EFFECT OF POTASSIUM, NITROGEN AND SILICON FERTILISATION ON SUGARCANE GROWTH AND QUALITY, NUTRIENT UPTAKE DYNAMICS AND SOIL CHEMISTRY IN TWO CONTRASTING SOILS OF KWAZULU-NATAL, SOUTH AFRICA

Ruth Rhodes

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College of Agriculture, Engineering and Science

University of KwaZulu-Natal

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ABSTRACT

The South African sugarcane industry covers an area of approximately 380 000 ha, producing an average of 2.2 million tonnes of sugar per year. South African sugarcane growers are supported by, amongst others, the South African Sugarcane Research Institute (SASRI), which conducts research and provides technical support and advice. The Fertiliser Advisory Service (FAS) at SASRI analyses growers' soil and plant samples and provides nutrient recommendations.

The three nutrients required in the largest amounts by sugarcane are potassium (K), nitrogen (N) and silicon (Si). Accurate estimates of the K, N and Si requirements of sugarcane are essential. This study was thus designed to examine the impact of K, N and Si treatments on sugarcane growth and quality. Also investigated were nutrient interactions, nutrient balances in the soil and crop, and rooting characteristics. The ultimate goal was to assist in the refinement of the industry nutrient recommendations given by the FAS.

Two contrasting soil types on the KwaZulu-Natal north coast were selected. One trial was situated on an Oxisol, and the other on an Inceptisol. At each trial site, three crops of sugarcane (*Saccharum officinarum* x *S. spontaneum* hybrid) were harvested: the 'plant crop' (the first crop harvested after planting) and the first two ratoon crops (ratoons one and two, which resprout following each harvest). Treatments were applied as potassium chloride at 0, 100, 200 and 300 kg K ha^{-1} (both sites); urea at 0, 80 and 160 kg N ha^{-1} (Oxisol) and 0, 105 and 210 kg N ha^{-1} (Inceptisol); and Calmasil®, a calcium silicate slag, at 0 and 300 kg Si ha^{-1} (both sites). The trial was factorial, with four replications of each nutrient combination in a randomised complete block design. Following harvest of the plant and first ratoon crops, K and N were re-applied. Silicon was reapplied, in the form of cement (CIMPOR NPC PRO blastfurnace Cement CEM III/A 32.5 N), following harvest of the first ratoon crop at both trial sites. The crops were harvested and stalk yield and percent estimated recoverable crystal (% ERC, a measure of extractable sucrose) determined.

Leaf samples were collected at both sites and analysed for nutrient content. Soil samples were collected in 20 cm increments to a depth of 80 cm following harvest of

each crop, and analysed at the FAS. Topsoils (0-20 cm) were analysed following fertiliser application at the start of each crop cycle. In addition, incremental depth 'topsoil' samples were collected at each site at 0-2.5, 2.5-7.5, 7.5-15 and 15-28 cm. Root samples were collected in 20 cm increments to a depth of 80 cm, and total root length per sample determined.

To investigate the behaviour of K further, a K-exhaustion pot trial was established using topsoil from each trial site and sown to ryegrass (*Lolium multiflorum* L.). The ryegrass was harvested periodically and analysed for K content. Total K removed by the plants over 340 days was determined and a K balance calculated.

In general, the K thresholds and recommendations currently used at the FAS appear appropriate for the soils under study. At the fertiliser and sucrose prices used, however, application of 200 kg K ha^{-1} was not economically justifiable over the three crops at each site, but it is possible that the economics of K application might have become more favourable in later ratoons, where response to K is usually more marked.

At present, the FAS uses only topsoil readily-available K results to formulate K recommendations. This study showed that combining subsoil K data (20-60 cm) with those from the topsoil (0-20 cm) improved K recommendations.

Both field trials and the pot experiment clearly indicated that previously 'unavailable' soil K was released and made available for crop use, more so in the Inceptisol than in the Oxisol. Such pools may contribute to crop nutrition to a greater extent than currently recognised. Further investigation is warranted.

Based on the results of this study, little change would be required to the N rates currently recommended by the FAS. This study confirmed that excessive N may depress sucrose percent, and that plant crops respond less to N than do ratoon crops. Crop yield, sucrose percent and total sucrose yield in the plant crops did not respond positively to applied N. On the humic Oxisol, N application served to decrease sucrose yield significantly, and this requires further investigation. Reduced N rates, as are currently recommended by FAS on humic soils and in plant crops, were justified, although the present results suggest that a zero N recommendation could be applicable.

Results showed that the current threshold for soil Si (extracted with 0.01 *M* $CaCl_2$) of 15 mg L^{-1} is insufficient to promote optimal yield. It is suggested that the FAS increase this to approximately 20 mg L^{-1} and that further trials are required to finalise this threshold.

High soil K limited calcium (Ca) and magnesium (Mg) uptake by the plant. This finding is of considerable significance to the South African sugar industry and has implications for lime recommendations. Although this cationic antagonism is not directly related to Si application, Si is, at present, applied as a calcium silicate slag (such as Calmasil®). This is used in place of dolomitic lime as it fulfils a similar role by providing Ca and Mg (as well as Si), and raising soil pH. Furthermore, the FAS currently gives higher K recommendations for soils with high levels of Ca and Mg. It is recommended, based on the outcomes of this study, that the reverse should also apply so that where K levels are high, soil Ca and Mg thresholds should be increased. The details of such a recommendation will need to be confirmed by further studies.

Leaf sample results did not prove a reliable means of establishing nutrient sufficiency levels. Moisture stress during the study likely played a role in this disparity. This study showed that the soil sampling depth recommended by the laboratory should be strictly adhered to. Collection of samples at a shallower or deeper depth than that used in field calibration studies, will lead to incorrect recommendations, possibly resulting in reduced yield or quality, or wasteful expenditure on inputs.

Root distribution appeared to be normal with about 70% of the roots found in the top 40 cm of both soils. Potassium application had no effect on total root length. It is possible that roots obtained some K from deeper in the soil profile, and also from less readily-available K pools, to maintain root growth in the zero-K treatment. Application of Si decreased total root length to a depth of 60 cm, significantly so in the Inceptisol. In addition, total root length in the Oxisol was less than in the Inceptisol. Both of these responses may have been due to water stress.

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DECLARATION 1 - PLAGIARISM

I, Ruth Rhodes, declare that

1. The research reported in this thesis, except where otherwise indicated, is my original research.

2. This thesis has not been submitted for any degree or examination at any other university.

3. This thesis does not contain other persons' data, pictures, graphs or other information, unless specifically acknowledged as being sourced from other persons.

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Signed: [redacted] .... Candidate name: R. Rhodes Date: 25 Oct 2020

As the candidate's supervisor I have/have not approved this dissertation for submission

Signed: [redacted] Name: Prof. J.C. Hughes Date: 22 Oct 2020

As the candidate's co-supervisor I have/have not approved this dissertation for submission

Signed: [redacted] Name: Dr. N. Miles Date: 18/10/20

DECLARATION 2 – PUBLICATION

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Signed: ..[redacted]......... Name: R Rhodes Date: ..25 October 2020..

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T H A N K   Y O U

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GLOSSARY

Explanation of sugarcane-related terms used in the thesis

FAS (Fertiliser Advisory Service): User-pays analytical laboratory, situated at SASRI, which conducts analyses on soil, plants, water and nutrient sources. The FAS provides nutrient recommendations based on soil test results. Situated at Mount Edgecombe, near Durban.

Furrows: shallow parallel trenches drawn into the soil, into which seedcane setts are placed. Some fertiliser is placed into the furrow, and the furrow is then closed by drawing soil over the sugarcane setts.

Interrow: the space between the rows of sugarcane.

Plant crop: the first crop of sugarcane, grown after planting sugarcane setts.

Ratoon crop: after harvesting a sugarcane crop, a new crop will resprout without replanting new sett material. This resprouted crop is called a ratoon crop. Ratoon crops are named successively, so that a field will typically grow a plant crop, first ratoon crop, second ratoon crop and so on.

Row, Row spacing: sugarcane is planted in rows; 'row' refers to the actual row of sugarcane, while row spacing refers to the distance between rows of sugarcane. Common row spacing in the South African sugar industry ranges from 0.9 m (rainfed) to 1.5 m (irrigated).

SASA (South African Sugar Association): an organisation which provides support to the growers and millers of the South African sugar industry and thereby works to sustain the industry's global competitiveness, profitability and sustainability. Under SASA's auspices, a number of divisions operate to provide specialist support to these clients. Head office is situated at Mount Edgecombe, near Durban.

SASRI (South African Sugarcane Research Institute): a division of SASA which conducts scientific research on sugarcane agriculture and provides specialist advice and support to sugarcane growers. Head office is situated at Mount Edgecombe, near Durban, while satellite stations are located throughout the industry.

Stool: sugarcane plant or clump. Sugarcane does not grow in uniform, one-by-one tillers spaced evenly within a row; rather, there are clumps of tillers or ‘stools’ originating from a bud on the planted sugarcane sett, from which a number of tillers emerge.

Sugarcane setts / seedcane: short sticks of sugarcane, planted into furrows in the soil to vegetatively propagate a new crop of sugarcane.

Tin and string method: Method of fertiliser application. A standard-sized tin is filled with fertiliser and weighed. Depending on the sugarcane row spacing and fertiliser rate required, a distance (length of row) can be calculated over which the full tin should be distributed, and a piece of string measured and cut. This length of string is used by the field supervisor to indicate the distance to the fertiliser application team.

CHAPTER 1

Introduction

1.1. Sugarcane industry overview

1.1.1. Location

The South African sugarcane industry is located along the eastern seaboard of the country. Most of the cane is grown in eastern KwaZulu-Natal and Mpumalanga, with a small portion in the Eastern Cape (Figure 1.1). The northern part is irrigated, with the remainder largely rainfed. Fourteen mills service the industry (Figure 1.1).

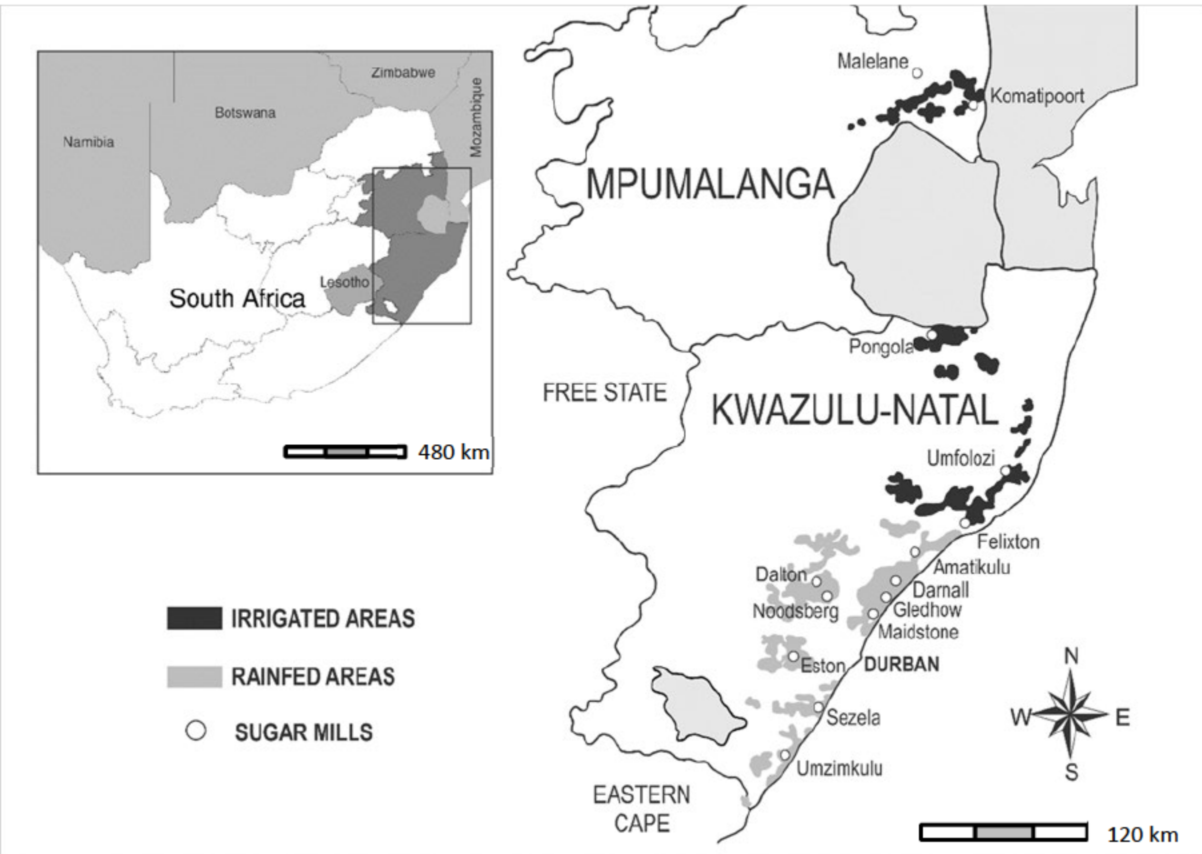


Figure 1.1: Location of the sugarcane-growing regions and sugar mills of South Africa. (Image: S. Doorsamy, South African Sugarcane Research Institute).

1.1.2. Economic contribution

An area of approximately 380 000 ha is currently under sugarcane (*Saccharum officinarum* x *S. spontaneum* hybrid), of which about 270 000 ha is harvested annually to produce an average of 2.2 million tonnes of sugar per year. South African sugar sales generate an annual average direct income of R14 billion (US$966 million[1]) (SASA, 2020), representing approximately 20% of agriculture, forestry and fishing's contribution towards South Africa's gross domestic product (Stats SA, 2019).

About 85 000 people are directly employed in the production, transport, milling, refining and by-product sectors of the sugar industry. Indirect employment is estimated at 350 000 people, with a total of approximately one million, including dependents, relying on the industry for their livelihood (SASA, 2015).

1.1.3. Industry support

South Africa's sugarcane growers and millers are supported by the South African Sugar Association (SASA) that works to sustain the industry's global competitiveness, profitability and sustainability. Under SASA's auspices, a number of divisions operate to provide specialist support to clients. One such division is the South African Sugarcane Research Institute (SASRI), which conducts scientific research on sugarcane agriculture and provides specialist advice to sugarcane growers on, amongst others, soil and crop nutrition management strategies.

1.1.4. Soils and soil testing

South African sugarbelt soils are characterised by considerable heterogeneity, with large differences in, *inter alia*, depth, base status and texture (SASEX, 1999). Such variation provides challenges in developing accurate, field-specific nutrient recommendations. Soil testing is thus strongly encouraged throughout the industry.

In order for soil analyses to be of practical use in terms of the derivation of nutrient recommendations, laboratory tests need to be calibrated with crop responses in the field. A commercial laboratory, the Fertiliser Advisory Service (FAS), was established at SASRI in 1954 to analyse soil, plant, water and fertiliser samples from the sugar industry. The FAS makes nutrient recommendations based on the results of

[1] Exchange rate of ZAR1 = 0.069 US$, 28 January 2020

hundreds of field trials conducted during the past 90 years. Trial work, of which the present study forms a part, is ongoing in order to improve nutrient recommendations.

1.2. Sugarcane crop nutrition

The three nutrients required in the largest amounts by sugarcane are potassium (K), nitrogen (N) and silicon (Si), and they have received significant research attention. Potassium fulfils a number of metabolic functions in sugarcane, including anionic charge balance and turgor control, and thus plays an important role in the growth, metabolism and ripening of the crop (Kingston, 2000; Wood and Schroeder, 2004). Potassium reserves in many topsoils in the rainfed sugarcane areas of South Africa are low (Miles and Farina, 2014) and more accurate estimates of the K requirements of sugarcane are required. Potassium's interaction with other nutrients such as N (Miles, 2010), calcium (Ca) and magnesium (Mg) (Gosnell and Long, 1971; Grunes *et al*., 1992; Marschner, 1995) makes understanding its patterns of uptake essential.

Nitrogen plays a key role in protein synthesis and is associated with vigorous vegetative growth (Anderson and Bowen, 1990). It continues to be investigated due to its pivotal role in sugarcane growth and yield and its characteristic as a 'driver' of the uptake of other nutrients (Miles, 2010).

The importance of Si has only been recognised by sugarcane researchers recently (Laing *et al*., 2006). Although not considered 'essential' for sugarcane growth, Si plays an important role in protecting the crop from both biotic and abiotic stress. Research has highlighted the extensive Si deficiency of sugarbelt soils in the rainfed parts of the country (Van der Laan and Miles, 2010) and further research is required to understand its uptake by, and effects on, sugarcane.

While the individual effects of nutrients on sugarcane uptake and performance are important and, in some cases, well documented, the interactions between nutrients are less well understood. South African sugarcane growers spend millions of rands each year on fertilisers for their crop, and it is essential that the nutrient recommendations provided by SASRI, via the FAS, are as appropriate as possible.

1.3. Purpose and outline of the study

1.3.1. Aims and objectives

This study was designed to examine, on two contrasting soil types that are representative of common soils of the sugarbelt, the effect of K, N and Si treatments on sugarcane growth and quality. Also investigated were nutrient interactions, nutrient balances in the soil and crop, and rooting characteristics. The ultimate goal was to assist in refinement of the industry nutrient recommendations given by the FAS.

1.3.2. Key questions

In particular, the following questions were addressed in this study, approved by SASRI as Project Number: 08RE05.

a) How do applied K, N and Si, and their interactions, influence sugarcane crop yield and quality?
b) How do different K, N and Si application rates affect plant uptake of these and other nutrients, and how is plant uptake related to crop yield and quality?
c) Does leaf analysis provide an accurate estimation of nutrient sufficiency or deficiency indicating the necessity of further nutrient application for optimal yield?
d) How do applied K, N and Si influence soil concentrations of these and other nutrients?
e) What is the soil profile distribution of K, N and Si following fertiliser application?
f) How does the movement of applied K, N and Si through the soil profile affect soil sampling results and hence fertiliser recommendations and costs?
g) Do different rates of K and Si application affect root distribution patterns?
h) What are the underlying reasons for any differences in crop behaviour on different soils?
i) What are the implications of the above for K, N and Si fertiliser recommendations in the South African sugarcane industry?

1.3.3. Dissertation structure and chapter outline

This dissertation contains nine chapters, the latter seven of which address the key questions identified above, as follows:

- Chapter 2 is a literature review of K, N and Si research in sugarcane soils.
- Chapter 3 gives details of the field experiments and examines the effects of different rates of K, N and Si, and their interactions, on sugarcane quality and yield.
- Chapter 4 reports the effect of K, N and Si on leaf nutrient concentrations and yield of sugarcane.
- Chapter 5 discusses the effect of K, N and Si application on topsoil and subsoil nutrient dynamics.
- Chapter 6 examines the movement and distribution of applied K, N and Si through the topsoil, and the possible effects on subsequent soil sample results and fertiliser costs.
- Chapter 7 investigates the effects of applied K, N and Si on root distribution throughout the soil profile.
- Chapter 8 reports on a K-exhaustion pot trial, using ryegrass (*Lolium multiflorum* L.) as an indicator crop, to assess the soils' K-supplying power in the absence of K fertilisation. This was carried out to investigate the limited yield response to applied K found on both soils in the field trials.
- Chapter 9 comprises a summary conceptual model, further discussion, conclusions, and proposed future work.

