

**A COMPARISON OF SOIL AND FOLIAR-APPLIED SILICON ON NUTRIENT
AVAILABILITY AND PLANT GROWTH AND SOIL- APPLIED SILICON ON
PHOSPHORUS AVAILABILITY**

by

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ABSTRACT

A greenhouse study was carried out to investigate the effectiveness of soil-applied silicon (Si) with that of foliar applications for sorghum growth. Silicon sources were soil-applied as calmasil (calcium silicate) at two rates (4 and 8t/ha) and foliar applied Si including pure K-silicate, K-humate and K-fulvate (all three foliar treatments at rates of 300 and 600 ppm). Another treatment included soil applied calmasil plus low rate of foliar applied K-humate. The soils used for the greenhouse trial were Cartref, Glenrosa, Nomanci and Fernwood. Results indicated that application of calcium silicate to the soil before planting increased sorghum yield and Si uptake in three of the four soils. Silicon uptake from different experimental treatments followed the order: Calmasil 8t/ha > calmasil 4t/ha ≥ calmasil + 300 ppm K-humate > K-humate = K-fulvate = pure-K silicate = control. Foliar sprays were ineffective at increasing yield, Si content of the plant tissues or Si uptake. The concentrations of exchangeable Ca, Mg as well as soil pH were significantly increased by calmasil treatments. Extractable Al concentrations were also reduced due to the liming effect of calcium silicate and also possibly formation of insoluble aluminosilicates. The yield response to applied calmasil seemed to be primarily related to its liming effect and reductions in extractable Al in the Cartref, Glenrosa and Nomanci soils. The dry matter yield was highest in Fernwood and lowest in Cartref soil. However, there was no significant yield response to calmasil in Fernwood soil which had an initial pH of 5.8 and insignificant extractable Al concentrations. Therefore application of calcium silicate had no significant effect on extractable Al concentration in this soil. Yield response to calmasil may also have been partly due to direct positive effects of applied Si on crop growth through mechanisms such as increased photosynthetic rate and reduced transpiration rate. Addition of calmasil increased the concentrations of Si in the plant tissues and reduced those of N, P and K in Nomanci and Fernwood soils respectively. This indicates that nutrient interactions were occurring in the plant.

It was concluded that foliar-application is not an effective way of applying Si to a Si-responsive crop such as sorghum when growing in soils low in extractable soil Si. This is because Si is accumulated in plant tissues in similar amounts to macronutrients. It was also concluded that in future, studies of crop response to applied Si should include the use of non-liming source of Si (e.g. silicic acid) so as to separate a liming effect of calcium silicate from effect of applied Si.

In a laboratory study, the effects of applied silicic acid, calcium silicate and calcium hydroxide on levels of extractable P in two Si-deficient soils were investigated. Two soils (Fernwood and Nomanci soils) were treated with two rates of P and three soil amendments (calcium silicate, calcium hydroxide and silicic acid) and incubated for six weeks at room temperature. Phosphorus was extracted using Truog, AMBIC and resin methods, and levels of exchangeable and solution Al and extractable and solution Si were also measured. Application of calcium silicate and calcium hydroxide increased soil pH in both soils while silicic acid additions had no significant effect compared with the control. The pH increase was much greater in the Fernwood than Nomanci soil because of the low buffering capacity of the sandy Fernwood soil. Exchangeable Al and concentrations of monomeric and total Al in soil solution generally followed the order: control \geq silicic acid > calcium silicate > calcium hydroxide. The lowering of soluble Al concentrations in the silicic acid treatments was attributed to formation of insoluble aluminosilicate compounds while that in the calcium silicate and calcium hydroxide treatments was attributed to their liming effects causing a rise in pH.

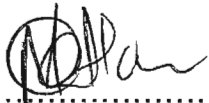
Concentrations of Si in soil solution were lower in the calcium hydroxide than the control treatment suggesting the solubility of Si decreased with increased pH. Additions of both Si sources increased Si concentrations in solution and the effect was more marked for the calcium silicate treatment. This was attributed to formation of insoluble aluminosilicates in the silicic acid treatment. Concentrations of H₂SO₄-extractable Si with treatment did not closely follow the same trends as those for Si concentrations in soil solution. That is, levels of extractable Si were very much higher in the calcium silicate than silicic acid treatment in both soils. In addition,

concentrations of extractable Si in the calcium hydroxide treatment were similar to control in the Nomanci soil, while for the Fernwood soil, concentrations in the calcium hydroxide treatment were exceptionally high. It was suggested that liming with calcium silicate or calcium hydroxide had rendered some Si-containing compounds in the soil acid-extractable and that the nature of acid-extractable Si fraction need further study in future.

The quantities of P extracted from the two soils by the various extractants followed the order: Truog > AMBIC > resin. The greatest increase in extractable P induced by additions of P was recorded for Truog P and the least for resin P. The effects of liming (addition of calcium silicate or calcium hydroxide) on extractable P levels differed depending on the soil and extractant used with increase, decrease or no effect being recorded. Such results confirm the complexity of lime and P interactions which occur in acid soils. Additions of silicic acid had no effect on levels of extractable P, compared to control. It was suggested that the reason for this was that phosphate is adsorbed to Al and Fe oxide surfaces much more strongly than silicate. As a result, additions of Si are ineffective at increasing extractable P levels.

DECLARATION

I hereby certify that the research reported in this thesis is my own work, except where otherwise indicated in the text, and the work has not been submitted for a higher degree in any other university.

Signed 

Mmakgabo Cordelia Matlou

Signed 

Prof. R. J. Haynes (Supervisor)

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TABLE OF CONTENTS

| | Page |
|---|-------------|
| ABSTRACT | i |
| DECLARATION | iv |
| ACKNOWLEDGEMENTS | v |
| LIST OF TABLES | x |
| LIST OF FIGURES | xii |
| | |
| CHAPTER 1: GENERAL INTRODUCTION | 1 |
| | |
| CHAPTER 2: LITERATURE REVIEW | 6 |
| | |
| 2.1 Introduction | 6 |
| 2.2 Sources of silicon in the soil | 6 |
| 2.2.1 Irrigation water | 7 |
| 2.2.2 Fertilizers | 7 |
| 2.2.2.1 Calcium silicate slag | 7 |
| 2.2.2.2 Fused magnesium phosphate | 8 |
| 2.2.2.3 Potassium silicate fertilizers | 9 |
| 2.2.2.4 Porous hydrate calcium silicate | 9 |
| 2.2.2.5 Silica gel | 9 |
| 2.3 Timing and rate of fertilizer application | 9 |
| 2.4 Method of fertilizer application | 11 |

| | |
|--|----|
| 2.4.1 Broadcasting | 11 |
| 2.4.2 Foliar application | 12 |
| 2.5 Forms of silicon in the soil | 13 |
| 2.6 Forms and distribution of silicon in the plant | 15 |
| 2.7 Factors affecting silicon content in the plant | 15 |
| 2.7.1 Soil | 15 |
| 2.7.2 Crop species | 16 |
| 2.7.3 Transpiration | 17 |
| 2.7.4 Nutrient supply | 17 |
| 2.8 Functions of silicon in plant growth..... | 18 |
| 2.8.1 Stimulation of photosynthesis | 18 |
| 2.8.2 Alleviation of physical stress | 19 |
| 2.8.2.1 Water stress | 19 |
| 2.8.2.2 Climatic stress | 20 |
| 2.8.2.3 Freeze alleviation | 20 |
| 2.8.3 Improvement of resistance to chemical stress | 21 |
| 2.8.3.1 Nitrogen stress | 21 |
| 2.8.3.1 Phosphorus | 21 |
| 2.8.4 Metal toxicity | 23 |
| 2.8.4.1 Excess sodium | 23 |
| 2.8.4.2 Iron toxicity | 24 |
| 2.8.4.3 Manganese toxicity | 24 |
| 2.8.4.4 Aluminium toxicity | 24 |
| 2.8.5 Increase resistance to biotic stress | 25 |
| 2.8.5.1 Diseases | 25 |

| | |
|---|-----------|
| 2.8.5.2 Pests | 26 |
| 2.9 CONCLUSIONS | 28 |
| | |
| CHAPTER 3: COMPARISON OF SOIL AND FOLIAR-APPLIED SILICON ON SOIL NUTRIENT AVAILABILITY AND ON GROWTH AND SILICON UPTAKE BY SORGHUM CROP..... | 29 |
| | |
| 3.1 INTRODUCTION | 29 |
| 3.2 MATERIALS AND METHODS | 32 |
| 3.2.1 Greenhouse trial | 32 |
| 3.2.2 Plant and soil analysis | 35 |
| 3.2.3 Statistical analysis | 36 |
| 3.3 RESULTS | 36 |
| 3. 3.1 Soil chemical properties | 48 |
| 3. 3.2 Effect of Si on yield and nutrient concentrations | 49 |
| 3. 4 DISCUSSION | 49 |
| 3. 4.1 Effect of silicon on soil chemical properties | 49 |
| 3. 4.2 Effect of Si on plant growth | 51 |
| 3.4.3 Moisture content and Si supply | 54 |
| 3. 5. CONCLUSIONS | 55 |
| | |
| CHAPTER 4: EFFECTS OF SOIL-APPLIED SILICON ON EXTRACTABLE PHOSPHORUS USING RESIN, TRUOG AND AMBIC METHODS ... | 56 |
| | |
| 4.1 INTRODUCTION | 56 |
| 4.2 MATERIALS AND METHODS | 59 |

| | |
|--|-----------|
| 4.3 RESULTS | 61 |
| 4. 3.1 Soil pH | 68 |
| 4. 3.2 Exchangeable and soluble Al | 68 |
| 4. 3.3 Extractable Si | 68 |
| 4.3 .4 Extractable P using different extractants | 69 |
| 4. 4 DISCUSSION | 69 |
| 4. 4.1 Effect of amendments on pH, exchangeable and soil solution Al | 69 |
| 4. 4.2 Levels of extractable and soil solution Si | 72 |
| 4.4.3 Levels of extractable P | 75 |
| 4. 5. CONCLUSIONS | 77 |
| | |
| CHAPTER 5: GENERAL CONCLUSIONS | 79 |
| | |
| REFERENCES | 82 |

LIST OF TABLES

| | | Page |
|-----|---|-------------|
| 2.1 | Influence of Si on yield of rice cultivar Oryzica 1 | 10 |
| 2.2 | Effect of Si application on transpiration rate in rice | 20 |
| 3.1 | Chemical and physical properties of four soils | 36 |
| 3.2 | Effect of Si treatment on pH, phosphorus, extractable cations and extractable soil Si concentrations in Cartref soil form | 37 |
| 3.3 | Effect of Si treatment on pH, phosphorus, extractable cations and extractable soil Si concentrations in Glenrosa soil form | 38 |
| 3.4 | Effect of Si treatment on pH, phosphorus, extractable cations and extractable soil Si concentrations in Nomanci soil form | 39 |
| 3.5 | Effect of Si treatment on pH, phosphorus, extractable cations and extractable soil Si concentrations in Fernwood soil form | 40 |
| 3.6 | Effect of Si treatment on cumulative yield, plant Si uptake, Si and moisture content in the plant tissues, amount of N, P, K, Ca and Mg in Cartref soil form | 41 |
| 3.7 | Effect of Si treatment on cumulative yield, plant Si uptake, Si and moisture content in the plant tissues, amount of N, P, K, Ca and Mg in Glenrosa soil form | 42 |
| 3.8 | Effect of Si treatment on cumulative yield, plant Si uptake, Si and moisture content in the plant tissues, amount of N, P, K, Ca and Mg in Nomanci soil | |

| | |
|---|----|
| form | 43 |
| 3.9 Effect of Si treatment on cumulative yield, plant Si uptake, Si and moisture content in the plant tissues, amount of N, P, K, Ca and Mg in Fernwood soil form | 44 |
| 4.1 Effect of incubation on extractable silicon and, AMBIC, resin and Truog extractable-P in Fernwood soil form | 61 |
| 4.2 Effect of incubation on extractable silicon and, AMBIC, resin and Truog extractable-P in Nomanci soil form | 62 |

LIST OF FIGURES

Page

| | | |
|-----|--|----|
| 2.1 | Effect of silica rates on panicle blast incidence (1, 5, and 10g/pot) | 26 |
| 3.1 | Relationship between dry yield and average Si uptake from mean of five harvests across all soils | 45 |
| 3.2 | Relationship between Si uptake and soil Si depletion | 46 |
| 3.3 | Relationship between average Si content in the plant tissues and tissue moisture content at harvest | 47 |
| 4.1 | Effect of incubation of amendments on soil $\text{pH}_{(\text{water})}$ in Fernwood and Nomanci soils | 63 |
| 4.2 | Effect of incubation of amendments on soil $\text{pH}_{(\text{KCl})}$ in Fernwood and Nomanci soils | 64 |
| 4.3 | Effect of incubation of amendments on exchangeable acidity Fernwood and Nomanci soils | 65 |
| 4.4 | Effect of incubation of amendments on monomeric (Al_{mono}) and total (Al_{T}) soluble Al in solution in Fernwood and Nomanci soils | 66 |
| 4.5 | Effect of incubation of amendments on Si concentration in soil solution in Fernwood and Nomanci soils | 67 |

CHAPTER 1

GENERAL INTRODUCTION

Agricultural activity tends to remove large quantities of nutrients like P and Si from soils. As a result, concentrations of these nutrients in the soil tend to decrease. With a rainfall of 400 to 1000 mm per annum in KwaZulu-Natal, nutrient leaching losses are likely to occur leading to soil acidity and yield decline. Removal of crop residues after harvest and excessive fertilizer applications (such as N) are some of the main factors leading to such yield decline. The use of Si fertilizers may solve some of these problems.

In South Africa, the use of Si as possible essential nutrient has received sporadic attention. Silicon fertilizers are expensive and many farmers are unaware of their importance in agricultural production. Although Si is not considered as an essential element of growth and development, addition of this element can increase growth and yield of Si accumulator plants, particularly sugarcane and rice (Savant *et al.*, 1999).

Silicon is the second most abundant element in the earth's crust after oxygen, and is an integral part of plants (Jones and Handreck, 1967; Epstein, 1999, Savant *et al.*, 1999). Most soils contain considerable quantities of this element, but repeated cropping can reduce the levels of plant-available Si to the point where supplemental Si fertilization is required for maximum production (Datnoff *et al.*, 2001; Savant *et al.*, 1999). Low-Si soils are typically highly weathered, leached, acidic and low in base saturation (Savant *et al.*, 1999). Highly organic soils that contain little mineral matter may contain little Si, and soils comprised mainly of quartz sand (SiO₂) may also be very low in plant-available Si (Datnoff *et al.*, 2001). In general, Si concentration in the solution phase of highly weathered acid Oxisols soils is several times less than in less weathered soils such as neutral to alkaline vertisols (Foy, 1992).

Although Si is generally considered to be non-essential for plant growth, there are numerous reports of increased plant vigour and yield with Si, particularly under biotic and abiotic stress (Lewin and Reimann, 1969). Favourable plant response is usually observed with monocotyledons on soils that are inherently low in plant available Si (Ayres, 1966; Gascho and Andries, 1974; Gascho, 1976). The mechanisms involved in this response are not fully understood (Gascho, 1977; Elewad *et al.*, 1982a); however, increased resistance to mineral stress, (Galvez *et al.*, 1987; Ma *et al.*, 1989; Barcelo *et al.*, 1993; Rahman *et al.*, 1988) disease and insect pests has been documented for several members of the family Gramineae (Jones and Handreck, 1965; Epstein, 1999).

On soils low in plant-available Si, fertilization of crops with calcium silicate slag increases plant Si content and yield (Deren *et al.*, 1993). However, Si fertilization is costly. Plants which are more efficient in accumulating available Si may have an economic advantage of requiring lower rates of Si fertilizer or less frequent applications. Higher plants vary in their capacity to accumulate Si (Datnoff *et al.*, 2001). Members of the grass family (gramineae), such as sugarcane (*Saccharum officinarum* L.) and rice (*Oryza sativa* L.), accumulate large amounts of Si in the form of silica gel ($\text{SiO}_2 \cdot n\text{H}_2\text{O}$) that is localised in specific cell types compared to dicotyledons (i.e. broadleaf plants) (Savant *et al.*, 1999; Datnoff and Rutherford, 2003). Gramineae species have been reported to contain 0.5 to 1.55 % Si, and dicotyledons less than 0.2 % (Jones and Handreck, 1967; Datnoff and Rutherford, 2003; Savant *et al.*, 1999). Therefore, Si can be accumulated from soil by plants in amounts that are several fold higher than those of other essential macro- and micronutrient elements. For example, Si accumulation may be twice that of nitrogen in rice (Liang *et al.*, 1994; Hammod *et al.*, 1995).

In plant leaves, Si is deposited in the epidermis, vascular bundles plus bundle sheath, and sclerenchyma in the form of amorphous silica gel ($\text{SiO}_2 \cdot n\text{H}_2\text{O}$) (Galvez *et al.*, 1987; Sarvant *et al.*, 1999). The Si layer forms in epidermal cell walls beneath the cuticle, which has been referred to as the cuticle-silica double layer (Elewad *et*

al., 1982 a,b). The cuticle-silica double layer in the epidermis has been suggested to control transpiration as well as prevent fungal and insect invasions (Savant *et al.*, 1999; Elewad *et al.*, 1982a).

Silicon can be applied to plants directly to the leaves (foliar spray) or in granular form, which is incorporated into the soil before planting. Reported sources of plant-available Si include irrigation water and fertilizers such as calcium silicate slag, silica gel, fused magnesium phosphate and potassium silicate (Gascho, 2001). Although these fertilizers contain a number of elements, it is the Si component that is usually most beneficial to plant growth (Datnoff *et al.*, 2001). Highly weathered soils tend to contain low concentrations of Si that require fertilization. Fertilization with soil amendments containing chemically activated Si has an effect on physical and chemical soil properties, including increasing soil exchange capacity, improving water and air regimes (Savant *et al.*, 1999). Method of fertilizer application has modifying effects on Si plant growth (Marshner, 1995).

High phosphate-fixing capacity and low P status are other problems that often limit crop production on highly weathered soils (Engelstad and Terman, 1980). Though P occurs in comparatively small amounts in soils, the chemistry of soil P, either organic or inorganic, is exceedingly complex. Its behaviour with respect to the plant is greatly influenced by physical and chemical components of the soil (Holford, 1989). When fertilizer P is added to soils it becomes progressively less available due to a combination of adsorption and precipitation reactions (Iyamuremye and Dick, 1995). The release of adsorbed P is very slow and, on impoverished or highly weathered, acidic soils, annual application of fertilizer P is necessary to maintain optimum available soil P. To reduce the amount of fertilizer P applied to soils it seems possible that Si could be incorporated into the soil before planting. For example, Smyth and Sanchez (1980) reported that when silicate fertilizers are applied to the soil, silicate is specifically adsorbed by soil colloids thus releasing previously adsorbed phosphate. This could cause an increase in the concentration of phosphate in soil solution and stimulate phosphate uptake and translocation by plants (Silva, 1971).

Fertilizer companies have suggested that soluble products that contain Si can be used as fertilizers for foliar application to improve crop growth. However, there is no experimental evidence to support such an idea. Indeed, because Si is accumulated in plants in amounts similar to those of macronutrients it is usually soil-applied at relatively high rates (e.g. 4 – 20 tonnes/ha).

Objectives of the study were to:

(i) Determine the response of sorghum growth to applied Si supplied either by soil application or foliar spray and select a suitable method for applying Si to the plants.

(ii) Evaluate dry matter production and response of sorghum grown on different soils at various rates of Si application.

(iii) Determine the effects of lime and silicate applications on P extractability using two soils treated with different P levels.

(iv) Compare three soil test methods for available P and determine how they are affected by lime and silicate applications.

(v) Compare the effects of applied Si and lime on levels of Si and Al in soil solution and in extractable forms.

This information will be useful for recommending methods to maintain adequate levels of Si in the soil.

This thesis is divided into five main sections. The introduction will be followed by a literature review concerning the effect of Si on crop growth and its interaction with other nutrients. Results from a greenhouse study to determine the effect of different Si sources on sorghum growth and soil chemical properties are discussed in chapter 3. In chapter 4, the effect of soil amendments and different P extractants on P

concentration are outlined and discussed. Conclusions and recommendations for research are outlined in chapter 5.

CHAPTER 2

LITERATURE REVIEW

2.1. Introduction

Silicon is not considered as an essential element for plant growth and development, but addition of this element to the soil or plants can increase growth and crop yields (Savant *et al.*, 1999). This review covers the relationship between Si and crop production, including how to best manage Si and methods of applying Si to soils and plants. The interaction of Si with other elements, functions of Si in soils and plants are also discussed.

2.2 SOURCES OF SILICON IN THE SOIL

Silicon is released by the weathering of minerals (quartz and feldspar), but only part of this soluble Si is lost through drainage or by crop removal and subsequent harvest (Savant *et al.*, 1999). Soluble Si may be introduced to the soil by runoff, capillary ascension from the water table, or by aeolian, alluvial or any other deposition of silicate material at the soil surface (Savant *et al.*, 1999). In places where organic and sandy soils predominate, soils contain only small amount of soluble Si available to plants.

Research suggests that microorganisms are involved in the Si cycle (i.e. in Si transformations) in nature (Vintikova, 1956). Certain bacteria possess an ability to decompose siliceous rocks and minerals, and aluminium-silicates and quartz sand (Vintikova, 1956). Webley *et al.* (1960), for example, found that bacteria lacking a mucous coat were more effective than those of the mucous type in the decomposition of amorphous synthetic silicates, crystalline wollastonite, apophyllite and olivine.

