in their accumulation of other nutrients. An experiment was conducted to compare nutritional efficiency in terms of response to Si fertilization in a randomized design with three coffee cultivars (“Catuaí, Mundo Novo” and “Icatu”) combined with six rates of calcium silicate (T0=0, T1=0.0625, T2=0.125, T3=0.25, T4=0.5, and T5=1.0g $CaSiO_3/dm^3$ of substrate). The cultivar “Icatu” had a more efficient uptake (EA) of Cu, Zn, Fe and Si, and more efficient utilization (EU) of N, K, Ca, B and Mn, and did not differ from the cultivar “Mundo Novo” for N, Ca and Mn. This cultivar also was more efficient in translocation (ET) for N, S, Zn and Fe. The cultivar “Catuaí” had more EA of P, K, B and Mn, and was not different from “Mundo Novo” for P, K and Mn, and had a higher EU for Mg, S, Cu, Zn, Fe and Si. This was probably due to a better ET of these nutrients with exception of Fe and Si. The cultivar “Mundo Novo” was more efficient in N, K, Ca, Mg, Mn and Si uptake, had a higher EU of P and Mn, and a higher ET of K, Ca, B, Mn and Si. It was concluded that fertilization with Si improved the nutritional efficiency of these coffee cultivars.

Index terms: translocation efficiency, uptake efficiency, utilization efficiency, *Coffea arabica*, nutrition, fertilization.

CHARACTERIZATION OF SILICON UPTAKE SYSTEM AND ISOLATION OF *LSI1* GENE FROM RICE ROOT

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All plant species contain Si in their tissue; however, Si accumulation in the shoots varies considerably among plant species. The uptake system of Si was investigated in terms of radical transport from external solution to root cortical cells and subsequent release to xylem in rice, cucumber, and tomato. In all species, Si concentration in the root-cell symplast was higher than in the external solution, but the concentration followed rice > cucumber > tomato. A kinetic study showed that the radical transport of Si was mediated by a kind of transporter, which showed a similar K_m value in all species, while the V_{max} value followed rice > cucumber > tomato. However, the Si concentration of xylem sap in rice was 10- and 15-fold higher than that in cucumber and tomato, respectively. In contrast to rice, the Si concentration in the xylem sap was lower than that in the external solution in cucumber and tomato. A kinetic study showed that xylem loading of Si was also mediated by a kind of transporter in rice, but by passive diffusion in cucumber and tomato. These results suggest that Si accumulation in the shoot is regulated by the capacity to release Si into the xylem. To understand xylem loading system in rice, a mutant (*lsi1*), which is defective in the xylem loading of Si, has been isolated previously. In the present study, the responsible gene *Lsi1* was cloned by map-based cloning technique. *Lsi1* encodes a membrane protein and this gene was not induced by Si and constitutively expressed mainly in the roots. To investigate cellular localization of *LSI1*, *Lsi1* was fused with GFP and introduced to onion epidermal cells. Microscopic observation showed that LSI1 was localized in the membrane. Further functional analysis of this gene is currently being undertaken.

Index terms: radial transport, plant species, silicon uptake, xylem loading, gene, map-based cloning.

ISOLATION AND CHARACTERIZATION OF A NOVEL RICE MUTANT DEFECTIVE IN Si UPTAKE

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Rice is a typical silicon (Si)-accumulating plant; however, the molecular mechanism responsible for high Si uptake by the roots is poorly understood. In the present study, mutants which were defective in Si uptake were screened from M3 seeds of rice (cultivar T-65) treated with N-methyl-N-nitrosourea by using Ge resistance as a selection parameter. As a result, a novel rice mutant (lsi2), which was resistant to Ge toxicity was isolated. A short-term uptake experiment showed that the Si uptake by lsi2 mutant was much lower than that by wild type (WT). At 12 h, the Si uptake by lsi2 was 25% of that by WT. When both lsi2 and WT were cultured in a nutrient solution containing 0.75mM Si for 1 month, the shoot Si concentration of WT was 2.5-fold higher than that of lsi2. However, there were no significant differences in the concentration of P and K between WT and lsi2. These results clearly show that lsi2 was a mutant which was defective in Si uptake. Further study showed that the Si concentration in the root symplastic sap was similar between lsi2 and WT but the concentration of Si in the xylem sap was much higher in WT than in lsi2. These results indicate that lsi2 was a mutant defective in xylem loading of Si rather than the transport of Si from external solution to the root cortical cells. Genetic analysis showed that the low Si uptake was controlled by a recessive gene. To map this gene, bulk segregant analysis was performed by pooling equal amounts of DNA from 10 low-Si uptake or 10 high-Si uptake F2 plants. Both microsatellite and EST-PCR markers were used for mapping the gene. As a result, the gene was mapped to the chromosome 3, a location that is different from Lsi1, another gene responsible for xylem loading of Si in rice. Fine mapping of this gene is being undertaken.

Index terms: gene, mutant, rice, silicon uptake, xylem loading.

EVALUATING SILICON UPTAKE IN COMMON FLORICULTURE PLANTS

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Silicon (Si) is not commonly added in floricultural crop fertilizer recipes in the United States because it is not considered to be an essential plant nutrient. Given the growing body of information showing a clear, beneficial effect on plant growth, inclusion of Si in fertilizer recipes could be a large benefit to greenhouse plant producers because more production is using soilless media that are devoid of Si. Therefore, Si would have to be supplied either as a foliar spray or nutrient solution amendment. Most of the common floriculture plant species have not been critically evaluated for Si uptake, and documenting that uptake is an initial step in determining the usefulness of Si inclusion for improved greenhouse management. We investigated the addition Si to New Guinea impatiens (*Impatiens hawkeri* Bull), bedding plant impatiens (*Impatiens wallerana* Hook.f), marigold (*Tagetes erecta* L.), geranium (*Pelargonium* × *hybrida*), dianthus (*Dianthus* spp.), verbena (*Verbena* × *hybrida* Voss) and orchid (*Phalaenopsis* spp.). Using SEM, energy dispersive X-ray analysis, and ICP analysis, Si content and location was determined. Of these seven species, four contained significant concentrations of Si in deposits on the leaf margin. Si was not just localized on the leaf margin in marigold, but rather distributed uniformly throughout the leaf parenchyma cells, based on x-ray analysis. There was no Si in stem or root sections of any of the plants. Regardless of its localization, the fact that Si is taken up by these plants opens the possibility for Si-activation of plant defense mechanisms and provides an opportunity to ameliorate micronutrient toxicity. This information and other growth characteristics will be used as a first step in determining the likelihood of using Si as a beneficial element in greenhouse fertilizer solutions for higher quality bedding plants with fewer agrochemical inputs in the United States.

Index Terms: floriculture, X-ray analysis, SEM, ICP, bedding plants, Si uptake

LEAF TRANSPIRATION AND WATER USE EFFICIENCY OF SILICON-TREATED RICE PLANTS

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The uptake of silicon by rice plants (*Oryza sativa* L.) benefits its growth and development, although it has not been determined to be an essential element for plant growth. The objective of this work was to evaluate the leaf transpiration (*E*), the water use efficiency (*WUE*) and other leaf gas exchange rates of silicon-treated rice (IAC 202 cultivar) plants, cultivated under 2 sprinkler-irrigated layers. The field study was set in split-plot experimental arrangement, in a completely randomized block design with four replications. Sprinkler-irrigated and non-irrigated fields were used as main plots, two soil dosages of silicon (SiO_4; Recmix®) (0 and 900 kg ha^{-1}) as sub-plots, and two foliar dosages of silicon (sodium metassilicate) (0 and 40 mM L^{-1}), as sub-sub plots. Gas exchange measurements were made with an open gas portable photosynthesis system (LI-6400, LI-COR, USA). Measurements were conducted between 09:00h and 12:00h, using two fully expanded mature leaves during the vegetative stage (midtillering (MT) - 46 days after emergency-DAE) and two flag leaves during the reproductive stage (panicle initiation (PI) – 70 DAE; booting (B) – 82 DAE; flowering (FL) – 92 DAE, and maturation (MA) – 112 DAE), in one plant, randomly chosen in each plot. In general, CO_2 assimilation rates and stomatal conductance was higher for all treatments considered under the irrigated plot, especially during spikelet formation. However, none of the treatments under the irrigated plot presented higher *WUE*. The non-irrigated plants showed higher *WUE* at B and FL, when under the highest soil and foliar silicon dosage. Nevertheless, this effect did not promote a valuable advantage for the non-irrigated plants.

Index terms: *Oryza sativa* L., gas exchange rates, irrigation.