CHAPTER 2

Potassium, nitrogen and silicon in soils and plants with special reference to sugarcane

2.1. Introduction

Modern sugarcane production began in Tahiti in 1768, and the crop is now grown in over 100 countries, occupying more than 20 million hectares of land (Meyer and St John Clowes, 2013). It is the eighth most planted crop in the world, after wheat (*Triticum aestivum*), maize (*Zea mays*), rice (*Oryza sativa*), soybeans (*Glycine max*), beans (*Phaseolus* spp), barley (*Hordeum vulgare*) and rapeseed (*Brassica napus*), for area harvested (Desjardins, 2014). As a provider of income and employment, sugarcane agriculture plays an important role, particularly in developing countries, which produce approximately 75% of the sugar derived from sugarcane (Voora *et al*., 2019).

Sugarcane was first grown commercially in South Africa in 1848 and crop nutrition began to receive scientific attention following the establishment of the South African Sugar Association Experiment Station in 1925 (renamed the South African Sugarcane Research Institute (SASRI) in 2004). Considerable research emphasis has been placed on the three major nutrients - nitrogen (N), phosphorus (P) and potassium (K) - and their role in sugarcane production. Of these, N and K are required in the greatest amounts (De Oliveira *et al*., 2017), and understanding their behaviour in soils is important in order to make informed fertiliser recommendations. In addition, silicon (Si) has received much research attention recently (De Camargo *et al*., 2014; Haynes, 2014, 2017; Miles *et al*., 2014).

The dynamics of K, N and Si in both soil and plants will be discussed in this review, with a particular focus on sugarcane. In addition, the interaction between these nutrients will be discussed, following the observation by Sumner and Farina (1986) that the interplay between nutrients in field cropping systems is seldom given the attention it deserves.

2.2. Potassium

Potassium is the cation required in the largest amounts by most plants (Askegaard *et al*., 2004). It performs a number of biochemical functions in plants such as activating enzymes used, for example, in protein synthesis, although for these roles only small amounts are required. Larger amounts of K are needed for its biophysical roles in osmoregulation, cation-anion balance and water balance (Askegaard *et al*., 2004). Potassium plays a major role in solute movement within the plant and, of particular interest to crop farmers, the movement of photosynthates to storage organs such as grains and tubers (Askegaard *et al*., 2004). It is also associated with protection of the plant against abiotic (frost, drought, heat, salinity) and biotic (fungal and pest) stresses (Huber and Arny, 1985; Askegaard *et al*., 2004; Ashraf *et al*., 2009).

In unamended systems, the main source of K for plants is from the weathering of soil minerals (Mengel and Kirkby, 2001). Despite the presence of large amounts of K in most soils, only a small portion is readily available to plants (Sparks and Huang, 1985); the rest is present in slowly available forms, released over longer time spans. As a plant nutrient, the importance of K is easily overlooked. The ability of soils to buffer K supply can mask their true K status (Krauss, 2001). Potassium can be washed out of senescent leaves, recycling it from the whole of the root zone into the topsoil and this can mask a decrease in overall soil K status if only the topsoil is sampled (Ritchey, 1979). The effects of K on crop growth are often subtle and, in contrast to the rapid, easily-visible crop response to applied N, for example, are often only apparent at harvest, as a function of yield (Krauss, 2001). Other less obvious benefits associated with K nutrition, such as protection against pests, diseases or climatic stress, are not often attributed to K (Krauss, 2001).

2.2.1. Potassium in soils

Potassium exists in four different forms or 'pools' in soils namely, K in solution, exchangeable K, 'fixed' (non-exchangeable) K, and structural or mineral K (Figure 2.1) and this order also reflects their ease of availability to plants and microbes (Sparks and Huang, 1985). The reactions between the four fractions of soil K (Figure 2.1) affect the concentration of K in soil solution at any one time (Sparks, 2001).

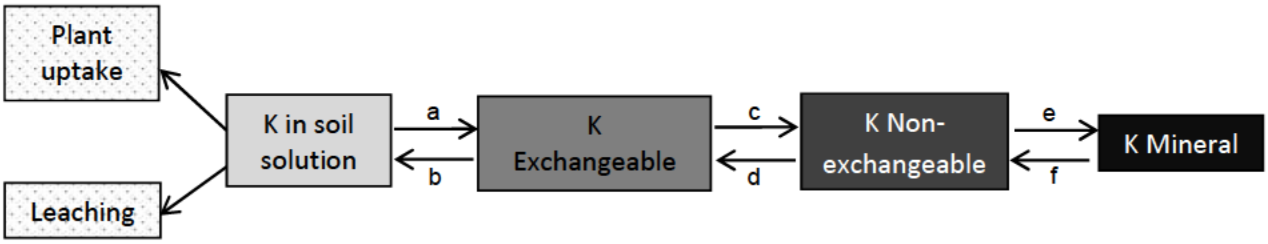


Figure 2.1: Kinetic reactions of potassium (K) in soil, where: a = adsorption, b = desorption, c = non-exchangeable fixation, d = non-exchangeable release, e = immobilisation, and f = mineralisation (adapted from Selim *et al*., 1976).

Reactions **a** and **b** (Figure 2.1) – adsorption and desorption – result in the transfer of exchangeable K from the soil solution to the surfaces of clay minerals and humic substances, and *vice versa*. The reaction rate between soil solution and exchangeable pools of K depends strongly on the type of clay minerals present (Sparks, 2001).

Reactions **c** and **d** – non-exchangeable fixation and release – significantly affect K availability (Sparks, 2001). Potassium may be 'fixed' or held within mineral layers; this non-exchangeable (or 'slowly exchangeable') K can normally be released again over a period of a season or year/s (Askegaard *et al*., 2004). The concentration of solution K markedly affects the release of non-exchangeable K from clays (Sparks and Huang, 1985). Release of non-exchangeable K to the exchangeable form occurs when amounts of exchangeable and soil solution K are decreased by crop removal, leaching and perhaps by high microbial activity (Sparks, 2000).

The degree of K fixation in clays and soils depends on the type of clay mineral and its charge density. The major clay minerals responsible for K fixation are the expanding 2:1 types, including montmorillonite and vermiculite, and weathered micas (Rich, 1968). Potassium fixation is also affected by soil moisture content, competing cations within the soil (Sparks and Huang, 1985) and soil pH (Martin *et al*., 1946; Rich and co-workers, summarised by Sparks and Huang, 1985). The degree of interlayering can also affect K fixation, with hydroxy-aluminium and -iron interlayer groups serving to decrease K fixation (Rich and Obenshaim, 1955; Rich and Black, 1964).

Reactions **e** (immobilisation) and **f** (mineralisation) occur between the non-exchangeable and mineral pools of K. Micas and feldspars are the most important mineral sources of K in soils. The release or mineralisation (reaction **f**) of lattice K is considered by some to be irreversible (Askegaard *et al*., 2004), indicating that, in reality, reaction **e** does not occur to a significant extent.

2.2.2. Potassium supply to crops

Potassium moves between the four pools (Figure 2.1) in response to soil conditions. With weathering, mineral K is converted into non-exchangeable and/or more readily-available forms (Kingston, 2000). Non-exchangeable, exchangeable and soil solution K are in dynamic equilibrium with each other. Therefore, any losses (e.g. leaching or crop uptake) of readily-available K may be replenished from the less available sources (Kingston, 2000). This so-called 'replenishing power' can be substantial, depending on the soil. Nonetheless, continued depletion of soil K reserves is unsustainable in the long term (Kingston, 2000) and it is not possible to continue 'mining' soil K without eventually decreasing crop production (Askegaard *et al*., 2004). Replenishment of K is thus necessary, particularly for sugarcane, where luxury uptake is common (Kingston, 2000).

Plant roots take up K from the soil solution in the form of the K^+ ion (Marschner, 1995). Depletion of K at the root surface sets up a gradient between the low concentrations (at the root surface) and the higher concentrations in the bulk soil, leading to diffusion of K towards the root surface (Jungk and Claassen, 1989, cited in Askegaard *et al*., 2004). A high rate of diffusion can be facilitated by applying K to the soil, or by the release of K from other fractions (Askegaard *et al*., 2004). The buffering power of a soil is related to clay content (Sharpley, 1990) and clay mineralogy (Mengel and Busch, 1982). In the short and medium term, the extent to which the solution and exchangeable K pools are maintained will depend on the amount of K added as fertiliser which has been retained in the exchangeable and non- (or slowly) exchangeable fractions (Askegaard *et al*., 2004). In the longer term, in soils with limited K inputs, the release of mineral K becomes an important source for plants (Askegaard *et al*., 2004).

2.2.3. Potassium in sugarcane nutrition

Sugarcane has a high demand for K and over 300 kg K ha^{-1} can be taken up in a single crop (Meyer, 2013). In sugarcane, K is required for starch and protein synthesis, photosynthesis, osmoregulation, electron balance in cells, and stimulation of phloem transport of sugars, amongst other functions (Kingston, 2000; Wood and Schroeder, 2004).

Low soil K can inhibit sugarcane germination (Anderson and Bowen, 1990), although ratoon crops respond more to added K than do plant crops (Du Toit, 1957; Wood and Meyer, 1986). Potassium deficiencies may also lead to a decrease in cane yield and quality (Wood and Schroeder, 2004). Although K deficiency symptoms may be apparent in sugarcane, yield depression, even where symptoms appear, may not be marked (Wood and Schroeder, 2004), possibly due to replenishment of soil solution and exchangeable K from the non-exchangeable and mineral pools.

Worldwide, it is estimated that approximately 31.5 million tons of fertiliser K was applied to all crops in 2019 (FAO, 2019). In South Africa, approximately 100 000 tons of K were applied to all crops in 2015 (the latest year for which data are available), of which 18% was applied to sugarcane (DAFF, 2016). Depending on the soil test result, most cane-growing countries recommend a maximum of between 100 and 250 kg K ha^{-1} (Kingston, 2000; Miles, 2014). At a cost of about R12 kg^{-1} and an assumed average of 150 kg K ha^{-1} applied to the 270 000 ha harvested annually, South African sugarcane growers apply 40.5 million kg K to their fields every year at a cost of over R485 million.

2.2.3.1. Consequences of excess potassium in sugarcane

The luxury uptake of K by sugarcane (Kingston, 2000) generally has little negative effect on the crop or production system and there have been no reports of harmful effects of K on the environment, or to humans (Anonymous, 1984, 1998, cited in Askegaard *et al*., 2004). Economically, however, this has a direct adverse effect on profits (Ritchey, 1979) if K fertiliser is applied in excess of that required for optimum yield. However, the major impact of excess K is in the milling operation, where increased ash in cane juice and raw sugar results in lower recovery of sugar crystal from cane (Kingston, 1982; Munsamy, 2013).

2.2.3.2. Potassium and moisture stress

Moisture stress may depress the amount of K taken up by sugarcane (Schroeder *et al*., 1993). Sugarcane leaves sampled after an extended dry period contained considerably less K than the same field sampled two months later, after ample rain (Schroeder *et al*., 1993). Possible reasons for this included better root growth and functioning after rainfall, increased mass flow of soil K and release of non-exchangeable soil K (Wood and Schroeder, 2004). Kee Kwong *et al*. (1990), however, reported that leaf K concentration could not be predicted by the moisture regime at or near the time of sampling. Where K was deficient, moisture stress tended to decrease sugarcane yields, while K-rich fields subjected to the same stress did not show this yield penalty (Wood and Schroeder, 2004).

Potassium supply plays an important role in drought tolerance of plants, including sugarcane. Potassium sufficiency affects cell osmosis, water potential and stomatal function (Huang *et al*., 2009a), assisting K-replete plants to withstand drought better than their K-deficient counterparts. Under conditions of moisture deficit, K increases the efficiency of water use and leaf biomass (Valeri *et al*., 2016). Foliar application of K has also been reported to improve growth, dry matter accumulation, relative water content, gas exchange capacity, stomatal conductance and net photosynthesis rate of drought stressed plants (Ihsan *et al*., 2013).

2.2.4. Nutrient interactions

Potassium is known to interact in various ways with other nutrients. Some interactions are fairly general. For instance, if another element such as P or N limits plant growth, K uptake will be low, even in the presence of large amounts in the soil (Ritchey, 1979). Other interactions, however, are more specific, as discussed below.

2.2.4.1. Potassium interactions with calcium and magnesium

Researchers have reported conflicting results with regard to interactions involving K, calcium (Ca) and magnesium (Mg), and their subsequent uptake by plants. Some have recorded a decrease in K absorption by plants as a consequence of Ca and/or Mg fertilisation (Stevens, 1970; Ritchey, 1979; Wood and Meyer, 1986). High levels of Ca and Mg favour uptake of these elements via mass flow, interfering with K uptake (Kingston, 2000). Other researchers have shown a depressive effect of K on Ca and Mg content of plants (Hossner and Doll, 1970; Ritchey, 1979; Jakobsen, 1993; Daliparthy *et al.*, 1994; Jaskulska *et al*., 2015; Bauw *et al*., 2016), while little or no interactive effects have also been reported (Rodriguez, 1975; Gonzalez, 1976). Liming further complicates the interpretation of K trial results, mainly through yield effects. Where the lime rate is varied, under conditions of high soil acidity, insufficient lime may lead to decreased yields, reducing K uptake and leading to more unused K remaining in the system, thus confounding the interpretation of K distribution patterns (Ritchey, 1979). Conversely, increased crop yields following liming may result in decreased K throughout the profile due to greater crop uptake of K (Ritchey, 1979). Results are less confounded when lime rates are within the range unlikely to affect yield or K uptake (Ritchey, 1979).

2.2.4.2. Potassium interactions with nitrogen

Although an increase in the amount of N supplied to the crop generally encourages growth and the uptake of K from the soil (Johnston, 1986), the opposite has also been reported. High NH_4^+ in the soil can interfere with K uptake (Spalding *et al*., 1999). Nitrogen deficiency can suppress K uptake by the plant (Miles, 2010). Similarly, inadequate K supply can lead to reduced crop yields, causing under-utilisation of N (and P) fertiliser, thereby rendering N vulnerable to loss by leaching, erosion or volatilisation (Krauss, 2001). In this regard, K has an important environmental function. An adequately nourished crop provides better soil anchorage, so reducing nutrient losses via erosion, and higher yields with sufficient nutrition promote greater N use efficiency, reducing the potentially harmful effects of N losses in runoff (Krauss, 2001).

2.2.4.3. Potassium interactions with aluminium and manganese

Although K and aluminium (Al) or manganese (Mn) do not compete for uptake by plants, high exchangeable Al and Mn, often present in acid soils, can seriously affect the healthy development of crop roots. A poorly functioning root system is therefore less efficient at K uptake (Ritchey, 1979). In such cases, liming would decrease Al and Mn availability, improving root growth and therefore K uptake. Liming also renders Al insoluble, thereby increasing the portion of the cation exchange capacity (CEC) available for K adsorption, along with the general increase in effective CEC due to the deprotonation of pH-dependent sites effected by liming (Ritchey, 1979).

2.2.5. Soil analysis and plant uptake

Unfortunately, the relationship between soil K and crop response to K fertiliser is often poorly defined. While glasshouse trials may show strong correlations, under field conditions relationships can be confounded by many factors (Askegaard *et al*., 2004). Whereas soil samples are typically taken from the plough layer, dried, ground, homogenised and extracted with chemicals targeting specific pools, plant roots *in situ* experience a very different environment. A wide range of factors affect the amount of K available to, and taken up by, plant roots in the field. These include (after Askegaard *et al*., 2004):

- *Soil texture and mineralogy*: the type of clay mineral, rather than the amount of clay present, tends to control the rate of available K replenishment (Rao and Khera, 1994).
- *Temperature and soil moisture content*: Low temperatures limit root extension and K uptake by plant roots (Schimansky, 1981), and affect the availability of K in the soil (Sparks and Liebhardt, 1982). Low soil moisture limits K diffusion (Kuchenbuch *et al*., 1986).
- *Soil compaction and waterlogging*: Soil compaction may impede root elongation and diffusion of K (Marschner, 1995), potentially causing K deficiency in plants. Waterlogging also inhibits K uptake, which is highly dependent on oxygen-controlled metabolic processes.
- *Potassium status*: Potassium taken up from the soil solution by plant roots can be replaced from the other pools (Sparks, 2001) with the result that, over a few years, slight positive or negative K balances in terms of crop uptake may have little effect on exchangeable K values.
- *Status of other nutrients in the plant:* In order for K to be efficiently taken up by the plant, other nutrients (N, in particular) need to be present in the plant at

adequate levels. Interactions are particularly important when both nutrients are near the deficiency range (Marschner, 1995).

- *Crop species and variety*: Monocotyledons tend to exploit soil K reserves more efficiently than dicotyledons (Johnston *et al*., 1998; Krauss, 2001), with the result that cereals and grasses frequently do not respond to K fertilisation (Mengel, 1982).
- *Crop uptake from the subsoil:* Plants can take up considerable amounts of K from the subsoil. Cereals can derive as much as 70% of their K from the subsoil.

2.3. Nitrogen

Nitrogen is a major constituent of nucleic acids, proteins, enzymes and chlorophyll (Kingston, 2000). It promotes vegetative growth, and the leaves of crops replete with N are a deep green colour. A shortage of N can have dramatic effects, such as yellowing of the leaves, stunted growth and reduced yield (Kingston, 2000).

Nitrogen may be lost from cropping systems by runoff, leaching, volatilisation and denitrification (Schumann, 2000), all of which may render N unavailable for crop use and represent wasteful expenditure. Excessive N may result in eutrophication of surface waters and, in drinking water, causes blue baby syndrome (Knobeloch *et al.,* 2000), while nitrogen oxides are potential atmospheric pollutants (Paton-Walsh *et al*., 2011; Davis *et al*., 2016). Nitrous oxide, a potent greenhouse gas, is emitted in exponentially greater amounts when N fertiliser is applied in excess of the crop's needs as opposed to applications which satisfy (but do not exceed) the plants' requirements (Shcherbak *et al*., 2014).

2.3.1. Nitrogen in sugarcane nutrition

Nitrogen deficiency in sugarcane results in thin, stunted stalks and reduced tiller numbers (Wood, 1968; Kingston, 2000). Yellowing of the leaves usually occurs, affecting the older leaves first, although yield reduction is usually experienced before chronic visual deficiency symptoms become evident (Kingston, 2000).

Excessive rates of applied N result in reduced sucrose concentration in the fresh mass of harvested sugarcane (Stevenson *et al*., 1992; Chapman, 1994; Muchow and Robertson, 1994; Muchow *et al*., 1996). According to Muchow *et al*. (1996), this reduction is related to an increase in moisture percent with increasing N application rates. An excess of available N too close to harvest can thus lead to lower sugarcane quality and affect profitability (Nassar *et al*., 2005). Excessive applied N may also be associated with lodging (Kingston, 2000). Stalk yield is typically increased (up to a point) with N application (Muchow *et al*., 1996). To enable optimal sugarcane growth, appropriate N recommendations must, therefore, achieve a balance between supplying enough N to maximise stalk yield, while avoiding luxury uptake of N.