The monomeric form of Si (H_4SiO_4) is recognized to be the main form in soil solution (Savant *et al.*, 1999). However, the overall composition of forms of Si is influenced by several factors such as pH, temperature, degree of supersaturation, and the presence of the other substances. Jones and Handreck (1965), for example, found that when soil pH in the field was in the range of 5.4 to 7.2, the concentration of silica in solution decreased from 70 to 23 ppm SiO_2 with increasing pH.

2.2.1 Irrigation water

Irrigation water can be a potential source of Si for sugarcane, because the following forms of Si may occur in natural waters: ionic and molecular Si, aggregate Si (as colloid, solid and/or gel), Si adsorbed onto sesquioxides, organic-Si complexes (humates), metal-Si complexes and in living organisms (Mitchell, 1975).

Fox *et al.* (1967) found that in Hawaii, mountain water at about 300m contained 2.5 mg dm^{-3} Si whereas irrigation water pumped from wells near sea level contained less than 0.2 mg dm^{-3} Si. Kobayashi (1960; cited by Fox *et al.*, 1967) reported similar observations in Japanese rivers where the average dissolved Si in those flowing through regions of sedimentary rocks was 4.7 mg dm^{-3} Si whereas it was 21 mg dm^{-3} Si for those in the neighbourhood of volcanic rocks. The rain water contained less than 0.2 mg dm^{-3} Si and was considered not enough to be of agronomic importance.

2.2.2 Fertilizers

Fertilizers containing more than 20 % soluble SiO_2 are recognised as silicate fertilizers.

2.2.2.1 Calcium silicate slag

One reported source of plant-available Si is calcium silicate slag, a by-product of electric furnace phosphate production (Ayres, 1966; Anderson, 1991). This material

is used as a liming material in Japan, Germany and United States of America (USA). Slag is a by-product of iron and steel manufacture. It is made by melting the ore containing iron (Fe), manganese (Mn), nickel (Ni) and chromium (Cr) with limestone in a blast or electric furnace, and then cooling (either by air or water) the material floating on the surface (Ma *et al.*, 2001). Silicon components in the ore react with limestone, leading to separation of calcium silicate. Iron and other metals in the ore are reduced and separated. After the metals needed are separated, slag remains as a by-product. The main components of slag are calcium silicate, Mg, Al, Fe and trace Mn, Si and Cr. In addition to containing Ca and Si it may contain various other elements or contaminants, some of which may under certain conditions have favourable and/or unfavourable effects on sugarcane growth (Ma *et al.*, 2001). Although slag contains a number of elements, it is the Si component that is most beneficial to plant growth (Datnoff *et al.*, 1991).

Applications of calcium silicate increase soil pH and can sometimes stimulate mineralization of soil organic nitrogen (Gascho, 2001). Nonetheless, the successive application of calcium silicate slag was found to cause neither a reduction of soil nitrogen nor a micronutrient imbalance in fine textured soils rich in organic matter (Gascho, 2001). By contrast, in coarse textured soils poor in organic matter, successive applications of calcium silicate could cause a reduction of soil nitrogen fertility and an imbalance in micronutrients, resulting in a yield decrease. Therefore, organic matter needs to be applied to these soils (Datnoff *et al.*, 2001).

2.2.2.2 Fused magnesium (Mg) phosphate

Fused magnesium phosphate is manufactured by melting phosphate rock with serpentine and the product is ground after quick cooling (Gascho, 2001). It contains P, Mg, Ca and Si (16-26 % soluble SiO₂). Although fused magnesium phosphate contains a number of elements, it is the Si component that is often most beneficial to plant growth (Datnoff *et al.*, 1991). Significant amounts of P (up to 67 kg ha⁻¹) could be added to soil using commercial rates of fused magnesium phosphate (up to 6 to 7 t ha⁻¹). However, Ma *et al.* (2001) reported that P applied through fused magnesium

phosphate was not biologically available to sugarcane and this was probably due to its low solubility.

2.2.2.3 Potassium (K) silicate fertilizers

Potassium silicate fertilizer is a fly ash-based slow releasing K fertilizer that is produced from coal power plants (Ma *et al.*, 2001). Fly ash is mixed with K, CO₃ or KOH and Mg (OH)₂, and heated at about 900 °C. Potassium in this fertilizer is slowly released. The fertilizer contains trace amounts of Mg.

2.2.2.4 Porous hydrate calcium silicate

The fertilizer is produced from quick lime, quartz and cement, which are reacted under 180 °C at 10 atm pressure (Gascho, 2001). This is carried out to produce plaster board for the building trade. Due to strict standards for wall material, a high percentage of non-standardized product is collected and used as a silicate fertilizer (Ma *et al.*, 2001).

2.2.2.5 Silica gel

Silica gel is often used as a desiccating agent and is made by neutralising water glass, gelling and finally dehydrating. It does not dissolve in HCl and must contain 80 % Si that is soluble in 0.5 N NaOH. Application of Si gel does not increase soil pH and it contains alkali components that tend to weaken the resistance of plants to diseases (Ma and Takahashi, 1991).

2.3 TIMING AND RATE OF FERTILIZER APPLICATION

Silicon application rates are mainly influenced by the chemical make-up of the Si source, Si levels in the soil, and in the plant (Savant *et al.*, 1999). Generally all Si fertilizers (granular) are applied to the soil before planting. Research in Florida

showed that if a response to the applied Si is obtained in the first year of application, no further applications of slags are needed for at least four years (Kidder and Gascho, 1977).

The benefits of Si fertilization are generally observed in sugarcane grown on Si-deficient soils such as weathered tropical soils and Histosols (Ayres, 1966). Some workers have suggested that large applications at infrequent intervals can be an effective strategy. Ayres (1966) reported an increased tonnage of sugarcane amounting to 18% in cane and 22% in sugar for a plant cane crop following the application of 6.2 t ha⁻¹ of electric furnace slag to aluminous humic ferruginous latosols in Hawaii.

Table 2.1 shows the effect of applied Si fertilizer on the yield of rice. High levels of fertilizer application increased rice yield. It has been observed that the effectiveness of applied Si fertilizers declines greatly with increasing time between application and the date in which the crop is grown (Ayres, 1966). The beneficial effect of Si fertilizer lasted on low Si soils for 2 years. For 3 t/ha Si, the yield was increased by about 60 % over the control. In the third year, 1 t/ha Si was applied to all treatments and the yield of the control plants was increased by 2-fold compared to that in the first year.

Table 2.1: Influence of Si on yield of rice cultivar Oryzica 1

| Silicon (t/ha) 1992 | Yield (t/ha) | | |
|------------------------|--------------|---------------------|--------------------------------|
| | 1992 | 1993 Residual 92 | 1993 Residual 92 + 1t/ha Si |
| 0 | 2.1a | 2.7a | 4.0b |
| 1 | 3.2ab | 3.6b | 4.1b |
| 2 | 3.6b | 3.7b | 3.9b |
| 3 | 3.7b | 3.8b | 4.2b |

From Correa- Victoria *et al.* (2001).

Economic use of fertilizers consists of choosing the right fertilizer and applying it at the right time. Silicate slag applications prior to a sugarcane crop and prior to a rice

crop in rotation with sugarcane showed positive agronomic response (Correa-Victoria *et al.*, 2001). Three timings of slag application were evaluated in the above crop production system: before rice, before sugarcane and before a rice-sugarcane rotation (Alvarez *et al.*, 1988). Results of the evaluation indicated that, under the costs and prices assumed; it was more profitable to apply slag prior to the rice crop in the rice-sugarcane rotation.

2.4 METHOD OF FERTILIZER APPLICATION

2. 4.1 Broadcasting (Soil application)

In order to apply Si to sugarcane, calcium silicate is typically broadcast and then incorporated into the soil before planting (Savant *et al.*, 1999). Generally, slag materials are incorporated into the soil as soon as possible after broadcasting to avoid caking on the ground surface. This is usually performed with a disc harrow, which is followed by complete land preparation (Jakeway, 1983). Broadcasting has an advantage of increasing the surface area of soil that the fertilizer comes in contact with (Heyler, 1998).

The particle size of the Si fertilizer is an important factor in controlling its dissolution rate when it is applied to soil (Savant *et al.*, 1999). Particle size is associated with increased surface area, consequently, the distribution and dissolution of smaller Si particles mixed in the soil is enhanced and the probability of root particle contact is increased. Soil application of silicate fertilizers has an advantage over foliar application because roots take up fertilizer from the soil over time.

The effectiveness of silicate material as a Si source for crops depends mainly on its particle size and chemical reactivity. In general, a finer Si source is more effective in supplying Si to sugarcane and rice (Savant *et al.*, 1999). Large particles result in less Si-soil contact, leading to reduced Si availability to the crop, although some particle degradation could occur during soil incorporation. If very fine, Si sources create

dusty conditions and can adversely affect material handling and application performance in the field. This dust problem may limit the use of silicate slag for sugarcane in developing countries where it will be mainly applied manually (Savant *et al.*, 1999).

2. 4.2 Foliar application

Soluble liquid fertilizers are often used when applying nutrients to leaves. This results in rapid absorption and has the advantage of near-immediate correction of nutrient deficiencies (Marschner, 1995). Leaf cells, like root cells, take up mineral elements from the apoplast. Leaf uptake is affected by external factors such as mineral nutrient concentration and ion valency as well as by temperature, and internal factors, such as metabolic activity (Chamel, 1988). For a given external concentration of mineral nutrients, the rates of uptake by intact leaves are, however, much lower than the corresponding rates of uptake by the roots, since the very small pores in the cuticle severely restrict diffusion from the external leaf surface into the bulk of the leaf apoplast and hence the plasma membrane of the leaf cells (Marschner, 1995). Foliar applications are commonly used to correct micronutrient deficiencies.

Foliar applications of Si are unusual since normally application rates are large (e.g. 4– 20 tonnes per ha; Savant *et al.*, 1999) and these are soil applies. However, foliar sprays can be useful in plants that are unable to transport Si through their vascular systems from roots to foliar parts of the plant (Menziez *et al.*, 1992).

Foliar applications have also showed some success in reducing disease damage. Work conducted in cucumbers showed a reduction in the severity of diseases through applications of foliar fertilizer containing 100, 500, 1000 and 2000 ppm SiO₂ (applied as soluble potassium silicate) (Menziez *et al.*, 1992). Foliar applications of 500 ppm Si or greater were found to significantly reduce the number of colonies of powdery mildew on the host leaves (Menziez *et al.*, 1992). The foliar application of Si

may be acting by creating a physical barrier to hyphal penetration or by inducing the accumulation of phenolics and/or other defense mechanisms (Menzies *et al.*, 2001).

2.5 FORMS OF SILICON IN THE SOIL

The solid-phase of Si occurs in various discrete and associated forms in soils in well-ordered (quartz) and disordered polymorphs (e.g. opal), and clay-mineral lattice structures. The solubility of disordered or amorphous Si in polymorphs in soils at an ambient temperature and neutral pH is approximately 50 to 60 mg Si L⁻¹, whereas that of quartz is much lower, commonly 3 to 7 mg Si L⁻¹ (Blatt, 1979; Hallmark *et al.*, 1982).

In soils, quartz is generally concentrated in sand and silt fractions, with secondary quantities in the clay fraction (Savant *et al.*, 1999). The parent material of the soils generally dictates which size fraction will have the maximum quartz content. The quartz content of clay fraction generally ranges from 0 to 250 g kg⁻¹, depending on the parent material and degree of weathering, although it may be as high as 750 to 850 g kg⁻¹ (Borchardt *et al.*, 1968; Le Roux, 1973). The quartz content of the sand fraction is considerably higher than that of clay. Generally, the most highly weathered soils have the lowest content of quartz (Savant *et al.*, 1999).

The liquid phase of Si in soil is more complex, but agronomically important (Savant *et al.*, 1999). It includes Si in soil solution mainly as monosilicic or orthosilicic acid (H₄SiO₄ or Si(OH)₄) and may range from 1 to 40 mg Si L⁻¹, with 16 to 20 mg Si L⁻¹ most common in soils near field capacity (Savant *et al.*, 1999).

Silicon forms may be defined in terms of the total, extractable, and soluble fractions (Savant *et al.*, 1999). Total Si content comprises all forms of Si that may be present and can be solubilized from soil by strong alkali fusion or acid digestion bomb methods. Extractable Si represents those forms removed by less severe dissolution

agents, such as sodium dithionite, ammonium oxalate, weak alkalis and sodium pyrophosphate. These extractants remove Si of intermediate stability that is often found associated with crystalline or amorphous soil components. Soluble Si represents the most labile form in soils and consists primarily of monomeric silicic acid (Savant *et al.*, 1999).

Some reagents extract adsorbed Si (capacity factor) as well as water-soluble Si (intensity factor) from soil (Fox *et al.*, 1969). Shaking time, ratio of soil to the extractant and temperature all affect the amount of Si extracted from soil. Most soluble Si seems to be released within the first hour of shaking a soil with water. Plant uptake of Si was found by Fox *et al.* (1969) to be most closely related to Si in the soil where a 1:10 soil:water (m/v) ratio was used. Amounts of water-extractable Si increase as soil pH decreases, reflecting Si solubility in soils and the pattern of Si uptake from applied fertilizer silicates (Medina-Gonzales *et al.*, 1988).

Other factors, such as soil sampling, storage time and extent of drying could also affect Si status of samples (Jersak *et al.*, 1992). The process of soil drying in the field and/or laboratory may increase aggregate stability and resistance to dispersion and therefore can affect the extractability of soil Si (Jersak *et al.*, 1992). Usually various extractions from dry soil samples are used for research into Si availability (Barsykova and Rochiev, 1979). However, results from dry soil extractions do not necessarily reflect actual contents of mobile Si forms. Drying of soil samples leads to essential change in equilibrium between soluble and solid Si substances. The soluble Si compounds (monosilicic, polysilicic acids and organo-Si substances) are adsorbed onto soil particles, being dehydrated in the process. To restore the natural equilibrium between various Si substances, it has been suggested that it is necessary to rewet soil samples for about one month prior to analysis (Sadzawka and Aomine, 1977). In addition, by using only dry soil extraction it is impossible to determine the distribution among monosilicic acids, polysilicic acids and organo-Si substances, which play very different roles in various soil bio-geochemical processes (Matichenkov and Ammosova, 1996).

2.6 FORMS AND DISTRIBUTION OF SILICON IN THE PLANT

The concentration of Si varies widely among different parts of one plant (Jones and Handreck, 1967). Studies of the xylem sap from several species have shown that silica enters the stems of plants as monosilicic acid. The monosilicic acid which is carried to the tops in the transpiration stream is polymerised to form solid silica as water is lost by transpiration (Ma *et al.*, 2001). This suggests that transpiration aids in the deposition of silica. Jones and Handreck (1967) also suggested that the accumulation of silica led to its deposition in those parts of the plant associated with conduction and transpiration.

In a study on the distribution of Si among the leaves of various plant species, Jones and Handreck (1967) reported that the upper leaves of wheat and barley contained higher concentrations of Si than the lower leaves. Furthermore, Jones and Handreck (1967) found that the uppermost or flagleaf (blade and sheath) of mature oat plants always contained the highest concentration of Si. They concluded that this is probably due to the light interception and rates of photosynthesis and transpiration being higher, especially in the flag leaf, than in other leaves.

2.7 FACTORS AFFECTING THE SILICA CONTENT OF PLANTS

2.7.1 Soil

Plants of one species contain different concentrations of silica when grown in different soils (Jones and Handreck, 1967). Many factors contribute to these differences. Several studies have demonstrated that sesquioxides, especially Al oxides, are largely responsible for the capacity of soils to sorb soluble Si, with the maximum capacity for sorption being between pH 8 and 10 (Beckwith and Reeve, 1964; Drees *et al.*, 1989). Jones and Handreck (1967) showed that aluminium oxides were more effective in sorbing monosilicic acid than iron oxides. The degree of crystallinity of the iron oxides did not greatly affect their adsorptive capacities, but that of the aluminium oxides did. The most crystalline aluminium oxide adsorbed only

one-third as much as the least crystalline one. Therefore, the solubility of Si in soils of the same pH is influenced by the amounts of free sesquioxides present.

The availability of Si in soils is highly pH dependent (Jones and Handreck, 1967). Low pH results in less sorption of Si by sesquioxides and greater sorption occurs at higher pH (Mc Keague and Cline, 1963). The solubility of Si (both crystalline and amorphous) is essentially constant between the pH limits of 2 and 8.5, but increases rapidly above. Below pH 8.0, Si is available as undissociated silicic acid molecule $(\text{H}_4\text{SiO}_4)_n$. The rapid rise in solubility above pH 9 is due to ionisation of monosilicic acid. Where Si in solution is higher (soluble Si), the plant content of this element generally is greater (Korndorfer *et al.*, 1999). The effect of pH was shown by Ayres (1966) who found that liming acid soil decreased the uptake of silica by various plants including oats, ryegrass, red clover, barley, sugarcane and rice. Conversely, the concentration of silica in the oats was increased from 1.68 to 2.77 percent SiO_2 by lowering the pH of the soil from 6.8 to 5.6 (Jones and Handreck, 1965).

Temperature and soil moisture dynamics also seem to play an important role in determining the concentration of Si in soil solution. Silicon is more soluble at high temperature. Soluble Si levels are often elevated under water-saturated and submerged soil conditions. Under reducing conditions Fe is solubilized and Si adsorbed to Fe oxides can be released (Mc Keague and Cline, 1963).

2.7.2 Crop species

Plants take up different amounts of silica according to their species (Jones and Handreck, 1967). Generally gramineae contain 10 to 20 times the concentrations of silica found in legumes and other dicotyledons (Jones and Handreck, 1967). Jones and Handreck (1967) compared gramineous and leguminous species in a humic sand of pH 5.2 and found that barley and ryegrass contained 1.95 and 1.58 percent SiO_2 , whereas red clover and blue lupin contained only 0.12 and 0.24 percent SiO_2 respectively. The characteristically low concentrations of total silica in dicotyledons

may be attributed to an exclusion of monosilicic acid from the transpiration stream, either within the root or at its external surface (Jones and Handreck, 1967).

2.7.3 Transpiration

Various workers have found that transpiration aids in the adsorption of silica. Jones and Handreck (1967) suggested that silica is absorbed in the transpiration stream by a non-selective process. The effect of transpiration on the concentration of silica in oat plants was investigated by Jones and Handreck (1965). Oats were grown in soils that contained concentrations of monosilicic acid ranging from 7 to 67 ppm. Water transpired, soluble soil SiO_2 and the amounts of silica absorbed were measured. The concentration of monosilicic acid increased as the water was lost by transpiration. Also, the concentration of monosilicic acid in the xylem sap has been found to be close to that of the external solution. These results suggest a role for Si in the water economy of plants. An increased rate of transpiration in Si-deficient plants could explain the wilting that can occur particularly under conditions of low humidity (Lewin and Reimann, 1969).

2.7.4 Nutrient supply

Si uptake by plants is controlled not only by the level of soluble Si but also by the concentration of other ions. Generally, increased plant Si results in lower N and P concentrations in the plant. Jones and Handreck (1967) found that fertilizing with either nitrogen (N) or phosphorus (P) caused a decrease in the concentration of Si in barley and wheat crops. In a study on the effect of ammonium nitrate (NH_4NO_3) on Si uptake, increased N fertilization increased the yield of dry matter and this was accompanied by decreased concentration of silica in the plant (Jones and Handreck, 1967). The explanation of these relationships may be found by considering the effect of nitrogen supply on the transpiration ratio. It has been reported that N fertilization leads to a more efficient use of water by plants. This phenomenon was studied by Ballard (1933; cited by Jones and Handreck, 1967), who showed that increasing the N supply to N-deficient plants decreases the transpiration ratio by as much as 30

percent. It may be concluded that the effect of increasing the N supply on the concentration of silica in the plant is an indirect one because the more efficient plant produces more dry matter for each unit of water and silica absorbed (Jones and Handreck, 1967).

Increasing the supply of P has also been reported to produce a systematic increase in the yield of dry matter that is accompanied by decreasing concentrations of Si in plants (Jones and Handreck, 1965). Again, increasing the supply of P has been found to decrease the transpiration ratios of phosphorus deficient cereals and grasses (Jones and Handreck, 1967). Phosphorus, like N, affects the concentration of silica in the plant indirectly by increasing the yield of dry matter.

The relationship between the supply of K and the concentration of Si in the plant is conflicting. Ishizuka and Tanaka (1950; cited by Jones and Handreck, 1967) found that in wheat and rice, the concentration of Si in the plant increased with increasing concentrations of K. However, Hart (1934; cited by Jones and Handreck, 1967) reported a slight decrease in the concentration of Si in sugarcane with increasing amounts of applied K. These observations are difficult to interpret but the effect seems to be small and varies with species.

2.8 FUNCTIONS OF SILICON IN PLANT GROWTH

2.8.1 Stimulation of photosynthesis

Silicon is involved in the promotion of plant growth (Epstein, 1999). Deposition of Si in the leaf blade keeps the leaf erect and stimulates canopy photosynthesis by improving light interception. This is important since it helps to minimize mutual shading in dense plant stands and when nitrogen fertilizers are heavily applied. In a study on the effect of Si on photosynthesis in rice, Takahashi *et al.* (1990) found that the amount of carbon dioxide assimilated per individual plant was higher in the plants with a high Si content than those with a low Si content. However, there was no

difference in the amount of carbon dioxide assimilated per leaf area among plants with a different Si content. Silicon can also increase the photosynthetic rate by facilitating the transmission of light (Ma *et al.*, 2001). Silica bodies in the leaf epidermal system might act as a “window” to facilitate the transmission of light to photosynthetic mesophyll tissue.