QUANTITATIVE PLANT GROWTH ANALYSIS OF SILICON-TREATED RICE PLANTS

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The uptake of silicon by rice plants (*Oryza sativa* L.) benefits its growth and development, although it has not been determined to be an essential element for plant growth. The objective of this work was to evaluate the quantitative plant growth of silicon-treated rice (IAC 202 cultivar) plants, cultivated under 2 sprinkler-irrigated layers. The field study was set in split-plot experimental arrangement, in a completely randomized block design with four replications. Sprinkler-irrigated and non-irrigated fields were used as main plots, two soil dosages of silicon (SiO_4; Recmix®) (0 and 900 kg ha^{-1}) as sub-plots, and two foliar dosages of silicon (sodium metassilicate) (0 and 40 mM L^{-1}), as sub-sub plots. For the non-irrigated plot, plant harvests occurred at 48, 68, 84, 96 and 130 days after emergence (DAE). For the irrigated plot, harvests were done at 48, 62, 82, 89 and 116 DAE. Measured variables were: plant height, total dry matter accumulation (TDMA), leaf area index (LAI), leaf area duration (LAD), crop growth rate (CGR), specific leaf area (SLA) and net assimilation rate (NAR). Silicon promoted no effects on plant height, but it was higher for irrigated plants. TDMA was higher for irrigated plants, as expected, and the smallest TDMA was observed when silicon was just applied on leaves. Silicon applied in the soil has raised LAI, especially between booting and flowering, and mainly for irrigated plants, as for LAD but to a lesser extent. CGR was higher for irrigated plants when silicon was present in the soil and applied on leaves. Finally, silicon had no effects on NAR, and showed progressive positive effects on SLA, but when present in the soil and applied on leaves its results started being negative, markedly for irrigated plants.

Index terms: *Oryza sativa* L., total dry matter accumulation, irrigation.

METHODS FOR STUDYING SILICON UPTAKE IN PLANTS

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One of the general problems in studying silicon (Si) uptake is the lack of adequate radioisotopes (e.g. too short half-life for ^{31}Si or extremely expensive ^{32}Si). In contrast to diatoms or even rat's brain, as far as we are aware, information on the feasibility of ^{68}Ge-tracer approach in studying Si transport are still lacking for higher plants. This paper reviewed the available methods for Si uptake and transport in plants and provides a special focus on uptake experiments, where $^{68}Ge(OH)_4$ was used as a tracer for $Si(OH)_4$. Different model plants (e.g. rice, barley, cucumber, and tomato), differing greatly in their shoot Si accumulation, showed a tendency to maintain the $^{68}Ge/Si$ molar ratio in their tissues similar to that in the nutrient solution (e.g. $6x10^{-8}$). Besides rice which is a known Si accumulator, Si uptake was also characterized for other Si accumulating plants. For instance, higher accumulation of $Si(OH)_4$ in rice has been clearly confirmed in comparison to barley or cucumber because of its lower K_m constant. The usefulness of this approach, particularly in short-term Si uptake studies, will be discussed.

Index terms: germanium, methods, silicon, tracer, uptake.

EFFECT OF SILICON ON ANTIOXIDATIVE REACTIONS IN CUCUMBER UNDER MANGANESE TOXICITY STRESS

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One of the beneficial effects of silicon (Si) in plants is to increase plant tolerance to heavy metal toxicity. The objective of this work was to study the effect of Si on manganese (Mn) compartmentation and its implication on the antioxidative reactions in roots and leaves of cucumber plants grown at high Mn concentrations. Typical Mn toxicity symptoms have never been found in leaves and roots of cucumber plants grown at high Mn concentrations (50 µM) if Si was supplied in the nutrient solution at 1 mM. Mn content in roots and leaves were higher in Si treated plants, indicating that the possible mechanism of Si protection might be Si-induced compartmentation of Mn (e.g. cell wall) rather than decrease of Mn uptake. With increasing symplastic Mn concentration in cucumber leaves and roots enhanced activity of antioxidant enzymes such as peroxidases (POD) and superoxide dismutase (SOD) were also confirmed by isoelectric focusing. In contrast, in Si treatments both POD and SOD activities were decreased, which is in accordance with decreasing symplastic Mn fraction. At extremely high Mn concentration (e.g. 100 µM), even in the presence of Si, expression of new isoforms of both enzymes was observed. Enhanced enzymes activities at higher Mn concentration were followed by decreasing amount of phenolic compounds (e.g. chlorogenic acid).

Index terms: antioxidative enzymes, cucumber, manganese toxicity, silicon.

NUTRIENT COMPOSITION AND SILICON ACCUMULATION IN TISSUES OF BLUEBERRY (*VACCINUM CORYMBOSUS*)

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An experiment was carried out at the Experimental Farm of Tohoku University in a greenhouse used for production of blueberry seedlings. Blueberry cuttings (*Vaccinum corymbosus*. cv. Bluecrop) were grown in a peat moss medium (pH 4.5) for one year. Blueberry cuttings were irrigated every day for 1 hour (140 ml per pot) with river water containing about 0.66 to 1.0 mol m^{-3} of SiO_2. Despite Si not being an essential element for growth of blueberries, it accumulated more than any other element in leaves with a mean content of 3.2 % and 6.0% for young and mature leaves, respectively. The mean Si content in young leaves was 3.1, 56.7, 4.8, 4.9 and 85 times higher than the mean contents of N, P, K, Ca and Mg, respectively; and was 5.4, 60.0, 8.8, 6.8 and 100 times in mature leaves. The mean contents of N, K, Mg, Cu and Zn in young leaves were statistically ($LSD_{0.05}$) the same as those in mature leaves. On the other hand, the mean contents of P, Ca, Si, Fe and Mn in mature leaves were higher than in young leaves. Scanning electron microscopy and energy-dispersive x-ray spectroscopy analysis of dry ash samples showed that the silicon accumulated in many parts of the leaves forming phytoliths in upper epidermis including some parts of palisade mesophyll, in lower epidermis around the stomata including guard cells and some parts of spongy mesophyll, in the veins and in upper epidermis. There also were silicon bodies on upper epidermis whose origin are unknown.

Index terms: blueberry, silicon accumulation, phytolith, silicon body.

THE EFFECT OF SILICON APPLICATION ON SOME ORNAMENTAL PLANTS

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Following the results of Si application on horticultural crops like cucumber and rose, the role of Si in some ornamental plants was studied. First of all, a screening was carried out to study the Si contents in plant tissue of different species, in order to detect crops for which Si potentially could play a role. From this initial list, two crops were chosen to investigate in more detail the effects of Si application on Si uptake and distribution, growth, plant development and disease resistance. With Poinsettia (*Euphorbia pulcherrima*), the trial was focused on the effect of Si application on plant quality and Mn distribution. Silicon was applied in two forms: as calcium silicate fertilizer mixed in the potting medium and as potassium-metasilicate in the nutrient solution. In contradiction with potassium-metasilicate, calcium silicate did not effectively increase the Si content in plant tissue. Although there was a clear effect of the Si application on the Si content of the crop, there were no significant differences in the quantitative or qualitative crop performance. With Saintpaulia (*Saintpaulia ionantha)*, the Si application treatments were combined with inoculation of the grey mould fungus, *Botrytis cinerea,* and powdery mildew fungus, *Oidium saintpauliae*. Silicon was added as potassium-metasilicate in the nutrient solution at a range of 0 to 1 mmol Si/l. The Si content in plant tissue showed clear relationship with the amount supplied. The Si application had no clear effect on the incidence of grey mould. For powdery mildew, Si reduced the susceptibility significantly for two of three cultivars.

Index terms: silicate, ornamental plants, diseases.

NEAR-ISOGENIC LINES FOR SILICON UPTAKE IN RICE

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Drought resistance is a complex trait which depends on action and interaction of different morphological, physiological, phenological and biochemical characters. Higher silicon content in rice increases photosynthesis, enhances strength of tissues and reduces transpiration of plants, resulting in increased resistance of plants to physical, chemical and biological stresses such as water deficiency, radiation damage, nutritional imbalances, metal toxicity, diseases and pests. Genetic dissection of such complex traits can be done using near isogenic lines (NILs). NILs have been widely used by plant breeders in the development of varieties as well as for mapping various traits. NILs serves as invaluable material for developing mapping population, isolating genes for cloning and use in transformation experiments. They help to identify and map desired genes more rapidly as compared to varieties with different genetic backgrounds. We have developed and tested a strategy for marker-assisted identification of NILs for silicon uptake with the help of 315 marker data on 154 double haploid population of CT9993/IR62266. We identified genotypes with differences ranging from 4 (1.27%) to 34 (10.48%). These genotypes were phenotyped in replicated experiments under contrast moisture regimes. Silicon content in grains, leaves and stem were estimated. Statistical analysis of data using clusters based phenotypic data of moisture regimes and correlations revealed pairs differed from zero to seven traits under well watered and from zero to six traits under stress.

Index terms: *Oryza sativa* L., near-isogenic lines, silicon uptake.

INFLUENCE OF SILICON APPLICATIONS ON COTTON PLANT DEVELOPMENT

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Although cotton is not considered to be an accumulator of silicon; other plant studies have demonstrated positive response to silicon fertilizer. Thus, the objective of this study was to evaluate the mode of silicon application on cotton plant development. A high quality Si fertilizer was applied (60% water soluble Si concentration) to the seed, at planting, flowering and first boll opening. For vegetative stages, silicon fertilizer was applied as a solid form, and for flowering stage as a liquid form. Silicon fertilizer increased the number of cotton bolls from 5.2 to 28% and weight of bolls from 5.8 to 8.9%. Silicon fertilizer also decreased boll disease from 15.6 to 25%.

Index terms: cotton, silicon, cotton development.