The plant crop (the first crop grown after planting sugarcane stalks or setts) often shows little response to N application, while ratoon crops usually respond better and more frequently than their plant crop counterparts (Du Toit, 1957; Wood, 1964; Chapman, 1994). This phenomenon is usually attributed to the amount of inorganic N released by increased soil micro-organism activity when soil organic matter is exposed to the atmosphere during land preparation (ploughing and drawing of furrows) (Wood 1964, 1965). Ratoon fields are not ploughed following the previous harvest, and so less N is released by the soil, justifying greater N application rates than for plant crops (Chapman, 1994). Du Toit (1959) also reported an increased response to applied N from the fourth ratoon crop, and greater responses to N, P and K with each successive crop following the plant crop. Meyer and Wood (1994) recommended a 20 kg ha^{-1} increase in N application from the fourth ratoon onwards.

The season during which a sugarcane field is harvested/ratooned affects the pattern in which N is taken up by the crop. In work by Thompson (1988), 82% of the final amount of N accumulated was taken up within the first four months of growth of a summer-cut crop. In contrast, only 12% of the final N tally was taken up in the first four months of an April (autumn)-harvested crop. This difference in N uptake has implications for the timing of N fertiliser applications. Nitrogen fertiliser may be applied shortly after the harvest of a summer-harvested crop, as the following crop will be growing actively and will be able to take up and utilise the N relatively rapidly. For an autumn/winter-harvested crop, however, where the next crop will only grow very slowly until spring, applying N too soon after harvest will leave the N unutilised and vulnerable to loss (Meyer *et al*., 2007).

Nitrogen is well documented to affect plant disease development, usually increasing the plants' susceptibility to disease (in the case of obligative parasites) with increasing N application rates (Dordas, 2008). However, less evidence exists to link N application rates with diseases of sugarcane. Pannuti *et al*. (2015) recorded increased infestation of the borer *Diatraea saccharalis* - red rot complex - with increasing N application in sugarcane. In South Africa, high plant N has been reported to favour increased damage by the stalk borer *Eldana saccharina* (Goebel *et al*., 2005; Meyer and Keeping, 2005). Lowering N application rates in an effort to reduce eldana damage, however, inevitably leads to yield reductions, and may be unwarranted on fine-textured soils where moisture stress, which is strongly correlated with eldana damage, is generally less severe (Rhodes *et al*., 2013).

2.3.2. Nutrient interactions

2.3.2.1. Nitrogen interactions with phosphorus and potassium

Nitrogen promotes the uptake of a number of nutrients, including P and K (Du Toit, 1957; Miles, 2010). Without adequate N nutrition, a crop is often unable to function effectively, reducing the uptake of other nutrients. However, maximum crop response to N is dependent on the availability of sufficient quantities of other nutrients, such as P and K (Du Toit, 1957).

2.3.2.2. Nitrogen interactions with silicon/ lime

Increases in plant N may decrease plant Si concentration, due to dilution by growth (Hsieh *et al*., 1983; Marschner, 1995). Silicon is required to minimise pest and disease levels which may increase with the amount of N required for maximum growth (Hsieh *et al*., 1983; Meyer and Keeping, 2005; Kumara *et al*., 2016). Plant-available N is affected in another way by Si sources. Calmasil®, for example, a calcium-magnesium silicate slag widely used in the South African sugar industry, acts similarly to dolomitic lime, and when moderately to highly acidic soils are limed, N mineralisation is greatly increased due to stimulation of nitrifying bacteria (Wood, 1979). Plant uptake of N is increased, in some cases to such an extent that sucrose percent is reduced, necessitating a lowering of N fertiliser recommendations following liming (Wood, 1979). This effect is not directly due to Si itself, but rather due to the changes in soil chemistry associated with application of the Si source. The reported responses may thus have been due to Ca, Mg or Si or any combination of these nutrients.

2.4. Silicon

Silicon and its functionality in plants have been studied for many years (Whittenberger, 1945), but it is only recently that the extent of its importance has been recognised (Epstein, 1999; Guntzer *et al*., 2012). It is not considered an ‘essential’ plant element, because most plants can grow in nutrient solutions to which no Si has been added. Due to its numerous roles in the plant, however, for example increasing mechanical strength and resistance to pests and diseases, Si is considered a ‘functional’ (Meyer and Keeping, 2000) or ‘quasi-essential’ (Epstein, 1999) plant nutrient.

2.4.1. Silicon in soils

Silica (SiO_2) is slowly dissolved to form neutral orthosilicic acid [$Si(OH)_4$] or monosilicic acid (H_4SiO_4) in soil solution at a pH below 9.0 (Ma *et al*., 2001). Monosilicic acid is the only form of soluble Si which plants can use (Epstein, 1999). Most gramineae, including sugarcane, actively take up Si and once absorbed by plants, the silicic acid is deposited in the stems and leaves as hydrated silica ($SiO_2 \cdot nH_2O$) to form deposits known as phytogenic Si (Smithson, 1956; Haynes, 2014). As plant matter decomposes, this silica is released and becomes incorporated into the soil. When sugarcane is burned pre-harvest, most of the plant Si is retained in the ash in an amorphous form, with a small proportion as quartz (Le Blond *et al*., 2010). Soil analysis may reveal the presence of silt-sized particles of phytogenic Si (termed phytolith Si) (Haynes, 2014). Their dissolution transforms the silica back into monomeric silicic acid, thus completing the biogeochemical cycle of Si (Sangster *et al*., 2001). In many forest and grassland systems, a large percentage of the Si taken up by plants is from phytogenic silica. This recycling of Si may be particularly important in highly weathered tropical and subtropical soils that have low available Si and where loss of mineral Si results in most of the Si in soil solution being supplied phytogenically (Cornelis *et al*., 2011; Haynes, 2014).

2.4.2. Plant availability and uptake of silicon

Under conditions of high rainfall and temperature, basic cations are stripped from the soil exchange complex leading to acidification of the soil, and dissolution of aluminosilicate clay minerals. The subsequent leaching of Si (desilication) is a natural process and results in relatively little plant-available Si. An Australian study of sugarcane soils on the wet, tropical coast of north Queensland showed that more than 85% of the soils tested had sub-optimal or marginal Si levels (<20 mg Si kg^{-1}) (Berthelsen *et al*., 2001a). Plant Si generally corresponded to the extractable soil Si, being low where soil Si was sub-optimal. Sumner *et al.* (1991) commented that natural leaching (and acidification) associated with highly weathered soils may result in these soils being an order of magnitude lower in soluble Si than less weathered (and naturally more fertile) soils. These findings concur with the general pattern found in the South African sugar industry, where higher rainfall areas have reduced soil and leaf Si, while the drier, irrigated regions with more base-rich soils have higher Si (Van der Laan and Miles, 2010).

Silicon availability (and hence plant uptake) may be reduced by factors other than desilication. Monosilicic acid may be adsorbed by iron (Fe) and Al oxides, so decreasing its concentration in soil solution (Jones and Handreck, 1963; Haynes, 2014). Within a particular soil, soluble Si tends to be higher at lower pH values, while increasing pH (up to ~pH 9) (McKeague and Cline, 1963; Haynes *et al*., 2013) leads to lower Si in solution (Haynes, 2014). Curtin and Smillie (1983) recorded a dramatic reduction in soil solution Si after liming. Ayres (1966) and Savant *et al*. (1999) also reported that addition of lime to a soil can reduce Si solubility, due to an increase in the soil pH. Jones and Handreck (1967) similarly reported a number of studies indicating that an increase in pH caused a reduction in plant uptake of Si. This was confirmed in sugarcane by Du Preez (1970), where leaf Si decreased following liming. De Camargo *et al*. (2007), however, reported that an increase in pH($CaCl_2$) from ~pH 4 to pH 6.3, without an added Si source, did not affect Si uptake by rice plants. If Si slag materials are applied, however, soil pH may increase (due to the liming effect of the product), along with soluble Si (due to the Si contained in the product) (Haynes, 2014). While increasing soil pH may render mineral Si less available (due to adsorption by Fe and Al oxides), the dissolution (and hence plant-availability) of phytolith Si is increased significantly (Haynes, 2014). The overall effect of pH on Si availability is, at present, unclear, and differs according to the Si source applied (Haynes, 2014). Keeping *et al.* (2017) applied lime to an acid soil simultaneously with, or 1 or 3 months prior to, the application of Calmasil®. They found that Si uptake by sugarcane plants and, in some cases, available soil Si itself, was not improved by liming either with or before Calmasil® application, in comparison with Calmasil® application alone.

Restricted plant uptake of Si may also be due, in part, to the low solubility of orthosilicic acid, which renders a practical limit to increasing the availability of Si to plants in the field (Côté-Beaulieu *et al*., 2009). Although applications of siliceous material may increase soil and leaf Si, these increases are often not enough to bring the plant above the critical Si threshold (Berthelsen *et al.,* 2001b). Keeping and Meyer (2002) applied 5 and 10 t ha^{-1} of calcium silicate to sugarcane plants, and found that leaf and stalk Si content was, in most cases, increased by 5 t ha^{-1}, but decreased at the higher rate. In Mauritius, Ross *et al*. (1974) reported low uptake of applied Si, such that, after six sugarcane crops, the amount of Si recovered from the original application at planting was only 11-14% of the total.

A further factor contributing to the depletion of plant-available Si in sugarcane systems may be continuous monocropping, with large annual removals of Si to the mill at each harvest (Meyer and Keeping, 2000). Kraska and Breitenbeck (2010) found similar patterns in rice where Si deficiency was most pronounced in strongly acidic soils, with a long history of rice production. In this case, however, the correlation between soil and plant Si was weaker than the (inverse) correlation between soil pH and plant Si, indicating that soil pH was a more important determinant of plant Si uptake than the duration of cropping (represented by available soil Si).

Fertilisation with Si has become a widespread practice for various crops. A number of Si sources exist, including potassium silicate, sodium silicate and meta-silicate, calcium silicate, cement, rock dust, silicic acid, magnesium silicate, silicon gel and industrial by-products such as fly-ash and bagasse furnace ash. The type of Si fertiliser applied affects plant uptake (Ranganathan *et al*., 2006), possibly due to the ease of formation of orthosilicic acid from the fertiliser products (Mecfel *et al*., 2007). Uptake of Si by plants is also affected by the water regime or rainfall pattern and is greater under adequate rainfall or irrigation than under conditions of water deficit (Eneji *et al*., 2008). Improved uptake of Si by sugarcane plants was recorded by Bell *et al*. (2002) after bare or crop fallows, or soil fumigation. Similar results were found for K. The authors did not record increased levels of these nutrients in the soil; rather, they attributed the increased plant uptake to a reduction in pathogen pressure, leading to an improved root system.

2.4.3. The effects of silicon on sugarcane production

Sugarcane is a Si accumulator plant, and takes up more Si than any other mineral nutrient, accumulating up to 380 kg Si ha^{-1} in a 100 t ha^{-1} crop (Savant *et al*., 1999). The effects of applying Si to sugarcane were described by Mauritian researchers in the 1940s (De Villiers, 1947, cited in Meyer and Keeping, 2000). Since then numerous researchers have recorded sugarcane yield increases (Clements, 1965; Ayres, 1966; Fox *et al*., 1967; Ross *et al*., 1974; Korndörfer and Lepsch, 2001; Huang *et al*., 2009b) and a reduction in the leaf freckling that is associated with Si deficiency (Clements, 1965; Fox *et al*., 1967; Wong You Cheong *et al*., 1973) following application of silicate sources. The yield increases are generally associated with longer stalks, larger stalk diameters and an increased number of millable stalks, rather than an increase in the sucrose percent (Korndörfer and Lepsch, 2001). Such yield responses may last for six crops or more after calcium silicate (Ca_2SiO_4) application at planting (Ross *et al*., 1974). Silicon deficiency has been shown to decrease the rate of photosynthesis and sugar production when compared to Si-rich cane, even when deficiency symptoms are not evident (Wong You Cheong *et al*., 1971).

When calcium silicate slags are applied, there is difficulty in differentiating between the sugarcane response to the applied Ca (and other nutrients), the increased pH, and that obtained as a result of the Si (Sumner *et al*., 1991). Du Preez (1970) grew sugarcane on various KwaZulu-Natal Midlands soils in pots, and added a number of Si sources, including slags and cement, as well as calcium carbonate ($CaCO_3$). In general, yields were increased by the addition of both siliceous materials and calcium carbonate and were attributed to both decreased Al and Mn, and increased Si in the soils. Silicate slag appeared to be superior to calcium carbonate because it caused a similar increase in pH, gave higher yields and the consequences of over-application were considered less harmful. Gascho and Andreis (1974) reported increased sugarcane and sugar yields following application of calcium silicate slags in Florida, USA, and concluded that increased Si, rather than any alteration in uptake of other nutrients (such as P, Mn or Fe), or a liming effect, was the reason for the yield increases.

Berthelson *et al*. (2001b) applied various siliceous products (calcium silicate slags, mill ash, mud ash, cement, cement board by-product and rock dust) to sugarcane soils in ‘product trials’ in the Mossman, Innisfail and Bundaberg districts of Australia. Several of these products, especially the calcium silicate slags, cement and mill ash, resulted in significantly higher sugarcane yields than the control on low-Si soils. In a report on the same study, Berthelsen *et al*. (2003) stated that a strong relationship existed between relative cane yield and the Si status of the top visible dewlap leaf (the plant part usually sampled for nutrient studies in sugarcane).

Some of the most widely reported benefits of Si include its protective role against pests and diseases. The physical effects of Si on insect pests can include both reduced growth and mandibular wear (Goussain *et al*., 2002; Massey and Hartley, 2009). In sugarcane, Si application has consistently been shown by South African researchers to reduce incidence, growth and damage of the eldana stalk borer (Keeping and Meyer, 2002; Kvedaras and Keeping, 2007; Kvedaras *et al*., 2007) through increased Si deposition in the epidermal tissue (Keeping *et al*., 2009). The application of Si has also resulted in a degree of control over other sugarcane pests, including Spittlebug (*Mahanarva fimbriolata*) in Brazil (Korndörfer *et al*., 2011), sugarcane top borer (*Scirpophaga nivella intacta*) in Indonesia (Saeroji *et. al*., 2010), and nematodes in South Africa (Berry *et al*., 2011) and South America (Silva *et al*., 2010). Silicon may also reduce the incidence and severity of fungal plant diseases as in the protection of sugarcane against common rust (*Puccinia melanocephala*) (Cadet *et al*., 2003).

Meyer and Keeping (2000) list a number of other benefits of Si, including enzyme regulation in sugar synthesis, storage and retention in the cane plant, and increasing the resistance of cane to “freeze damage”. Savant *et al*. (1999) also mention the latter, as well as other benefits such as improved water economy and reduced lodging. As a result of the numerous recorded benefits, Si is widely added as a sugarcane fertiliser in Brazil, Australia, South Africa, India and the USA (Epstein, 1999; Savant *et al*., 1999).

2.4.4. Nutrient interactions

2.4.4.1. Silicon interactions with potassium

After application of calcium silicate to sugarcane, Huang *et al*. (2009b) found that increased rates of Si were associated with a decrease in plant K at 12 months. Miao *et al*. (2010) applied Si to K-deficient soybean seedlings, increasing root and shoot mass and increasing the K concentration in the leaves, stems and roots by between 59 and 105%. The authors concluded that Si not only increases tolerance to nutrient toxicity, but also that deficiency symptoms associated with essential nutrients can be ameliorated by Si (Miao *et al*., 2010). Silicon application to wheat seedlings also increased K concentration in the shoots, enhancing salinity tolerance by increasing K uptake and hence increasing the K:Na ratio, thereby lowering Na translocation to the shoot (Tahir *et al*., 2010). Potassium fertilisation has been reported to have an effect on Si uptake, though this effect is variable and often small. Hartt (1934) found that increased K caused a slight decrease in the Si content of sugarcane.

2.4.4.2. Silicon interactions with nitrogen

When plants are N-deficient, application of N generally leads to decreased Si uptake because N fertilisation leads to more efficient water use by plants. The effect on Si is therefore an indirect one, because the more efficient plant produces more dry matter for each unit of water and Si absorbed (Jones and Handreck, 1967). This interaction would be particularly notable in plants in which Si uptake is passive (and hence driven by water uptake). Once plants are receiving adequate N, dry matter production, and hence Si content, level off.

Dilution by growth effects (Marschner, 1995) were also reported by Hsieh *et al*. (1983), who studied the effects of dolomitic lime, N rates and rice hull (a Si source) applications on the Si content and growth of rice in Taiwan. As N rates increased, growth generally improved, but the Si content of the rice tended to decrease. Dolomitic lime and rice hull applications at the highest N rates tended to increase rice growth and yield, and improved resistance to lodging and blast. Lower N rates did not facilitate maximum growth. Thus the highest rate of N was required to improve growth and yield, while lime and Si were needed for resistance to lodging and blast (Hsieh *et al*., 1983). Huang *et al*. (2009b) found that increasing application rates of calcium silicate to sugarcane were associated with a decrease in plant N at 12 months. Eneji *et al*. (2008), however, found that Si uptake by four grass species was positively correlated with N uptake under deficit irrigation.

2.4.4.3. Silicon interactions with phosphorus

Many researchers have reported beneficial effects of Si on plant growth when available P is low, but the reasons for this are poorly understood (Tavakkoli *et al*., 2011a). It is suggested that increases in extractable P (and plant uptake) following Si application could be due to Si displacing P from the soil adsorption sites, or to an increase in P solubility resulting from an increase in soil pH (Berthelsen *et al*., 2003; Eneji *et al*., 2008). Adding P to P-deficient plants tends to decrease plant Si, via dilution by growth, similar to N (Jones and Handreck, 1967).

2.4.4.4. Silicon interactions with calcium and magnesium

In rice, Ma and Takahashi (1993) found that Si addition resulted in a decrease in Ca content of the shoots, as well as Ca uptake, at each Ca level tested. The authors believed that this mainly resulted from a decreased transpiration rate caused by Si. Silicon uptake was not affected when Ca levels were increased.

Anderson (1991) reported nutrient antagonism between Si and Mg in sugarcane. The author suggested that application of Mg fertiliser may be necessary to maintain high Mg availability when Si is applied. Kidder and Gascho (1977) also recommended concurrent Mg fertilisation (along with Si) as a precaution if the soil Mg test value was below a certain threshold.

2.5. Nutrient recommendations

2.5.1. Potassium

In most countries, fertiliser K recommendations for sugarcane are based on the topsoil test K value, and are modified according to various factors, as determined by field trials. Most of the countries listed by Kingston (2000) and Meyer (2013) base their K recommendations on concentrations of exchangeable soil K. In Australia and Mauritius, K recommendations are also modified according to non-exchangeable soil K reserves (Schroeder and Wood, 2002; Meyer, 2013). Potassium recommendations may be further adjusted by taking one or more of the following factors into account:

- Texture and base status of the soil, attainable (potential) yield, harvesting method (green or burnt cane harvesting) (South Africa) (Miles, 2014).
- Crop age (plant versus ratoon) (Brazil, Cuba, USA and South Africa) (Meyer, 2013).
- Leaf K concentration (Cuba) (Meyer, 2013).
- Potassium concentration in irrigation water (Hawaii, USA) (Meyer, 2013).
- Percentage of total CEC occupied by K (Dominican Republic) (Redman, 1991).
- Soil acidity (Indonesia) (Soepardi, 1991).
- Soil parent material (Indonesia) (Meyer, 2013).