2.8.2 Alleviation of physical stress

2.8.2.1 Water stress

Water stress is common under field conditions and it affects crop yields (Ma *et al.*, 2001). Improved Si nutrition may reduce excessive leaf transpiration by reducing stomatal opening of the leaves (Wong You Cheong *et al.*, 1972). Excess transpiration causes stomatal closure resulting in a decrease in the photosynthetic rate of a plant. Transpiration from the leaves is made mainly through the stomata and partly through the cuticle. As Si is deposited beneath the cuticle of the leaves it forms a Si-cuticle double layer and the transpiration through the cuticle is decreased by Si deposition (Wong You Cheong *et al.*, 1972).

Results in Table 2.2 demonstrate the effect of Si on the transpiration rate of the plant. Transpiration rate decreased from 200 to 154 g H₂O/g dry weight as the Si percentage was increased. The rate of transpiration is presumably influenced by the amount of silica gel associated with the cellulose in the cell wall of epidermal cells. Hence a well-thickened layer of silica gel should help retard water loss, while epidermal cell walls with less Si gel will allow water to escape at an accelerated rate (Lewin and Reimann, 1969). In a study on the effects of Si on the transpiration rate of plants, Match *et al.* (1986) found that the photosynthetic rate was higher in +Si plants than in –Si plants. This was due to a decrease in transpiration rate in +Si plants.

Table 2.2: Effect of Si application on transpiration in rice.

| % SiO ₂ content | Transpiration (g H ₂ O/g dry wt.) |
|----------------------------|---|
| 0.02 | 200 |
| 1.59 | 181 |
| 10.3 | 168 |
| 13.2 | 154 |

From Ma *et al.* (2001).

2.8.2.2 Climatic stress

Silicon application in plants is very effective in alleviating damage caused by climatic stress such as typhoons, low temperature and insufficient sunshine during the summer season (Ma *et al.*, 2001). A typhoon attack usually causes lodging resulting in the reduction of yield. Deposition of Si in the plant enhances the strength of the stem and decreases susceptibility to lodging by increasing the thickness of the cell (culm) wall and the size of the vascular bundle (Ma *et al.*, 2001).

Strong winds also cause excess water loss from the spikelets of rice plants, resulting in sterility (Ma *et al.*, 2001). Silicon deposited in the hull is effective in preventing excess water loss (Savant *et al.*, 1999).

2.8.2.3 Freeze alleviation

Freeze damage during the winter in the sub-tropical areas can be one of the major constraints to sugarcane production (Savant *et al.*, 1999). Anderson (1991) reported an increased tolerance to freeze damage of commercial sugarcane following treatment with calcium silicate. Other results of strip tests with silicate suggest that applications of silicates have ameliorated mild freeze effects on sugarcane (Savant *et al.*, 1999).

2.8.3 Improvement of resistance to chemical stress

Chemical stresses include deficiency and excess of nutrients, low and high soil pH, metal toxicity, pesticide and herbicide damage (Ma *et al.*, 2001). Silicon has been reported to improve plant resistance to these chemical stresses.

2.8.3.1 Nitrogen (N) stress

Application of N fertilizers is an important practice for increasing crop yields. Leaf erectness is known to be one of the important factors that affect light conditions in a plant population (Yoshida *et al.*, 1969). The degree of leaf erectness is a varietal characteristic and it is also affected by nutritional conditions. For instance, a N deficient plant has more erect leaves than the normal plant (Yoshida *et al.*, 1969).

In a study on the effect of N and Si on rice, Yoshida *et al.* (1969) observed that increased N supply resulted in higher leaf openness values, and increased Si decreased leaf openness markedly. Indeed, it was shown that Si application can reverse the effect of applied N on leaf openness. Excessive application of N makes the leaf blade droopy, resulting in mutual shading and thereby reduction in photosynthesis. It also increases the susceptibility to diseases and lodging (Yoshida *et al.*, 1969).

2.8.3.2 Phosphorus

Silicate applications to soils not only supply Si, but may also produce beneficial effects on the growth of plants especially in acid soils deficient in P (Ma and Takahashi, 1991). Silicon has been reported to improve the availability of P in soil by acting as a liming material, thus raising pH and increasing desorption of previously fixed P (Ma *et al.*, 2001). Silicon could also affect P availability by displacing fixed P and/or reducing P fixation by masking adsorption sites on active Al and Fe oxides.

Silicic acid has also been shown to compete against phosphate for adsorption sites on the surfaces of hydrated sesquioxides (Ma and Takahashi, 1991). It could also lower activity of Al ion in solution and prevent it from precipitating with phosphate (Ma *et al.*, 2001).

The source of Si affects the P availability in the soil. For example, a study conducted by applying both silicic acid and sodium silicate as Si-sources to a P-deficient soil showed that addition of silicic acid to the soil did not change the pH (Ma *et al.*, 2001). In terms of P availability of the soil, application of silicic acid at various concentrations did not affect the P sorption by the soil. In addition, the P displacement by Si was not increased by increasing Si concentrations in the soil with or without P supplied. These results suggest that Si as silicic acid does not affect P availability in the soil and P uptake by the roots, and that the beneficial effects of Si on the growth resulted from improved availability of P within the plant (Ma and Takahashi, 1991).

When sodium silicate was applied to a P-deficient soil, the pH of the soil was raised by one unit (Ma *et al.*, 2001). The growth of rice on the soil was increased by sodium silicate applications under flooded and upland conditions. Application of sodium silicate significantly decreased the Mn content, resulting in a higher P/Mn ratio in the plant. This was due to the reduction of Mn under wet conditions that resulted in decreased Mn uptake by the plant. Neither the P adsorption by the soil nor P displacement by Si was affected by sodium silicate and carbonate. Similar results were obtained by application of Si as silicic acid (Ma *et al.*, 2001). These results also suggest that application of Si as silicate did not affect soil P availability and P uptake by the roots, and that the beneficial effects of Si were attributable to the improved availability of internal P within the plant through decreased Mn uptake. It has been demonstrated that Si improves the availability of internal P by decreasing Mn and Fe uptake (Ma *et al.*, 2001).

Plants can suffer excess P stress where P fertilizers are heavily applied or in nutrient solution culture where P is supplied at high concentrations (Yoshida *et al.*, 1969). Studies have shown that high concentrations of P result in leaf chlorosis, probably due to decreased availability of essential metals such as Fe and Zn (Yoshida *et al.*, 1969; Ma *et al.*, 2001). However, in the presence of Si, chlorosis did not occur at a high P concentration. This beneficial effect of Si might be attributed to the lower P uptake caused by Si.

2.8.4 Metal toxicity

2.8.4.1 Excess sodium (Na)

Silicon reduces the transpiration rate and there is a possibility that Si suppresses the translocation of salt from the rhizosphere to the shoot and thereby alleviates salt stress. In a study using nutrient solution with or without Si (100 ppm SiO₂) in the presence of 100 mM NaCl, Match *et al.* (1986) found that the concentration of Na in the shoot was decreased to about half by Si addition, suggesting that Si suppresses the translocation of Na from the root to the shoot.

In addition, high exchangeable Na can result in degradation in soil physical conditions. Sodium causes dispersion of soil particles resulting in poor soil structure (Ma *et al.*, 2001). Applied silica forms gels that bridge between soil particles on dehydration resulting in an increase in soil strength (Ma and Takahashi, 1991). Thus applied Si can also improve soil physical conditions where soil sodicity is a problem.

2.8.4.2 Iron (Fe) toxicity

Silicon has been reported to alleviate Fe toxicity. Okuda and Takahashi (1962) investigated the mechanism of the reduction in Fe uptake following Si application. Results showed that the presence of Si significantly reduced Fe uptake from ferrous Fe and improved crop growth. Furthermore, in the absence of Si during the Fe

uptake period, less Fe was taken up in the Si-containing plants and that Fe uptake decreased with increasing Si content of the shoot. However, no difference in Fe uptake was observed between the plants with Si and those without Si when shoots were exposed to the ferrous Fe solution. These results suggest that Si enhances the oxidising capacity of the roots probably by promoting oxygen supply from the shoot to the root. This could result in the oxidation of ferrous Fe to ferric Fe at the root surface, thereby suppressing excess uptake of Fe and translocation of Fe from the root to the shoot (Ma *et al.*, 2001).

2.8.4.3 Manganese (Mn) toxicity

Silicon has been shown to alleviate Mn toxicity by promoting the Mn oxidising capacity of roots. In a study conducted to investigate the mechanism of Si-induced alleviation of Mn toxicity, Iwasaki and Matsumara (1999) found that exposure of certain plants to high Mn significantly inhibited the growth of plant roots and shoots in the absence of Si. However, in the presence of Si, high Mn did not inhibit plant growth but decreased the shoot dry weight.

In another study on the effect of Si on Mn toxicity, Jones and Handreck (1967) reported that Si alleviated the symptomatic brown spots which occurred on the older leaves as a result of Mn toxicity. The yields were also increased by threefold. The main effect of Si appears to be that it distributes the Mn more evenly through the leaves, thereby preventing it from collecting into localized areas which become necrotic (Jones and Handreck, 1967).

2.8.4.4 Aluminium (Al) toxicity

Aluminium toxicity is a major factor limiting crop production in acid soils (Ma *et al.*, 2001). Ionic Al inhibits root growth and nutrient uptake. Silicon applied to the soil alleviates Al toxicity (Ma and Takahashi, 1991). In a study on the effect of silicic acid on Al, Si addition as silicic acid significantly alleviated Al-induced inhibition of root

elongation (Ma *et al.*, 1997). The concentration of toxic Al^{3+} in the soil is decreased by the presence of silicic acid. These results suggest that interaction between Si and Al occurs in soil solution, probably by formation of Al-Si complexes.

2.8.5 Increase resistance to biotic stress

2. 8.5.1 Diseases

Disease damage is a major problem reducing crop yields (Savant *et al.*, 1999). Silica has frequently been implicated as a factor influencing the degree of susceptibility of cereals to fungal attack (Jones and Handreck, 1967). Silicon deposited in the tissue surface acts as a physical barrier and prevents physical penetration and/or makes the plant cell less susceptible to enzymatic degradation by fungal pathogens. Blast and grain discoloration are major factors responsible for significant losses of grain yield and quality in rice production (Datnoff *et al.*, 2001). In a study on the effect of Si fertilizers on the severity of fungal diseases, Datnoff *et al.* (2001) found that when there was a significant increase in the Si content of the leaf blade, there was also a great reduction in the severity of both leaf and ear blast. Increased amounts of N fertilizer increased the severity of leaf blast, but application of calcium silicate increased the ratio of Si to N in leaves and resulted in suppression of ear blast.

Figure 2.1 shows the effect of different Si sources (silica gel and solid silicate) on the incidence of panicle blast in rice. For all sources of Si, panicle blast was reduced as the rate of Si application was increased. Generally, at lower rates of application, solid silicate was more effective in reducing panicle blast compared to silica gel. Silicon has also been reported to prevent powdery mildew and stem rot diseases in sugarcane (Savant *et al.*, 1999). A Si content of 1.5 % or above is very effective in suppressing powdery mildew in the leaf (Datnoff *et al.*, 2001).

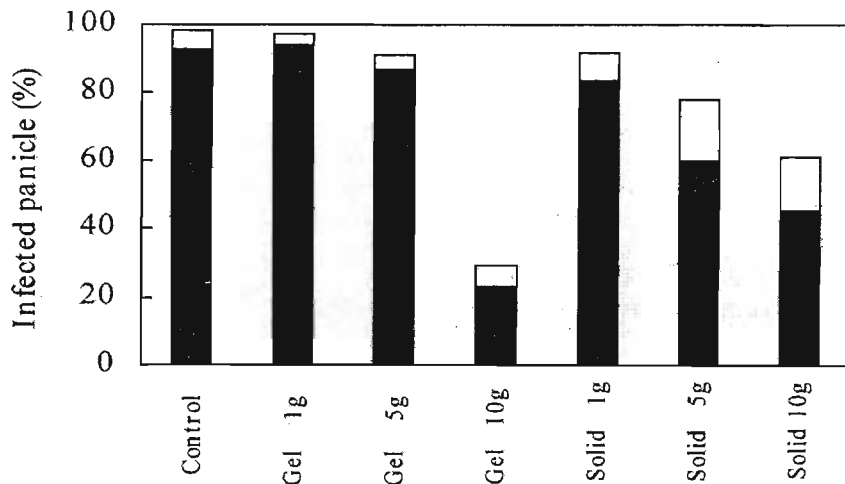


Fig. 2.1: Effect of silica rates on panicle blast incidence (1, 5, and 10g/pot). Each pot contains 4kg sandy soil. Black bars: heavily infected panicles; blank bars: slightly infected panicles. Gel: silica gel; solid: solid silicate. From Ishiguro (2001).

In sugarcane, small rust-coloured or brownish spots on the leaves of cane growing on highly weathered soils characterize a leaf disorder called freckling and leaves are less efficient in performing photosynthesis. In severe cases, affected lower leaves may die prematurely and can affect cane yield. This is thought to be a physiological disorder rather than a disease. Elawad *et al.* (1982a) observed a significant decrease in percent freckling in the plant crop as well as the ratoon crop with application of 20 t ha⁻¹ of TVA slag to the soil. The mechanism of leaf freckling in sugarcane and its alleviation following Si application is not known but has been attributed to the reduction of toxic levels of Fe, Al, Mn and Zn in the soil solution (Savant *et al.*, 1999).

2.8.5.2 Pests

Evidence suggests that Si deposition in the plant may reinforce plant insect resistance by providing a mechanical barrier against insect pests (Laing and Adandonon, 2005). Silicon may well also act as an activator by stimulating the expression of natural defensive reactions such as production of chemicals (such as phenols).

Eldana Saccharina Walker is one of the most serious threats to sugarcane production in South Africa and recent studies have focussed on the association between Si assimilation and host-plant resistance (Meyer and Keeping, 2000; Keeping and Meyer, 2002). Keeping and Meyer (2003) conducted both large pot and field trials to determine the effect of different Si sources (fly ash, boiler ash from the mills, slagment and calcium silicate slag at rates of 0, 2.5 and 5t/ha) on resistance of six sugarcane varieties (N11, N12, N16, N17, N21 and Nco 376) to *Eldana*. Evidence from a large scale pot trial 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. An assessment of the six varieties tested showed a positive response in Si uptake with Si treatment. Generally, the more susceptible varieties (N11 and N16) showed the highest Si uptake and greatest reduced stalk damage from Si treatment. In addition, results from field trials showed reductions of 31 % in borer numbers and 23 % in length of stalk damaged. They concluded that the Si status of the stalk is also closely related to borer damage, and application of Si sources can improve the resistance of sugarcane to the eldana borer and reduce the risk of damage in susceptible varieties by as much as 40%.

Furthermore, Sasamoto, (1958; cited by Raid *et al.*, 1992) investigated the relationship between Si content of plants and behaviour of stem borer in rice (*Chillo suppressalis*). He found that the stems attacked by the stem borer contained less Si. The large jaws of the stem borer gnawing rice with a high Si content would wear out more easily than that gnawing rice with a low Si content. He further investigated the behaviour of the borer in a petri dish containing stem pieces with various Si contents, which was prepared by application of silica gel. He found that most larvae moved to the stem with low Si content. The Si content of the rice stem was negatively correlated with the number of larvae bored into the stem. The reason is because newly hatched larvae, when starting their attacks on rice plants, start by feeding on epidermal tissue of the sheath, leaves and developing internodes in the immature top of the plants. The presence of Si crystals in the plant hinders the feeding of the insect by damaging their mandibles.

2.9. CONCLUSIONS

Although Si is not considered to be an essential nutrient, it can promote the growth of many plants, especially rice and sugarcane. The effects of applied Si are more obvious under stress conditions. Plants are exposed to various biotic and abiotic stresses in the field during the growth period and therefore silicon in plants plays a role in maintaining healthy growth. Furthermore in plants such as sugarcane and rice, Si fertilization may even directly increase growth and yield in addition to reducing transpiration rate, nutrient imbalance, metal toxicities and damage due to pests and disease infections.

CHAPTER 3

COMPARISON OF SOIL AND FOLIAR-APPLIED SILICON ON SOIL NUTRIENT AVAILABILITY AND ON GROWTH AND SILICON UPTAKE BY SORGHUM CROP

3.1 Introduction

In South Africa, the use of Silicon (Si) as a foliar spray has received little attention even though products are marketed for this purpose. However, it is well known that foliar application of nutrients can, in some cases increase yields and correct nutrient deficiencies (Marschner, 1995). Silicon is the second most abundant element in the earth's crust after oxygen, and is an integral part of plants (Jones and Handreck, 1967; Epstein, 1999, Savant *et al.*, 1999). Most soils contain considerable quantities of this element, but repeated cropping can reduce the levels of plant-available Si to the point that supplemental Si fertilization is required for maximum production (Datnoff *et al.*, 2001). Low-Si soils are typically highly weathered, leached, acidic and low in base saturation (Savant *et al.*, 1999). Highly-organic soils that contain little mineral matter may also contain little Si, and soils comprised mainly of quartz sand (SiO₂) may also be very low in plant-available Si (Datnoff *et al.*, 2001).

The role of Si in plants has been sporadically investigated and has focused on various aspects of plant pathology, physiology and biochemistry (Hodson and Sangster, 1989; cited by Snyder, 2001). Some studies indicate that sugarcane yield responses to Si may be associated with induced resistance to biotic and abiotic stress, such as disease and pest resistance, alleviation of Al, Mn and Fe toxicity, increased P availability, reduced lodging, improved leaf and stalk erectness, freeze resistance and improvement in plant water economy (Savant *et al.*, 1999). Deposition of Si in the leaf blade keeps the leaf erect and stimulates canopy photosynthesis by improving light interception (Savant *et al.*, 1999). Water stress under field conditions is common and affects cane yields. However, improved Si

nutrition tends to reduce excessive leaf transpiration (Wong You Cheong *et al.*, 1972).

Silicon sorption by soils is pH-dependent with low pH resulting in less sorption with greater sorption occurring at a high pH (McKeague and Cline, 1963). The mechanisms responsible for the different concentrations of silica in solution in soils and for the undersaturation of soil solutions are complex. There are reports which indicate that the adsorption of silica by soils is related to their content of Fe and Al oxides. In addition, there is a marked effect of pH on the solubility of silica in soils. Sesquioxides, especially Al oxides, are largely responsible for much of the capacity of soils to adsorb soluble Si and maximum adsorption capacity is between pH 8 and 10. Jones and Handreck (1965) and Mc Keague and Cline (1963), for example found that monosilicic acid was adsorbed by Fe and Al oxides. Adsorption depended on pH in a manner resembling the adsorption of monosilicic acid by soils, i.e. adsorption decreased at about pH 9 and Al oxides were more effective in adsorbing monosilicic acid than Fe oxides. They concluded that the concentration of monosilicic acid in soil solution is controlled by adsorption reactions that are pH dependent.

Silicon in solution at pH below 9 exists as uncharged monosilicic acid, $\text{Si}(\text{OH})_4$ (Jones and Handreck, 1965). This is the form of silicon taken up by higher plants (Epstein, 1999). Plants take up different amounts and proportions of Si from culture solutions depending on their species and the concentration of dissolved silicic acid present. The proportion of Si, for example, in gramineous species is 10 to 20 times that found in leguminous species (Jones and Handreck, 1965). The amount of Si present in the plants (as percentage of dry weight) increases in direct proportion to the amount of silicic acid dissolved in the soil solution or culture medium. For example, Grosse-Branckmann (1953; cited by Jones and Handreck, 1965) compared gramineous and leguminous species in a humic sand of pH 5.2 and found that barley and ryegrass contained 1.45 and 1.58 % Si respectively, whereas red clover and blue lupin contained only 0.12 and 0.24 % Si respectively. Therefore, Si can be accumulated from soil by plants in amounts that are several fold higher than

those of other essential macro- and micronutrients. For example, Si accumulation may be twice that of N and P in rice (Datnoff *et al.*, 2001).

In the plant, Si becomes immobilized and accumulates in the epidermal cells and cell walls (Epstein, 1999). The uptake of undissociated monosilicic acid may be non-selective and energetically passive, and it is transported from root to shoot in the transpiration stream in the xylem. The assumption has sometimes been made that the movement of Si follows that of water (Jones and Handreck, 1965). For example, in a pot experiment, Mayland *et al.* (1991) found that Si uptake by oat plants (*Avena Sativa* L.) increased as the transpiration stream increased. They concluded that if the transpiration rate is known, Si uptake can be calculated.

Silicon can be applied to crops either directly to the leaves (foliar spray) or in granular form, which is incorporated into the soil before planting. One reported source of plant-available Si is calcium silicate (calmasil), a by-product of the cement industry. Although it contains a number of elements, it is the Si component that is most beneficial to plant growth (Datnoff *et al.*, 2001). Sugarcane growers often apply calcium silicate at the rates of 4t/ha, although higher rates, up to approximately 8t/ha, have been shown beneficial for increasing sugarcane yield (Datnoff *et al.*, 2001). On soils low in plant-available Si, fertilization of sugarcane with calcium silicate has been shown to increase plant Si content and yield (Jones and Handreck, 1965). Calcium silicate applications may neutralize soil acidity through the formation of silicic acid, and could thus reduce the solubility of such elements as Mn, Fe and Al (Savant *et al.*, 1999). Several studies also found that silicate fertilizers increased sugarcane yields in pot trials (du Preez, 1970; Datnoff *et al.*, 2001).