EFFECT OF SILICON ON WATER CONSUMPTION BY COTTON PLANTS

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The accumulation of silicon in transpiration organs causes the formation of a cuticular silica layer which, due to its thickness, is believed to promote the reduction in transpiration and result in a decrease in water demand by the plant. Based on this information, a study was done to verify the effect of 5 levels of soluble silica (Ca and Mg Silicate -0.0, 1.1, 2.2, 3.3 and 4.4 g of SiO_2 per pot with 25 kg of soil) in 5 cultivars of cotton ("Camaçari, BRS 201, CNPH 8H, BRS 200 Marrom and BRS Verde") on plant water consumption (ETc). The experiment, 5x5 factorial design, was conducted in a greenhouse at the Centre of Sciences and Technology of the Federal University of Paraiba. The experimental unit consisted of single plastic pot containing 25 kg of sandy loam soil. A significant ($P < 0.01$) effect was observed for silica level and cultivar while the interaction term was nonsignificant. BRS200 Marrom had the highest water consumption (ETc) of 1051 mm and differed statistically from the other cultivars, which presented, on average, water consumption equal to 1034mm, the lowest being 1032 mm for Camaçari. The water consumption at the vegetative, flowering and the fruitification stages of development was 18.53, 53.44 and 22.02%, respectively. Among the silicon levels, the highest water consumption was observed at 0.0 and 1.1g SiO_2 per pot with a mean ETc of 1049 and 1039mm, respectively.A significant decrease in water consumption was observed as the silica level increased in the soil, with mean value of 1033mm.

Index terms: silicon, cotton, irrigation.

QUALITY OF THE FIBER OF THE WHITE AND COLORED COTTON SUBMITTED TO THE SILICATE MANURING

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This research aimed to to study the effect of the silicate manuring on 5 cultivates of cotton (Camaçari, BRS 201, CNPA 8:00, BRS 200 Brown and BRS Green) submitted to 5 silicon levels (0.0; 1.1; 2.2; 3.3; 4.4 g of SiO_2 per vase of 25 kg), with factorial scheme 5 x 5 in entirely randomized design, with 3 repetitions. The medium weight, length, uniformity, index of short fibers, resistance, prolongation to the rupture and reflectance of the cotton feathers were evaluated. The results were similar for the length, the uniformity and the index of short fibers in all treatments. The weight of feathers didn't result in a tendency, however the largest value (4.07 g) was obtained with the cultivate BRS 201 in the level 1.1 g SiO_2. In the fiber resistance and prolongation to the rupture a tendency was not verified also, however, the cultivate BRS 200 Brown obtained the largest values, which were 36,97 g tex^{-1} and 12.4%, respectively, in the level 3.3 g SiO_2. The prolongation to the rupture of the cotton fiber was larger when 4.4 g SiO_2 was applied in all cultivates. Among the cultivates of colored cotton, BRS 200 Brown obtained better reflectance with 40% in the level 2.2 g SiO_2.

Index terms: silicon, cotton, feather

SILICON ACCUMULATION IN RICE UNDER DIFFERENT RHIZOSPHERE pH CONDITIONS

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The amount of silicon accumulated by plants depends on the concentration of available silicon, and the soil pH. It is possible that the absorption and accumulation of silicon in grasses is associated with the value of rhizosphere pH. This work evaluated the effect of rhizosphere pH in the absorption and accumulation of Si in rice (cultivar "Epagri 109"). This experiment was arried out in a greenhouse in a 5x2 factorial design. The treatments consisted of a single dose of N (200 mg kg^{-1}) applied in the following proportions of $N\text{-}NO_3^-$ and $N\text{-}NH_4^+$: 100% $N\text{-}NO_3^-$; 75% $N\text{-}NO_3^-$ + 25% $N\text{-}NH_4^+$; 50% $N\text{-}NO_3^-$ + 50% $N\text{-}NH_4^+$; 25% $N\text{-}NO_3^-$ + 75% $N\text{-}NH_4^+$; 100% $N\text{-}NH_4^+$. The factor subplot received the application of 200 mg kg^{-1} Si. The sources of N used were calcium nitrate and ammonium sulfate (with nitrification inhibitor) and the Si source was silicon tetrachloride, applied to a Ustoxic Quartzipsamment soil. The values of rhizosphere pH decreased with the increase of $N\text{-}NH_4^+$ concentration. The values of rhizosphere pH influenced in a significant manner the Si concentration in the soil, the greater the pH, the greater was the available Si in soil solution. On the other hand, the Si concentration in plant tissue varied in function of the Si in the soil. However, rhizosphere pH had neither influence on the Si availability nor Si accumulation in rice.

Index terms: silicon, rhizozphere, silicon tetrachloride

THE EFFECT OF SILICON ON GROWTH AND DEVELOPMENT OF SOYBEANS, OATS AND WHEAT UNDER HYDROPONIC CONDITIONS

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The role of silicon on the growth and development of soybean, oat and wheat plants was studied under hydroponic conditions at different silicon rates ($Na_2SiO_3.5H_2O$) kept at pH of 6.0 for soybean and at pH of 5.0 for oat and wheat. The soybean plants were inoculated with *Bradyrhizobium japonicum*, strain CB 1809. Another group of soybean plants were kept axenically without *B. japonicum* inoculation. Mineral nitrogen was supplied at constant rates of 12 mM for the non-inoculated treatments and 3mM for all nodulated soybeans. Soybean plants grown at 3.57 mM of silicon showed increases of approximately 20% in nodulation when compared to the control without silicon. Significant increases in panicle and grain biomasses were observed for oat, although no significant differences were observed for plant biomass. Wheat responded the best to the addition of silicon by increasing shoot, root, spikelet and grain biomass.

Index terms: soybean, oat, wheat, nodulation, plant growth, yield, silicon.

EFFECT OF SILICON ON VARIETAL AND GROWTH RESPONSE OF WHEAT UNDER HYDROPONIC CONDITIONS

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Three wheat cultivars (“BR 18”, “BR 40” and “IPR 85”) were evaluated throughout the plant development to maturity under hydroponic conditions with silicon supplied as $Na_2SiO_3.5H_2O$, at rates of 0; 0.36; 0.89; 1.78 and 3.57 mM. The pH was maintained at 6.0 with 6 replications per treatment. Silicon stimulated shoot and root biomasses with correspondent increases in spikelet and grain production. The height, number and individual grain mass were also stimulated. The average increases obtained from the treatment with 1.78 and/or 3.57 mM of silicon for all parameters when compared to control (no silicon) were: a) shoot for BR 18 = 23%; BR 40 = 30%; IPR 85 = 16%; b) roots: BR 18 = 100%; BR 40 = 34%; IPR 85 = 57%; c) spikelet for BR 18 = 75%; BR 40 = 41%; IPR 85 = 52%; d) grains for BR 18 = 75%; BR 40 = 41%; IPR 85 = 38%; e) individual grain mass for BR 18 = 25%; BR 40 = 44%; IPR 85 = 31%. The silicon content in the plant shoot at harvest ranged from 0.2 to 3.1%; 0.1 to 2.4% and 0.2 to 4.0% for the cultivars BR 18, BR 40 and IPR 85, respectively.

Index terms: wheat, plant growth, yield, grain, silicon.

SILICON ACCUMULATION IN MEDICINAL PLANTS AND NATIVE TREES FROM A BRAZILIAN SAVANNA REGION

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A collection of 101 medicinal plants grown at Arboretum belonging to the “Universidade Federal de Mato Grosso do Sul” and 59 species aging from 2 to 3 years old from the Natural Park of the “Centro de Pesquisa Agropecuária do Oeste, EMBRAPA”, both located within a Brazilian Savanna Region in Dourados, MS, were studied for foliar silicon accumulation. Fully mature leaves were randomly collected for Si content analysis. Foliar Si in native plants varied from 0.3 to 1.4%, with an average of 0.6%, while in medicinal plants, a broader range was found from 0.3 to 3.9%. Trees showing a high Si content were *Cecropia pachystachya* (1.4%) and *Curatella americana* (1.3%). The medicinal plants that had a high level of Si accumulation in leaves were *Maranta arundinaceae, Piper umbellatum, Piper aduncum* L., *Vernonia polianthes, Costus spiralis, Alpinia zerumpet (Pers.), Wendita calysina, Vernonia polianthes, Mikania glomerata* Spreng, *Urtica dioica* and *Symphytum officinale* L.

Index terms: medicinal plants, savanna native tree, silicon.