Meyer (2013) presents a summary of selected soil K threshold values and K fertiliser recommendations for a number of sugarcane-producing areas.

2.5.2. Nitrogen

Soil N tends to be ephemeral, with N liable to change form due to biological and chemical reactions and to be lost by various mechanisms. For these reasons, N fertiliser recommendations for sugarcane are not typically based on N soil tests. Rather, N recommendations tend to be based on N response trials, and are modified according to a number of factors. Nitrogen mineralisation potential of the soil (Schroeder *et al*., 2005, 2007; Meyer, 2013; Miles, 2014), district yield potentials (Schroeder *et al*., 2006) and attainable yield (yield target per field) (Miles, 2014) are some of the main drivers of N fertiliser recommendations. Other factors used to modify N recommendations include:

- Crop age (plant versus ratoon) (Australia, USA, Brazil, India and South Africa) (Meyer, 2013).
- Residual N from leguminous cover crops (South Africa (Miles, 2014); Australia (Schroeder *et al*., 2005); India (Meyer, 2013)).

Meyer (2013) presents a summary of selected N fertiliser recommendations for a number of sugarcane-producing areas.

2.5.3. Silicon

Plant-available Si in soils may be estimated using both acid and neutral extractants (Sauer *et al*., 2006). Threshold values for the various extractants have been established through field trials and soils with Si concentrations below these thresholds should receive Si applications in order to attain optimal sugarcane yields.

In South Africa, recommendations for Si application are not routinely made by the FAS. Rather, when soil Si falls below the threshold of 15 mg Si L^{-1} in 0.01 *M* $CaCl_2$ (Miles, 2014), it is suggested that growers consider some form of Si application. At present, Calmasil® is commonly used to replace some, or all, of the dolomitic lime recommendation.

2.6. The thesis in context: Gap analysis and motivation for the study

As shown by this review, K, N and Si have been the subject of extensive research on a number of different crops, and much is known about their functions and requirements in sugarcane. Questions remain, however, which require addressing in order to refine the recommendations currently made by soil testing laboratories, and the FAS in particular.

2.6.1. Potassium

Dynamics between the different pools of K (Section 2.2.1) result in a range of K availability to plants. Potassium release from less readily-available pools can buffer K availability, satisfying a crop's needs even when exchangeable (readily-available) K is low. The extent of this availability has not, until recently, been explored in the South African sugar industry, and the K supplying power of local soils is not well established. The extent to which even low reserve K can contribute to crop K supply has not been investigated in South African sugarcane soils and, because excessive K may reduce mill sucrose recovery, appropriate K recommendations are essential.

Fertiliser recommendations are typically based on measurements of readily-available K in the top 20 cm of soil. However, international research suggests that plant roots can source K from greater depths. This has not been studied in the South African sugar industry and it is not known if subsoil K should be taken into account when making K fertiliser recommendations. Stratification of K, especially in higher clay soils, may also affect soil sampling and general management, and requires investigation. The effect of K application on sugarcane root growth (depth and general root proliferation) is also largely unknown.

Potassium's interactions with other nutrients, particularly Ca and Mg, have been well documented in a number of crops. In sugarcane, high Ca and Mg are known to inhibit K uptake, necessitating higher K recommendations under certain conditions. The reverse, however, has not been widely investigated internationally, and not at all in the South African sugarcane industry. Understanding the interactive effects of high soil K on Ca and Mg uptake may lead to improved nutrient recommendations within the industry. In addition, interactions between K and other nutrients, including N and Si, require further elucidation. Potassium fertilisation of sugarcane may affect Si uptake, though this effect is variable and often small. The extent and regularity with which K application affects plant Si uptake needs further study.

2.6.2. Nitrogen

Although N nutrition in sugarcane has been the subject of substantial research, some knowledge gaps remain. One relates to N fertiliser recommendations in plant crops in comparison with the ratoon crops. In the South African set of recommendations, plant crops routinely receive less N than ratoon crops, assuming N release following land preparation. In humic soils, it may be possible to reduce the N application further, but no substantial trial work to investigate this suggestion has been performed.

Other gaps involve the interactions between N and other nutrients. For example, increased plant N may lead to a decrease in plant Si concentration, following dilution by growth. This phenomenon, little studied in sugarcane, may have relevance in the South African context where adequate plant Si concentrations are required to offset increased N in restricting eldana damage. A further consideration is that the application of Si products (which usually have a liming effect) may lead to the proliferation of soil bacteria, stimulating N release and subsequent plant uptake. Further study is required to investigate the possible effects of Si application on N uptake and, consequently, sucrose concentration.

Nitrogen is a driver of plant growth and may, therefore, alter the uptake and concentration of other applied nutrients. A study of nutrient application rates, and K in particular, is more complete when the effects of different N levels are taken into consideration.

2.6.3. Silicon

While the benefits to sugarcane of added Si are well documented, the appropriate soil threshold under South African conditions is still a matter of debate. The current industry soil Si threshold of 15 mg L^{-1} has not been researched sufficiently to be confident that this level provides the known benefits.

Whatever the threshold used, it has proven challenging to increase plant uptake of Si from products such as Calmasil®. Further work is required to establish the extent to which plant Si can be increased by the application of Calmasil® or other products, and whether this is sufficient to reach (or exceed) threshold values. It is necessary to know, in cases where Si application increases plant Si without actually reaching the threshold, whether sugarcane yield is nonetheless increased. The general effects of Si application on cane yield also require confirmation on South African soils. Understanding will be improved if Si-related sucrose yield increases (if any) can be apportioned to either increased stalk yield or sucrose concentration, or both.

The behaviour of applied Si in soil also requires elucidation. The extent to which Si moves in the soil, or results in stratification, has not been investigated locally. In addition, little is known of the effects of Si on sugarcane rooting and whether such effects can explain why drought tolerance is improved with Si application.

These aspects are reflected in the key questions given in Chapter 1 (Section 1.3.2). They centre around the effects of K, N and Si on sugarcane crop yield and quality, which, in turn, will inform the nutrient recommendations which are made by the FAS in order to achieve optimal yield.

CHAPTER 3

The effect of application rates of potassium, nitrogen and silicon on sugarcane harvest characteristics

3.1. Introduction

Potassium (K) fertiliser recommendations for sugarcane have not kept pace with K removals and unsustainable K ‘mining’ has occurred, both in South Africa and overseas (Kingston, 2000). In South Africa, this has resulted in low K reserves in many topsoils of the rainfed sugarcane areas (Van der Laan and Miles, 2010). The importance of K can be underestimated for a number of reasons (Section 2.2). The role of K in soils [and plants] is, however, “prodigious” (Sparks and Huang, 1985), and accurate estimates of the K requirements of sugarcane are needed.

Nitrogen (N) has been extensively studied, and continues to be investigated due to its pivotal role in sugarcane growth and yield (Stranack and Miles, 2011), its characteristic as a ‘driver’ of the uptake of other nutrients (Miles, 2010) and the widely differing extent to which N is supplied by different soils (Meyer *et al*., 1986). Too much N adversely affects crop quality (Singh, 1973), and the effect of excessive N on crop susceptibility to pests (Carnegie, 1981) and diseases (Mengel and Kirkby, 2001) is well known.

Silicon (Si), although not considered essential for sugarcane, is a ‘beneficial’ nutrient (Meyer, 2013) due to its importance in protecting against biotic and abiotic stress. Research has highlighted the extensive Si deficiency of sugarbelt soils in the rainfed parts of the country (Van der Laan and Miles, 2010) and further research is required to understand its effects on sugarcane growth and to establish sound approaches for correcting Si deficiencies.

While the individual effects of nutrients on sugarcane are important and, in some cases, well documented, the interactions between nutrients are less well understood. Interactions between N and Si, for example, have been recorded by Meyer and Keeping (2005). Other interactions between K, N and Si, on different soils, require elucidation. This study was therefore designed to determine the effect of various application rates of K, N and Si, along with their interactions, on sugarcane yield and other harvest characteristics, to assist in refinement of the industry nutrient recommendations.

3.2. Materials and methods

3.2.1. Trial sites

The contrasting soil types at the two trial sites on the KwaZulu-Natal north coast were selected as they represent approximately 70% of the rainfed area of the South African sugar industry and 50-60% of the total area cropped to sugarcane. One trial was situated in the Inanda area, on the farm 'Inanda' (29.629°S, 30.928°E; 560 m a.s.l.), inland of Verulam (Figure 3.1). Mean annual rainfall is approximately 1 090 mm, with most (74%) occurring during the summer months (October to March). The area has mean daily maximum and minimum temperatures of 25.7ºC and 16.2ºC, respectively. The soil is an Oxisol (Humic Eutrustox; Soil Survey Staff, 2014); Humic Ferralsol (IUSS Working Group WRB, 2014); Inanda form, Glenariff family (Soil Classification Working Group, 1991), with an effective rooting depth of over 100 cm.

The second trial was located on the farm 'Thornwood' at Doringkop (29.220ºS, 31.240ºE; 427 m a.s.l.), inland of KwaDukuza (Stanger) (Figure 3.1). Mean annual rainfall is 1 130 mm, with most (77%) occurring between September and March. The mean daily maximum temperature is 26.7ºC and the mean daily minimum 16.5ºC. The soil is an Inceptisol (Typic Haplustept; Soil Survey Staff, 2014); Leptic Cambisol (IUSS Working Group WRB, 2014); Glenrosa form, Dumisa family (Soil Classification Working Group, 1991), with an effective rooting depth of approximately 80 cm. The parent material at both trial sites is Natal Group Sandstone (Mariannhill Formation, Tulini Member) (Marshall and Von Brunn, 1999). The trial sites are henceforth referred to by their soil type, i.e. Oxisol and Inceptisol.

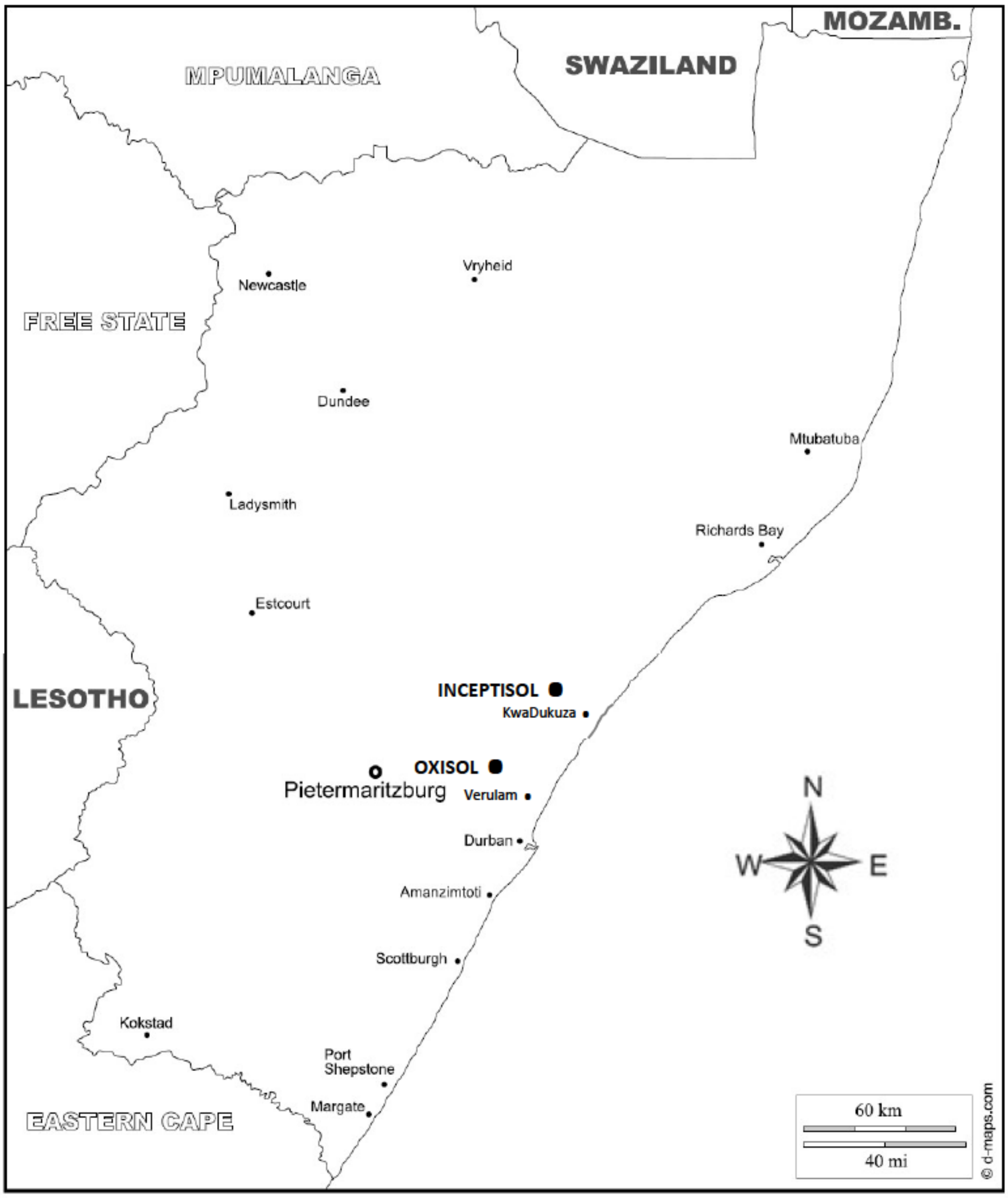
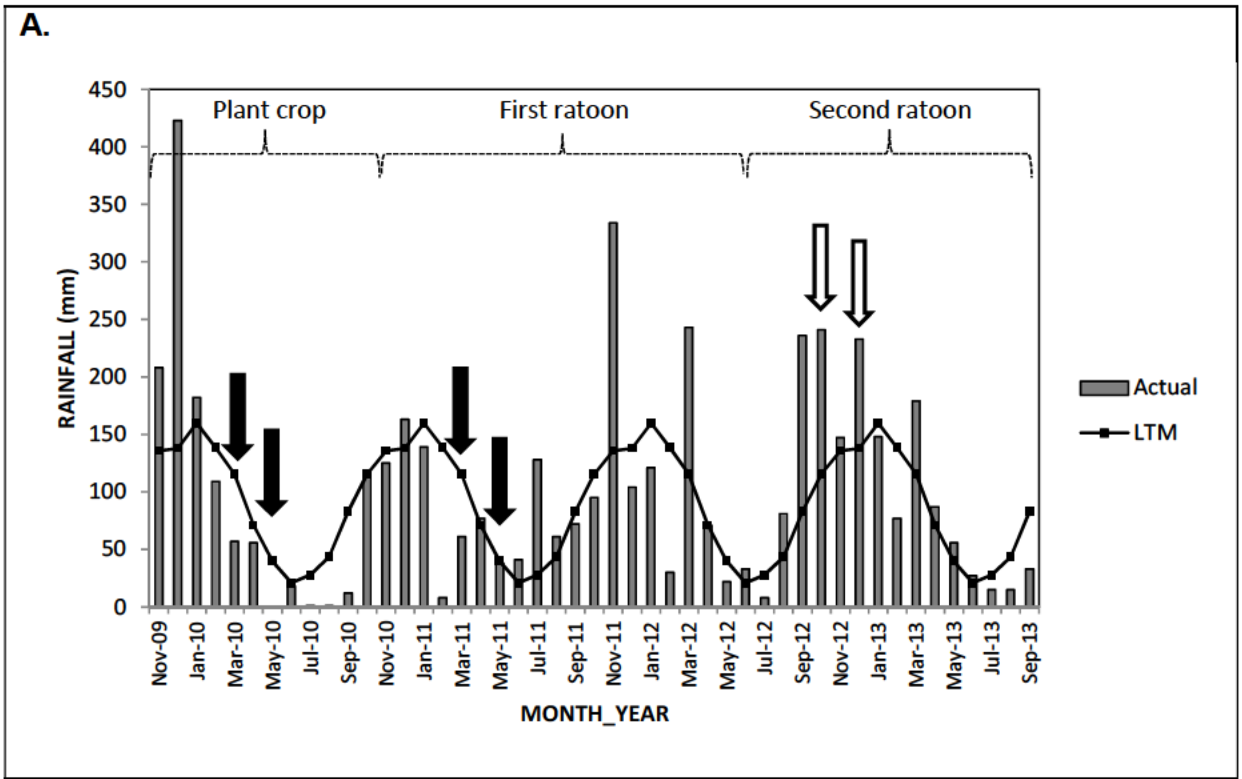


Figure 3.1: Location of trial sites (Oxisol and Inceptisol) within the Province of KwaZulu-Natal, South Africa. (Image: modified from http://d-maps.com/m/africa/southafrica/kwazulu-natal/kwazulu-natal22.pdf accessed 19 Sep 2017).

3.2.1.1. Rainfall

The Oxisol (Figure 3.2A) received 101%, 103% and 134% and the Inceptisol (Figure 3.2B) 98%, 115% and 104% of the long-term mean (LTM) for each of the three growing seasons, respectively.