Plants are known to absorb nutrients through their leaves. However, very little is known about Si absorption through leaves. Leaf cells, like root cells, take up mineral elements from the apoplasm. Leaf uptake is affected by external factors such as mineral nutrient concentration and ion valency as well as by temperature, and internal factors, such as metabolic activity (Chamel, 1988). For a given external

concentration of mineral nutrients, the rates of uptake by intact leaves are, however, much lower than the corresponding rates of uptake by the roots, since the very small pores in the cuticle severely restrict diffusion from the external leaf surface into the bulk of the leaf apoplasm and hence the plasma membrane of the leaf cells (Marschner, 1995). The foliar application of mineral nutrients by means of sprays offers a method of supplying nutrients to higher plants more rapidly than methods involving root application (Marschner, 1995). The supply is more temporary and low penetration rates, rapid drying of spray solutions, washing off by rain and limited rates of retranslocation from the sites of uptake to other plant parts are some of the problems associated with foliar sprays (Marschner, 1995).

This study was undertaken to compare the effects and effectiveness of Si application as granular calcium silicate with those of foliar applications. Four soils were used that were suspected to have different Si status and the test plant used was sorghum because it is a rapid-growing crop and it is known to respond to Si applications. Three forms of Si were used as foliar sprays, that is, K-humate and K-fulvate both containing 15% Si, and pure K-silicate containing 26 % Si.

3. 2 Materials and methods

3. 2.1 Greenhouse trial

A greenhouse trial was conducted to determine the effect of Si on growth and yield of sorghum. Soils with different nutrient status were collected from different sites in KwaZulu-Natal. Four soils used in the pot trial were:

Nomanci soil form:

Thick brown powdery humic (topsoil) clay loam to clay overlying lithocutanic B horizon (Soil Classification Working Group, 1991). The soil is derived from Natal Group Sandstone and Vryheid sediments belonging to the Mistbelt. Base status is very low with moderate to high Al toxicity. Organic matter content, N and S

mineralization capacity are very high. The soil is classified as a Humic (strongly) Cambisol (USDA) or a Humic Acrisol (FAO) (South African Sugar Association Experiment Station, 1999). The soil is highly weathered and the dominant mineral is gibbsite ($\text{Al}(\text{OH})_3$) (Beater, 1970). Drainage is good and erosion hazard is moderate. A site where the soil was collected has been used for a lime trial for 10 years, and there were excellent responses to lime.

Glenrosa soil form:

Shallow dark grey loamy sand and clay orthic topsoil overlying both lithocutanic B horizon and saprolite (Soil Classification Working Group, 1991). The soil is formed from Granite parent material in the coastal lowlands of KwaZulu-Natal. The soil is dominated by 1:1 lattice type minerals (kaolinite mainly) and illite ($\text{K}_{0.6}\text{Mg}_{0.25}\text{Al}_{2.3}\text{Si}_{3.5}\text{O}_{10}(\text{OH})_2$). The base status, organic matter content, N and S mineralization capacity and K reserves are low and erosion hazard is high. The soil is classified as an Aridisol/ Inceptisol (USDA) or an Ochric Lithosol/ Cambisol (FAO). Drainage is good and erosion hazard is moderate (South African Sugar Association Experiment Station, 1999). The bulk soil samples were collected from Kearsney experimental farm and the site has been under commercial cane production for 12 years.

Cartref soil form:

Grey sand to sandy loam orthic topsoil clay loam overlying lithocutanic B horizon, and bleached grey E-horizon (eluvial) in the middle of both horizons (Soil Classification Working Group, 1991). The soil is formed from weathering of Natal Group Sandstone and Vryheid sediments belonging to Mistbelt in KwaZulu-Natal. Almost 20% of the cane grown in the sugar industry is harvested from this series. Clay mineralogy is kaolinitic ($\text{Al}_2\text{Si}_2\text{O}_5(\text{OH})_4$). Salinity or sodicity hazard is low. According to USDA the soil is classified as an Inceptisol and by FAO classification it is a Gleyic Luvisol. Drainage is moderate and erosion hazard is high (South African Sugar Association Experiment Station, 1999). The soil was collected from Eshowe. The site has been cropped with cane for at least 30 years.

Fernwood soil form:

Grey to dark grey sandy topsoil overlying deep light grey to white loose sandy subsoil (with mottling and yellow staining). The soil is derived from weathering of grey recent sands (Soil Classification Working Group, 1991). Clay mineralogy is dominated by kaolinite (about 25% derived from feldspar decomposition with some 10% micaceous material, probably illite) (Beater, 1970). Drainage is excessive and erosion hazard is very high. Base status, organic matter content, Al toxicity and P fixation are very low. The soil is classified as an Entisol (USDA) or a Dystric/ Eutric Rhegosol (FAO) (South African Sugar Association Experiment Station, 1999). The site is located at the South African Sugarcane Research Institute (Mount Edgecombe) and it was left fallow for five years prior to planting sugarcane.

Bulk soils were air-dried and passed through a 5mm sieve. Each soil was weighed (about 1kg), transferred into a pot and kept in a greenhouse for the duration of the study. Sampling for laboratory analysis was made by collecting samples at random from each pot before planting. Sorghum (*Sorghum bicolor* Moench L.) was planted at a rate of 98 seeds (about 2g) per pot. Nutrients were added to the pots once a week. The basal composition of nutrient solution was: 50 ppm Mg and 65 ppm S as $\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$, 2 ppm N and 12 ppm S as $(\text{NH}_4)\text{SO}_4$, 70 ppm P and 64 ppm N as $(\text{NH}_4)_2\text{HPO}_4$, 148 ppm K and 60 ppm S as K_2SO_4 , 90 ppm Ca as $\text{CaCl}_2 \cdot 2\text{H}_2\text{O}$ and 45 ppm K as KCl.

The trial was arranged in a randomised block design with 10 treatments and 4 replications, making a total of 160 pots. The treatments were control, two levels of granular Si (4 and 8t/ha as calcium silicate) and two levels of liquid Si (foliar treatments), 300 and 600 ppm as K-humate, K-fulvate and pure K-silicate. Calcium silicate treatments were mixed with the soil before planting. Potassium-humate, and K-fulvate contained 15 % Si and pure K-silicate contained 26 % Si as SiO_2 . Foliar treatments were begun (used) 15 days after planting. "Breakthrough" was used as a wetting agent and pH of the solutions was adjusted between 6.2 and 7.0 using acetic acid.

In the greenhouse trials in which the experiment was conducted, plants were grown under ideal conditions: no moisture stress, no lack of nutrients and no attack by pests or pathogens. The plants were harvested 5 times (i.e leaves harvested and the stalks allowed to re-grow and produce new leaves). Harvested herbage was weighed and oven-dried at 70 °C for 48 hours. After oven-drying, the plant material was re-weighed and moisture content determined. The herbage was ground (<0.5 mm mesh sample) and analysed.

3. 2.2 Plant and soil analysis

For plant Si, 0.5g of finely ground leaves was placed in a furnace at a temperature of 650 °C overnight. To dissolve the ashed material, 15 % NaOH was added into a nickel crucible and heated. The contents in a nickel crucible were transferred into 100 ml of 0.6 N HCl and made to 250 ml with deionised water. Silicon in the extracts was determined spectrophotometrically using the blue silicomolybdenous method of Fox *et al.* (1969). Total N in plant samples was determined by Kjeldahl digestion (Bremner, 1965). For analysis of K, Ca, Mg and P in plant tissues, samples were dry-ashed, digested in H₂SO₄ and cations in extracts were analysed by atomic absorption spectrophotometry and P by the molybdenum blue method (Murphy and Riley, 1962).

Soil pH was determined by shaking air-dried soil with deionised water (1: 2.5 soil to extractant ratio). Exchangeable K, Ca and Mg were extracted from soils with 1M ammonium acetate (1: 10 m/v ratio) for 20 minutes (Beater, 1962) and cations in the extracts were measured by atomic absorption spectroscopy. Extractable Al was extracted with 0.2 M ammonium chloride (1: 10 m/v ratio) for 20 minutes and Al in the extracts was measured by atomic absorption spectroscopy. Extractable P was determined by Truog's method (0.02N H₂SO₄ solution using 1:50 m/v ratio for 20 minutes) (du Toit *et al.*, 1962). Soil organic matter (organic C x 1.72) was determined by the Walkley and Black method (Blakemore *et al.*, 1972) and total N was determined by Kjeldahl digestion (Bremner, 1965). Cation exchange capacity

was determined using method by Chapman (1965). Soil Si was extracted by shaking samples with 0.02N H₂SO₄ (1:10 m/v ratio for 20 minutes). The Si in soil extracts was determined spectrophotometrically using the blue silicomolybdous method of Fox *et al.* (1969).

3. 2.3 Statistical analysis

The experimental treatments were analysed statistically by an analysis of variance. Least significant difference (LSD) was calculated at the 5 % levels.

3.3. Results

Table 3.1: Chemical and physical properties of four soils

| Soil series | pH | Org M ——— % | Clay ——— | Total N ——— ppm | Extractable Si ——— | CEC cmol _c kg ⁻¹ |
|-----------------|-----|----------------|-------------|-----------------------|--------------------------|---|
| Cartref | 5.0 | 5.0 | 14.0 | 3500.0 | 8.1 | 5.0 |
| Glenrosa | 5.1 | 4.5 | 17.0 | 4000.0 | 8.8 | 8.0 |
| Nomanci | 5.1 | 9.2 | 20.0 | 5000.0 | 18.0 | 10.0 |
| Fernwood | 5.8 | 4.0 | 10.0 | 2000.0 | 6.3 | 2.0 |

Table 3.2: Effect of Si treatment on pH, phosphorus, extractable cations and extractable soil Si concentrations in Cartref soil form

| Treatment | pH _(water) | P | K | Ca | Mg | Al | Si | Si | Soil |
|-----------------------------------|-----------------------|--------|--------|--------|--------|-------|-----------------|------------------|-----------|
| | | | | | | | before planting | after harvesting | depletion |
| | | | | | | | (ppm) | | |
| Control | 5.24 | 102.91 | 95.00 | 129.85 | 40.58 | 15.25 | 8.08 | 2.58 | 5.50 |
| 300ppm K-humate | 5.12 | 94.27 | 99.83 | 133.10 | 41.08 | 15.25 | 8.35 | 2.23 | 6.13 |
| 600 ppm K-humate | 5.10 | 82.90 | 89.28 | 135.65 | 40.88 | 17.00 | 9.20 | 2.95 | 6.25 |
| 300 ppm K-fulvate | 5.06 | 87.99 | 88.48 | 135.60 | 41.13 | 15.75 | 8.43 | 2.73 | 5.70 |
| 600 ppm K-fulvate | 5.03 | 80.26 | 95.03 | 142.50 | 40.88 | 17.25 | 8.15 | 4.18 | 3.98 |
| 300 ppm pure-K silicate | 5.02 | 85.86 | 105.50 | 147.73 | 41.30 | 13.75 | 8.83 | 4.20 | 4.63 |
| 600 ppm pure-K silicate | 5.08 | 83.34 | 87.15 | 141.33 | 40.55 | 16.75 | 7.13 | 5.25 | 1.88 |
| Calmasil 4t/ha | 5.60 | 75.20 | 89.38 | 504.18 | 83.20 | 0.00 | 165.00 | 21.75 | 143.25 |
| Calmasil 8t/ha | 5.95 | 83.15 | 96.35 | 771.30 | 111.13 | 0.00 | 207.50 | 60.50 | 147.00 |
| Calmasil 4t/ha + 300 ppm K-humate | 5.66 | 88.15 | 96.25 | 468.20 | 77.53 | 0.00 | 112.75 | 27.00 | 85.75 |
| LSD (P≤0.05) | 0.11 | 12.7 | 16.6 | 65.4 | 7.11 | 2.88 | 38.27 | 6.2 | 10.7 |

Table 3.3: Effect of Si treatment on pH, phosphorus, extractable cations and extractable soil Si concentrations in Glenrosa soil form

| Treatment | pH _(water) | P | K | Ca | Mg | Al | Si | Si after | Soil |
|-----------------------------------|-----------------------|-------|--------|---------|--------|-------|--------------------|------------|-----------|
| | | | | | | | before Planting | harvesting | depletion |
| | | | | | | | (ppm) | | |
| Control | 5.10 | 11.01 | 102.88 | 153.30 | 86.13 | 34.50 | 9.09 | 8.33 | 0.76 |
| 300ppm K-humate | 5.03 | 10.86 | 108.58 | 106.40 | 77.68 | 41.00 | 9.93 | 8.03 | 1.90 |
| 600 ppm K-humate | 4.92 | 11.12 | 104.23 | 134.03 | 73.78 | 48.00 | 8.78 | 7.80 | 0.98 |
| 300 ppm K-fulvate | 5.10 | 14.78 | 102.10 | 134.80 | 75.68 | 56.50 | 7.98 | 7.25 | 0.73 |
| 600 ppm K-fulvate | 4.96 | 9.63 | 93.08 | 149.28 | 82.95 | 38.25 | 9.48 | 7.38 | 2.10 |
| 300 ppm pure-K silicate | 5.09 | 10.29 | 102.40 | 139.85 | 77.55 | 47.25 | 9.80 | 9.25 | 0.55 |
| 600 ppm pure-K silicate | 5.15 | 10.04 | 109.08 | 141.98 | 77.10 | 45.50 | 9.95 | 7.50 | 2.45 |
| Calmasil 4t/ha | 5.29 | 9.84 | 101.83 | 505.65 | 128.03 | 8.25 | 170.00 | 19.50 | 150.50 |
| Calmasil 8t/ha | 5.68 | 9.96 | 101.43 | 1045.20 | 177.78 | 0.00 | 372.50 | 52.25 | 320.25 |
| Calmasil 4t/ha + 300 ppm K-humate | 5.35 | 10.48 | 103.98 | 609.30 | 136.33 | 13.50 | 262.50 | 21.25 | 241.25 |
| LSD (P≤0.05) | 0.15 | 3.19 | 15.70 | 102.40 | 12.40 | 5.73 | 28.69 | 3.22 | 24.61 |

Table 3.4: Effect of Si treatment on pH, phosphorus, extractable cations and extractable soil Si concentrations in Nomanci soil form

| Treatment | pH _(water) | P | K | Ca | Mg | Al | Si | | |
|-----------------------------------|-----------------------|-------|--------|---------|--------|-------|-----------------|---------------------|----------------|
| | | | | | | | before planting | Si after harvesting | Soil depletion |
| | | | | | | | (ppm) | | |
| Control | 5.02 | 52.76 | 105.60 | 377.75 | 71.50 | 51.25 | 18.00 | 9.50 | 8.50 |
| 300ppm K-humate | 4.98 | 49.09 | 101.23 | 350.40 | 66.30 | 53.25 | 17.50 | 12.50 | 5.00 |
| 600 ppm K-humate | 5.01 | 49.57 | 100.08 | 359.03 | 66.75 | 53.00 | 16.50 | 9.75 | 6.75 |
| 300 ppm K-fulvate | 4.99 | 50.91 | 102.85 | 364.28 | 69.85 | 52.75 | 15.00 | 10.50 | 4.50 |
| 600 ppm K-fulvate | 4.99 | 48.16 | 94.70 | 339.23 | 65.05 | 55.75 | 19.50 | 12.00 | 7.50 |
| 300 ppm pure-K silicate | 4.98 | 46.67 | 85.05 | 314.05 | 60.20 | 63.50 | 15.50 | 10.50 | 5.00 |
| 600 ppm pure-K silicate | 5.01 | 48.68 | 90.40 | 349.45 | 66.30 | 44.75 | 20.00 | 8.50 | 11.50 |
| Calmasil 4t/ha | 5.16 | 45.08 | 84.93 | 714.38 | 116.58 | 18.75 | 156.75 | 16.75 | 140.00 |
| Calmasil 8t/ha | 5.36 | 49.59 | 83.43 | 1208.43 | 163.28 | 0.00 | 262.50 | 34 .50 | 228.00 |
| Calmasil 4t/ha + 300 ppm K-humate | 5.21 | 52.20 | 103.23 | 650.18 | 108.00 | 16.50 | 144.50 | 15.50 | 129.00 |
| LSD (P≤0.05) | 0.06 | 3.99 | 17.10 | 163.00 | 17.06 | 5.19 | 18.78 | 3.89 | 19.82 |

Table 3.5: Effect of Si treatment on pH, phosphorus, extractable cations and Extractable soil Si concentrations in Fernwood soil form

| Treatment | pH _(water) | P | K | Ca | Mg | Al | Si | | |
|-----------------------------------|-----------------------|-------|-------|--------|-------|------|-----------------|---------------------|----------------|
| | | | | | | | before planting | Si after harvesting | Soil depletion |
| (ppm) | | | | | | | | | |
| Control | 6.18 | 15.40 | 52.90 | 112.03 | 29.30 | 0.00 | 6.25 | 4.25 | 2.00 |
| 300ppm K-humate | 6.10 | 14.59 | 53.28 | 112.15 | 29.55 | 0.00 | 8.00 | 6.75 | 1.25 |
| 600 ppm K-humate | 6.01 | 13.07 | 53.73 | 113.53 | 29.70 | 0.00 | 5.50 | 4.50 | 1.00 |
| 300 ppm K-fulvate | 6.00 | 13.00 | 54.33 | 109.73 | 29.23 | 0.00 | 7.65 | 6.25 | 1.40 |
| 600 ppm K-fulvate | 5.98 | 13.52 | 58.80 | 107.38 | 29.53 | 0.00 | 7.75 | 4.00 | 3.75 |
| 300 ppm pure-K silicate | 6.01 | 13.01 | 44.00 | 113.55 | 29.35 | 0.00 | 7.50 | 4.00 | 3.50 |
| 600 ppm pure-K silicate | 6.00 | 13.15 | 50.53 | 113.30 | 30.45 | 0.00 | 8.45 | 4.50 | 3.95 |
| Calmasil 4t/ha | 6.88 | 14.09 | 52.08 | 423.00 | 68.03 | 0.00 | 143.00 | 21.00 | 122.00 |
| Calmasil 8t/ha | 7.58 | 13.84 | 51.20 | 680.75 | 91.45 | 0.00 | 342.50 | 40.25 | 302.25 |
| Calmasil 4t/ha + 300 ppm K-humate | 7.05 | 13.52 | 53.48 | 416.83 | 67.08 | 0.00 | 131.00 | 23.25 | 107.75 |
| LSD (P≤0.05) | 0.15 | 2.25 | 19.30 | 60.90 | 6.29 | 0.00 | 32.75 | 2.16 | 3.25 |

Table 3. 6: Effect of Si treatment on cumulative yield, plant Si uptake, Si and moisture content in the plant tissues, amount of N, P, K, Ca and Mg in Cartref soil form

| Treatment | Cumulative yield | Si content | Si uptake | Moisture content | N | P | K | Ca | Mg |
|-----------------------------------|------------------|------------|-----------|------------------|------|------|------|------|------|
| | (g/pot) | (%) | (mg/pot) | (%) | % | | | | |
| Control | 8.60 | 0.53 | 45.57 | 75.27 | 1.74 | 0.43 | 3.20 | 0.36 | 0.42 |
| 300ppm K-humate | 9.86 | 0.53 | 52.63 | 74.59 | 1.80 | 0.43 | 3.37 | 0.42 | 0.46 |
| 600 ppm K-humate | 11.27 | 0.56 | 63.44 | 71.61 | 1.67 | 0.37 | 2.92 | 0.33 | 0.38 |
| 300 ppm K-fulvate | 10.78 | 0.64 | 69.49 | 72.21 | 1.93 | 0.43 | 3.13 | 0.42 | 0.42 |
| 600 ppm K-fulvate | 7.65 | 0.61 | 46.61 | 67.36 | 2.19 | 0.49 | 3.18 | 0.42 | 0.48 |
| 300 ppm pure-K silicate | 7.11 | 0.53 | 37.66 | 71.12 | 1.78 | 0.42 | 3.17 | 0.34 | 0.42 |
| 600 ppm pure-K silicate | 5.94 | 0.65 | 38.43 | 64.65 | 1.86 | 0.45 | 3.25 | 0.35 | 0.45 |
| Calmasil 4t/ha | 14.43 | 1.31 | 189.04 | 76.04 | 1.86 | 0.44 | 2.88 | 0.38 | 0.46 |
| Calmasil 8t/ha | 15.57 | 1.48 | 230.42 | 76.47 | 1.95 | 0.44 | 3.01 | 0.48 | 0.50 |
| Calmasil 4t/ha + 300 ppm K-humate | 13.61 | 1.39 | 189.66 | 77.69 | 2.06 | 0.44 | 3.07 | 0.46 | 0.49 |
| LSD (P≤0.05) | 1.79 | 0.09 | 13.20 | 4.83 | 0.35 | 0.10 | 0.39 | 0.10 | 0.08 |

Table 3. 7: Effect of Si treatment on cumulative yield, plant Si uptake, Si and moisture content in the plant tissues, amount of N, P, K, Ca and Mg in Glenrosa soil form