EFFECTS OF CALCIUM SILICATE (AGROSILÍCIO®), LIMESTONE AND PHOSPHORUS APPLICATION ON PLANT DEVELOPMENT OF "BRACHIARÃO" (*Brachiaria brizantha*)

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This study was done at an experimental field in Univale, Governador Valadares, Minas Gerais. The experimental plot was of 4.0 x 4.0 meters and the treatments were: control, phosphorus (112.5 kg ha^{-1}), calcium silicate (Agrosilício®, 1875 kg ha^{-1}), limestone (1875 kg ha^{-1}), calcium silicate + limestone (937.5 kg + 937.5 kg ha^{-1}), calcium silicate + phosphorus (1875 kg + 112.5 kg ha^{-1}), limestone + phosphorus (1875 kg + 112,5 kg) and calcium silicate + limestone + phosphorus (937.5 kg + 937.5 kg + 112.5 kg ha^{-1}). All the portions form fertilized with nitrogen and potassium. After the sowing the seeds of *B. brizantha*, the seeds were lightly soil incorporated. Seventy-five days after planting, plants were harvested 10 cm from soil surface in an area of 0.5 m^2 and fresh and dry weights were recorded.. For fresh weight, the greatest weights were recorded for calcium silicate + limestone + phosphorus followed by calcium silicate + limestone and calcium silicate + phosphorus. Limestone alone (1875 kg ha^{-1}) did not influence plant development, and were similar to the control. In the decomposition of the factorsthe treatments that used calcium silicate presented a production 21% upper the treatments without calcium silicate. In the treatments with and without limestone, this difference was of 10% and for the phosphorus of 9%. For dry weights the greatest weights were recorded for calcium silicate + limestone + phosphorus followed by the calcium silicate + limestone and calcium silicate + phosphorus. Lower values were recorded for pure limestone and pure calcium silicate. In decomposition of the factors, the treatments with calcium silicate presented productivity 17% upper to the without calcium silicate. For the limestone this variation was of 12% and for the phosphorus, 17%. These results demonstrate that the fertilizers, correctives and your elements act jointly in the soil, turning difficult and little representative the individualized action of the inputs.

Index terms: *Brachiaria brizantha*, silicate, limestone

SILICON NUTRITION AND N_2 FIXATION IN SYMBIOTIC LEGUMES

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Applying silicon to symbiotic legumes raised in liquid culture has been shown to increase plant growth, root length, root mass, and total biomass. With cowpea, in particular, exogenous supply of silicon to pre-infected hydroponically-grown seedlings increased nodule numbers, nodule dry matter and N_2 fixation. When cultured permanently in sand, cowpea plants still showed an increase in nodule number and nodule mass. Ultrastructural studies of these root nodules showed that the improved symbiotic performance in cowpea with silicon supply was due to an increase in the number of bacteriods and symbiosomes per infected cell, the units that reduce N_2 to NH_3 in root nodules. In addition to these structural alterations caused in nodules by silicon supply, whole-plant mechanical strength was increased. Because silicon application is also reported to increase plant defence presumably via isoflavanoid biosynthesis, it is possible that silicon nutrition in symbiotic legumes also elicits the synthesis of flavonoid *nod*-gene inducers, which are the signal molecules involved in the early stages of nodule formation. An increase in the level of inducer molecules would enhance the expression of *nod*-genes in rhizobia and increase legume nodulation and N_2 fixation. This paper summarizes studies done on silicon nutrition of N_2 fixing legumes, with special reference to symbiotic performance.

Index terms: silicon, legumes, nodulation, N_2 fixation, mechanical strength.

SILICON CONTENT IN DIFFERENT SUGARCANE VARIETIES

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Enhanced drought tolerance is one of the benefits of silicon. In West region of São Paulo State, Brazil, some sugarcane varieties show tolerance to long dry periods. The present study was undertaken to determine the silicon content in six sugarcane varieties ("RB85-5536, RB85-5036, RB85-5035, SP81 3250, RB84-5486, RB85-5113") related with drought tolerance. The experiment was carried out at Moema Mill, São Paulo, Brazil (Oxisol soil with low silicon content) using a randomized complete block design with 6 treatments (sugarcane varieties) and 4 replications. Sugarcane varieties were planted in plots with five 10 m rows spaced 1.15 m apart. Lime (1.8 $t.ha^{-1}$), triple superphosphate (220 $kg.ha^{-1}$) and 5-25-30 fertilizer (450 $kg.ha^{-1}$) was applied before planting. No silicon source was applied. Samples (old leaves, the first leave with visible dewlap (FVD), extracted juice and bagasse) were taken in the first ratoon before harvest from 10 plants collected in each plot. Silicon was analyzed using the colorimetric method. Silicon content was found to be higher in old leaves in comparison to FVD, bagasse and juice. Extracted juice had the lowest silicon content (ppm). Differences were found to exist between varities in silicon content. The sugarcane varieties RB84-5486 and RB85-5035 were found to have a high level of silicon in plant tissue and were the two varieties that exhibited a greater tolerance to drought. These results suggest that a high silicon content in sugarcane may be related to drought tolerance.

Index Terms: *Saccharum* spp., sugarcane varieties, silicon.

EFFECT OF SILICON APPLICATION ON THE DEFENSE OF *DAVILLA ELLIPTICA* (DILLENIACEAE) AGAINST HERBIVORY

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Herbivores can be grazers, seeders, leaf, sprout and floral bud eaters, they can eat most plant structures. The silicon uptake may enhance plant crop protection against herbivores in many different ways like hardening leaves, increasing the number of thricomes or inducing phenolics content. The objective of this work was to evaluate the effect of silicon accumulation in chemical and physical defenses against insect herbivores on *Davilla elliptica* (Dilleniaceae) St. Hil. The treatments consisted of two groups of plants, in witch one group (control) was maintained in natural conditions and the second (treatment) had received 300g of calcium silicate (42% SiO_2) applied on the soil surface without incorporation around each plant (40 cm diameter). Plants treated with calcium silicate showed higher silicon content in the leaves and also significantly ($p < 0,05$, Mann-Whitney, U - test) harder leaves and higher number of thricomes as well as significantly smaller herbivory. The accumulation of this element possibly turns the plant less palatable to herbivore insects.

Index terms: herbivory, plant defense, silicon.

OPTIMIZATION OF SOIL TEST BASED K FERTILIZER FOR LOW LAND RICE UNDER THE INFLUENCE OF SILICON FERTILIZATION

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A field experiment was conducted to study the effect of graded levels of soil test best K (STB K) in combination with different silicon source applications: rice straw (RS), silicate solubilizing bacteria (SSB), RS + SSB and sodium meta silicate (SMS) on grain yield of rice in a *Udic Haplustalf.* The yield data was subjected to linear and quadratic models for optimization of STB K as influenced by RS, SSB, RS + SSB and SMS. A good fit was observed only with the quadratic model based on the response of increasing grain yield to decreasing level of applied Soil Test Based K. Further, the rate of response to the added K varied as indicated by the slope of the curve. The magnitude of response was greater in control followed of SMS, SSB and RS. The lowest response to the added STB K was observed in the RS + SSB treatment since it had a lower physical and economic optima of 43.6 and 17.2 % STB K, respectively.

Index terms: recycling of rice straw, soil test based K, silicate solubilizing bacteria

USING OF SILICON-RICH SOIL AMENDMENTS FOR REDUCTION OF NUTRIENT LEACHING FROM CULTIVATED AREAS.

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Contamination of natural waters has been accelerated by nutrient-bearing runoff water from cultivated areas, and today is considered one of the most important problems in the world. Liming of agricultural lands and using of Al or Fe bearing chemicals has been found to be responsible for transformation of plant-available P into plant-unavailable forms. Another approach to reduce nutrient leaching is to decrease its application rate in mineral fertilizers. Both approaches can dramatically reduce agricultural benefits. We hypothesized that using Si-rich substances would reduce nutrient leaching and keep them into plant available forms. Laboratory, greenhouse and field investigations were conducted to test this hypothesis. Chemically pure SiO_2, $CaSiO_3$, agricultural grade limestone and two commercial Si fertilizers were incorporated into the soils in four fields in Central and North Florida. A new algorithm for calculation of the level of P leaching reduction was suggested. The use of Si-rich soil amendments and chemically pure Si-rich substances decreased P leaching 50 to 90% and maintained P in plant-available forms. The level of the reduction of P leaching ranged from 50 to 3500 kg of P per ha. The leaching of N (NO_3^-) was reduced from 5 to 40%.

Index terms: leaching, water contamination, phosphorus, silicon-rich substances.

SOIL CLASSIFICATION ON DEFICIENCY OF ACTIVATED SI

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Simple, universal and highly informative methods for soil testing and new classification of the soil on the deficiency of plant-available and active forms of silicon (Si) in the soil are necessary for wide using of Si fertilizers in the world. Actual (soluble and weakly adsorbed) forms of Si and potential forms of Si, which can be the sources for the actual forms of Si are primary parameters which used in the suggested methods for soil testing and So soil classification. The unit deficiency parameter of activated Si and the soil classification of deficiency of activated Si were discussed using both factors. The content of plant-available Si (water extraction from fresh soil) and amount of biogeochemically active Si (0.2 N HCl extraction from dry soil) is parts of the parameter under discussion. This parameter was tested on various soils from Russia, Ukraine, UK, US, Australia and other countries and was found to have a good relationship with the Si content of plants (r^2=0.96-0.98). Four gradations for Si deficiency in soils were determined: (1) soil without deficiency of activated Si, (2) soils with low level of deficiency, (3) soils with deficiency and (4) soil with critical deficiency of activated Si. Soil samples taken from various regions of Florida were analyzed for there active Si content and the value were used to create a map showing the Si deficient areas of Florida. Determination of Si deficiency in the soil and the mapping should help to solve practical problems involving the need for Si fertilizers and soil amendments.

Index terms: soil mapping, Ukraine, biogeochemichal.