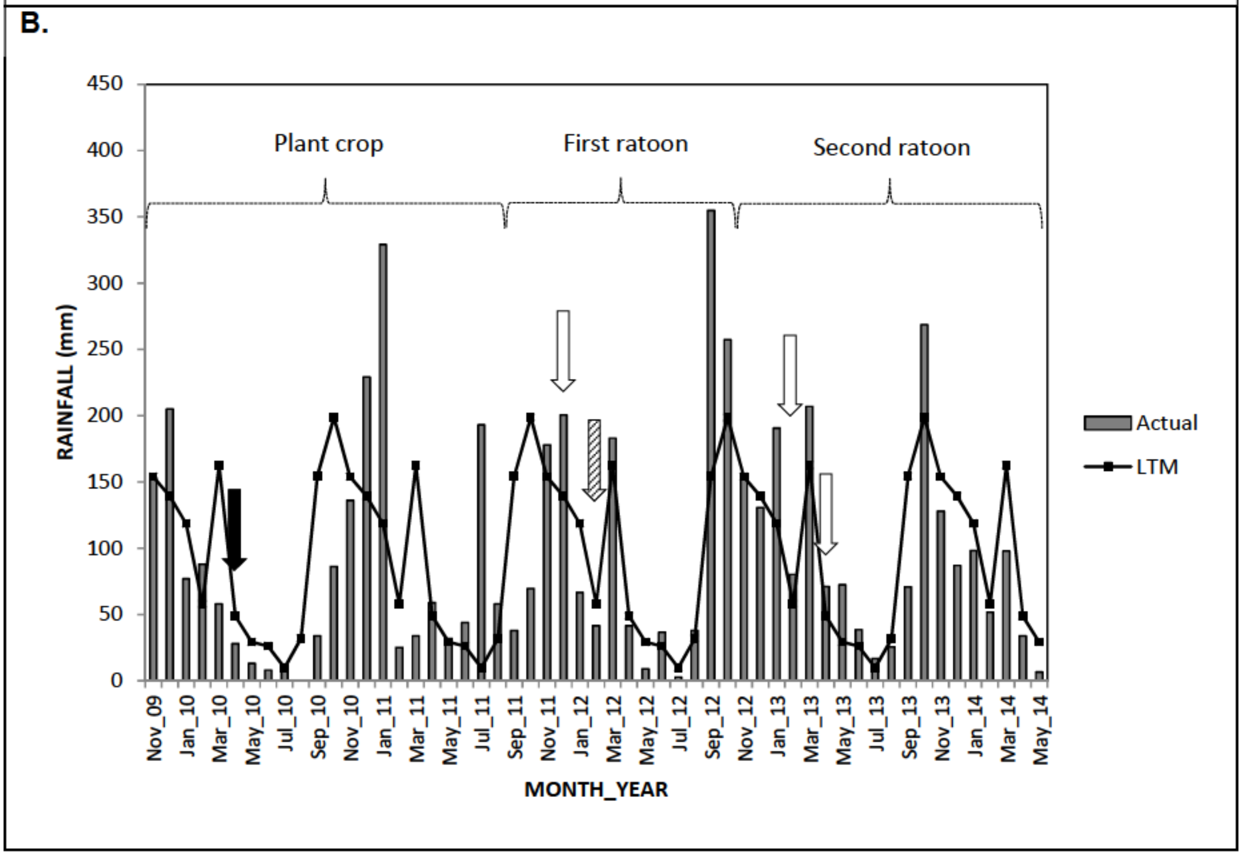


Figure 3.2: Monthly long-term mean (LTM) and actual rainfall for the duration of the trial on the (A) Oxisol and (B) Inceptisol. Arrows indicate the months in which leaf sampling (Section 4.2.2) was done. Black, hatched and white arrows indicate possible limiting, marginal and acceptable moisture conditions, respectively, at the time of leaf sampling.

There was, however, a severe drought during the winter of 2010. From February to September 2010, the Oxisol received only 47% of its LTM; the Inceptisol, 46%. Both sites received some rainfall into April 2010 (Figure 3.2), lessening the effects of the drought.

Following the 2010 drought, each site experienced intermittent periods of above- or below-average rainfall, but the higher than average rainfall of spring 2012 was the only other period where rainfall was consistently different to the LTM over a period of three to four months.

3.2.2. Soil sampling

Soil samples were collected with an auger, from 0-20, 20-40, 40-60 and 60-80 cm at both sites in October 2009, before trial establishment. Composite samples were taken to represent each trial site: four on the Oxisol, and three on the Inceptisol. Soils were analysed by the Fertiliser Advisory Service (FAS) at the South African Sugarcane Research Institute (SASRI) according to the methods given in Appendix 3.1. Topsoils (0-20 cm) were also sampled and analysed after each harvest to monitor nutrient levels.

3.2.3. Trial establishment and treatments

Both trials were established during summer 2009/2010 (Table 3.1). South African-bred sugarcane varieties N37 (Oxisol) and N39 (Inceptisol) were chosen due to their general suitability to the soils and areas (SASRI, 2006a and b). At each trial site, three crops of sugarcane were harvested: the ‘plant crop’ (the first crop harvested after planting) and the first two ratoon crops (ratoons one and two) (Figure 3.2).

The trials were factorial, and four replications of each combination of nutrients were broadcast in a randomised complete block design. Potassium (as potassium chloride) was applied at rates of 0, 100, 200 and 300 kg K ha^{-1} at both sites, to all crops. The FAS recommendation was 250 kg K ha^{-1} (plant crop) and approximately 200 kg K ha^{-1} (ratoon crops) for both soils. The N rates (as urea) were 0, 80 and 160 kg N ha^{-1} on the Oxisol, and 0, 105 and 210 kg ha^{-1} on the Inceptisol. The middle N rates corresponded to the FAS recommendation for each soil. At both sites 300 kg Si ha^{-1} (as Calmasil®, a calcium silicate slag) was applied to the plant crop.

This was the standard FAS recommendation for any soil where Si was below the threshold of 15 mg L^{-1} (Miles, 2014). The Calmasil® treatment also provided approximately 870 kg ha^{-1} and 195 kg ha^{-1} of calcium (Ca) and magnesium (Mg), respectively.

Due to the shape of the fields, treatment application and incorporation differed between the two sites (Table 3.1). On the Oxisol, the K, N and Si were applied between four and ten days prior to planting, and disced into the soil to a depth of 15 cm. On the Inceptisol, use of a tractor for incorporation was not possible, and treatments were applied three weeks after planting and raked into the soil to a depth of 3-5 cm.

At each site, basal rates of phosphorus (P), zinc (Zn) and dolomitic lime were broadcast across the entire trial at planting, in accordance with site-specific recommendations. Each site received 20 kg P ha^{-1} (as single superphosphate 10.5% P), 5 kg Zn ha^{-1} (as zinc sulphate, 22% Zn) and 2.5 t dolomitic lime ha^{-1}. In addition, gypsum was applied to the Oxisol (5 t ha^{-1}) and the Inceptisol (3 t ha^{-1}).

Table 3.1: General trial details for the Oxisol and Inceptisol sites

Parameter	Oxisol	Inceptisol
Sugarcane variety	N37	N39
Date of planting	20 November 2009	12 December 2009
Plot size	63 m^2 (7 rows x 9 m, 1 m row spacing)	56 m^2 (7 rows x 8 m, 1 m row spacing)
Horizontal (end to end) spacing between plots	1 m	1 m
Number of guard rows flanking each plot	1	1
Number of replicates	4	4
Total number of plots	96	96
Method of fertiliser incorporation	[1]Tractor-drawn disc harrow (to ~15 cm)	[2]Raked in by hand (to ~5 cm)

[1]Rectangular field, allowing the trial to be pegged, treatments applied and incorporated (by tractor), and planting furrows drawn in straight lines whilst leaving the existing pegs in place.

[2]Curved field, necessitating planting of sugarcane first, followed by pegging and treatment application. Treatments then incorporated by hand between the rows, so as not to damage the cane.

Following harvest of the plant and first ratoon crops, K and N fertilisers were re-applied (see Appendix 3.2 for application dates). In accordance with FAS recommendations, 30 kg P ha^{-1} (as single superphosphate) was also broadcast across the entire trial at the Oxisol site after harvest of the first ratoon crop. No P was required at the Inceptisol site as soil P levels were above the threshold.

Silicon uptake in sugarcane can be limited under certain conditions (Keeping, 2017), and even increasing soil Si by Si application may not raise plant levels above local thresholds (Keeping *et al*., 2017). Due to limited plant uptake of Si in the first two crops, the decision was made to use a different Si source after harvest of the first ratoon crop at both trial sites. Cement (CIMPOR NPC PRO blastfurnace Cement CEM III/A 32.5 N) was applied at a rate of 6 t ha^{-1} (equivalent to 300 kg Si ha^{-1}) to all plots that had received Si previously. In addition to the Si, this quantity of cement supplied 1 600 kg Ca ha^{-1} and 223 kg Mg ha^{-1}. The dry cement was broadcast and the plots hand-raked to incorporate the cement to approximately 3 cm. The zero Si plots, which received no cement, were also hand-raked to treat the plots equitably.

At each trial site, weeds were controlled by the grower, according to the standard procedure and herbicide formulation used on the rest of the farm.

3.2.4. Trial harvest

The crops were harvested (see Appendix 3.3 for harvest dates) according to the area, milling season and grower preference. At each harvest, the sugarcane was burnt a maximum of 12 h before sampling. After burning, 12 stalks of sugarcane were randomly selected and cut from each plot. All leaf material (including the green tops) was removed from these stalks, and the bundles sent to the SASRI millroom where percent estimated recoverable crystal (%ERC) was determined. Estimated recoverable crystal indicates the amount of sucrose that will be extracted per unit mass of sugarcane during the milling process, and is used as a measure of cane quality.

Plots were harvested manually using cane knives. The outermost edge row (guard row) at the top and bottom of each plot was left standing, and the remaining 5 net rows cut. The green tops and immature meristem area were cut off as per commercial practice, and the harvested stalks weighed using a grab and balance mounted on a vehicle to determine yield.

At the Inceptisol site, 32 plots were accidentally sprayed with a hormonal ripening agent by the grower during the growth of the second ratoon crop, necessitating that they be destroyed. The second ratoon harvest, therefore, was conducted on only 64 plots.

3.2.5. Statistical analysis

Mean sugarcane yield (t ha^{-1}), %ERC and sucrose yield (t ERC ha^{-1}) (yield x %ERC; on which sugarcane growers' payments are based), per treatment were analysed using analysis of variance (three-way ANOVA) and, in the case of the unbalanced dataset from the Inceptisol second ratoon harvest, residual maximum likelihood (REML) (Genstat, 14th Edition, VSN International, 2011). Where treatments showed significant effects, values were analysed using the Holm Sidak multiple comparison separation or Fisher's protected least significant difference (LSD) test to identify where the differences between treatment means lay. Differences were considered to be significant at $P< 0.05$.

3.2.6. Economic analysis

Partial net returns (partial budgets) were calculated to determine the economic viability of various fertiliser (type and rate) applications. A partial budget allows evaluation of the financial effect of management decisions, and only includes costs that will be changed; it does not consider resources that are left unchanged (Tigner, 2018). The partial budgets included costs for fertiliser/Calmasil® purchase and application, harvesting and transport (Tweddle, 2020), and increases in sucrose yield (t ERC ha^{-1}).

3.3. Results and discussion

3.3.1. Initial soil conditions

Pre-trial soil conditions are summarised in Table 3.2. The Oxisol had higher clay and organic matter and thus a lower sample density than the Inceptisol. Both soils had moderately low pH values, while acid saturation was high, particularly at depth in the Oxisol. Topsoil (0-20 cm) K was relatively low in both soils, and topsoil Si marginally lower than the FAS threshold of 15 mg L^{-1}. Topsoil Ca and Mg were above their FAS threshold values of 300 and 50 mg L^{-1}, respectively (Miles, 2014).

Table 3.2: Selected pre-trial soil properties (mean ± s.e.) of the Oxisol (n=4) and the Inceptisol (n=3)

Soil	**Depth** (cm)	**Clay**	**Organic C**	**pH ($CaCl_2$)**	**[a]Total cations** ($cmol_c$ L^{-1})	**[b]Acid sat.** (%)	**Sample density** (g mL^{-1})
		---- (g kg^{-1}) ----					
Oxisol	0-20	410 ± 12	39.0 ± 0.7	4.43 ± 0.02	8.4 ± 0.2	24.7 ± 1.1	1.09 ± 0.01
	20-40	400 ± 4	34.3 ± 1.6	4.29 ± 0.03	7.0 ± 0.2	44.0 ± 2.7	1.11 ± 0.01
	40-60	410 ± 10	26.7 ± 0.5	4.29 ± 0.03	7.5 ± 0.4	55.3 ± 5.1	1.14 ± 0.01
	60-80	420 ± 25	22.1 ± 1.1	4.30 ± 0.04	5.2 ± 0.2	60.0 ± 5.0	1.15 ± 0.01
Incepti-sol	0-20	240 ± 2	14.0 ± 1.3	4.17 ± 0.02	5.7 ± 0.4	23.7 ± 2.0	1.26 ± 0.01
	20-40	250 ± 10	12.8 ± 0.5	4.06 ± 0.06	5.3 ± 0.8	39.3 ± 4.8	1.26 ± 0.01
	40-60	280 ± 7	12.2 ± 0.6	4.37 ± 0.07	5.2 ± 1.0	22.6 ± 4.1	1.24 ± 0.01
	60-80	390 ± 29	9.9 ± 0.2	4.46 ± 0.07	7.8 ± 0.8	19.6 ± 3.4	1.16 ± 0.01

Soil	**Depth** (cm)	**P**	**K**	**Ca**	**Mg**	**Si**
		----------------	----------------	(mg L^{-1})	----------------	----------------
Oxisol	0-20	52 ± 5	55 ± 2	415 ± 121	164 ± 39	13.8 ± 0.9
	20-40	24 ± 4	29 ± 1	313 ± 99	118 ± 32	15.2 ± 1.4
	40-60	8 ± 2	17 ± 2	264 ± 54	109 ± 20	11.8 ± 1.7
	60-80	9 ± 1	13 ± 0	243 ± 54	102 ± 21	7.2 ± 1.9
Incepti-sol	0-20	16 ± 5	44 ± 3	324 ± 55	110 ± 9	12.3 ± 1.1
	20-40	6 ± 1	41 ± 2	227 ± 47	71 ± 12	13.7 ± 1.2
	40-60	8 ± 3	40 ± 2	238 ± 64	77 ± 15	8.3 ± 1.5
	60-80	13 ± 7	47 ± 3	301 ± 40	147 ± 32	8.4 ± 0.9

[a]Total cations = sum of (Al^{Ψ} + H^{Ψ} + K + Ca + Mg + Na^{Ψ}); [Ψ]Data not shown
[b]Acid saturation = 100 * [(Al + H) / (Al + H + K + Ca + Mg + Na)]

3.3.2. Effect of potassium on sugarcane harvest characteristics

3.3.2.1. Oxisol

3.3.2.1.1. Stalk yield

Yields of the plant, first and second ratoon crops, and when all three crop yields were combined, showed no significant differences at any of the K rates applied (data not shown). However, when only the two ratoon crops were combined, the yield from the 300 kg K ha^{-1} treatment (103.1 t ha^{-1}) was significantly ($P < 0.05$) greater than the zero K treatment (97.7 t ha^{-1}). Neither of the intermediate K rates yielded significantly higher than the control (data not shown). Removal of K by successive crops in the three lowest K treatments led to increasing K deficiency, with the consequent response to K becoming significant in the later crops. Du Toit (1957) and Wood and Meyer (1986) also noted that ratoon crops responded more to added K than plant crops.

3.3.2.1.2. Sucrose percent

As was the case for yield, the first two crops on the Oxisol showed no effect of K application rate on sucrose percent (%ERC), but in the second ratoon, all rates of K increased %ERC significantly compared to the control (Figure 3.3). The sum of all crops, as well as the ratoon crops only, showed a similar pattern. The effect of K on %ERC is not surprising, given the role that K plays in the stimulation of phloem transport of sugars (Kingston, 2000; Wood and Schroeder, 2004). This effect has not been widely reported in the industry, however, perhaps because the %ERC of cane will not usually increase with increased K application on K-sufficient soils (Du Toit, 1960).

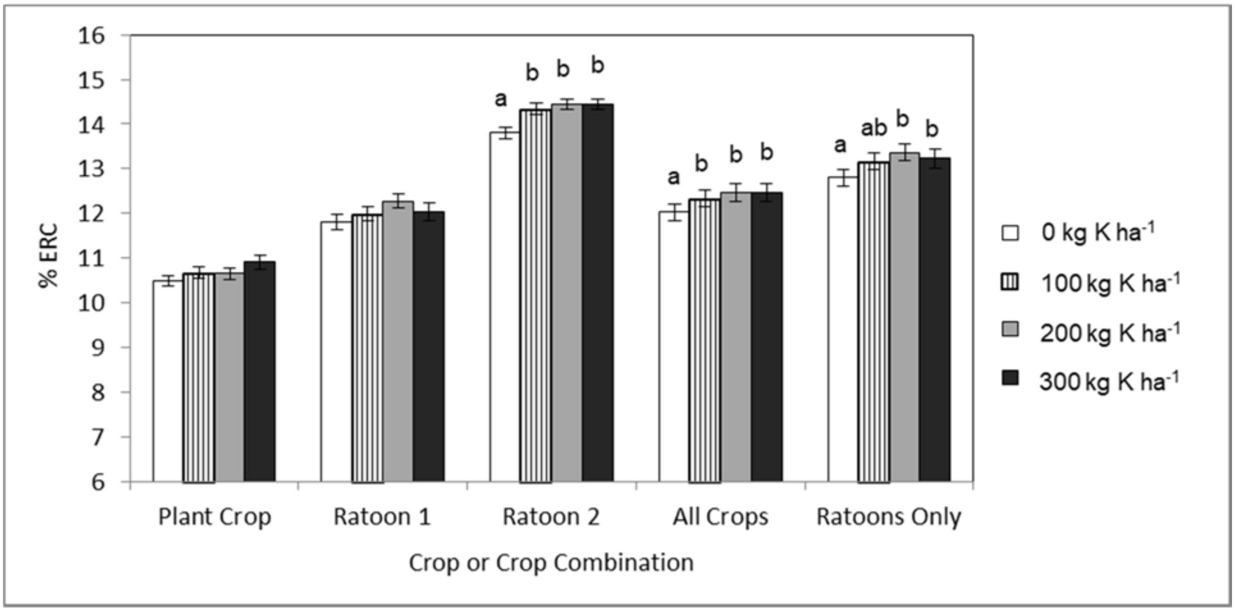


Figure 3.3: Oxisol: The effect of potassium (K) application rate on percent estimated recoverable crystal (%ERC) for each individual crop (Plant Crop, Ratoon 1, Ratoon 2), the average over all three crops (All Crops) and the ratoon crops (Ratoons Only). Within crops or crop combinations, columns with different letters are significantly different to each other (P < 0.001).

3.3.2.1.3. Sucrose yield

Although sugarcane stalk yields (t cane ha^{-1}) on the Oxisol were generally unaffected by K application, the significant effect of K on %ERC resulted in similar significant effects of K on the tonnes of sucrose obtained (Figure 3.4). The t ERC ha^{-1} were significantly increased by K application rates of 200 and 300 kg ha^{-1}, compared to the zero K treatment, in the second ratoon, the average over all crops, and the ratoon crops only.