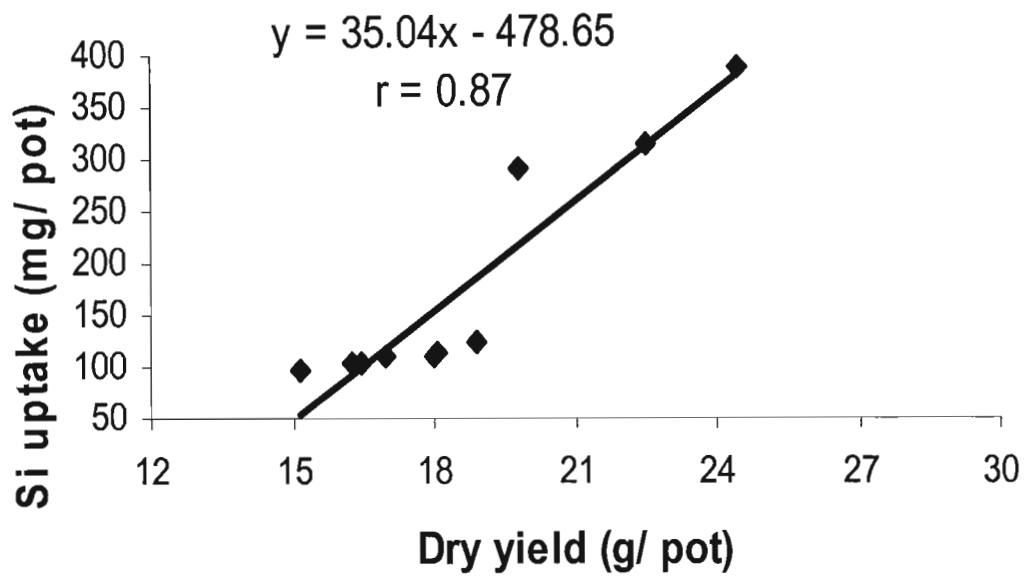
| Treatment | Cumulative yield | Si content | Si uptake | Moisture content | N | P | K | Ca | Mg |
|-----------------------------------|------------------|------------|-----------|------------------|------|------|------|------|------|
| | (g/pot) | (%) | (mg/pot) | (%) | | | % | | |
| Control | 9.95 | 0.47 | 46.95 | 71.01 | 1.82 | 0.21 | 3.01 | 0.54 | 0.55 |
| 300ppm K-humate | 6.71 | 0.55 | 36.65 | 67.34 | 1.95 | 0.24 | 2.82 | 0.47 | 0.55 |
| 600 ppm K-humate | 11.45 | 0.55 | 62.59 | 72.50 | 1.91 | 0.20 | 3.16 | 0.44 | 0.56 |
| 300 ppm K-fulvate | 8.22 | 0.51 | 41.98 | 69.14 | 1.96 | 0.19 | 3.02 | 0.43 | 0.54 |
| 600 ppm K-fulvate | 10.21 | 0.53 | 54.53 | 74.86 | 1.74 | 0.17 | 2.98 | 0.36 | 0.55 |
| 300 ppm pure-K silicate | 7.52 | 0.53 | 40.17 | 71.27 | 1.96 | 0.19 | 3.21 | 0.35 | 0.55 |
| 600 ppm pure-K silicate | 9.73 | 0.56 | 54.61 | 66.79 | 2.30 | 0.23 | 3.24 | 0.32 | 0.54 |
| Calmasil 4t/ha | 18.60 | 1.43 | 265.48 | 69.12 | 2.06 | 0.21 | 3.06 | 0.41 | 0.48 |
| Calmasil 8t/ha | 22.14 | 1.68 | 372.47 | 72.65 | 2.30 | 0.20 | 2.78 | 0.43 | 0.51 |
| Calmasil 4t/ha + 300 ppm K-humate | 14.20 | 1.47 | 208.46 | 75.20 | 2.31 | 0.23 | 3.31 | 0.43 | 0.45 |
| LSD (P≤0.05) | 2.34 | 0.10 | 17.31 | 4.20 | 0.21 | 0.06 | 0.26 | 0.11 | 0.04 |

Table 3. 8: Effect of Si treatment on cumulative yield, plant Si uptake, Si and moisture content in the plant tissues, amount of N, P, K, Ca and Mg in Nomanci soil form

| Treatment | Cumulative yield | Si content | Si uptake | Moisture content | N | P | K | Ca | Mg |
|-----------------------------------|------------------|------------|-----------|------------------|------|------|------|------|------|
| | (g/pot) | (%) | (mg/pot) | (%) | | | % | | |
| Control | 21.80 | 0.68 | 148.15 | 71.92 | 2.54 | 0.25 | 3.09 | 0.37 | 0.46 |
| 300ppm K-humate | 18.07 | 0.72 | 129.99 | 73.09 | 2.76 | 0.24 | 3.08 | 0.47 | 0.48 |
| 600 ppm K-humate | 21.53 | 0.68 | 147.04 | 71.14 | 2.70 | 0.22 | 3.14 | 0.54 | 0.51 |
| 300 ppm K-fulvate | 18.30 | 0.64 | 117.42 | 68.38 | 2.76 | 0.23 | 3.22 | 0.55 | 0.50 |
| 600 ppm K-fulvate | 21.61 | 0.59 | 127.16 | 67.27 | 2.68 | 0.27 | 3.05 | 0.57 | 0.50 |
| 300 ppm pure-K silicate | 19.31 | 0.62 | 118.94 | 69.50 | 2.77 | 0.24 | 2.98 | 0.53 | 0.51 |
| 600 ppm pure-K silicate | 20.27 | 0.68 | 136.85 | 71.14 | 2.53 | 0.22 | 3.10 | 0.53 | 0.48 |
| Calmasil 4t/ha | 23.87 | 1.41 | 337.27 | 68.30 | 1.76 | 0.16 | 2.37 | 0.45 | 0.53 |
| Calmasil 8t/ha | 26.81 | 1.63 | 436.59 | 69.15 | 1.88 | 0.17 | 2.17 | 0.42 | 0.50 |
| Calmasil 4t/ha + 300 ppm K-humate | 23.70 | 1.46 | 346.09 | 68.20 | 1.88 | 0.19 | 2.29 | 0.36 | 0.49 |
| LSD (P≤0.05) | 3.07 | 0.09 | 29.3 | 2.61 | 0.39 | 0.03 | 0.20 | 0.11 | 0.04 |

Table 3. 9: Effect of Si treatment on cumulative yield, plant Si uptake, Si and moisture content in the plant tissues, amount of N, P, K, Ca and Mg Fernwood soil form

| Treatment | Cumulative yield | Si content | Si uptake | Moisture content | N | P | K | Ca | Mg |
|-----------------------------------|------------------|------------|-----------|------------------|------|------|------|------|------|
| | (g/pot) | (%) | (mg/pot) | (%) | | | | | |
| Control | 31.62 | 0.62 | 194.48 | 64.95 | 1.66 | 0.36 | 2.86 | 0.51 | 0.49 |
| 300ppm K-humate | 31.17 | 0.64 | 200.14 | 64.18 | 1.64 | 0.39 | 2.80 | 0.52 | 0.49 |
| 600 ppm K-humate | 31.25 | 0.69 | 216.27 | 62.66 | 1.61 | 0.36 | 2.69 | 0.58 | 0.50 |
| 300 ppm K-fulvate | 27.65 | 0.67 | 185.65 | 61.61 | 1.69 | 0.37 | 2.72 | 0.59 | 0.52 |
| 600 ppm K-fulvate | 32.73 | 0.70 | 228.62 | 65.77 | 1.79 | 0.38 | 2.87 | 0.55 | 0.50 |
| 300 ppm pure-K silicate | 26.72 | 0.69 | 183.43 | 59.96 | 1.89 | 0.35 | 2.80 | 0.55 | 0.50 |
| 600 ppm pure-K silicate | 31.81 | 0.67 | 214.42 | 61.65 | 1.93 | 0.37 | 2.82 | 0.51 | 0.52 |
| Calmasil 4t/ha | 33.20 | 1.38 | 458.71 | 71.77 | 1.59 | 0.28 | 2.22 | 0.37 | 0.47 |
| Calmasil 8t/ha | 33.30 | 1.54 | 512.21 | 72.96 | 1.70 | 0.28 | 2.26 | 0.39 | 0.49 |
| Calmasil 4t/ha + 300 ppm K-humate | 27.82 | 1.50 | 416.64 | 73.19 | 1.89 | 0.32 | 2.28 | 0.42 | 0.51 |
| LSD (P≤0.05) | 4.36 | 0.10 | 28.79 | 3.25 | 0.22 | 0.05 | 0.21 | 0.17 | 0.03 |



**Figure 3.1: Relationship between dry matter yield and average Si uptake
meaned across the four soils. Average Si uptake and dry matter
yield were calculated from mean of five harvests. Regression
equation and line of the best fit are shown.**

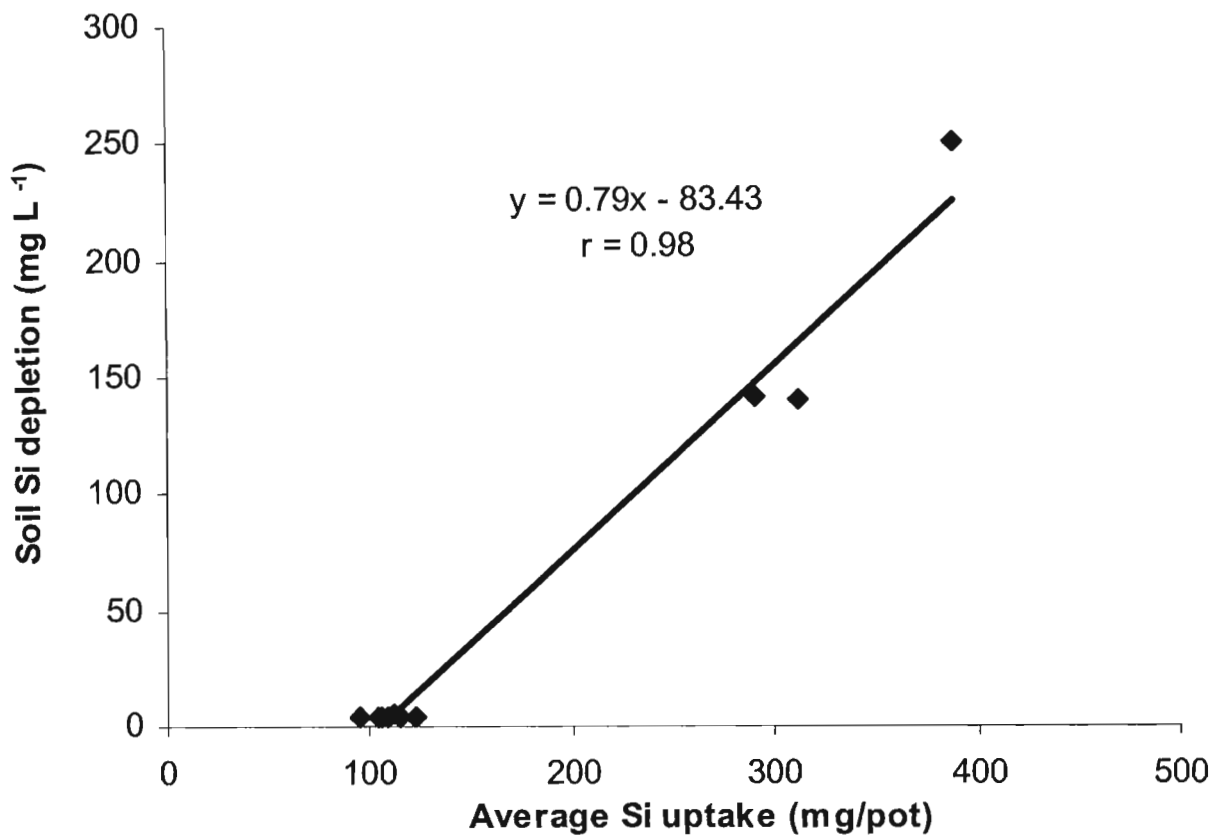


FIGURE 3.2: Relationship between Si uptake and soil Si depletion meaned across the four soils. Soil Si depletion was calculated as the difference between initial extractable soil Si (before planting) and final Si concentration (after fifth harvest). Regression equation and line of the best fit are shown.

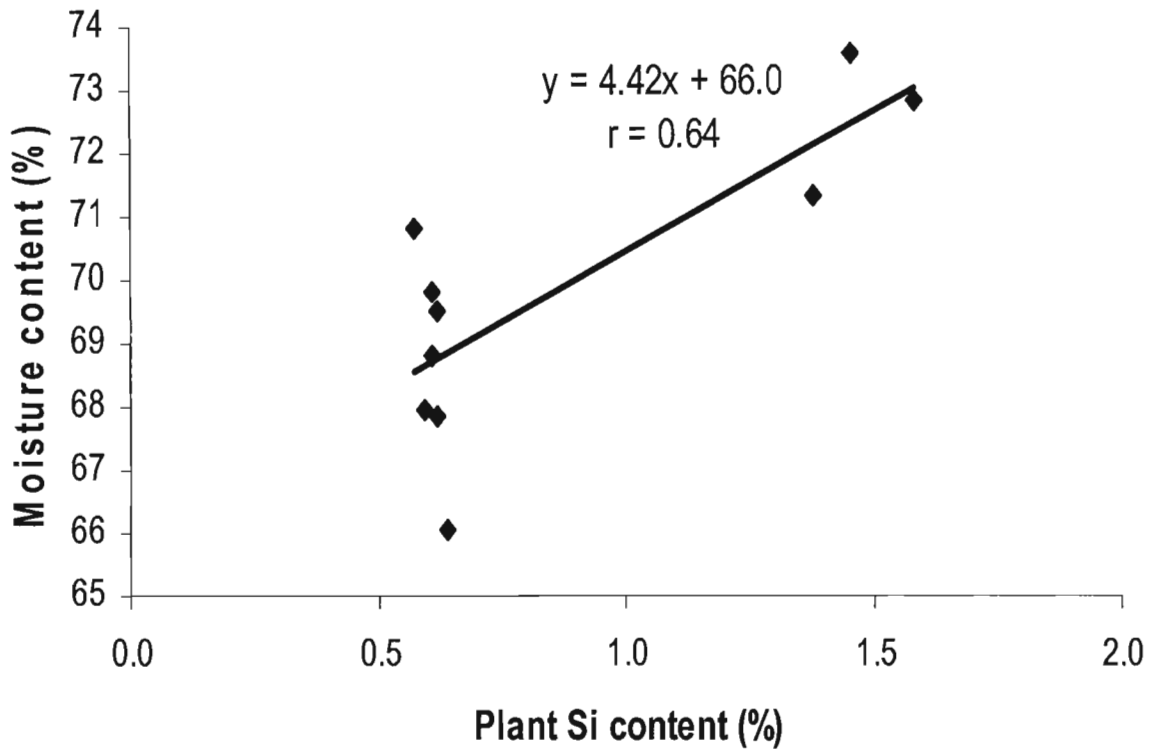


FIGURE 3.3: Relationship between average Si content in the plant tissues and tissue moisture content at harvest. Data meaned for the four soils. Regression equation and line of the best fit are shown.

3.3.1 Soil chemical properties

Extractable Si concentration, $\text{pH}_{(\text{water})}$, CEC, percentage organic matter, nitrogen and clay for the four soils are presented in Table 3. 1. The amount of N, CEC and clay percentage were highest in Nomanci soil form and lowest in Fernwood. The amount of organic matter in Fernwood, Cartref and Glenrosa soils was significantly lower than that in the Nomanci soil form (Table 3.1). Concentrations of exchangeable cations, soil Si depletion and extractable P are presented in Tables 3.2 to 3.5. Extractable levels of P (in Glenrosa, Nomanci and Fernwood soils) and K were unaffected by calmasil applications but levels of extractable Ca and Mg were increased and those of extractable Al were lowered (Tables 3.2 to 3.5).

The pH values ranged from 5 to 5.8 in control soils. Extractable Al was high in the control of the Nomanci (51 ppm) and Glenrosa (34 ppm) soils. It was much lower in the Cartref soil (15 ppm) and below the level of detection in the Fernwood soil. With increasing levels of calmasil fertilizer applications to the soil, pH values increased resulting in decreased Al concentrations. The greatest increase was in 8t/ha calmasil (Tables 3.2 to 3. 5). Initial soil pH was less than 5.3 in the Cartref, Glenrosa and Nomanci soils and 6.2 in the Fernwood soil. Soil pH was unaffected by foliar sprays of Si (as were some of the other measured soil properties) but pH was increased by calmasil treatments. Highest pH values were measured at the higher rate of calmasil (8t/ ha).

Extractable soil Si was unaffected by foliar applications of Si but were increased by soil applications of Si. As expected, extractable Si levels were greater at the higher level of application of calmasil (8t/ ha). Depletion of soil Si was calculated by subtracting final extractable Si concentration after harvest from initial extractable Si before planting. It is evident that in each soil, Si depletion was greater from the calmasil treatments and it was greatest from the higher rate of application (Tables 3.2 to 3.5).

3.3.2 Effect of Si on yield and nutrient concentrations

Cumulative yields and nutrient uptake by sorghum are presented in Tables 3. 6 to 3.9. In Glenrosa, Nomanci and Fernwood soils; dry matter yield, plant Si content and Si uptake were unaffected by foliar applications of Si. For Cartref, Glenrosa and Nomanci soils, applications of calmasil increased yields. For Cartref and Glenrosa soils, the 4t/ha rate resulted in a large significant yield increase and yields were further increased by the 8t/ha rate. For Nomanci soil, the 4t/ha rate did not result in a significant yield increase but the 8t/ha rate did (Table 3.8). Yields were unaffected by calmasil applications in Fernwood soil.

For all four soils, calmasil applications increased tissue Si concentrations and Si uptake and values tended to be greater at the 8 t/ha than 4 t/ha rate. There were generally no significant effects of experimental treatments on tissue N, P, K, Ca and Mg concentrations (Tables 3. 6 to 3. 9). The exceptions were that calmasil applications resulted in a significant decrease in tissue N, P and K concentrations in the Nomanci soil and tissue P, K and Ca concentrations in Fernwood soil. Moisture content of plant tissue at harvest was not affected by treatment except in the Fernwood soil where it was significantly greater in calmasil treatments.

The relationship between various measured parameters was investigated by regression analysis using meaned treatment data across all four soils. Results showed that dry matter yield was linearly correlated with Si uptake and Si uptake was linearly related to soil Si depletion (Figures 3.1 and 3.2). Tissue moisture content was linearly ($r = 0.64$) related to Si content in the plant tissues (Figure 3.3).

3.4 Discussion

3.4.1 Effect of silicon on soil chemical properties

The close relationship between total N content and organic matter content (i.e. highest for Nomanci soil; Table 3.1) occurs because about 95 % of N is in organic form (Heden *et al.*, 1995). Soil organic matter contributes to the cation exchange capacity of soils, so CEC was also highest in the Nomanci soil (Currie *et al.*, 1996). Calmasil altered soil solution composition by increasing pH and exchangeable Ca and Mg concentrations since it contains both Ca and Mg. The increase in pH was expected since calcium silicate is used as a liming material (Datnoff *et al.*, 1991). When calcium silicate dissolves in acid soils, silicic acid is formed; it is weakly dissociated so soil pH is raised.

Silicon has been reported to improve the availability of P in soil and plants by acting as a liming material (Ma and Takahashi, 1991). Soil applied Si could also affect the P availability by displacing fixed P and/or reducing P fixation by blocking active adsorption on Al and Fe oxides. In addition, an increase in pH has been reported to decrease P adsorption and increase its availability (Fox *et al.*, 1967). However, in this study, extractable P was unaffected by calmasil applications in Glenrosa, Nomanci and Fernwood soils respectively. Addition of calmasil to the soil apparently did not result in desorption of P. The reason may be that soils have a much higher affinity for phosphate than silicate; therefore addition of Si did not increase P extractability. The results are consistent with those found by other workers. For example, Ma and Takahashi (1991) found that for a given soil, P had a high affinity for adsorption sites and added Si could not decrease P adsorption nor could it displace adsorbed P, but added P could displace adsorbed Si.

Application of calmasil to the soil decreased the concentration of Al in soil solution. This is primarily attributable to the liming effect of calmasil. The increased pH resulted in precipitation of soluble and exchangeable Al as hydroxyl-Al compounds (Savant *et al.*, 1999). In addition, the concentration of toxic Al³⁺ in the soil is

decreased by the presence of silicic acid (Savant *et al.*, 1999). For example, in a study on the effect of silicic acid on Al, Ma *et al.* (1997) found that addition of Si as silicic acid significantly alleviated Al-induced inhibition of root elongation. The results suggested that interaction between Si and Al occurs in soil solution, probably by formation of Al-Si complexes.

3.4.2 Effect of Si on plant growth

Plants of one species contain different concentrations of silica when grown in different soils (Jones and Handreck, 1967). Deposition of Si in the plant is influenced by soil factors such as Si concentration in solution, nutrient and water content, pH and soil type. In this trial, plants grown in soils low in extractable Si generally had lower yields, low Si content and Si uptake. After application of calmasil, the yield increased substantially in the Cartref, Glenrosa and Nomanci soils. The observed increase in yield with Si application to plants would have the potential to enhance the root's absorptive capacity and nutrient uptake in natural and agricultural ecosystems (Korndorfer *et al.*, 1999).

The results presented indicate that the method of fertilizer application used has very large effects on Si uptake. Where Si in soil solution is higher (soluble Si), the plant content of this element is generally greater (Korndorfer *et al.*, 1999). In this study, dry matter yield was linearly related to plant Si uptake, and Si uptake was correlated with Si depletion from the soil (Figures 3.1 and 3.2). In addition, sorghum plants generally removed larger quantities of Si from soils which had received Si treatments than from untreated soils. Increased yield in soil-applied treatments is a typical characteristic found by other workers working with Si-deficient soils. For example, both Jones and Handreck (1967) and Ma and Takahashi (1991) emphasized that silicate fertilizers increased sugarcane yields in pot trials.