SOLUBLE SILICON IN SOILS: LIME AND PHOSPHORUS INTERFERENCE

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The soluble silicon content in the soils are function of soil mineralogy, its clay content, Fe and Al oxides and pH. Lime and phosphorus fertilization are common practices that could change soluble silicon but there is a paucity of published information on tropical soils. The objective of this work was to evaluate soluble silicon treated with lime and phosphorus by using different extractants. The experiment was designed in a completely randomized design and treatments were: 0, 2, 4 and 6 ton ha^{-1} of lime, 6 different soils type (A horizon), 2 P level and 4 replications. The soil samples were collected under cerrado vegetation and placed in pots of 250 g. The soils were maintained at 80% of water holding capacity. After 90 days of incubation, homogeneous samples were collected from the pots to determined pH, $CaCl_2$ and soluble Si in soil (0.5 mol L^{-1}acetic acid, 0.01 mol L^{-1} $CaCl_2$ and water). As expected, the 0.5 mol L^{-1}acetic acid extracted higher amounts of soluble silicon than 0.01 mol L^{-1} $CaCl_2$, and water and pH increased with lime application. A positive correlation was only observed between soil pH and soluble silicon where 0.5 mol L^{-1} acetic acid was used. Lime and phosphorus application in the clay soils decreased soluble silicon extracted by 0.01 mol L^{-1} of $CaCl_2$ and water probably due to the formation of insoluble silicon compounds (P-Ca). The lime and phosphorus application reduced soluble Si extracted by 0.5 mol L^{-1} acetic acid compared with treatments without phosphorus. The acetic acid in this case was able to dissolve compounds of Si-P besides Si-Ca. More studies should be done to prove if these compounds could be absorbed by plants and to determine the best extractant for this situation.

Index terms: extractants, silicon, phosphorus, soils.

COMPARISON OF THE EFFECTIVENESS OF FOLIAR AND SOIL-APPLIED SILICON ON SORGHUM GROWTH

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Silicon (Si) is conventionally applied to the soil at relatively high rates to improve yield as well as to increase disease and pest resistance of Si accumulator plants such as sugarcane and sorghum. However, it has been suggested by fertilizer company representatives that soluble products that contain Si can be used as foliar sprays and that this is an effective way of applying Si to crops. For that reason, the effects of soil applications of granular $CaSiO_4$ (Calmasil) at 4 and 8 ton/ha on yield and Si uptake by sorghum were compared with liquid Si fertilizers applied as foliar sprays on a weekly basis at concentrations of 300 and 600 µg/mL. Plants were grown under greenhouse conditions for a period of 6 months (plants were cut to near ground level 5 times and allowed to regrow) in 4 soils low in soluble Si. Applications of soil-applied calmasil raised soil pH, exchangeable Ca and soluble Si, increased yields and Si uptake by sorghum. The rate of 8 t/ha generally had a greater effect than the 4 ton/ha rate. Calmisil applications resulted in elevated concentrations of leaf Si and depressed concentrations of N and P. Compared to untreated control, foliar applications of soluble Si as potassium silicate (26% Si), potassium humate (15% Si) and potassium fulvate (15% Si) at either 300 or 600 µg/ml had no significant effect on either yield or leaf Si content. It was concluded that because Si is accumulated in sorghum at concentrations equivalent to those of macronutrients, foliar application is not a practicable method of applying Si to the plants.

Index terms: foliar spray of silicon; sorghum; potassium silicate, potassium humate, potassium fulvate.

SOIL CLASSIFICATION ON DEFICIENCY OF ACTIVE SILICON

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The absence of simple, universal and highly informative methods for soil classification on the deficiency of plant-available and active forms of silicon (Si) had a great negative influence on the practical use of Si fertilizers in the world. The soil fertility and crop responses to Si fertilization depend on the following soil factors: [(1)] actual (soluble and weakly adsorbed) Si and [(2)] potential Si, which can serve as a source for the actual Si. Using both factors, the parameter for describing deficiency of activated Si was suggested. The parameter includes plant-available Si (water-extractable from a fresh soil) and biogeochemically active Si (0.2 N HCl- extractable from a dry soil). This parameter was evaluated for various soils of Russia, Ukraine, UK, USA, and other countries. It was found to have a good relationship with the plant Si (r^2=0.96-0.98). Four gradations of activated Si deficiency in soils were distinguished: [(1)] not deficient soil, [(2)] low deficient soil, [(3)] deficient soil, and [(4)] critically deficient soil. Soil samples taken from various regions of Florida were analyzed for the active Si and the results were used for mapping of the Si deficiency in Florida soils. Evaluation of soil Si deficiency using the parameter proposed and the map should help to solve agricultural problems, including the need for Si fertilizers and soil amendments.

Index terms: plant silicon content, silicon deficient soils, method for soil classification.

THE EFFECT OF CALCIUM SILICATE AND LIMESTONE ON THE DEVELOPMENT OF "BRACHIARÃO" PLANTS (*Brachiaria brizantha*)

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The rural zone of the River Candy's valley has about 3.3 million hectares and 70% is in pastures. During decades, the wrong handling of the animals in the pastures turned the area more degraded from Minas Gerais. Your recovery involves the use of low cost inputs as the silicatos originating from of the production of the steel, common in the area. This work had as objective compares the effects of the limestone and of the agrosilício used in a soil of average fertility collected of horizon B textural, common in the degraded areas of the region. The work was developed in green house in vases with 30 liters of capacity. The used treatments were: limestone, calcium silicate (agrosilício®), limestone+calcium silicate and control. A planting manuring was accomplished with NPK and, soon after, the inputs were applied and mixed superficially in the soil, to five centimeters of depth. The brachiarão was sowed (*Brachiaria brizantha*) and collected 75 days after the planting. The use of the inputs increased the bud germination number for plant that varied between 3,55 and 3,33 in relation to the control (2,88). In the dry weight of the roots, the tendency of larger development happened in the treatments with calcium silicate pure or mixed with limestone, that were 22% superiors on average to the treatment with pure limestone. In the development of the aerial part, the behaviors were shown plenty similar, with small superiority for the treatment with calcium silicate. In the matter total drought, the treatment with calcium silicate presented values 10% superiors to the treatment with limestone. In spite of have not happened significant statistical differences, the calcium silicate showed larger efficiency in the development of the plants in restricted environment.

Index terms: *Brachiaria brizantha*, silicate, limestone.

STATUS OF SILICON IN SOILS OF EL-MINIA GOVERNORATE IN MIDDLE EGYPT.

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The present investigation was carried out on the alluvial soils of the Nile valley as well as those of the transitional belts of the desert plateaus in El-Minia Governorate in Middle Egypt. Representative soil profiles were chosen to cover the whole area. Total silicon, as % of SiO_2,varied greatly from one site to another and ranged between 40.2 and 90%. The highest values were obtained from the coarse-textured soils which are located in/or near both Eastern and Western Plateaus, while the lowest values were obtained from the alluvial soils of medium to heavy texture grades Amorphous silicon determined in the different soils ranged between 0.06 and 3.34%. Fine textured soils showed the highest values of amorphous silica. Silicon was increased from the desert plateaus toward the Nile steam. As a percentage of total silicon fraction, amorphous silicon was found to constitute from 0.07 to 7.55%. Amounts of water soluble silicon ranged between 0.05 and 2.34 mg SiO_2/100 g soil. Fine textured soils showed the highest values of soluble silicon. Determinations carried out on different values of soil:water ratios showed that, in most cases, soluble silicon gradually increased by increasing dilution. Values obtained from four successive extractions of 1:20 soil:water suspensions revealed that there was a gradual increase of soluble silicon with increasing the number of extraction and the highest values were obtained from the third extraction. Relatively small amounts of soluble silicon were obtained when centrifugation was applied than when normal filtration was used. Some positive or negative correlations were found between the studied silicon fractions and sand, silt, clay, organic matter, CEC and total carbonate.

Index terms: total silicon, amorphous silica, water-soluble silicon.

AN IMPROVED FLOW INJECTION SYSTEM FOR TO THE SPECTROPHOTOMETRIC DETERMINATION OF SILICON IN PLANT DIGESTS AND SOIL EXTRACTS

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Silicon (Si) is an important element for plant development and its presence has been related to increase plant resistance against both biotic and abiotic stresses. Development of automatic procedures for its evaluation in the soil-plant system represents an important advance. In this context, flow analysis plays a relevant role due to the need for simple instrumentation, suitability for full automation and the favourable analytical characteristics of accuracy, reproductibility, sensitivity, sampling rate and reagent consumption. This communication reports the design of an improved flow injection system for spectrophotometric determination of Si. For plant analysis, the method involves monitoring (410 nm) of the yellowish molybdosilicate acid formed by reaction of Si with ammonium molybdate in HCl medium. Soil analysis was accomplished by adding ascorbic acid as reducing agent in order to form the blue chemical species (660 nm). Interference from phosphate was circumvented by adding oxalic acid. The proposed system handles 75 samples per hour, meaning 0.32 mg ammonium molybdate, 80 mg oxalic acid and 20 mg ascorbic acid per determination. Baseline drift is usually < 0.01 absorbance per hour and the analytical signals for 0.[5] 6.0 mg l^{-1} Si range within *ca* 0.03 – 0.50 absorbance. Linearity of the analytical curve is fair (r > 0.998, n = 6) and detection limit was estimated as 0.2 mg l^{-1} Si. Results are precise (r.s.d. < 0,1 %, n = 10) and in agreement with ICP-OES.