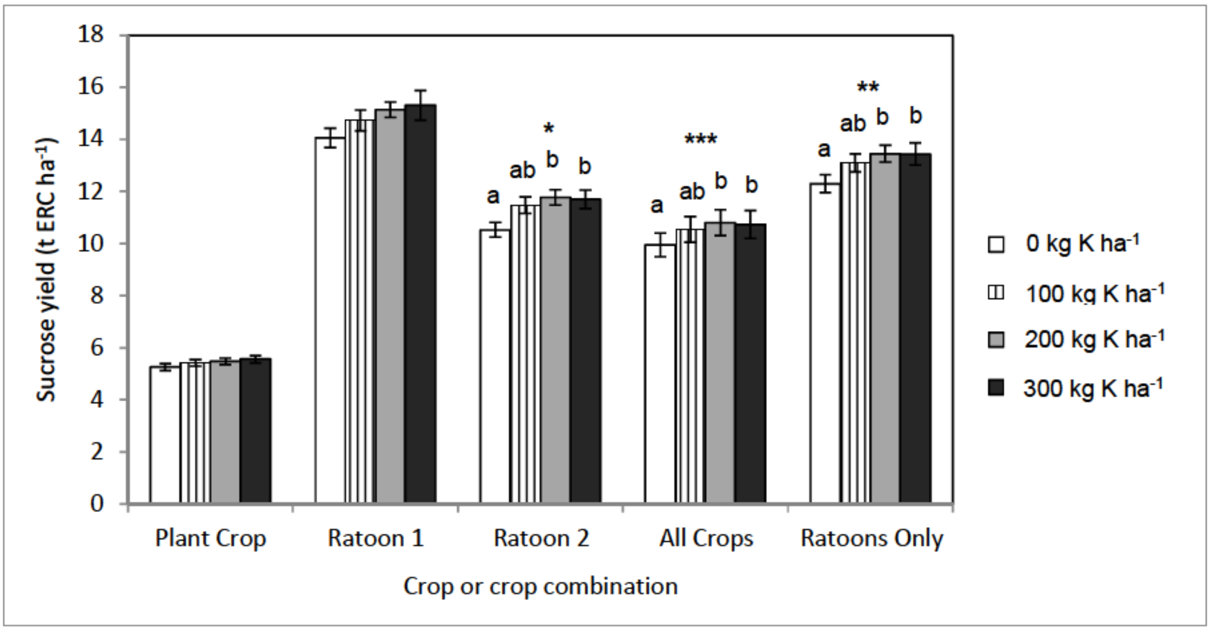


Figure 3.4: Oxisol: The effect of potassium (K) application rate on sucrose yield for each individual crop (Plant Crop, Ratoon 1, Ratoon 2), the average over all three crops (All Crops) and the ratoon crops (Ratoons Only). Within crops or crop combinations, columns with different letters are significantly different to each other (*$P < 0.05$; **$P < 0.01$; ***$P < 0.001$).

3.3.2.2. Inceptisol

3.3.2.2.1. Stalk yield

In contrast to the Oxisol, K application to the Inceptisol significantly increased sugarcane yield in the first ratoon, as well as when all crop data were combined and when the ratoons only were considered (Figure 3.5). In each case, yields from the 200 kg K ha^{-1} treatment were significantly greater than those from the control plots; neither the 100 nor the 300 kg K ha^{-1} treatments were significantly different to the control. As found on the Oxisol, ratoon crop yields responded more to K than the plant crop.

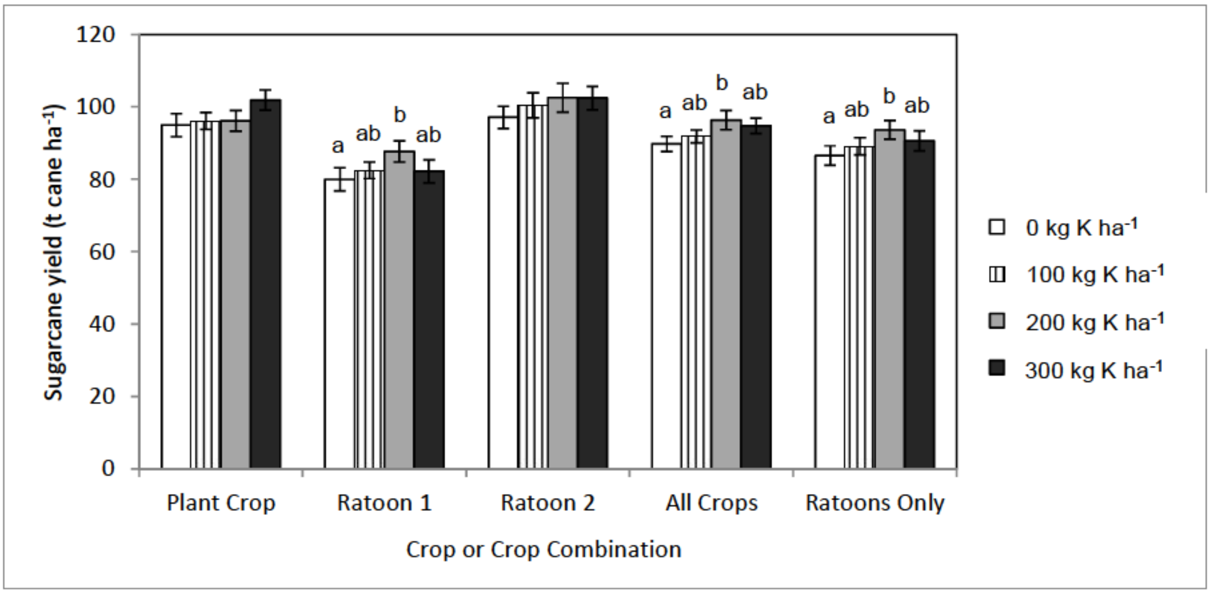


Figure 3.5: Inceptisol: The effect of potassium (K) application rate on sugarcane stalk yield for each individual crop (Plant Crop, Ratoon 1, Ratoon 2), the average over all three crops (All Crops) and the ratoon crops (Ratoons Only). Within crops or crop combinations, columns with different letters are significantly different to each other ($P < 0.05$).

3.3.2.2.2. Sucrose percent and yield

In contrast to the Oxisol, there was no significant effect of K on %ERC in any of the crops or crop combinations on the Inceptisol (data not shown). Application of K to the Inceptisol led to increases in sucrose yield in all crops and crop combinations except the second ratoon (Figure 3.6). In contrast to the Oxisol, however, these increases were attributable to increases in cane yield rather than %ERC. Compared to the control, sucrose yields on the Inceptisol were significantly increased by 200 kg K ha^{-1} in the first ratoon, all crops together and ratoon crops only, and by 300 kg K ha^{-1} in the plant crop.

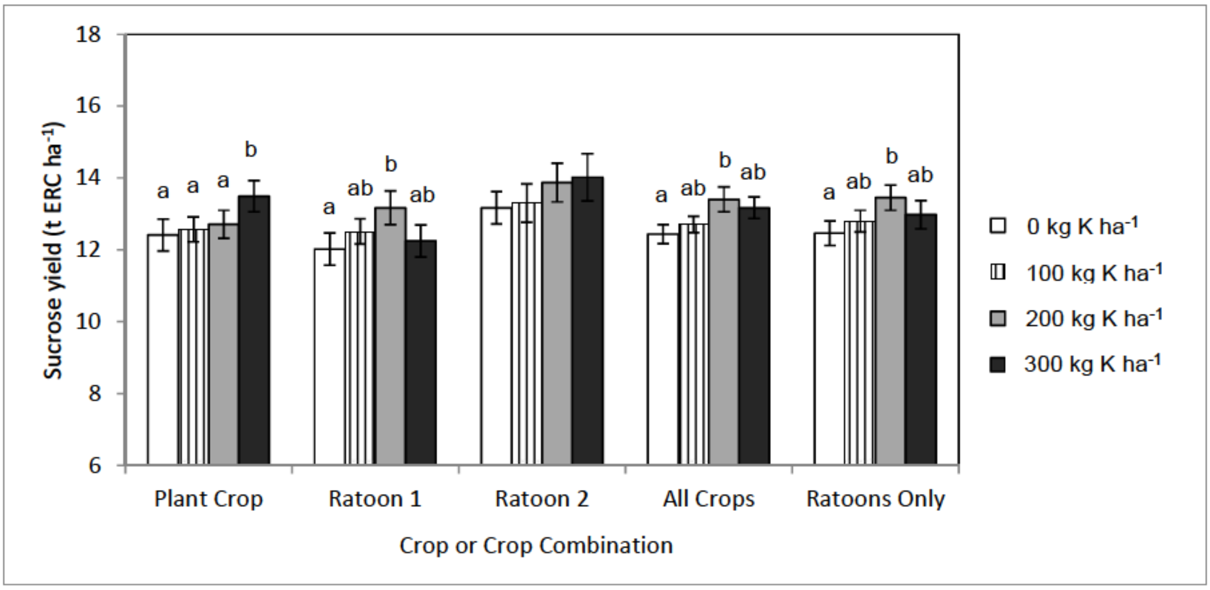


Figure 3.6: Inceptisol: The effect of potassium (K) application rate on sucrose yield for each individual crop (Plant Crop, Ratoon 1, Ratoon 2), the average over all three crops (All Crops) and the ratoon crops (Ratoons Only). Within crops or crop combinations, columns with different letters are significantly different to each other ($P < 0.05$).

3.3.2.3. Economic aspects

On the Oxisol, the 200 kg K ha^{-1} treatment yielded an additional 1.24 t ERC ha^{-1} in the second ratoon; the plant crop and first ratoon were unaffected by K rate. This K application would therefore have resulted in a loss of R3 377 ha^{-1} in comparison with the zero treatment (Table 3.3A).

On the Inceptisol, the addition of 200 kg K ha^{-1} yielded an additional 1.15 t ERC ha^{-1} in the first ratoon. The second ratoon was unaffected by K and the plant crop only showed a sucrose yield increase with 300 kg K ha^{-1}. Potassium application at 200 kg ha^{-1} would therefore have resulted in a loss of R3 665 ha^{-1} over the three crops (Table 3.3B).

Table 3.3: Partial budget for the application of 200 kg K ha^{-1} (as opposed to 0 kg K ha^{-1}) in the plant and first two ratoon crops on the (A) Oxisol and (B) Inceptisol

A: Oxisol			
[1]Added income due to change:	**(R ha^{-1})**	**[1]Added costs due to change:**	**(R ha^{-1})**
Additional 1.24 t ERC ha^{-1}	5 518	Cost of K fertiliser (R12 kg^{-1} K)	7 200
(R4 450 t^{-1} ERC)		(Potassium chloride)	
		Cost of K application (R0.26 kg^{-1} KCl[€])	156
		Harvest cost (manual harvest) ([2]R88.90 t^{-1} cane)	919
		Transport cost ([2]R60.03 t^{-1} cane)	620
Reduced costs due to change:	**(R ha^{-1})**	**Reduced income due to change:**	**(R ha^{-1})**
None		None	
Subtotal	5 518	**Subtotal**	8 895
Net change: R5 518 – R8 895 = –R3 377 ha^{-1}			

B: Inceptisol			
[1]Added income due to change:	**(R ha^{-1})**	**[1]Added costs due to change:**	**(R ha^{-1})**
Additional 1.15 t ERC ha^{-1}	5 118	Cost of K fertiliser (R12 kg^{-1} K)	7 200
(R4 450 t^{-1} ERC)		(Potassium chloride)	
		Cost of K application (R0.26 kg^{-1} KCl[€])	156
		Harvest cost (manual harvest) ([2]R88.90 t^{-1} cane)	852
		Transport cost ([2]R60.03 t^{-1} cane)	575
Reduced costs due to change:	**(R ha^{-1})**	**Reduced income due to change:**	**(R ha^{-1})**
None		None	
Subtotal	5 118	**Subtotal**	8 783
Net change: R5 118 – R8 783 = –R3 665 ha^{-1}			

[1]Sum over three crops
[2]At 12% estimated recoverable crystal, such that 8.33 t cane ha^{-1} produced 1 t ERC ha^{-1}.
[€]Tin and string method (see Glossary)

Figure 3.7 shows that in the plant crop, the 200 kg K ha^{-1} application rate resulted in very little sucrose yield (t ERC ha^{-1}) response on either soil but by the second ratoon, the response was noticeably greater on the Oxisol. The yield response to K may have continued into further ratoon crops, and possibly even increased as K deficiency became more marked in the zero treatment. The economics of K application at both sites might therefore become more favourable in the latter part of the crop cycle. Successful farming hinges upon a balance between short- and long-term sustainability. Although a reduction in K application may save money in the short term, it is important that soils are not mined, leading to very low soil K that compromises longer-term sustainability.

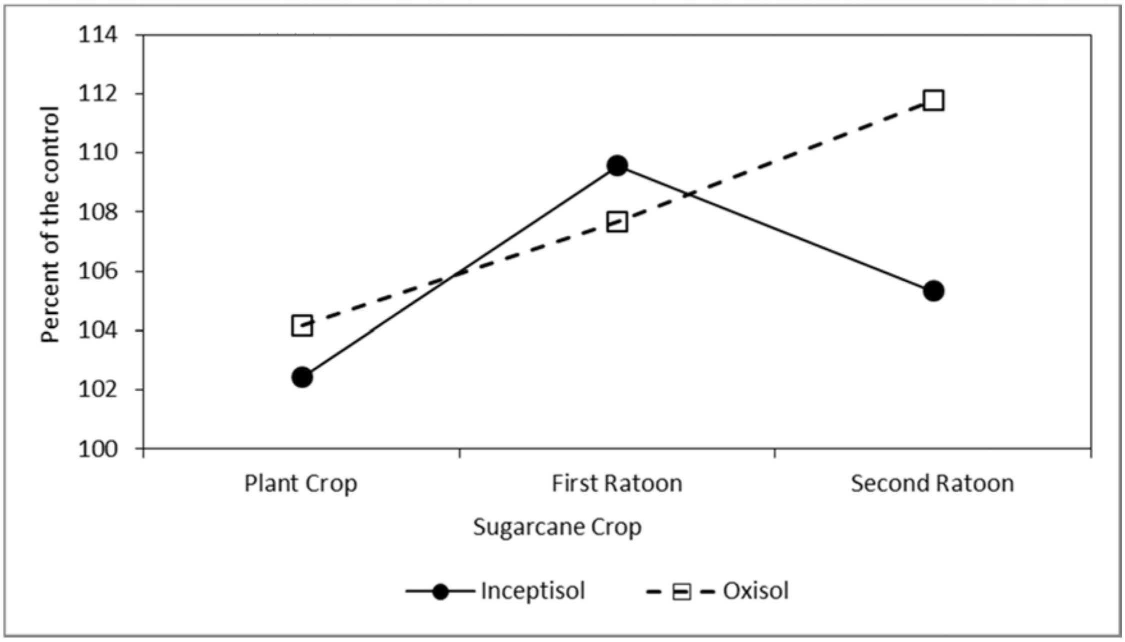


Figure 3.7: Sucrose yield (t ERC ha^{-1}) response to the 200 kg K ha^{-1} application rate as a percentage of the 0 kg K ha^{-1} control for the three crops on the Oxisol and the Inceptisol. n=24 in all crops except Inceptisol second ratoon, where n=16.

3.3.3. Effect of nitrogen on sugarcane harvest characteristics

3.3.3.1. Oxisol

3.3.3.1.1. Stalk yield

Application of 80 kg N ha^{-1} to the Oxisol had a significant depressive effect on the plant crop yield (Figure 3.8). The topsoil had high organic matter (3.9% organic carbon) (Table 3.2), and during field preparation a considerable amount of N could have been released. Approximately 82-88 kg N ha^{-1} was released from an Inanda (Oxisol) topsoil (Wood, 1964, 1965), and Wood (1965) noted that, on certain soils, the rate of N mineralisation may be so high that no yield response is obtained from N application. There is thus little surprise that plant crop yields were not improved by the application of N as the crop’s N needs were already supplied by the soil. The reason for the depression (rather than the absence of an increase) is less clear. Wood (1964) refers to “[a] negative or small response to applied nitrogen shown by plant cane", and concluded that high N release from the soil was responsible, although a full explanation was not given.

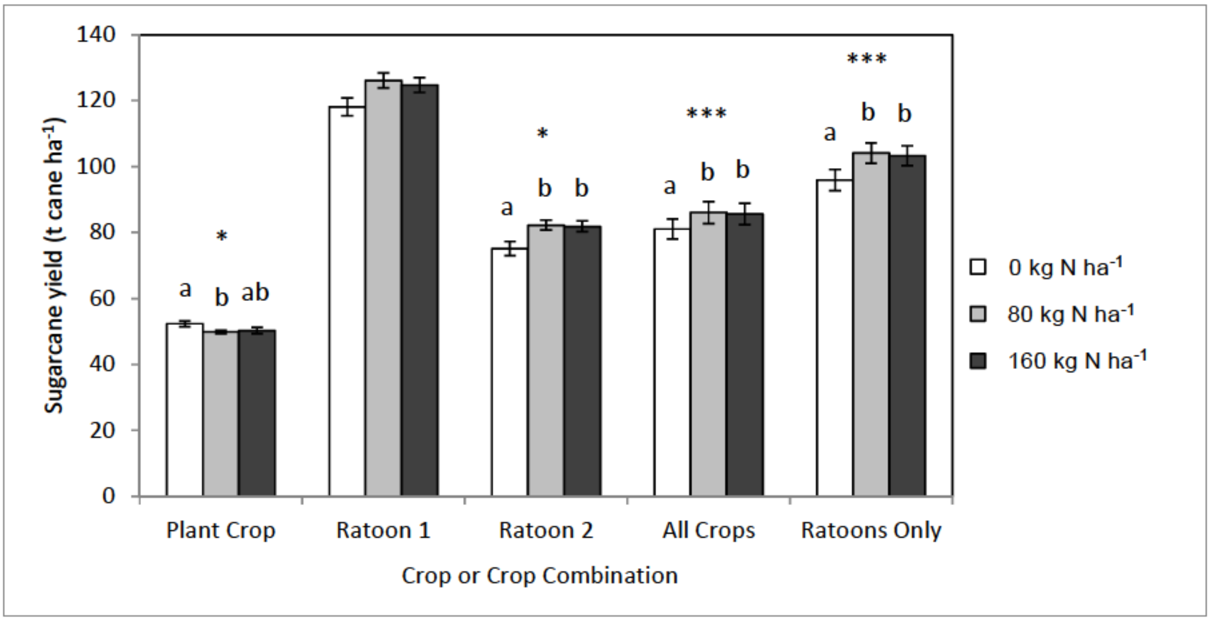


Figure 3.8: Oxisol: The effect of nitrogen (N) application rate on sugarcane stalk yield for each individual crop (Plant Crop, Ratoon 1, Ratoon 2), the average over all three crops (All Crops) and the ratoon crops (Ratoons Only). Within crops or crop combinations, columns with different letters are significantly different to each other (*$P < 0.05$; ***$P < 0.001$).

Nitrogen rate did not influence yield significantly in the first ratoon crop on the Oxisol (Figure 3.8). Wood (1964) stated that mineralisation effects were likely to persist into ratoon cane on heavier soils with high organic matter content. In the second ratoon, however, and for all crops in combination, as well as the ratoon crops only, N application significantly increased sugarcane yield (Figure 3.8) but only at 80 kg ha^{-1}. Doubling the N rate had no further effect on yield.

3.3.3.1.2. Sucrose percent

In every crop grown on the Oxisol, N application reduced %ERC (Figure 3.9). This reduction was significant in all crops except the first ratoon. In the plant crop, 80 kg N ha^{-1} significantly reduced %ERC, while in the second ratoon crop, only the higher rate of 160 kg ha^{-1} led to a significant reduction. The amount of N mineralised during land preparation was evidently sufficient to decrease %ERC with only a small (80 kg ha^{-1}) addition of N to the plant crop. By the second ratoon crop, however, N mineralisation would have been lower so that only the larger application of N (160 kg ha^{-1}) was sufficient to cause sucrose reduction.