The beneficial effect of silicate may result from both a pH effect and a Si effect. That is, at soil pH values less than 5.5 (i.e. for the Cartref, Glenrosa and Nomanci soils), Al toxicity can limit crop growth and an increase in pH results in precipitation of

phytotoxic soluble and exchangeable Al as hydroxy-Al polymers (Ma and Takahashi, 1991). The lack of yield response to calmasil in the Fernwood soil, even though extractable Si levels were initially low in the control treatment, suggests that the liming effect of calmasil was important. That is, in the Fernwood soil, pH values were already above 6.0 and soluble Al concentrations were low. The liming effect of calmasil was therefore of little significance and as a result there was no yield increase. By contrast, in the other three soils where there was a significant effect of calmasil on soil pH which was initially between 5.0 and 5.2 and the calmasil treatment reduced soluble Al appreciably. In the Nomanci soil, the 4t/ha rate did not result in a significant yield increase since soluble Al concentrations remained high (i.e. 18 ppm). However, the 8t/ha rate, reduced soluble Al to insignificant levels and there was also a measurable yield increase. The work clearly demonstrated that application of Si in the form of calcium silicate was considerably more effective at increasing yield of sorghum than foliar applied Si.

The uptake of Si through foliar applications was clearly very low since foliar sprays had no effect on tissue Si content and plant yield. The ineffectiveness of foliar spray was further demonstrated by yields, Si content and Si uptake being generally similar between the calmasil 4t/ ha treatment and the calmasil 4t/ha plus 300 ppm K-humate treatment. By contrast, Okamoto (1993) and Hooda and Srivastava (1996) found that spraying of soluble Si as 0.1 to 0.2 mg L⁻¹ solution of Na₂SiO₃ or 1% solution of Na₂SiO₃ on leaves of rice plants increased plant growth and the effect was attributed to a reduced rate of transpiration. Several factors may be contributed to ineffective absorption of foliar-applied Si. One factor might be less efficient transport of Si from the leaves to different parts of the plant compared with the transport of nutrients from the roots. Ion uptake rates from foliar sprays are usually higher at night, when the stomata are closed, than during the day when the stomata are open (Marschner, 1995). Sorghum plants were sprayed in the morning and this might have inhibited the rate of Si uptake. Another reason may be that plants had low leaf surface area which resulted in less fertilizer being applied to the leaf surface. Temperature and wind might have also affected the Si uptake. Marschner (1995) reported that during the daytime, as the ambient temperature increases, there is usually a decrease in

relative humidity, leading to more rapid water evaporation from foliar sprays and thus more rapid drying of the sprays at the leaf surface.

A major factor contributing to the ineffectiveness of foliar Si was, however, probably that the rate of application was low. Clearly, much greater rates of addition can be achieved by soil applications. This is an important consideration since Si was accumulated into sorghum in similar quantities to those of most macronutrients (Tables 3.6 to 3.9). Thus, in order to supply appropriate quantities of fertilizer Si, basal soil applications are required.

The total Si in the plants was proportional to the concentrations of extractable Si in four soils. Since the amounts of Si in solution in these four soils differed over a wide range, it is possible to compare more critically the uptake of Si as found by analysis with the uptake expected from measurements of the concentration of Si in the soil solution. Throughout the period of growth, there was close agreement between the expected uptake of Si and the amounts found in analysis. These results suggest that these soils are capable of maintaining a steady concentration of Si in solution despite repeated withdrawals.

Nevertheless, results clearly demonstrated that application of Si to the soil in the form of calcium silicate was more effective at increasing tissue Si concentrations than regular foliar applications of Si. A higher Si content in the plant can have many beneficial effects as reviewed by Ma and Takahashi (1991). High Si content probably resulted in increased photosynthetic rate because of more erect leaves and improved light interception. This would have resulted in an increased yield and Si uptake. Certainly, in this study, there was a significant correlation between plant Si uptake and dry matter yield.

The fact that calmasil applications resulted in significant decrease in tissue N, P and K in the Nomanci soil and P, K and Ca in the Fernwood soil indicates that nutrient

interactions were occurring. The decrease in N content may be attributable to a dilution effect as a result of increased biomass production, and/ or to soil reactions that resulted in reduced N uptake (Elawad *et al.*, 1982a). A decrease in P is typical of the results found by other workers. In one study on the uptake of P by rice, the uptake of silicic acid was slightly depressed in the presence of phosphate. However, Lewin and Reimann (1969) found that most of the Si absorbed by rice roots was translocated rapidly into the shoots, while most of the P remained in the roots. They concluded that Si seems to retard excessive uptake of P by rice plants.

When applying calcium silicate to the soil, it is important to separate a Si-effect from a Ca effect. In a study on the effect of different Ca sources on sugarcane yield, Ayres (1966) found that both calcium silicate and calcium carbonate treatments increased yield of sugarcane. The calcium supply probably was not the factor causing higher yields in the study, since calcium carbonate had been added to control plots to maintain pH and supply adequate Ca. Similarly, in this study Ca was added weekly in the basal nutrient solution. In addition, tissue Ca concentrations were generally unaffected by experimental treatments. Magnesium and K were also applied weekly to sorghum plants and this resulted in similar concentrations in plant tissues from different treatments.

3.4.3 Moisture content and Si supply

Although there was no discernable relationship between calmasil and plant moisture content, except in the Fernwood soil, when average treatment data across four soils were analysed, a positive correlation was found between tissue Si content and plant moisture content (Figure 3.3). Silicon has been reported to reduce transpiration rate and increase moisture content of the plant (Savant *et al.*, 1999). Certainly, results from this greenhouse trial tend to confirm such a relationship. The effect of transpiration on Si uptake by rice has been investigated by various workers. Datnoff *et al.* (2001) found that only a 5 % increase in the total amount of silica in the tops caused the rate of transpiration to be decreased by as much as 70 %. Baba (1956; cited by Jones and Handreck, 1965) found that transpiration had a substantial effect

on the distribution of silica in the rice plant. A 4.5 % reduction in the amount of water transpired per unit area increased the silica concentration by 9.6 %. Baba (1956) concluded that Si concentration in the stems actually increased when the transpiration rate was reduced. These observations suggest that although the overall uptake of Si by rice is largely independent of transpiration, the subsequent translocation of Si towards the leaves is affected by the transpiration rate.

If silica is absorbed passively in the transpiration stream, one would expect a change in the transpiration rate to be reflected in the amount of silica in the plant. Furthermore, Jones and Handreck (1965) reasoned that knowing the concentration of silicic acid in the soil solution and the moisture content of the plant, it should then be possible to calculate the amount of silica in the plant. Thus, it seems that the uptake of silicic acid was passive and Si content in the plant tissues depends on the transpiration rate of the plant. The rate of transpiration is presumably influenced by the amount of silica gel associated with the cellulose in the cell walls of epidermal cells. Hence, a well-thickened layer of silica gel should help retard water loss, while epidermal cell wall with less silica gel will allow water to escape at an accelerated rate (Savant *et al.*, 1999).

3.5 Conclusions

Foliar applications are not an effective method of applying Si to Si-responsive crops that are growing in soils low in extractable soil Si. This is because Si is accumulated in the plant tissues in amounts similar to that of macronutrients (e.g. K, P, Ca and Mg). As a result, soil applied Si is the most effective method of supplying Si to the plants. When using foliar sprays, only small quantities of Si can be applied.

Results found in this study also suggest that the yield response of sorghum to soil-applied calcium silicate were primarily attributable to its liming effect. That is, its application increased soil pH and reduced soluble soil Al to low levels thus promoting crop growth.

Future research on crop response to soil-applied Si should compare the effects of calcium silicate with that of a non-liming Si source (i.e silicic acid). This would separate between a liming effect and a specific Si effect.

CHAPTER 4

EFFECTS OF SOIL-APPLIED SILICON ON EXTRACTABLE PHOSPHORUS USING RESIN, TRUOG AND AMBIC METHODS

4.1 Introduction

Phosphorus (P) is an essential element for plant growth and is often applied to agricultural land to increase crop production. However, P is very reactive, immobile, inaccessible and the least available of all nutrient elements in the soil (Holford, 1989). These characteristics reduce the solubility of added P and make it resistant to leaching in most soils, but at the same time they make deficiency of P a common phenomenon in agricultural production. Inorganic soil P is present in soils in several different forms. In order of increasing stability, these are: (i) P in the soil solution (<1% of the total); (ii) inorganic P in plant residues; (iii) inorganic P adsorbed on surfaces of colloidal mineral particles (clay) and (iv) inorganic P occluded or absorbed in P reactive minerals (Holford, 1989).

The availability of the applied P is controlled by the retention (sorption) and release (desorption) characteristics of the soil (Owusu-Bennoah and Acquage, 1989). Tropical soils, particularly the highly weathered types, often have a high sorption power (Sayers *et al.* 1971; cited by Owusu-Bennoah and Acquage, 1989). The major factors that influence P sorption include: type and amount of clay, amount of hydrated oxides of Fe and Al, soil pH and organic matter (Owusu-Bennoah and Acquage, 1989). Soils with high clay content tend to absorb more P than those soils with low clay content. 1:1 clay minerals have a large number of exposed OH⁻ groups and adsorb more P than 2:1 clay minerals (Phillips and Webb, 1971). Highly weathered soils containing substantial quantities of amorphous Al and Fe hydrous oxides adsorb large amounts of P (Engelstad and Terman, 1980). Generally, P is available to plants in very small amounts in acid soils, because of adsorption by Fe or Al oxides or by its precipitation with soluble Al and Fe. By contrast, in alkaline soils P readily reacts with Ca to form insoluble precipitates (Iyamuremye and Dick, 1995).

Phosphorus availability is generally greatest in the soil pH range of 6 to 7 (Engelstad and Terman, 1980).

To increase the efficiency of P fertilizer usage, it would be useful to identify and implement fertility management strategies that might reduce the magnitude of P sorption. Phosphorus uptake by plants can be increased by adding lime or silicate fertilizers to the soil. The use of lime and silicates are considered by several authors to decrease P sorption (Obihara and Russell, 1972; Ma *et al.*, 2001) while other studies imply this effect is not important or even detrimental (Amarasiri and Olsen, 1973; Reeve and Sumner, 1970). Lime, which is usually added to acid soils to eliminate Al and Mn toxicity, has a number of effects on soil properties and P behaviour which may influence the availability of native and/or added fertilizer P (Holford, 1989). Liming acid soils often, but not always, increases P uptake by plants. The obvious primary effects of lime are to raise pH and Ca activity. Nonetheless, liming has been reported to increase, decrease or not affect the amount of phosphate that can be extracted from acid soils (Haynes and Ludecke, 1981; Haynes, 1984b; Naidu *et al.*, 1987).

Increasing soil pH is believed to increase the availability of P because it inhibits the adsorption-precipitation reactions between P and Fe or Al and also accelerates organic matter decomposition (Adams and Odom, 1985). Increasing soil pH above 7.0 can decrease the availability of P because of precipitation Ca phosphates (Kuo *et al.*, 1988). Changes in soil pH brought about by liming may have profound effects on the availability of many elements absorbed by crops. In addition, most liming materials contain significant quantities of both Ca and Mg and often also Si. The interpretation of lime responses, particularly in field experimentation, is complicated by numerous possible confounding effects (Sumner and Farina, 1986). This is particularly true of P-lime interaction studies as Ca, Mg, and silicate ions have all been shown to interact with P and many other elements are also affected by pH changes (Sumner and Farina, 1986).

Silicate applications to soils not only supply Si, but may also produce beneficial effects on the growth of plants especially in acid soils deficient in P (Ma and Takahashi, 1991). Calcium silicates react with soil much as lime does and resultant pH changes in highly acid soils can be expected to have similar beneficial effects on P nutrition. There is evidence suggesting that Si, independent of any pH effect, results in increased P availability in many soils (Silva, 1971; Obihara and Russell, 1972). Ma *et al.* (2001) found that Si improved the availability of P in soil by acting as a liming material, which is known to liberate phosphate from its union with Fe and Al, displacing fixed P and/or reducing P fixation by masking active Al and Fe. It could also lower activity of Al ion in solution and prevent it from precipitating with phosphate. Silicic acid has also been suggested to compete against phosphate for a place on the surface of hydrated sesquioxides (Ma and Takahashi, 1991) thus improving its availability in the soil.

Indices of the abilities of soils to supply P to plants can be determined by (a) extractive tests that measure the concentration of P in solution and the amount of P in a labile form or (b) the soils phosphate (buffering) sorption characteristics (Kamparth, 1991). The availability of the applied P is controlled by the retention (sorption) and release (desorption) characteristics of the soil. Limited availability of P is often the main constraint for plant growth in highly weathered soils of the tropics (Kamparth, 1991). A better understanding of soil P dynamics is required to improve management practices in tropical systems.

Various tests have been developed in different countries to suit the forms of P present in their agricultural soils so as to estimate fertilizer P requirements for specific crop yield goals. Conventional soil test methods (Bray I, Olsen P, Truog and Mehlich) use a wide range of chemical reagents that dissolve not only the fraction of labile P (i.e. the portion of soil P that is relatively loosely bound onto or associated with soil minerals or amorphous materials), but also a portion of soil P that can be mobilized and used slowly by plants (Idianti, 2000). These solutions were originally developed to extract P from soils containing specific P components; therefore their usefulness across a wide range of climatic variability can be somewhat limited.

The purpose of this study was to compare the application of silicic acid, calcium silicate (at the same rate of applied Si) and calcium hydroxide (at the same rate of applied Ca) on the extractability of P in two Si-deficient soils. The soils were supplied with three rates of P (0, 30 and 60 kg ha⁻¹). To determine the effectiveness of each soil amendment, exchangeable and soil solution Al were measured along with extractable and soil solution Si.

4.2 Materials and methods

Two soils (Nomanci and Fernwood, from chapter 3) with differing P-fixing capacity were selected for the study. There were five main experiments (i) control, (ii) phosphorus (P₁ and P₂), (iii) silicic acid (SP₀, SP₁ and SP₂), (iv) calcium silicate (CSP₀, CSP₁ and CSP₂) and (v) calcium hydroxide (CHP₀, CHP₁ and CHP₂). The P application rates were 0.13 (P₁) and 0.26 mg g⁻¹(P₂) as KH₂PO₄ which are equivalent to 30 and 60 kg P ha⁻¹ respectively. Calcium silicate, silicic acid and calcium hydroxide were applied at rates of 8.0, 5.38 and 5.08 mg g⁻¹ respectively. These rates apply the equivalent of 4t Si ha⁻¹ as calcium silicate and silicic acid. Calcium hydroxide was applied at the same rate of Ca as the calcium silicate treatment. Each treatment had three replicates, giving a total of 36 treatments per soil. Soil amendments were thoroughly mixed with soil samples (0.5 kg) and placed in 2 L plastic containers (closed with lids to conserve moisture). The soil samples were wetted to 70 % of water holding capacity and incubated at room temperature for six weeks. Samples were arranged in a randomised block design. Containers were opened once a week to mix soil and allow aeration. Water was added where necessary to maintain the soil at the predetermined soil water content.

After six weeks, a subsample of soil was air-dried and used for chemical analyses. Soil pH was measured in a 1: 2.5 soil: solution ratio (in both water and 1M KCl) using a glass electrode. Exchangeable Al was measured by extracting soil with 1M KCl (1: 10 m/v ratio). The solution (25 ml) was then titrated with 0.01 M NaOH and exchangeable Al calculated from the volume of 0.01 M NaOH used (Rowell, 1994). Soil Si was extracted by shaking samples with 0.02N H₂SO₄ (1:10 m/v ratio). The

Si in soil extracts was determined spectrophotometrically using the blue silicomolybdous method of Fox *et al.* (1969).

Truog P was extracted with 0.02N H₂SO₄ (1:50 m/v ratio) for 20 minutes (du Toit *et al.*, 1962). AMBIC P was extracted with AMBIC extractant (0.025 M ammonium bicarbonate, 0.01 M NH₄F and 0.01 M disodium-EDTA, superfloc at pH 8.5) (Van der Merwe *et al.*, 1984) using a 1: 10 m/v ratio and extraction time of 15 minutes. Resin-extractable P was extracted overnight with two resin strips (9 X 62 mm) placed in a 50 ml centrifuge tube (1: 60 m/v ratio). After shaking, the resin strips were washed with water and shaken again for 16 hours with 20 ml of 0.5 M HCl (Tiessen and Moir, 1993). Phosphorus in the resin-extracts was determined using molybdenum method by Murphy and Riley (1962).

Another field-moist subsample was adjusted to 100 % water holding capacity and equilibrated for 24 hours. Soil solution was then obtained by a rapid centrifugation method (Elkhatib *et al.*, 1987) and analysed for Si and Al. Monomeric Al (Al_{mono}) in solution was measured in the filtrate (0.05 μM Millipore filter extract) by the pyrocatechol violet (PCV) method (Kerven *et al.*, 1989), and total soluble Al (Al_T) was determined by a modified PCV method using LaCl₃ -Fe reagent after the solution had been passed through a 0.22 μM filter (Menzies *et al.*, 1992) It is accepted that the PCV method for measuring Al_{mono} measures Al_{mono} plus a small amount of Al present in soluble Al-organic matter complexes (Parfitt *et al.*, 1995). Silicon in the soil solution was determined as outlined in chapter 3.

4.3 Results

Table 4.1: Extractable silicon and, AMBIC, resin and Truog extractable-P in Fernwood soil form.

| Treatments | Extractable | Extractable P | | |
|--------------|-------------|------------------------------|-------|-------|
| | Si | AMBIC mg kg ⁻¹ | Resin | Truog |
| P0 | 66.00 | 8.00 | 1.80 | 11.67 |
| P1 | 56.70 | 26.67 | 6.00 | 28.33 |
| P2 | 50.30 | 46.40 | 14.00 | 55.00 |
| SP0 | 70.70 | 8.80 | 1.80 | 11.67 |
| SP1 | 66.70 | 25.60 | 6.00 | 31.67 |
| SP2 | 72.70 | 46.93 | 12.00 | 55.00 |
| CSP0 | 510.30 | 15.47 | 6.00 | 30.00 |
| CS P1 | 503.00 | 41.60 | 12.00 | 53.33 |
| CSP2 | 512.00 | 64.53 | 18.00 | 50.00 |
| CH P0 | 766.30 | 19.73 | 6.00 | 16.67 |
| CH P1 | 755.70 | 41.60 | 6.00 | 30.00 |
| CH P2 | 741.30 | 60.80 | 12.00 | 93.33 |
| LSD (P≤0.05) | 54.30 | 3.50 | 1.70 | 14.30 |

P0 = without phosphorus, P1 = phosphorus (low rate), P2 = phosphorus (high rate),
S = silicic acid, CS = calcium silicate, CH = calcium hydroxide.

Table 4.2: Extractable silicon and, AMBIC, resin and Truog extractable-P in Nomanci soil form.

| Treatments | Extractable | Extractable P | | |
|--------------|-------------|------------------------------|-------|-------|
| | Si | AMBIC mg kg ⁻¹ | Resin | Truog |
| P0 | 148.70 | 38.93 | 6.00 | 63.33 |
| P1 | 138.30 | 43.20 | 6.00 | 80.00 |
| P2 | 137.70 | 54.40 | 6.00 | 88.33 |
| SP0 | 186.00 | 42.93 | 6.00 | 65.00 |
| SP1 | 180.00 | 45.87 | 6.00 | 78.33 |
| SP2 | 167.00 | 56.00 | 10.00 | 88.33 |
| CSP0 | 404.30 | 40.27 | 8.00 | 73.33 |
| CS P1 | 400.70 | 45.87 | 6.00 | 80.00 |
| CSP2 | 430.00 | 53.87 | 8.00 | 88.33 |
| CH P0 | 151.30 | 24.27 | 6.00 | 75.00 |
| CH P1 | 139.30 | 26.67 | 6.00 | 96.67 |
| CH P2 | 116.00 | 33.07 | 8.00 | 98.33 |
| LSD (P≤0.05) | 18.70 | 2.96 | 3.27 | 9.58 |

P0 = without phosphorus, P1 = phosphorus (low rate), P2 = phosphorus (high rate),
S = silicic acid, CS = calcium silicate, CH = calcium hydroxide.