Index terms: silicon, flow injection analysis, spectrophotometric, plant and soil

INFLUENCE OF SILICON ON THE FERTILITY OF SANDY LOAM SOIL

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The experiment was conducted in greenhouse using the Red-Yellow Argissoil, which is one of the most representative soil, of Ceará State for sugarcane growth. The purpose of this study was to evaluate the influence of silicon on nutrient status in the soil, pH, electric conductivity and other chemical attributes of this sandy loam soil. A completely randomized design in 5x2x4 factorial was used. Factors were the five silicon rates: 0; 2.5; 5.0; 10.0 and 15.0 g per pot^{-1} of calcium and magnesium silicate (Recmix®, 11% of soluble SiO_2), two cultivars of sugarcane and four replications. The concentration of macronutrients (N, P, K, Ca, Mg, S), micronutrients (Zn, Cu, Fe and Mn) and the silicon in the soil as well as Na, Al, CTC, CE and pH of the soil were evaluated. It was concluded that silicon application to the soil increased Si, P, Zn, Cu and Mn concentration as well as elevated pH and electric conductivity but decreased, as expected, the content of Al^{3+} in the soil.

Index terms: silicon, soil, fertility.

EFFECT OF THE APPLICATION OF SILICATE IN SUBSTITUTION TO THE CARBONATE, IN SOILS WITH DIFFERENT TEXTURES AND MINERALOGIES IN THE PRODUCTION OF *Brachiaria brizantha*

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The silicon can move (adsorption/dessorption) the anions of the solid phase for the liquid, affecting, in that way, the nutrients availability in the soils and plant uptake. Aiming at to evaluate the influence of the silicate in substitution to the carbonate, in soils with different textures and mineralogies in the production of *B. brizantha*, was conduced an experiment in DIC arranged in factorial with 3 soils and 5 levels of substitution of the carbonate for silicate. The treatments were constituted of the combinations: T1=100% $CaCO_3$/0%$CaSiO_3$, T2=75%$CaCO_3$/25%$CaSiO_3$, T3=50%$CaCO_3$/50%$CaSiO_3$, T4=25%$CaCO_3$/75%$CaSiO_3$ and T5=0%$CaCO_3$/100%$CaSiO_3$, containing the same amount of CaO for all the treatments, seeking to reach V=50%. Each composed portion for vases containing 3 dm^{-3} of the soils Latossolo Yellow Red dystrophic (LVAd-1), Latossolo Yellow Red dystrophic (LVAd-2) and Latossolo dark Red dystrophic (LVd) they were fertilized with, 300 mg dm^{-3} of N, 200 mg dm^{-3} of P, 300 mg dm-3 of K, 30 mg dm^{-3} of Mg, 50 mg dm^{-3} of S, 0.5 mg dm^{-3} of B, 1.5 mg dm^{-3} of Cu, 3.0 mg dm^{-3} of Mn, 0.1 mg dm^{-3} of Mo, 5.0 mg dm^{-3} of Zn and 5.0 mg dm^{-3} of Fe. The P-source was incorporated 30 days after the application of the treatments, and the other nutrients were applied in the solution form and mixed to the soil before the sowing. Three *B. brizantha* plants were led by portion in which it was evaluated the production of dry matter and the mineral composition of the aerial part of the plants. Significant interaction of the doses was observed with the soils for all the nutrients. The increase of the silicate supply promoted increase in the weight of the dry matter, in the first cut, second cut and in the total for the different soils. It was observed that the silicate supply altered the nutrients availability for the plants and the productivity of the braquiaria. Some nutrients as Ca, Mg, S, B and the element Si, they had your content increased with the increase of the silicate supply, other like N, P, K, Cu, Fe, Mn and Zn reduced.

Index-terms: nutrition, silicon, forage, nutrients availability

SILICON FERTILIZERS: PAST, PRESENT AND FUTURE

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In agriculture of ancient Roman and China Empires some types of silicon (Si) fertilizers including plant ash were used for optimization of plant Si nutrition and for restoration of degraded soils. In the XIX century, the first investigation of the role of Si in plant growth and the use of Si fertilizers were just beginning. Sir Humphey Day, Alexander von Humboldt, Justius von Liebig, J.B. Lawes, D. Mendeleev, Isenoke Onodera, V. Vernadsky were pioneers in this area that involved Si chemistry. Laboratory, greenhouse and field experiments on all continents and all climatic zones have shown substantial benefits for silicon fertilization of rice, corn, wheat, barley, sugar cane as well as several other crops. There are three main reasons for silicon fertilization: (1) improved silicon nutrition in the plant reinforces the plant natural protective properties against diseases, insect attack and unfavorable climatic conditions; (2) the soil treatment with biogeochemically active substances containing silicon optimizes soil fertility through improved water, physical, and chemical soil properties and aids the maintenance of other nutrients in plant-available form; and (3) various ecologically safe industrial by-products may be used as silicon fertilizers, many of which help solve the problem of proper utilization of numerous industrial wastes. Because of these reasons, it is evident that silicon fertilizers should be used more extensively than they are presently. Frankly, silicon fertilizers are not used more extensively world-wide because there is a critical lack of specialists working to show the importance of silicon as a fertilizer material.

Index terms: silicon fertilization, silicon history.

EVALUATION OF TWO SILICON SOURCES ON CHEMICAL CHARACTERISTICS OF AN ACID SOIL FROM THE CERRADO AND DRY MATTER YIELD OF TWO SORGHUM GENOTYPES

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The effect of two sources of silicon on dry weights of two sorghum genotypes and on some soil chemical characteristics were evaluated in greenhouse The sources of silicon were: yoorin thermophosphate (TFY) containing 18% of P_2O_5 and 10% of silicon (Si) and a steel industry byproduct called “Agrosilício” (Recmix do Brasil S.A) with 6.46% Si, 0.42% P_2O_5, 36% CaO and 6% Mg0. The two sorghum genotypes used were from the breeding programme of Embrapa Maize and Sorghum Center. The treatments consisted of three levels of Si of each source: 0.120 and 240 mg Si kg^{-1} soil for the TFY and due to its composition, 0, 86 and 172 mg P kg^{-1} soil were added to the soil and 0, 150 and 300 mg Si kg^{-1} soil for the “Agrosilício”. The levels of phosphorus were compensated in every treatment independently of the Si source based on the highest Si level. The results showed that increases rates of Si resulted in significant increases in the pH and base saturation (V%) values, thus dramatically decreasing the aluminium saturation (Al%), especially when the Si source was the TFY. The Ca:Mg ratios, in the abscense of Si, varied from 1:14 to 1:28 with TFY and “Agrosilício”, respectively, to 1:2,5 at the highest Si level for both sources. No great differences were observed between the dry weights of the genotypes for either Si source, but values were slightly higher with the TFY source. The most significant effects of Si sources in these trial were on the soil variables, principally on the Ca:Mg ratios and for changes in soil acidity, especially when the source was the “Agrosilício” byproduct probably due to its high content of calcium and magnesium silicate.

Index terms: silicon, soil acidity, sorghum genotypes.

SILICON SOURCES FOR RICE

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Although silicon is not considered an essential element for growth and development of plants, silicon absorption promotes many positive benefits. The objective of this study was to evaluate different sources of silicon considered to be agronomically efficient and economically viable for the use in agriculture. An experiment was conducted using rice planted in Quartzipsamments (quartz sand) in greenhouse. The experiment was a randomized complete block design and each treatment had 4 replication. Twenty five sources of silicon were applied at rates of 250 kg ha^{-1} of Si and the witness. A response curve was developed for Si using the source control (wollastonite) at the rates of 0, 125, 250, 375 and 500 kg ha^{-1} of Si. The treatments received $CaCO_3$ and $MgCO_3$ in order to balance pH, Ca and Mg. Ninety five days after seed sowing, plants were harvested for dry matter yield of plant tissue on aerial parts and seeds for all Si rates. There was a linear relationship between increasing rates of wollastonite in soil and increasing content of Si in plant tissue. The sources of blast furnace slag, rock powder and clay had the lowest liberation of Si for rice and for soil extracted with $CaCl_2$ while wollastonite and furnace steel slag had a medium level of Si liberation. Silica gel had the greatest liberation of Si.. Because of the high silicate doses associated to the carbonate of Ca+Mg, the pH of the soil came high in these treatments, this pH elevation also increased the liberation of Si extracted with $CaCl_2$ in the soil and it interfered negatively in the productivity when compared the treatment control (-Si and +carbonate) with the treatment control (-Si and -carbonate).

Index terms: rice, slag, residues, plant nutrition and calcium silicate.