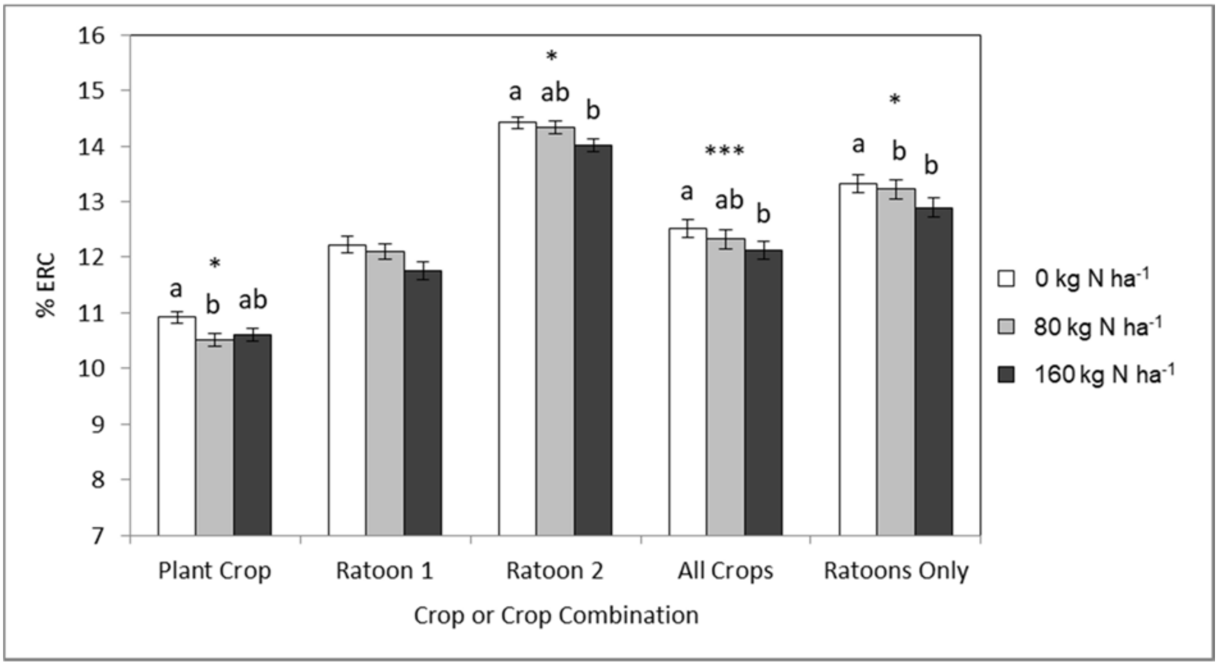


Figure 3.9: Oxisol: The effect of nitrogen (N) application rate on percent estimated recoverable crystal (%ERC) for each individual crop (Plant Crop, Ratoon 1, Ratoon 2), the average over all three crops (All Crops) and the ratoon crops (Ratoons Only). Within crops or crop combinations, columns with different letters are significantly different to each other (*P < 0.05; ***P < 0.001).

The negative effect of N on sucrose concentration is characteristic of most sugarcane varieties, and has been widely reported (Singh, 1973; Muchow *et al*., 1996; Meyer and Wood, 2001; Nassar *et al*., 2005; Inoue *et al*., 2009). Increasing N application tends to increase crop yields, lowering stalk dry matter content with a concomitant reduction in %ERC through dilution (Muchow *et al*., 1996). Meyer and Wood (2001) reported an average 0.38 percentage unit decrease in sucrose per 50 kg of applied N, at application rates ranging from 50 to 150 kg N ha^{-1}. It was not specified whether this average was for plant or ratoon crops, or both. In the present study, the equivalent value for the Oxisol's ratoon crops was a 0.21 percentage unit drop in sucrose, per 50 kg applied N, from 80 to 160 kg ha^{-1} applied N. The difference is likely accounted for by variety, amongst other factors, as reported by Meyer and Wood (2001).

3.3.3.1.3. Sucrose yield

Sucrose yield (t ERC ha^{-1}) on the Oxisol was significantly reduced by N application in the plant crop (Figure 3.10), but in the later crops there was an overall increase in sucrose yield, significant in the second ratoon and combined ratoon crops. The plant crop reduction in total sucrose yield is attributable to the reduction in %ERC with N application, while the significant cane yield increases in the ratoon crops resulted in an overall increase in sucrose yield. Muchow *et al*. (1996) and Nassar *et al*. (2005) reported similar results where, although increased N application led to a decrease in sucrose concentration, there was an overall increase in crop biomass and hence sucrose yield.

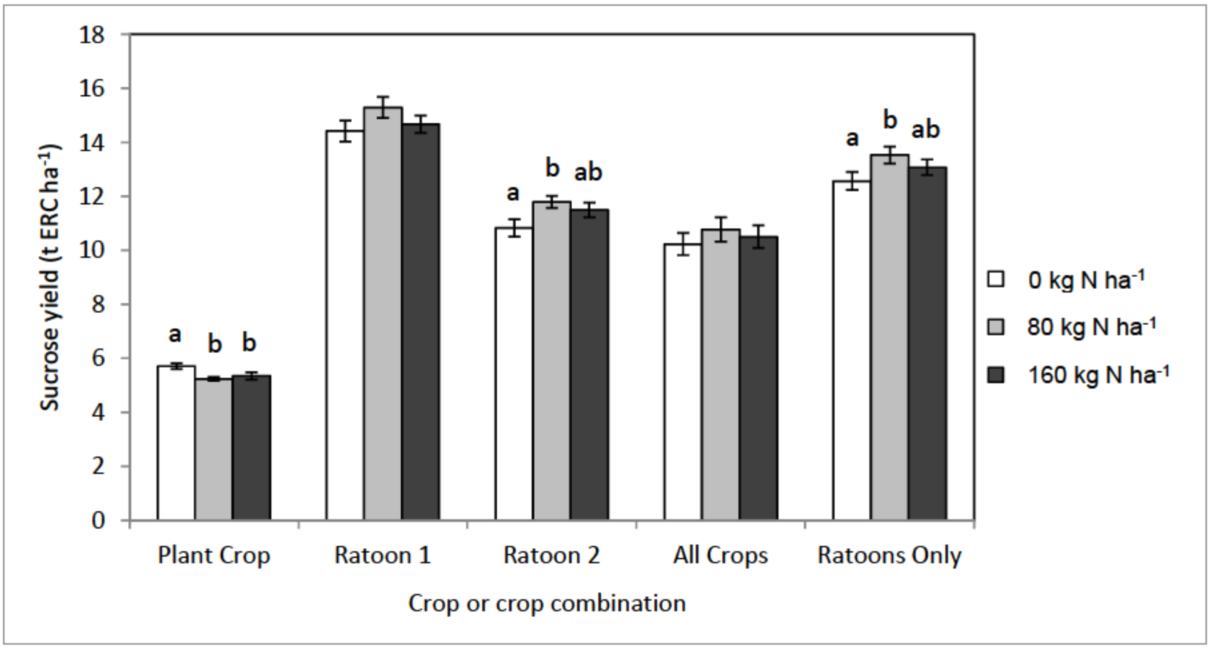


Figure 3.10: Oxisol: The effect of nitrogen (N) application rate on sucrose yield for each individual crop (Plant Crop, Ratoon 1, Ratoon 2), the average over all three crops (All Crops) and the ratoon crops (Ratoons Only). Within crops or crop combinations, columns with different letters are significantly different to each other ($P < 0.05$).

3.3.3.2. Inceptisol

3.3.3.2.1. Stalk yield

The application of N to the Inceptisol did not affect sugarcane yield in the plant crop (Figure 3.11). With a topsoil (0-20 cm) organic carbon content of 1.4% (Table 3.2), approximately 45 – 60 kg N ha^{-1} could have been released during cultivation and land preparation, according to figures reported by Wood (1965). This would have partly satisfied the N requirement of the plant crop.

Both ratoon crops and the crop combinations showed a significant increase in sugarcane yield with N application (Figure 3.11). In the first ratoon, a significant response was found up to the highest N level (210 kg N ha^{-1}). In the second ratoon and crop combinations, however, no further significant yield response was recorded above 105 kg N ha^{-1}. In this regard, the two trial sites were similar in that the intermediate N level (which would have been recommended at each site by the FAS) was sufficient for the crop.

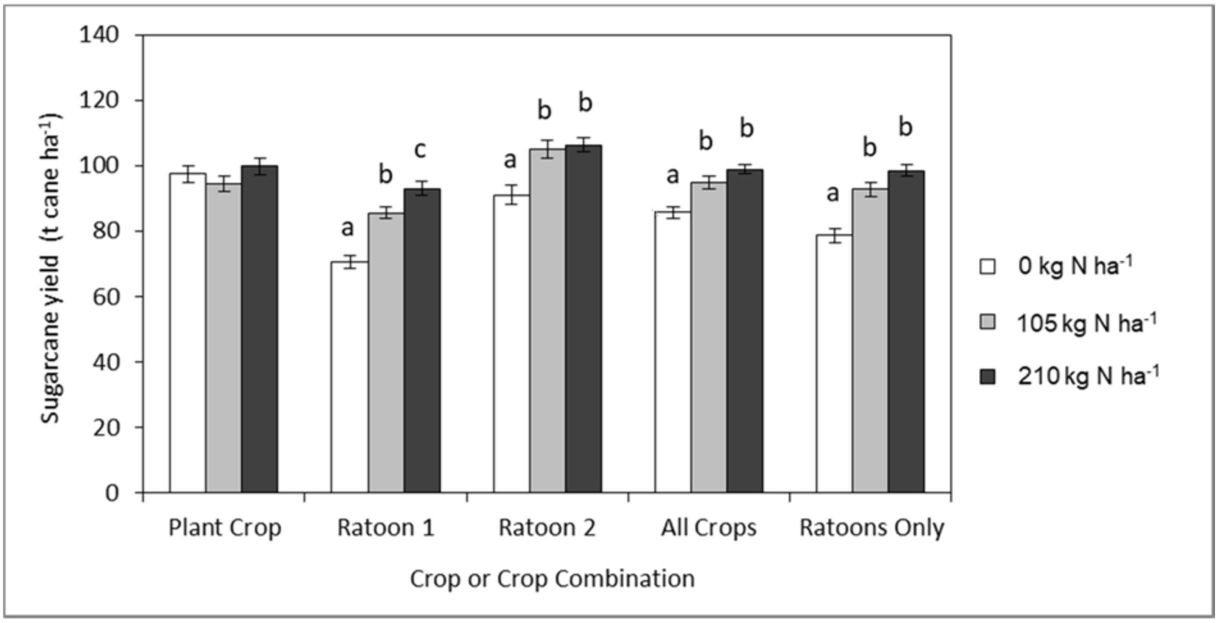


Figure 3.11: Inceptisol: The effect of nitrogen (N) application rate on sugarcane stalk yield for each individual crop (Plant Crop, Ratoon 1, Ratoon 2), the average over all three crops (All Crops) and the ratoon crops (Ratoons Only). Within crops or crop combinations, columns with different letters are significantly different to each other ($P < 0.001$).

3.3.3.2.2. Sucrose percent

In sharp contrast to the Oxisol, N application to the Inceptisol did not affect %ERC in any of the crops or crop combinations (data not shown), except in the second ratoon crop, where %ERC increased at the highest N level. The mean of 13.2 ± 0.1 %ERC at 0 kg N ha^{-1} was significantly lower than 13.8 ± 0.2 %ERC at 210 kg N ha^{-1}, while the intermediate N level of 105 kg N ha^{-1}, at 13.4 ± 0.1 %ERC, did not differ significantly from either. This increase with N in the second ratoon, with no significant effects in the other crops, may have indicated N deficiency in the zero control.

3.3.3.2.3. Sucrose yield

Sucrose yield (t ERC ha^{-1}) on the Inceptisol was significantly increased by N application in all crops and crop combinations, except for the plant crop (Figure 3.12). With the exception of the first ratoon, where sucrose yield increased up to the highest N rate, there was no further response to N application above 105 kg N ha^{-1}. Sucrose yield increases mirrored the stalk yield increases, indicating the underlying cause of this response. Again, this pattern was similar to those reported by Muchow *et al*. (1996) and Nassar *et al*. (2005).

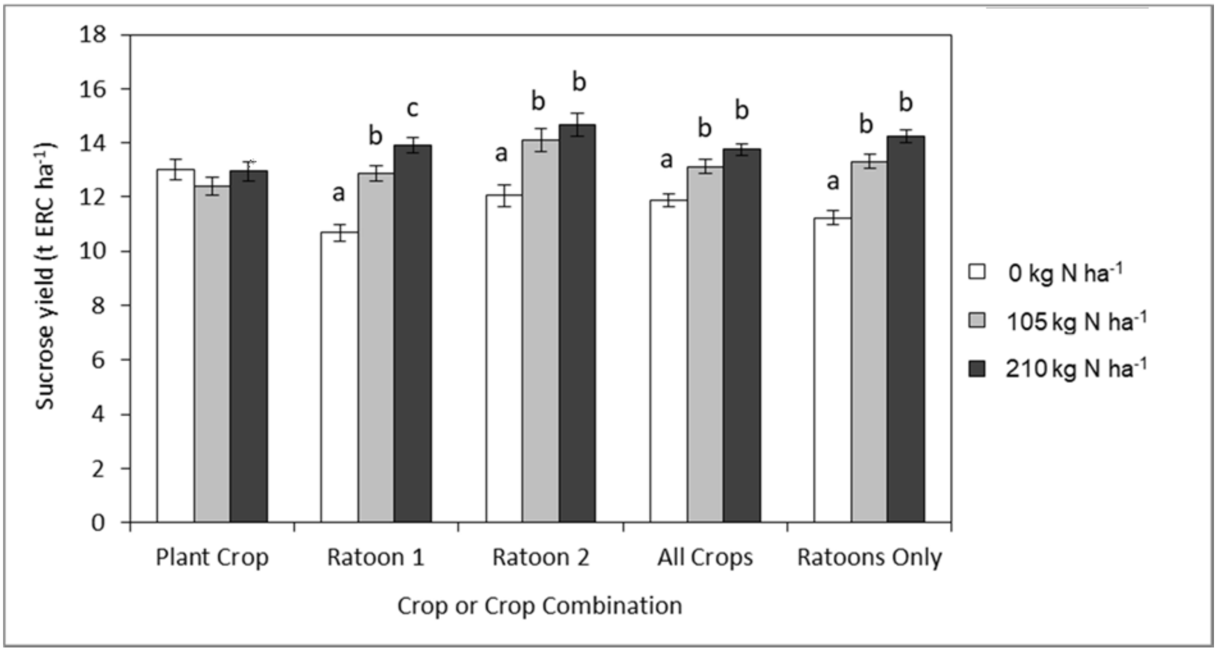


Figure 3.12: Inceptisol: The effect of nitrogen (N) application rate on sucrose yield for each individual crop (Plant Crop, Ratoon 1, Ratoon 2), the average over all three crops (All Crops) and the ratoon crops (Ratoons Only). Within crops or crop combinations, columns with different letters are significantly different to each other ($P < 0.001$).

3.3.3.3. Economic aspects

A partial budget, calculated to determine the economic effect of applying 80 kg N ha^{-1} to each crop grown on the Oxisol (Table 3.4A), indicated a cost : benefit ratio of 1 : 1.43 when compared to zero N application. As with K, however, the response to N in the ratoons was greater than that in the plant crop (Figure 3.13). When only the ratoons were considered, the cost : benefit ratio increased to 1 : 2.05 (Table 3.4B).

Table 3.4: Oxisol: Partial budget for the application of 80 kg N ha^{-1} (as opposed to 0 kg N ha^{-1}) in the (A) plant and first two ratoon crops and (B) first and second ratoon crops only

A: Plant, first ratoon and second ratoon crops:			
[1]Added income due to change:	**(R ha^{-1})**	**[1]Added costs due to change:**	**(R ha^{-1})**
Additional 1.35 t ERC ha^{-1} (R4 450 t^{-1} ERC)	6 007	Cost of N fertiliser (R10 kg^{-1} N) (Urea)	2 400
		Cost of N application (R0.26 kg^{-1} urea[€])	136
		Harvest cost (manual harvest) ([3]R88.90 t^{-1} cane)	1000
		Transport cost ([3]R60.03 t^{-1} cane)	675
Reduced costs due to change:	**(R ha^{-1})**	**Reduced income due to change:**	**(R ha^{-1})**
None		None	
Subtotal	6 007	**Subtotal**	4 211
Net change: R6 007 – R4 211 = R1 796 ha^{-1}			

B: First ratoon and second ratoon crops only:			
[2]Added income due to change:	**(R ha^{-1})**	**[2]Added costs due to change:**	**(R ha^{-1})**
Additional 1.82 t ERC ha^{-1} (R4 450 t^{-1} ERC)	8 099	Cost of N fertiliser (R10 kg^{-1} N) (Urea)	1 600
		Cost of N application (R0.26 kg^{-1} urea[€])	90
		Harvest cost (manual harvest) ([3]R88.90 t^{-1} cane)	1 348
		Transport cost ([3]R60.03 t^{-1} cane)	910
Reduced costs due to change:	**(R ha^{-1})**	**Reduced income due to change:**	**(R ha^{-1})**
None		None	
Subtotal	8 099	**Subtotal**	3 948
Net change: R8 099 – R3 948 = R4 151 ha^{-1}			

[1]Sum over three crops [2]Sum over two crops
[3]At 12% estimated recoverable crystal, such that 8.33 t cane ha^{-1} produced 1 t ERC ha^{-1}.
[€]Tin and string method

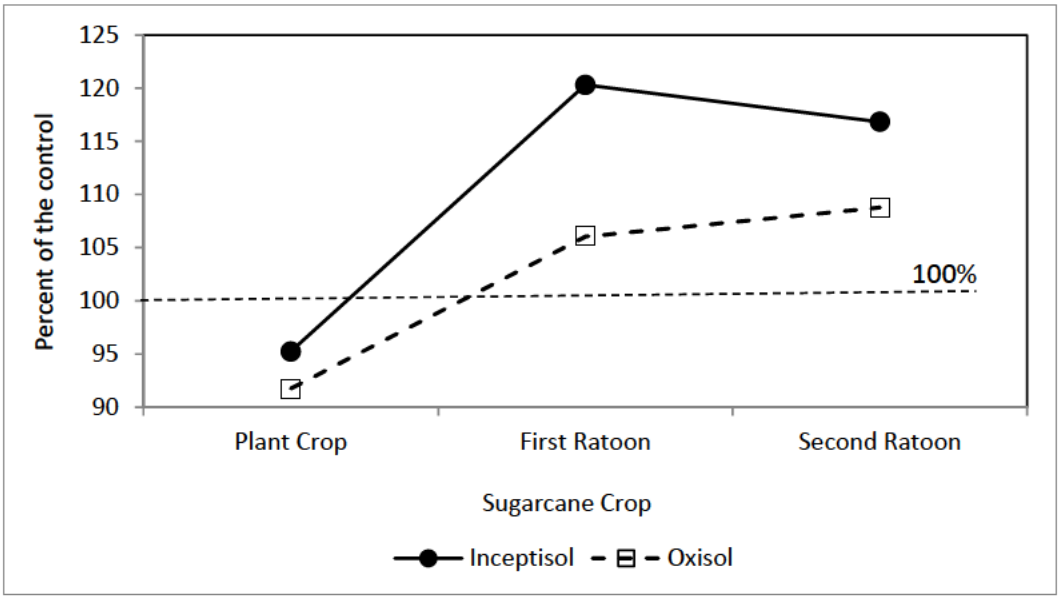


Figure 3.13: Sucrose yield (t ERC ha^{-1}) response to the intermediate N application rates (80 kg ha^{-1} (Oxisol), 105 kg ha^{-1} (Inceptisol)), as a percentage of the 0 kg ha^{-1} N control for the three crops on each soil. n=32 in all crops except Inceptisol second ratoon, where n=19.