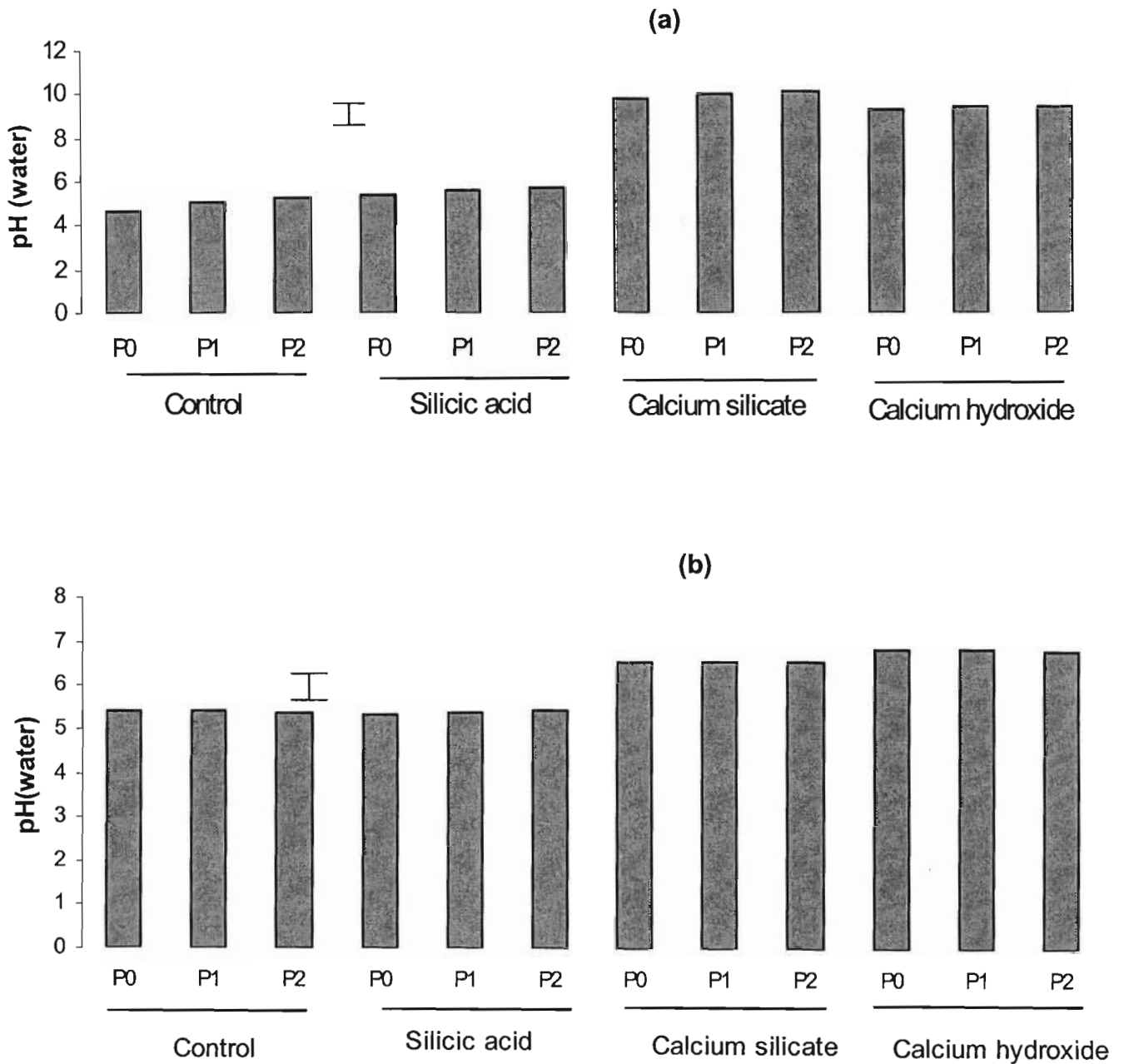


FIGURE 4.1: Effect of incubation of amendments on soil $pH_{(water)}$ in (a) Fernwood and (b) Nomanci soil. Rates of P were P0 = 0, P1 = 30 and P2 = 60 kg ha⁻¹. LSD ($P \leq 0.05$) shown.

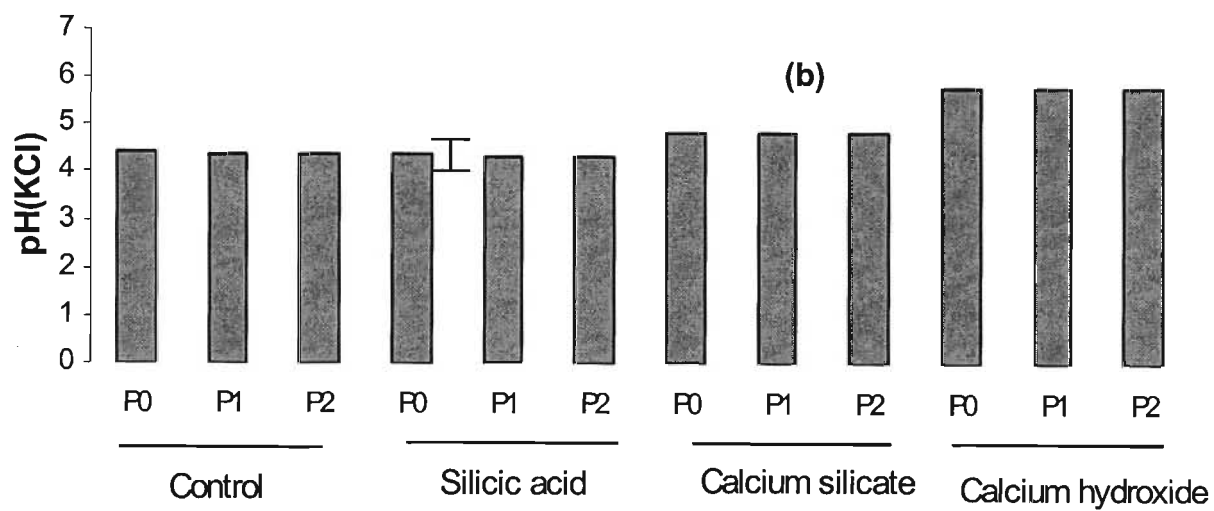
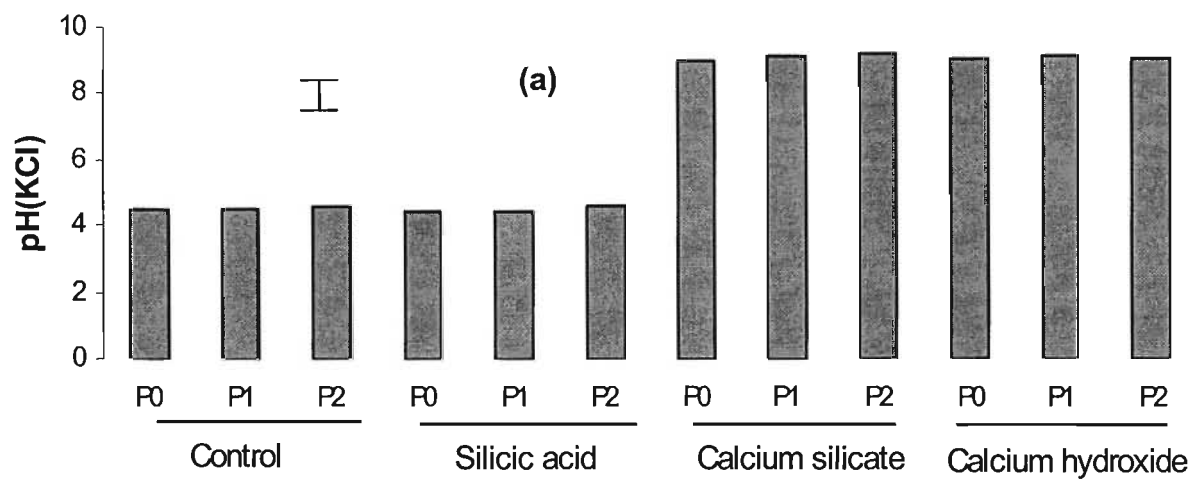


FIGURE 4.2: Effect of incubation of amendments on soil $pH_{(KCl)}$ in (a) Fernwood and (b) Nomanci soil. LSD ($P \leq 0.05$) shown.

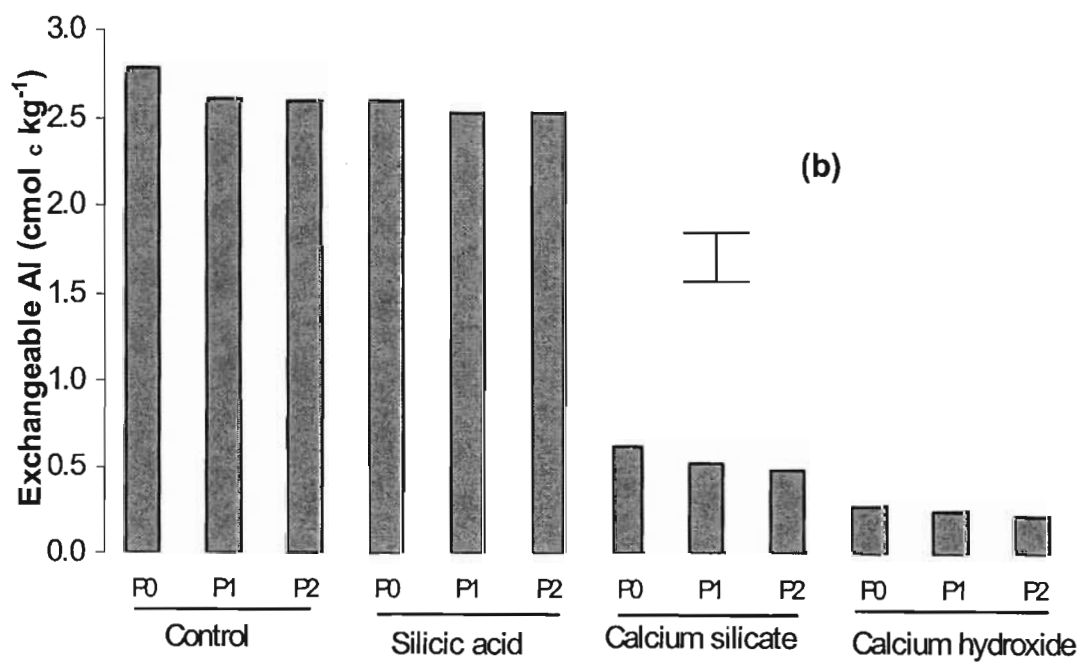
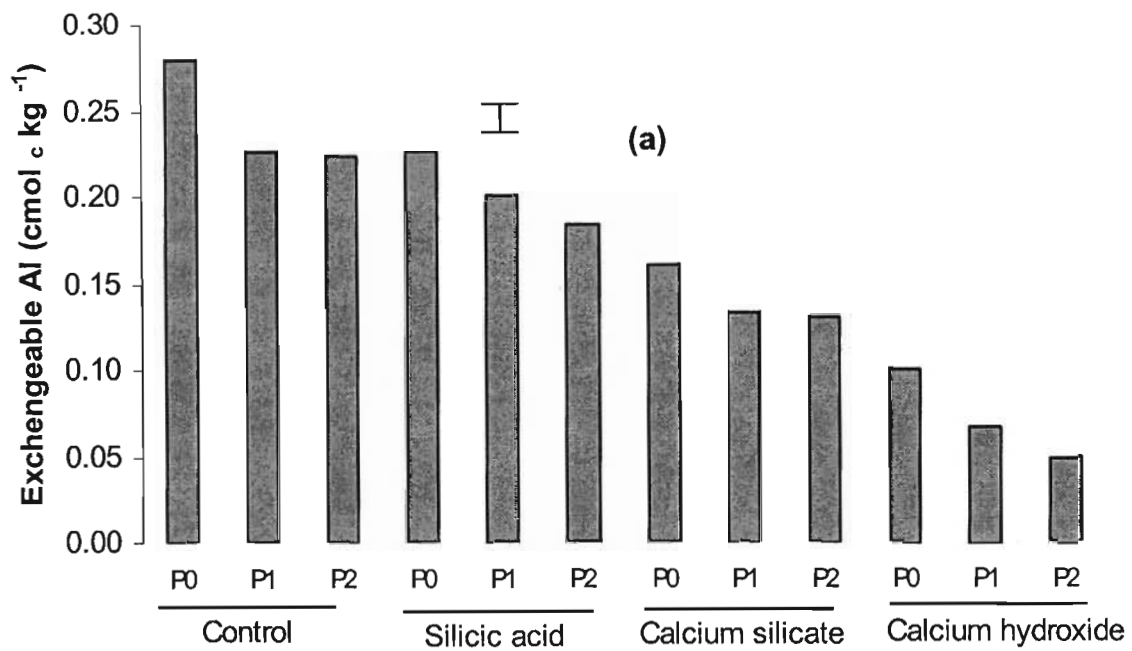


FIGURE 4.3: Effect of incubation of amendments on exchangeable acidity (a) Fernwood and (b) Nomanci soil. LSD ($P \leq 0.05$) shown.

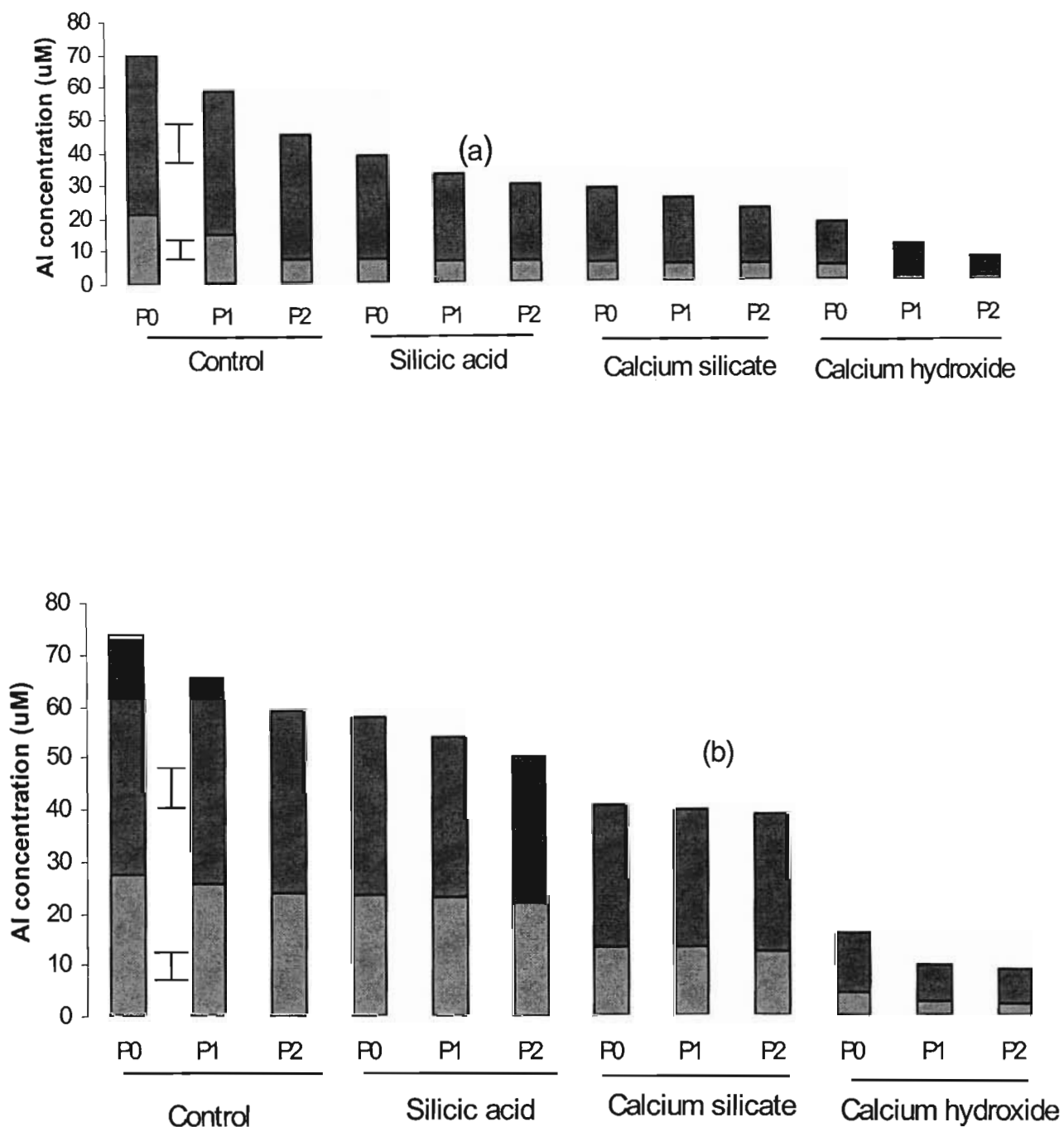


FIGURE 4.4: Effect of incubation of amendments on monomeric (Al_{mono}) and total (Al_T) soluble Al in solution, (a) Fernwood and (b) Nomanci soil. Total height of histograms represents concentrations of Al_T in solution, height of light-shaded portions represents Al_{mono} in solution. LSD (P ≤ 0.05) shown.

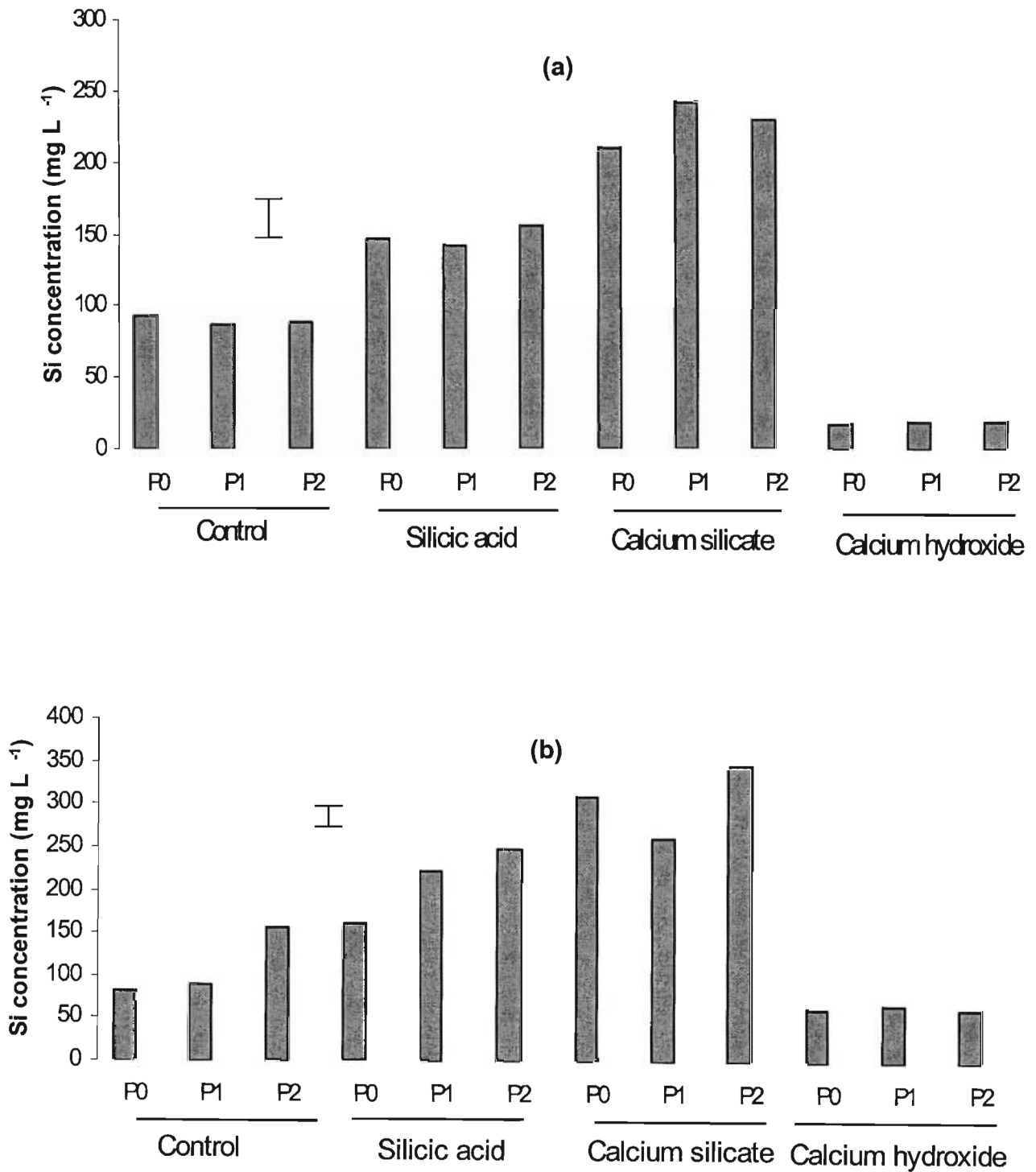


FIGURE 4.5: Effect of incubation of amendments on Si concentration in soil solution (a) Fernwood and (b) Nomanci soil. LSD ($P \leq 0.05$) shown.

4.3.1 Soil pH

Additions of P and silicic acid had no significant effect on pH, while additions of calcium silicate and calcium hydroxide caused increases in soil pH (Figures 4.1 and 4.2). There were no significant differences in pH between the calcium silicate and the calcium hydroxide treatments in either soil. The pH measured in water and KCl followed the order calcium hydroxide = calcium silicate > silicic acid = control. The pH values were greater when measured in water rather than KCl particularly for Fernwood soil.

4.3.2 Exchangeable and soluble Al

Concentrations of soluble (Al_{mono} and Al_T) and exchangeable Al were reduced by soil amendments in both soils, but the effect was more pronounced for the Nomanci than the Fernwood soil (Figures 4.3 and 4. 4). Analyses of soils amended with calcium hydroxide and calcium silicate showed highly significant reductions in exchangeable and soluble Al compared with control. Concentrations of exchangeable and soluble Al followed the order control > silicic acid > calcium silicate > calcium hydroxide in both soils. Increased soil pH greatly reduced Al concentrations (Figures 4.1, 4.2, 4.3 and 4.4). Addition of P had little effect on exchangeable Al concentrations in both soils. There was a tendency for Al_T to be reduced by increasing rates of P in the control and silicic acid treatments in both soils. For Si- carriers (treatments), the most effective amendment in reducing Al concentrations was calcium silicate.