BIOCHEMICAL RESPONSES OF WHEAT UNDER OIDIUM ATTACK IN THE PRESENCE OF SILICON UNDER HYDROPONIC CONDITIONS

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Wheat plants cultivar “BR40” were cultivated in Johnson nutrient solution with increasing rates of silicon ($Na_2SiO_3.5H_2O$): 0; 0.36; 0.89, 1.78 and 3.57 mM. Approximately 30 days after emergency (DAE), a natural infestation of *Oidium* occurred in the greenhouse, which infected all plants. Visual evaluations at 60 and 63 DAE were carried out in three branches using the second and first leaves from the main ear. Two different disease rating were scored from 1 to 5 based on the James’s scale. The disease symptoms exhibited a gradual decrease as silicon concentration increased in the nutrient solution. At 65 DAE, the first and the second leaves from each treatment were collected and stored at ultrafreezer for polyphenols analysis and determination of the antioxidant enzymes - catalase (CAT), ascorbate peroxidase (APX) and superoxide dismutase (SOD). The lipid peroxidation levels using malondialdehyde (MDA) was also performed. Under stress conditions, reactive oxygen species (ROS) can accumulate in tissues resulting in CAT, APX and SOD activity alterations and lipoperoxide production. In the aerial parts of the plants, the activities of antioxidant enzymes and lipid peroxidation (MDA) were shown to decrease with the increase in silicon concentration. Furthermore, phenol synthesis in the highest silicon treatment was stimulated. These results suggest that the increase in wheat resistance to *Oidium* in the sampling period tested may be of chemical as well as of mechanical nature. The increase in polyphenols in plants with high levels of silicon indicates a probable resistance mechanism of chemical nature whereas the reduction in antioxidant enzymes activities and lipoperoxidation suggest a protective effect of silicon of mechanical nature.

Index terms: *Triticum aestivum* L., *Erysiphe graminis* f.sp. *tritici*, catalase, ascorbate peroxidase, superoxide dismutase, malondialdehyde, polyphenol, silicon.

RELATIONSHIP BETWEEN SILICON CONTENTAND SOME PHYSICAL AND CHEMICAL PARAMETERS OF TROPICAL SAVANNA SOILS

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Natural and undisturbed soil samples collected from 35 sites in the state of "Mato Grosso do Sul" at 0-20 cm depth and corresponding to the main representative soil units were studied for silicon content and correlated with their chemical composition and physical parameters. The soils were classified as Lixisol, Acrisol, Nitisol, Phaeozem, Gleysol, Ferralsol, Fluvisol, Histosol, Planosol, Plinthosol and Vertisol located in Amambai, Anastácio, Aparecida do Taboado, Aquidauana, Bodoquena, Camapuã, Chapadão do Sul, Dourados, Guia Lopes da Laguna, Iguatemi, Itaquiraí, Maracaju, Miranda, Mundo Novo, Nioaque, Paranaíba, Ponta Porã, Rio Negro, Santa Rita do Pardo, Selvíria, Tacuru and Três Lagoas, respectively. Physical and chemical determinations included pH in water and in $CaCl_2$; Al, Ca, Mg, H + Al and K ($cmol_c$ dm^{-3}), P-Mehlich 1 (mg dm^{-3}); organic matter (g kg^{-1}); cation exchange capacity at pH 7.0 (total CEC) and the effective cation exchange capacity - CEC_e ($cmol_c$ dm^{-3}), aluminum saturation (m%), base saturation (V %), Cu, Fe, Mn, Zn (mg dm^{-3}) and Si (mg kg^{-1}) using two extractors: acetic acid 0.5 mol L^{-1} and calcium chloride 0.01 mol L^{-1}. The available silicon content ranged from 1.2 mg kg^{-1} to 53 mg kg^{-1} in calcium chloride or from 2.3 mg kg^{-1} to 270 mg kg^{-1} in acetic acid. These values were positively correlated with the organic matter, potassium, calcium and magnesium contents, base saturation, base sum, total CEC, effective CEC and pH. This is the first report showing the possibility of relating Si content to chemical and physical parameters of natural and undisturbed tropical savanna soils.

Index terms: silicon, soil fertility, organic matter, CEC, pH.

THE SILICON EFFECT ON PLANT GROWTH UNDER HYDROPONIC CONDITIONS: PRODUCTION AND FIBER QUALITY IN COTTON (*Gossypium hirsutum* L.)

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Silicon can be considered as an important alternative nutritional source and field crop protection, especially when considering annual crops such as cotton. Few data are available for this crop and more recently, evidences were obtained on yield increases of cotton and fiber quality when Si was applied at usual rates. The phenology of four commercial cotton cultivars was evaluated from early growth stages till maturity under hydroponic conditions to determine the effect of Si as $Na_2SiO_3.5H_2O$ (0, 10, 25, 50, 100 and 200 mg/L), on the plant development including photosynthesis, mineral composition, root and shoot mass, fiber quality and productivity. The use of Si in cotton is discussed for future recommendation as nutrient for achievement of higher yield and fiber quality.

Index terms: silicon, cotton, photosynthesis, productivity, fiber quality

SOLUBLE SILICON AND PH EFFECT ON SOILS

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Silicon has been considered a beneficial element for some crops, but still very little is known about the chemistry of this element in the soil in the relationship to the different forms available to plants. This study had as its objective the study of the behavior of to Si available for plants in different acid conditions in the principal soils of the Triângulo Mineiro region. The adsorption of Si was compared to that of P, using 13 different types of soil. Samples of soil (250g) were incubated in plastic containers and were maintained at 80% of field capacity. The experiment was laid out in random blocks in a factorial scheme 13x4x2x2, corresponding to 13 different types of soils, 4 doses of calcium carbonate (0,2,4 and 6 t ha^{-1}), 2 doses of phosphorus (0 and 400 mg kg^{-1}) and 2 doses of silicon (0 and 400mg kg^{-1}), with 3 repetitions. After the incubation period (90 days), the chemical characteristics of the soils were analyzed. The conclusion was that the application of phosphorus to the soil increased the disponability of the silicon. The solubility of silicon in the soils was also affected by pH when the extractor $CaCl_2$ was used. However, in some situation the solubility of Si increased and in others it decreased. The capacity for the adsorption of P varied in accordance with the soil, however it was much greater than that of Si. The silicon was much less affected by adsorption reactions compared to those of P.

Index terms: adsorption, silicon, phosphorus.

EFFECT OF POTASSIUM SILICATE IN CARROTS USING FERTIGATION

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Silicon is not considered an essential element for plants, but its use has provided an increase yield in many different crops. This work aimed to evaluate the effect of the potassium silicate (K_2SiO_3) applied by fertigation system in carrot crop. The treatments consisted of five rates of the product (220, 440, 880, 1760 and 3250 kg ha^{-1}) as well as the standart procedure, in which silicate was not fertilized. The experimental was a randomized blocks design with four replications. The potassium silicate rates were applied three times, split in the proportions of 40% thirty days before planting, 30% ten days after planting and the rest, sixty days after planting. At harvest (110 days after the planting), carrots root yield, dry matter yield and silicon in the aerial part of plant were determined. It was observed that potassium silicate did not affect yield but Si in the tissue increase according to the silicate rates.It has been observed that the potassium silicate was moved by the water of irrigation for the deepest lays, which was proved by greatest concentration of silicon observed. However, the product did not modify the values of the pH of the soil.

Index terms: potassium silicate, carrots

EFFICIENCY OF SOURCES AND RATES OF FERTILIZERS CONTAINING SILICON IN THE MANAGING OF THE FLOODED RICE AND SORGHUM.

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The serpentinite is a mineral rich in silicon and magnesium and has showed many beneficial effects mainly in grass, increasing the production of dry matter and grains. The objective of this essay was to evaluate doses and the agronomic efficiency of the natural serpentinite, calcinated and calcinated associate to the potassium as for the silicon supply in rice and sorghum. To increase the reactivity of the serpentinite in the soil and to eliminate the fibers, the material was submitted to the calcination process. The used treatments were: silica gel in the doses of 0, 50, 100, 200, 400 kg ha^{-1} of silicon, and natural serpentinite, calcinated serpentinite (950°C), it physics mixes of 85% of calcinated serpentinite + 15% of KCl and 85% of natural serpentinite + 15% of KCl (calcinated after the mixture), all in the dose of 150 kg ha^{-1} of silicon. The experimental design was in randomized blocks (DBC) with four replications and the averages compared by Tukey test. In the soil it was evaluated pH, silicon extractible, Ca and Mg. In the plant, evaluations of the tenors of Si, Si accumulated in the aerial part, length of the system roots, production of dry matter and grains were made. The length of the system roots of sorghum and rice increased with the doses of silica gel applied to the soil. For the rice, the sources silica gel, 85% natural serpentinite + 15% KCl and the calcinated serpentinite were the sources that presented the largest accumulation of Si in the aerial part. The silica gel was the source that provided the largest accumulation of Si in the aerial part of the sorghum plants, not differing meantime, of the sources natural serpentinite and 85% natural serpentinite + 15% KCl (calcinated after the mixture).

Index terms: Oryza Sativa L., Sorghum bicolor, (L.) Moench, serpentinite, silicon, calcination.

EVALUATION OF SILICON EXTRACTORS FOR SOIL

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Although silicon is not an essential element, silicon application is beneficial for plant growth and development. With the objective of evaluating silicon sources in relation to agronomic efficiency and economic viability of their use in rice (Oryza sativa, L), an experiment was carried out in the greenhouse. The soil tested was a Quartzipsamments. The experiment was a complete block design with 4 replication. The treatments composted of 25 silicon sources and the control silicon application. Silicon was applied at rated of 250 kg ha^{-1} of Si. The treatments received $CaCO_3$ and $MgCO_3$ in order to balance pH, Ca and Mg. Ninety days after sowing, dry matter yield of aerial parts; the soil and plant tissue Si content were determined. Significant differences among silicon sources in relations to Si uptake were observed. Evaluating the soil extractors, the high Si extraction was obtained with the acetic acid. Calcium chloride was the extractor with the better correlation between Si extraction and Si uptake by the rice crop. Ammonium carbonate and ammonium acetate are also good methods with the advantage of having larger distribution of the points compared to calcium cloride, which discriminate better the variations among different Si sources. The productivity was affected due to the increasing Si doses.

Index terms: slag, extractors of silicon, silicate, oryza.

SILICON SOURCES AND BIOMASS PRODUCTION ON RICE CROP

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The ability of different fertilizer to provide silicon (Si) for rice crop was evaluated in an greenhouse experiment using a sandy and a clay soil. The Si sources evaluated were H_4SiO_4, Ca and Mg silicate and Wollastonite (Ca silicate) at rates of 0, 200, 400 and 800 kg ha^{-1} of Si. The fertilizers were incorporated in the soil volume 30 days before planting. In order to eliminate Ca, Mg and pH interference, the soils were balanced with $CaCO_3$ and $MgCO_3$. Soil samples were collected at planting date and after harvest to determine available silicon. Plant silicon content was determined in the above-ground parts, roots and grain. The available Si in the clay soil was always greater than sandy soil. Ca and Mg silicate was the Si source that showed the greatest values for Si accumulation in the plant. The greater the Si rate applied, the greater the Si level in the soil and in the plant. Grain and biomass weight increased where Si was applied as Ca and Mg silicate only in the clay soil. Silicon rates increased root dry weight in both soils, with greater values where Ca and Mg silicate fertilizer was applied. Silicon content in the aboveground parts of the plant and husks were greater when Ca and Mg silicate was used in both soils. The H_4SiO_4 fertilizer was practically not soluble.

Index terms: slag, silicon, biomass, rice.

POTASSIUM SILICATE AS FOLIAR APPLICATION AND RICE BLAST CONTROL

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Silicon has been commonly applied via soil as silicates or slag for increasing productivity and disease control. However, its use as a foliar spray is recent and demands more studies, such as the adequate solution pH, fractioning of the volume, and its impact disease resistance. This study had the objective to determined the best foliar spray doses and number of application during rice juvenile stage to control rice blast disease. Silicon was applied as potassium silicate solution at pH varying from alkaline (10.5-11.0) and acid (5.5–6.0). The experiment was carried out in the greenhouse with paddy rice, cultivar Metica I, susceptible to blast. Potassium silicate was sprayed at 0, 200, 400, 800, 1,600 and 3,200 g Si ha^{-1}; pH effect was evaluated spraying at 800 g ha^{-1}. *Pyricularia oryzae* was inoculated on rice at the juvenile stage. There were no significant differences among doses or pH effect, with no leaf absorption of either Si or K^+. Even though there was no absorption, rice blast incidence was reduced by increasing potassium silicate doses.

Index terms: silicon, rice, foliar application, potassium silicate.

CALCIUM CARBONATE AND CALCIUM SILICATE SOLUBILITY IN SOIL

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Soil acidity is a chemical degradation factor of soils. Lime and silicates are materials used to neutralize aluminum, raise pH and supply calcium and magnesium to the soil. Silicates are more soluble than lime, which can favor its movement in the soil profile. The reaction of calcium silicate and carbonate on the surface and in the soil was compared by a study in 200-kg pots containing an Ustoxic Quartzipsamment soil previously fertilized. The equivalent to 0, 1500, 3000, 6000 and 12000 kg ha^{-1} $CaCO_3$ or $CaSiO_3$ was applied over the soil surface. Soybean (BRS/MG-68) was cultivated for 120 days in the soils after mulching with 10 Mg ha^{-1} sugarcane straw, when the soil was sampled at the depths 0-0.10; 0.10-0.20 and 0.20-0.30 m. The parameters pH-H_2O, exchangeable calcium, magnesium and aluminum (KCl 1 mol L^{-1}) and silicon ($CaCl_2$ 0.01 mol L^{-1}) were determined. The lime products ($CaCO_3$ or $CaSiO_3$) increased pH and the levels of calcium in the top layer. After the first crop cycle (soybean), calcium silicate increased Si content and was less effective than $CaCO_3$ in correcting soil acidity and increasing calcium levels at greater depths.

Index terms: soil acidity correction, nutrient supply, soil depth

SOIL SOLUBLE SILICON FROM DIFFERENT SILICATES

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A silicon source should have high levels of soluble Si, high Ca and Mg content, low level of contaminants and be easy to apply in the field. A soil incubation experiment was carrying out using different silicon sources (200 mg kg^{-1} of Si) that were mixed with 250 g of two types of soils (sandy and clay). The soils were kept in a plastic pot during 60 days to measure silicon release from the fertilizer. In the first trial, the soil was a sandy soil and the Si sources were: silicon (powder), cyclone powder, Siligran AWM®, brown mica, fused brown mica, white silicon (course), white quartz (powder) and Wollastonite. In the second trial, a clay soil was incubated and the silicon sources tested were Wollastonite, Siligran AWM®; aluminum silicate, iron and aluminum silicate, Siligran®; Silipar B®, metassilicate and charchol SP. Soluble Si in the soil was determined by using acetic acid 0.5 mol L^{-1} and $CaCl_2$ 0.01 mol L^{-1} extractors. The clay soil, due to its mineralogical composition, presented greater silicon levels compared to the sandy soil. In boths soils, Si level was greater when extracted by acetic acid 0.5 mol L^{-1}. The best sources for supplying silicon for the sandy soil were Siligran AWM® and Wollastonite. Siligran®, Siligran AWM® and Wollastonite, were the best sources of silicon for the clay soil.

Index terms: extractors, sources of silicon, silicates.

SILICON ACCUMULATION IN PADDY RICE CULTIVATED UNDER DIFFERENT PARTICLE SIZE AND SOURCES

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The importance of silicon in rice crop is mostly related to yield increases resulted from the resistance to pests and diseases. The efficiency of silicates on releasing silicon for rice crop was evaluated in a sandy soil. The experiment was carry out in the greenhouse and the treatments were 200 mg kg^{-1} of Si applied in two different Si sources (Siligran® and Siligran AWM®). The Si sources were applied in two different particle size (powder or granulated). Wollastonite was used as a standard silicon source, in the doses of 0, 50, 100, 200 and 400 mg kg^{-1} of Si. Paddy rice crop, cultivar Rio Formoso was growth for 180 days. The Si content in the soil and leaf and dry matter yield were determined. It was showed that Wollastonite application increased Si uptake by the rice crop according to the Si rates. The calculated agronomic efficiency index was maximum for Siligran® granulated when considered Si uptake by the rice plant.

Index terms: rice, silicon sources, and fertilization.

STRATEGY FOR THE USE OF A FOLIAR SPRAY WITH STABILIZED OLIGOMERIC SILICIC ACID + BORIC ACID (= OSAB®).

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Most plants require silicic acid in order to fully express their natural resistance to biotic and abiotic stress. Only the small oligomeric silicic acid molecule (OSA) is bioavailable for plants while on the other hand OSA is instable because it polymerizes fast. Due to the variability (mostly too low) content of OSA in soils and water, the uptake by plants is variable and often too low.When applied as foliar spray plants can profit of an optimal absorption of OSA by which they can “siliconize” their tissues and synthsize (or stimulate the synthesis) of important metabolites. The combination with boron leads to a synergetic effect. In our ongoing studies we observed a better quality of fruits like apples, pears (skin toughness, sugar content), a higher glycogen content of potatoes, a higher sugar content of grapes, etc. Some observations of using OSA in “overdose” will be presented, particularly the growth retardant. Delay in maturation of fruit creates the impression that the OSA content has an effect on the ethylene hormone (proper wording!?)Because the effects of Silicon in plants are expressed as improved natural resistance to biotic and abiotic stress, positive results of applying a foliar spray with OSAB (combination of silicic and boric acid) tend not to be clearly observable in just one or two crop cycles, especially in crops where the conditions are optimum (as per high-tech greenhouse cultivation). However, a constantly replenished and optimum level of silicic acid in plants represents their best possible insurance policy against stress; the ability to react naturally to stress factors when they arrive. The foliar spray with OSAB also has a regulatory effect on the uptake of certain minerals and can to an extent regulate growth. In these respects, the substance will contribute to better yields and improved product quality and to a reduction in the application of agro-chemicals and to more nutrient food and a cleaner environment.Based on all observations so far we formulated a series of questions.How can responsible agriculture, as nature intended, be promoted? How can agricultural and horticultural growers be convinced that Silicon is an essential (rather than just beneficial) element for plants and the environment? How can such a product be distributed through traditional channels operated by the agrochemical industry, when it will potentially reduce sales of agrochemicals? How can OSAB be distributed and sold internationally while at the same time being subject to commercial and professional trials commissioned by growers? A Business & Operation Plan (BOP) has been realized that tackles these questions. It provides a valuable ‘ready to go’ plan that will accelerate the use of Silicon in agriculture and horticulture throughout the world and contribute significantly to related scientific and cultural information. The BOP is addressed to agricultural entrepreneurs and to the produce and retail industry that deal directly with plantation crops on contract. This abstract refers to the Introduction paper on the BOP which is available on request.

Index terms: silicon, silicic acid, business plan, technical & marketing strategy