4.3.3 Extractable Silicon

Si concentration in soil solution was significantly increased by Si-containing amendments (Figure 4.5). Addition of P had no significant effect on solution Si concentrations. Silicon concentration in solution followed the order calcium silicate > silicic acid > control > calcium hydroxide (Figure 4.5). Thus, an increase in pH induced by calcium hydroxide addition decreased soluble Si concentrations in solution in both soils, but the effect was more marked for the Fernwood than Nomanci soil.

As shown in Tables 4.1 and 4.2, extractable Si in air-dried soil followed the order calcium hydroxide > calcium silicate > silicic acid > control in Fernwood soil, and calcium silicate > silicic acid > calcium hydroxide > control in the Nomanci soil. In both soils, extractable Si was marked greater in the calcium silicate than silicic acid treatment. While extractable Si was the greatest in the calcium hydroxide treatment in the Fernwood soil, it was the least (along with the control) in that treatment for the Nomanci soil.

4.3.4 Extractable P using different extractants

Extractable P followed the order Truog > AMBIC > Resin in both soils (Tables 4.1 and 4.2). Although addition of P increased extractable P using all the extractants, the greatest increase in P with P fertilization was observed in Truog and least with resin extractant. In the Nomamci soil, P additions had no measurable effects on resin P. Addition of calcium hydroxide to the Nomanci soil decreased AMBIC extractable P, but Truog P was significantly increased and resin P was not significantly affected. In the Fernwood soil, addition of calcium hydroxide increased AMBIC P but had no consistent effect on resin or Truog P. Addition of silicic acid had no significant effect (compared to the control) on levels of extractable P in either soil.

4.4 Discussion

4. 4.1 Effect of amendments on pH, exchangeable and soil solution Al

Equivalent rates of calcium hydroxide and calcium silicate resulted in virtually identical pH values in water and KCl (Figures 4. 1 and 4.2) indicating that calcium silicate had reacted to a similar extend to calcium hydroxide. As expected, $pH_{(KCl)}$ values were lower than $pH_{(water)}$. Nevertheless, although pH values of the control treatments were higher in the Nomanci soil, the increase in soil pH following additions of calcium silicate and calcium hydroxide was more pronounced for the

Fernwood soil. The greater increase in pH in the Fernwood than Nomanci soil is associated with the low buffering capacity of the sandy Fernwood soil. By contrast, the Nomanci soil has high clay and organic matter content and therefore a high buffering capacity (Beater, 1970).

Although the initial pH of the Nomanci soil was higher than that of Fernwood, initial levels of exchangeable Al were considerably higher in the Nomanci soil. This can be attributed to the differences in clay mineralogy between the two soils. The Nomanci soil is a highly-weathered soil with a clay content of 20 % and mineralogy dominated by gibbsite and poorly ordered hydroxyl-Al compounds. It therefore has a large buffering reserve of Al that can supply the exchangeable fraction. By contrast, the Fernwood is a sandy soil with low clay content (10 %) dominated by kaolinite; therefore, there is small amount of buffering Al (Beater, 1970).

Although 4t/ha of calcium silicate is a typical rate of application for Si-deficient soils, results presented here show that for a sandy soil with little buffering capacity such as the Fernwood soil, a rise in pH can be very large. The pH of above 8.0 in the Fernwood soil could have negative effects on plant growth. For example, over-liming commonly results in micronutrient deficiencies (Fe, Mn, Zn, Cu, Co, and B). The use of a Si source that does not raise pH to any great extent would be more appropriate in such soil.

In the pot experiment (Chapter 3) very high soil pH values were not encountered. This might have happened because of several factors. The calmasil used in the pot experiment was a commercial product (not a laboratory calcium silicate as used in the incubation study) with large particle size. In that experiment, soil analysis was carried out after a one week period after calmasil had been applied to the soil and it had probably not fully-reacted. Therefore, pH would probably have risen further during the early stages of the pot experiment. However, a nutrient solution was applied each week during the growing period. Nitrification of NH_4^+ to NO_3^- generates

two H^+ per unit of NH_4^+ converted to NO_3^- (Graham *et al.*, 2000). This would have also reduced the liming effect of calmasil.

Acid soil infertility is a major limitation to crop production on highly-weathered acid soils in both tropical and temperate regions of the world (Rowell, 1988). One of the primary reasons for the positive response of plants to liming of such soils is the neutralization of soluble and exchangeable Al (Haynes, 1984a). The phytotoxic exchangeable and soluble Al are precipitated as hydroxyl-Al compounds (Haynes, 1984b). Thus, as pH was raised by addition of calcium silicate or calcium hydroxide, there was a reduction in exchangeable Al, particularly in the Nomanci soil where Al levels were initially high.

The silicic acid treatment had little effect on exchangeable Al concentrations particularly in the Nomanci soil where levels were initially high. The lack of such effect is attributable to the pH being similar in the control and silicic acid treatments. For the Fernwood soil, where concentrations of exchangeable Al were initially low, silicic acid additions tended to lower exchangeable Al. This is probably attributable to the formation and precipitation of insoluble aluminosilicates (Schulthness and Tokunda, 1996; Lumsdon and Farmer, 1995).

While exchangeable Al was slightly lower in the calcium hydroxide than calcium silicate treatments in the Nomanci soil, this difference was more pronounced for both total and monomeric Al in soil solution. It is possible that formation of soluble aluminosilicate compounds in the calcium silicate treatment maintained unexpectedly high concentrations of total Al in soil solution. Silicic acid is known to be able to react with soluble Al to form both soluble and insoluble aluminosilicate compounds in acid soils (Lumsdon and Farmer, 1995). The formation of such compounds would temporarily reduce monomeric Al concentrations but by equilibrium, this would result in greater dissolution of Al-containing minerals thus increasing monomeric Al concentrations. A tendency for a slightly lower pH in the calcium silicate than calcium

hydroxide treatment in the Nomanci soil would also have favoured higher Al concentration in solution in the calcium silicate treatment.

The tendency for additions of P to lower exchangeable Al in the Fernwood soil and monomeric and total Al in both the Fernwood and Nomanci soils is attributable to the formation and precipitation of insoluble Al phosphates (Iyamuremye and Dick, 1995). Such a decrease in exchangeable and soluble Al following fertilizer P addition has been noted by other workers (Haynes, 1984a; Iyamuremye and Dick, 1995; Naidu *et al.*, 1990).

4.4.2 Levels extractable and soil solution Si

At least three main types of mobile Si compounds exist in soil solution: monosilicic acid, polysilicic acids and water-soluble organo-silicon compounds (Matichenkov and Ammosova, 1989). The most dominant form of Si at normal pH values is monosilicic acid. Silicon is slowly released by weathering of primary Si minerals (e.g. quartz) and aluminosilicate feldspar minerals. However, part of this is lost through leaching and drainage (Meyer and Keeping, 2000). The rate of loss of soil Si (desilication) can be ranked with respect to Si content and Si solubility as follows: 2: 1 clays > 1: 1 clay (e.g. kaolinite) > Al and Fe oxides (e.g. gibbsite) (Fox *et al.*, 1967). Generally, soluble Si concentrations in highly-weathered acid soils (e.g. Nomanci) are several times less than those of less weathered neutral and alkaline soils (e.g. Vertisols) (Foy, 1992). Soils with high percentages of sand (e.g. Fernwood) also tend to show low soluble Si contents and little capacity to supply Si to plants. Sand particles are primarily quartz minerals containing a high Si content but they have a low Si-release potential in the short and medium terms. Sandy soils also have good drainage which favours leaching of soluble Si rather than its accumulation (Meyer and Keeping, 2000).

Beckwith and Reeve (1964) observed that the amount of monosilicic acid remaining in soil solution following Si additions to a soil depends on the concentration added, the nature of the soil and constituent minerals and the pH of the soil suspension. As

expected, additions of silicic acid and calcium silicate increased concentrations of Si in soil solution. In general, concentrations of Si in solution were greater in calcium silicate treatment in both soils. This was unexpected since the availability of Si is generally thought to decrease with increasing pH (Beckwith and Reeve, 1964) and pH in the calcium silicate treatments was much greater than that in the silicic acid ones. It was generally reported that alkaline soils sorb more added monosilicic acid than acid soils, and soil in alkaline suspensions release less native Si than under acid conditions (Beckwith and Reeve, 1964).

Beckwith and Reeve (1964) also observed that as pH is increased, sorption is favoured and concentrations of monosilicic acid in solution decrease. Nevertheless, several recent studies have reported that with increasing pH, soluble Si decreases in some soils but is increased or is unaffected in others (de Camargo *et al.*, 2005; Zhang *et al.*, 2005). The reason for this is unclear but is probably related to differences in mineralogy and solubility of Si-containing minerals in different soils. In this study, concentrations of Si in soil solution were lower in the calcium hydroxide than control treatment in both soils suggesting that the solubility of native soil Si was decreased with increased pH.

The lower concentrations of Si in soil solution in the silicic acid than calcium silicate treatments are probably related to the modes of action by which the two ameliorants affected exchangeable and soluble Al. As previously discussed, for silicic acid the main mechanism is likely to be precipitation of insoluble aluminosilicates while for calcium silicate the main mechanism is probably the rise in pH causing precipitation of hydroxyl-Al compounds. The precipitation of aluminosilicates in the silicic acid treatments would tend to lower concentrations of Si in soil solution in comparison with the equivalent rates of Si addition as calcium silicate.

Sulphuric acid is used as an extractant for available soil Si in order to measure Si in soil solution plus the buffering reserve of potentially available Si (Monger and Kelly, 2002). The mode of extraction is probably a combination of the ability of the acid to

dissolve Al and Fe oxide surfaces and thus releasing adsorbed silicic acid plus the displacing ability of the SO_4^{2-} to desorb previously adsorbed silicic acid. It will also tend to dissolve polymerised insoluble polysilicic acids and solid phase aluminosilicate compounds (Berthelsen and Korndorfer, 2005).

Measured concentrations of H_2SO_4 –extractable Si showed unexpected results. For example, concentrations were higher for the calcium silicate than silicic acid treatment even though equivalent amounts of Si were applied. Furthermore, concentrations of extractable Si were similar in the control and calcium hydroxide treatment for the Nomanci soil but were exceptionally high in the calcium hydroxide treatment for the Fernwood soil. The increased extractability of Si with increased pH, particularly in the calcium hydroxide treatment in the Fernwood soil suggests that some Si-containing compounds have been rendered extractable. Soils were air-dried prior to acid extraction so this effect could be the result of an interaction between the high pH and drying rendering some Si-containing compounds extractable.

Furthermore, the much greater amounts of Si extracted from the calcium silicate than silicic acid treatments in both soils suggests that at the much higher pH of the calcium silicate treatments, some Si-containing compounds has been rendered acid-extractable. In a study on the effect of different extractants on Si concentration, de Camargo *et al.* (2005) found that when using acetic acid rather than sulphuric acid as an extractant, acid was able to dissolve some Si-containing compound other than calcium silicate particularly at high soil pH. Korndorfer *et al.* (2005) also noted that when acetic acid was used as an extractant, the greater amount of Si was extracted with increased soil pH. However, when 0.01 M CaCl_2 was used as an extractant in the same soil, the solubility of Si increased in some soils while in others it decreased. Korndorfer *et al.* (2005) did not offer an explanation why these effects occurred.

The increase in pH to above 8.0 in the calcium silicate and calcium hydroxide treatments for the Fernwood soil would be expected to increase soil Si solubility. That is, the solubility of silicate minerals is very pH dependent, and the solubility increases sharply above pH 8.0 because of the formation of silicate ions (Marion *et*

al., 1976; Elgawhary and Lindsay, 1972). In the calcium hydroxide treatment there was obvious indication of this since concentrations of Si in soil solution were low. Nevertheless, such an effect might have caused some silica-containing minerals to become much more acid-extractable thus explaining extremely high values for H₂SO₄-extractable Si in this treatment in the Fernwood soil.

Although addition of P had no consistent effect on H₂SO₄-extractable Si, there was a tendency for concentrations of Si in soil solution to be increased. This effect was significant in the control and silicic acid treatments in the Nomanci soil. Such an effect suggests that added phosphate may have displaced some silicic acid that was previously adsorbed on to soil colloid surfaces (Al and Fe oxides) thus increasing concentrations of Si in soil solution (Fox *et al.*, 1967).

4.4.3 Levels of extractable P

The amount of P extracted from the soil followed the order: resin < AMBIC < Truog. These particular methods were used since they are the most widely used for making fertilizer recommendations in KwaZulu-Natal. The Truog method is used at the South African Sugarcane Research Institute, AMBIC at the KwaZulu-Natal Department of Agriculture and Environmental Affairs (Cedara) and resin at the Institute for Commercial Forestry Research. Extracting solutions such as AMBIC and Truog remove P from solid phase in soils by a number of different mechanisms. Thomas and Peaslee (1973) summarized the mechanisms of action of soil test extractants for P as being a combination of: (1) the dissolving action of acids, (2) anion replacement to enhance desorption, (3) complexing of polyvalent cations binding P (i.e. Fe and Al), and (4) hydrolysis of polyvalent cations binding to P. For the Truog reagent (0.02 N H₂SO₄), the main extraction mechanism is likely to be the dissolving action of acid on Al and Fe oxides to which P is bound. The presence of the SO₄²⁻ anion may also have some effect on enhancing desorption of previously adsorbed P. For AMBIC (0.025 M ammonium bicarbonate, 0.01 M NH₄F and 0.01 M disodium-EDTA, superfloc at pH 8.5), the main extraction mechanism is likely to be hydrolysis of cations binding to P. That is, at very high pH (i.e. >8.0), Al compounds (e.g Al oxides

and hydroxides) become solubilized as negatively charged aluminates. The dissolution of Al oxide surfaces will release previously adsorbed P. In addition, the presence of the carbonate anion will tend to cause desorption of adsorbed P (Haynes, 1984b).

Anion resins are often used by soil testing laboratories because they mimic the action of plant roots in removing phosphate from soil solution (Sissingh, 1971). During equilibration of soil with the resin, P in solution becomes sorbed to the resin surface. By equilibrium, adsorbed and precipitated solid-phase P comes into solution where it is in turn sorbed to the resin surface. It is evident from the results found in this study that the resin technique extracted considerably less P than the AMBIC and Truog methods. The Nomanci soil has a large P adsorption capacity because of its high content of clay, Al and Fe oxides. Thus, the added P was strongly adsorbed and the resin was unable to cause desorption of the added P. In order to overcome such a problem, the use of a greater quantity of resin (i.e. more resin strips) would be desirable when soil testing for P in high P-fixing soils.

Studies of the effects of liming on the extractable P from acid soils have revealed variable and conflicting results with increases, decreases and no effect being reported (Haynes, 1984a). For example, in this study, addition of both calcium hydroxide and calcium silicate increased AMBIC P in the Fernwood soil, but in the Nomanci soil, additions of calcium silicate had no effect whilst those of calcium hydroxide decreased AMBIC P. Levels of Truog P were increased by additions of both calcium silicate and calcium hydroxide in the Fernwood soil but in the Nomanci soil they were increased by calcium hydroxide addition but unaffected by calcium silicate addition. For resin extraction, calcium silicate and calcium hydroxide additions increased extractable P levels at P₀ in the Fernwood soil but in the Nomanci soil there was no effect.

The interaction of factors that are responsible for such variable effects are complex and have been discussed by Haynes (1984 a, b). On one hand, increasing the pH of an acid soil decreases adsorption of P onto metal oxide surfaces because the charge conferred on the surfaces becomes more negative. In addition, Al and Fe in soil solution precipitate as Al and Fe hydroxides thus reducing the possibility of precipitation of added P as Al and Fe phosphates (Haynes and Ludecke, 1981). On the other hand, in soils with initially high levels of exchangeable Al, liming causes precipitation of this Al as amorphous hydroxyl-Al polymers and this forms new P adsorption surfaces, thus increasing P adsorption (Haynes, 1984a). Increasing the pH above 6.5 can also favour precipitation of calcium phosphates thus reducing P availability (Naidu *et al.*, 1990; Haynes, 1984a) the interaction of these factors along with the different extraction mechanisms of the different soil text procedures results in very variable results.

An important aim of this study was to determine whether addition of Si to the soil would increase extractable P levels. This could occur by adsorption of silicate onto Fe and Al oxide surfaces thus blocking phosphate adsorption sites and/or displacing previously adsorbed P. However, no such effect was observed. For example, addition of silicic acid had no effect on extractable P levels in both soils. This suggests that P is adsorbed much more strongly than silicate so that addition of Si is ineffective at increasing P extractability. Such results support those of others who have concluded that additions of Si are ineffective at increasing P availability (Hingston *et al.*, 1968; Smyth and Sanchez, 1980; Ma and Takahashi, 1991).

4.5. Conclusions

Calcium silicate is the most commonly used form of fertilizer Si and results of this study have confirmed that it acts as Si source and a liming material. Results also demonstrated that on sandy soils with low buffering capacity (e.g. Fernwood), routine application of calcium silicate can result in very high pH values which could have negative effects on plant growth. On such soils, the use of Si sources that have little effect on pH (e.g. silicic acid) would be more appropriate.

Application of Si in conjunction with P has no measurable effects on extractable P suggesting that P is more strongly adsorbed to soil colloids than silicic acid. As a result, its application has little effect on P availability. Results found in this study also agree with those found by other workers that levels of extractable P can be increased, decreased or unaffected by increase in soil pH depending on the soil type and extractant used.

The increase in extractable Si in Fernwood soil at high pH requires further study to determine the nature of the soil components responsible for such an increase. The very high sulphuric acid extractable Si in calcium hydroxide treatment in the Fernwood soil suggests that Si compounds are acid extractable. Therefore, it will be important in future to characterize the nature of the acid-extractable Si fraction in soils because acid extractable Si is often used as an index of available soil Si.

CHAPTER 5

GENERAL CONCLUSIONS

Yield and Si uptake data from the pot experiment do not support the theory that foliar application of Si increases plant growth and Si uptake. Indeed, Si content in the plant tissues, Si uptake and yield for the foliar treatments were generally not significant to the control. As shown in this study, Si is accumulated into plants in similar quantities to those of macronutrients such as N and K. As a result, soil application of Si is the most effective way to supply Si to plants. Large basal dressings can be made (e.g. 4-20 tonnes/ha). However, when foliar sprays are used, only small quantities of Si can be applied.

The results suggest that soil application of Si-containing fertilizers could be of value in improving soil quality and crop yields in KwaZulu-Natal. In South Africa, water is a scarce resource and Si might be used in dry areas of the country to improve crop growth because as noted in the literature review, it has been reported to increase moisture content in the plant tissues by reduced transpiration rate. Silicon can also be useful in preventing lodging, improving photosynthesis, overcoming toxicities of Al and Mn and conferring greater disease and pest resistance on crop plants. In this study, the major positive effect of calcium silicate applications on sorghum growth appeared to occur through its liming effect and the consequent reduction in extractable soil Al concentrations. However, other direct effects of Si on plant growth might have also occurred.

One of the aims of this study was to investigate if addition of lime as calcium silicate rather than calcium hydroxide would increase P extractability through desorption of adsorbed P by added silicate. No such effects were found suggesting that phosphate is so strongly adsorbed by soil components compared with silicic acid that additions of silicate do not significantly increase P availability. In agreement with this conclusion, it was also found that application of silicic acid had no measurable effect

on extractable P in comparison with the control treatment. Therefore, it seems that addition of Si to soils is unlikely to have any considerable effect on the availability of soil P.

The three soil test methods for P used in this study extracted different amounts of P from soils. This was attributed to their different modes of action in extracting soil P. Truog and AMBIC extractant removed P from solid phase (i.e. P complexed by Fe and Al), whilst for the resin phosphate was removed from soil solution by strips mimicking the action of plant roots. It is difficult to determine the best suitable method for extracting P from the soil, because on one hand the Truog method might have overestimated the extractable P and this might underestimate the amount of fertilizer P required for crop growth. On the other hand, the resin might have underestimated extractable P and this might result in less amount of phosphate fertilizer being applied to the soil. Levels of extractable P were increased, decreased or unaffected by increased pH depending on the extractant used and the soil being considered. Such results emphasise the complexity of lime and P interactions that can occur in acid soils.

The concentration of extractable Al in soils is partially related to the clay mineralogy, with concentrations increasing in highly weathered soils. It is evident that addition of calcium silicate, silicic acid and calcium hydroxide used in this study reduced exchangeable and soluble Al in the Nomanci and Fernwood soil. The major mechanisms responsible for this decrease probably differed. In the silicic acid treatment a decrease was due to the formation and precipitation of insoluble silicates, whilst increased pH caused a small decrease in calcium silicate and calcium hydroxide. Concentrations of exchangeable and soluble Al were also decreased by application of phosphate fertilizer mainly due to the precipitation of Al phosphates. Nevertheless, the effects of added silicic acid and P on Al solubility were only small and the way of reducing potentially-phytotoxic levels of soluble and exchangeable Al to low levels is to raise soil pH by adding a liming material (e.g. calcium carbonate or calcium hydroxide).

Adsorption of Si by soil components has been reported to increase with increased pH so that its extractability decreases. However, unexpected results were found in the calcium hydroxide treatment in the Fernwood soil since acid- extractable Si was greatest in this treatment (extractable Si higher than in Si-containing treatments). The Si concentration in soil solution was very low in this treatment. It was suggested that a combination of increased pH, and perhaps drying, rendered some Si-containing compounds acid- extractable. Such findings indicate that the use of acid-extractable fraction of Si as an indicator of available Si does not reflect plant available Si (i.e. it overestimates plant available Si). Future research needs to characterize the nature of acid-extractable Si fraction in soils in more detail.

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