On the Oxisol, N application of either 80 or 160 kg N ha^{-1} to the plant crop led to a significant decrease in sucrose yield (Figure 3.10). This response was likely caused by the high organic matter in the topsoil that released a substantial amount of N during land preparation. It is therefore necessary to consider the financial implications of applying no N to the plant crop on the Oxisol. In comparison to the application of 80 kg N ha^{-1}, zero N application would have saved fertiliser costs and negated the yield ‘penalty’ associated with N application. Applying no N to the plant crop on the Oxisol would thus have resulted in a financial benefit of R2 354 ha^{-1} over the application of 80 kg N ha^{-1} (Table 3.5).

Table 3.5: Oxisol: Partial budget for the application of 0 kg N ha^{-1} (as opposed to 80 kg N ha^{-1}) in the plant crop

Added income due to change:	**(R ha^{-1})**	**Added costs due to change:**	**(R ha^{-1})**
Additional 0.47 t ERC ha^{-1} (R4 450 t^{-1} ERC)	2 092	Harvest cost (manual harvest) ([1]R88.90 t^{-1} cane)	348
		Transport cost ([1]R60.03 t^{-1} cane)	235
Reduced costs due to change:	**(R ha^{-1})**	**Reduced income due to change:**	**(R ha^{-1})**
Cost of N fertiliser (R10 kg^{-1} N) (Urea)	800	None	
Cost of N application (R0.26 kg^{-1} urea[€])	45		
Subtotal	2 937	**Subtotal**	583
Net change: R2 937 – R583 = R2 354 ha^{-1}			

[1]At 12% estimated recoverable crystal, such that 8.33 t cane ha^{-1} produced 1 t ERC ha^{-1}.
[€]Tin and string method

On the Inceptisol, application of 105 kg N ha^{-1} to each crop yielded an additional 4.2 t ERC ha^{-1} over that of the zero N control (Table 3.6), resulting in a cost : benefit ratio of 1 : 2.19. Again the response to N in the ratoons was greater than that in the plant crop (Figure 3.13). At both sites if the patterns of N response (Figure 3.13) were to continue into later ratoons, the economics of N application would likely remain favourable.

Table 3.6: Inceptisol: Partial budget for the application of 105 kg N ha^{-1} (as opposed to 0 kg N ha^{-1}) in the plant and first two ratoon crops

A: Plant, first ratoon and second ratoon crops:			
[1]Added income due to change:	**(R ha^{-1})**	**[1]Added costs due to change:**	**(R ha^{-1})**
Additional 4.20 t ERC ha^{-1} (R4 450 t^{-1} ERC)	18 690	Cost of N fertiliser (R10 kg^{-1}) (Urea)	3 150
		Cost of N application (R0.26 kg^{-1} urea[€])	178
		Harvest cost (manual harvest) ([2]R88.90 t^{-1} cane)	3 111
		Transport cost ([2]R60.03 t^{-1} cane)	2 101
Reduced costs due to change:	**(R ha^{-1})**	**Reduced income due to change:**	**(R ha^{-1})**
None		None	
Subtotal	18 690	**Subtotal**	8 540
Net change: R18 690 – R8 540 = R10 150 ha^{-1}			

[1]Sum over three crops
[2]At 12% estimated recoverable crystal, such that 8.33 t cane ha^{-1} produced 1 t ERC ha^{-1}.
[€]Tin and string method

3.3.4. Effect of silicon on sugarcane harvest characteristics

3.3.4.1. Oxisol

3.3.4.1.1. Stalk yield, sucrose percent and sucrose yield

The effect of the application of 300 kg Si ha^{-1} was limited (results not shown). Stalk yield was significantly increased by Si application in the second ratoon crop only, from 77.7 t cane ha^{-1} (control), to 81.8 t cane ha^{-1}. Silicon had no effect on %ERC in any of the harvested crops. Silicon application does not commonly result in increased sucrose concentration in sugarcane. According to Korndörfer and Lepsch (2001), the yield increases associated with Si application are generally due to longer stalks, larger stalk diameters and an increase in stalk number, rather than an increase in pol (apparent sucrose) percent. The increase in stalk yield in the second ratoon translated into a significant increase in sucrose yield in the same crop, from 11.09 t ERC ha^{-1} (control) to 11.65 t ERC ha^{-1}.

The inconsistent response to Si was unexpected, considering the extensive literature reporting improvements in sugarcane stalk and sucrose yield after application of Si (as calcium silicate slag, in most cases) (Clements, 1965; Ayres, 1966; Fox *et al.*, 1967; Gascho and Andreis, 1974; Ross *et al.*, 1974; Berthelsen *et al.*, 2001b (calcium silicate slag and cement); Korndörfer and Lepsch, 2001). Highly weathered soils (Ross *et al*., 1974; Korndörfer and Lepsch, 2001) and soils with low Si levels (Ross *et al*., 1974; Berthelsen *et al*., 2001b) were reported to be particularly likely to respond. Silicon deficiencies are common in sugarcane grown on the KwaZulu-Natal north coast (Van der Laan and Miles, 2010), where the trial was situated. The limited response to Si obtained may be due to poor plant uptake of Si on this soil, possibly due to its moderately high acid saturation (Table 3.2).

3.3.4.2. Inceptisol

3.3.4.2.1. Stalk yield, sucrose percent and sucrose yield

The effect of Si application was more pronounced on the Inceptisol than the Oxisol. Stalk yield on the Inceptisol was significantly increased by the application of Calmasil® or cement in all crops and crop combinations except the plant crop (Figure 3.14A). In the second ratoon and both crop combinations, the differences in stalk yield were highly significant ($P < 0.01$) and the average yield increase with Si application in the ratoon crops was 5.3 t cane ha^{-1}. Silicon application did not affect %ERC in any of the crops, but sucrose yield was significantly increased in all crops and combinations, by an average of 0.69 t ERC ha^{-1} $crop^{-1}$ (Figure 3.14B).

This response in stalk and sucrose yield to Si application was expected although the Si in the Inceptisol topsoil, at 12.3 mg L^{-1} (Table 3.2), was close to that of the Oxisol (13.8 mg L^{-1}), making the lack of response to Si on the Oxisol even more puzzling. The response to Si on the Inceptisol might be linked to slightly improved Si uptake by the plant (Section 4.3.3.1) which, in turn, could have been facilitated by lower acid saturation in the Inceptisol (26% mean acid saturation over 0-80 cm compared to 46% in the Oxisol).

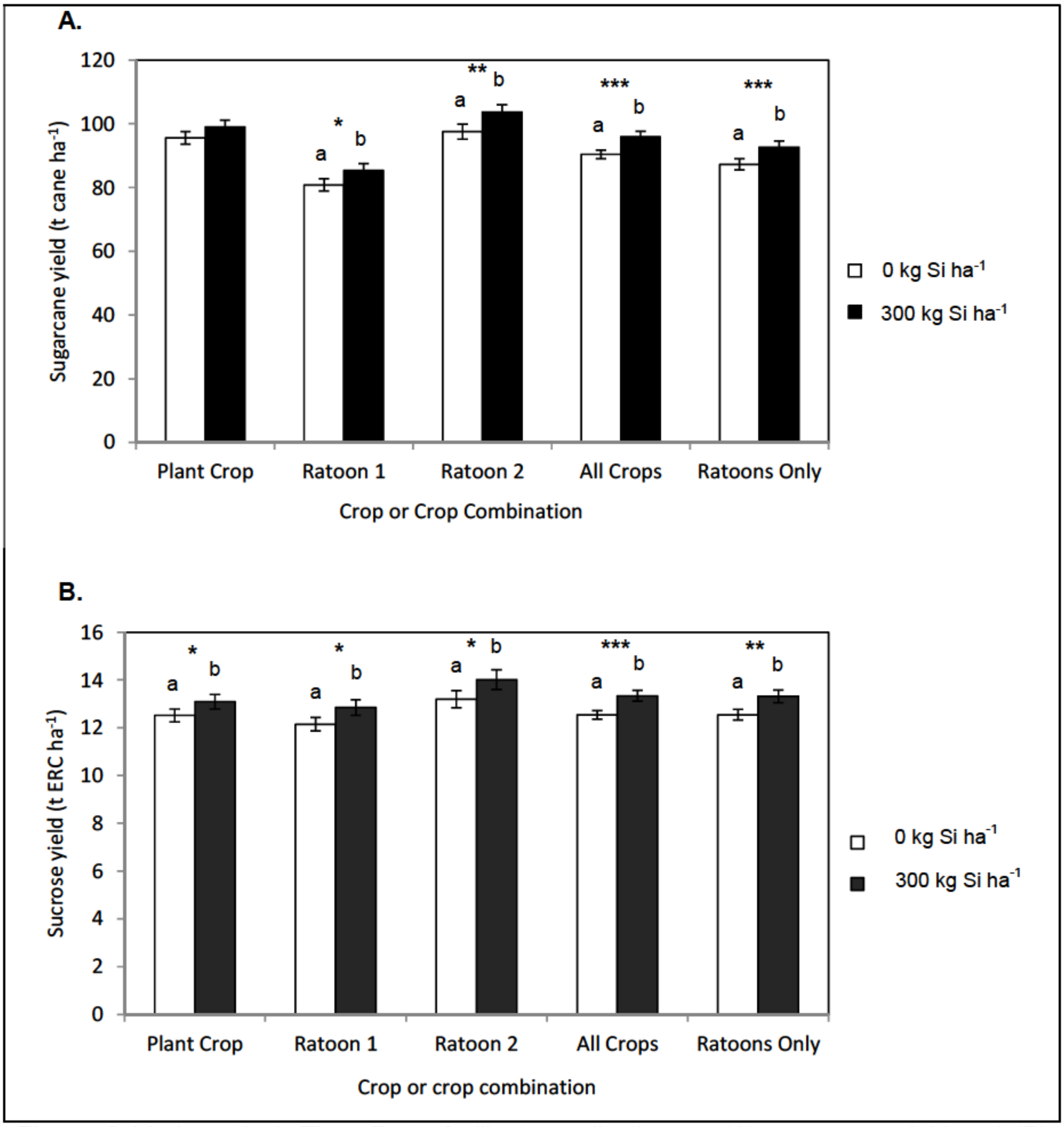


Figure 3.14: Inceptisol: The effect of silicate application on (A) sugarcane yield and (B) sucrose yield for each individual crop (Plant Crop, Ratoon 1, Ratoon 2), the average over all three crops (All Crops) and the ratoon crops (Ratoons Only). Within sites and crops or crop combinations, columns with different letters are significantly different to each other (*P < 0.05; **P < 0.01; ***P < 0.001).

It is not clear whether the increase in sucrose yield obtained on the Inceptisol was due to the Si in the amendments, or the other constituents (Ca and Mg). Prior to establishment, soil Ca and Mg at both trial sites, at all soil depths, were greater than the FAS thresholds. Dolomitic lime, applied at each site before crop establishment, increased the soil Ca and Mg further. In addition, Ca and Mg in leaf samples collected at both sites, during each crop, were, in every case, greater than the FAS threshold levels (Section 4.3.3.3). It is likely therefore that the yield responses observed in the Calmasil® / cement treatments were due to Si, although it is also possible that the crop might have responded to the increased Ca, even though leaf concentrations were above the threshold.

3.3.4.3. Economic aspects

Costs were calculated based on Calmasil®, as cement is expensive and would be unlikely to be applied by a commercial agricultural enterprise. Applications of Si on the Oxisol yielded only 0.99 t ERC ha^{-1} extra over three crops, generating a loss of R5 208 ha^{-1} (Table 3.7A). On the Inceptisol, an application of 300 kg Si ha^{-1} to the plant crop, and a second application prior to the second ratoon, would have resulted in a loss of R1 711 ha^{-1} over the three crops combined (Table 3.7B). In practice, Calmasil® would usually be applied in place of (not in addition to) dolomitic lime. The difference in cost would therefore only be that between the cost of dolomitic lime and Calmasil® (R354 ton^{-1} versus R308 ton^{-1}, respectively, excluding delivery costs), along with the harvest and transport costs associated with any increase in yields with Si application. Liming materials, and Calmasil® in particular, are not commonly topdressed during the ratoon crops, so any further yield increases accruing to Calmasil® application would be obtained without further application costs.

Table 3.7: Partial budget for the application of 300 kg Si ha^{-1} (as opposed to 0 kg Si ha^{-1}), as Calmasil®, in the plant crop and second ratoon crop on the A) Oxisol and B) Inceptisol

A: Oxisol:

[1]**Added income due to change:**	**(R ha^{-1})**	**Added costs due to change:**	**(R ha^{-1})**
Additional 0.99 t ERC ha^{-1} (R4 450 t^{-1} ERC)	4 406	[2]Cost of Si fertiliser (R7 kg^{-1} Si) (Calmasil®)	4 200
		[2]Cost of Si application (R165 t^{-1})	990
		[2]Cost of Si incorporation (R1598 ha^{-1})	3 196
		[1]Harvest cost (manual harvest) ([3]R88.90 t^{-1} cane)	733
		[1]Transport cost ([3]R60.03 t^{-1} cane)	495
Reduced costs due to change:	**(R ha^{-1})**	**Reduced income due to change:**	**(R ha^{-1})**
None		None	
Subtotal	4 406	**Subtotal**	9 614

Net change: R4 406 – R9 614 = - R5 208 ha^{-1}

B: Inceptisol:

[1]**Added income due to change:**	**(R ha^{-1})**	**Added costs due to change:**	**(R ha^{-1})**
Additional 2.08 t ERC ha^{-1} (R4 450 t^{-1} ERC)	9 256	[2]Cost of Si fertiliser (R7 kg^{-1} Si) (Calmasil®)	4 200
		[2]Cost of Si application (R165 t^{-1})	990
		[2]Cost of Si incorporation (R1598 ha^{-1})	3 196
		[1]Harvest cost (manual harvest) ([3]R88.90 t^{-1} cane)	1 541
		[1]Transport cost ([3]R60.03 t^{-1} cane)	1 040
Reduced costs due to change:	**(R ha^{-1})**	**Reduced income due to change:**	**(R ha^{-1})**
None		None	
Subtotal	9 256	**Subtotal**	10 967

Net change: R9 256 – R10 967 = - R1 711 ha^{-1}

[1]Sum over three crops [2]Sum over two applications
[3]At 12% estimated recoverable crystal, such that 8.33 t cane ha^{-1} produced 1 t ERC ha^{-1}.

3.3.5. Effect of nutrient interactions on sugarcane harvest characteristics

3.3.5.1. Oxisol

There were generally few interactions between nutrients in terms of their effect on harvest characteristics. One exception was the interactive effect of N and Si on %ERC in the second ratoon crop on the Oxisol (Figure 3.15).

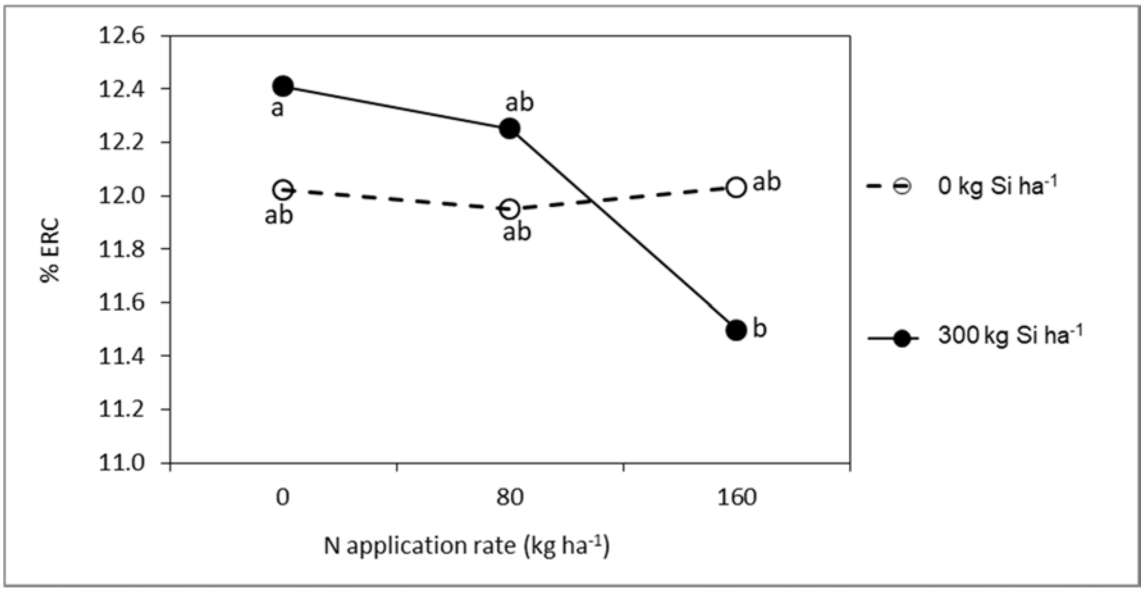


Figure 3.15: Oxisol: Second ratoon crop. The effect of nitrogen (N) application rate on percent estimated recoverable crystal (%ERC) at different rates of silicon (Si). Within and between Si rates, points with different letters are significantly different to each other ($P < 0.05$).

With zero applied Si, increasing N had no effect on %ERC. Where Si was applied, however, increasing N caused a significant decrease. However, this was most likely to be an effect of the Si-containing liming material, rather than the Si itself. Calmasil® contains Ca and Mg carbonates, along with Si. Cement similarly contains a large amount of Ca, and some Mg. It is therefore likely that the increased soil N release that often accompanies liming (Lyngstad, 1992; Garbuio *et al.*, 2011) increased the amount of available N to such an extent in the highest N treatment, that sucrose content was significantly compromised. Without Calmasil® or cement application, soil N was insufficient to reduce the sugarcane quality in this way. This effect was only seen in the second ratoon crop, which had cement applied during early growth.

There was also a significant interaction between the effect of K, N and Si on %ERC in the second ratoon crop, as well as when ratoon crops, and all crops, were combined. The highest level of N, with zero K, lowered %ERC in the crop. At a higher rate of K (200 kg K ha^{-1}), however, the effects of high (160 kg ha^{-1}) N were mitigated and, in that treatment, %ERC was significantly higher than where no K was applied (Figure 3.16). This effect was not evident in the zero Si plots. These results show that, under certain conditions, the deleterious effect of high N rates on %ERC can be mitigated by the application of sufficient K. Qualifying conditions may include soils where a low N response is likely, i.e., those with high organic matter, such as the Oxisol. Similar effects were reported by Meyer and Wood (2001), and are likely linked to the role that K plays in the stimulation of phloem transport of sugars (Wood and Schroeder, 2004).

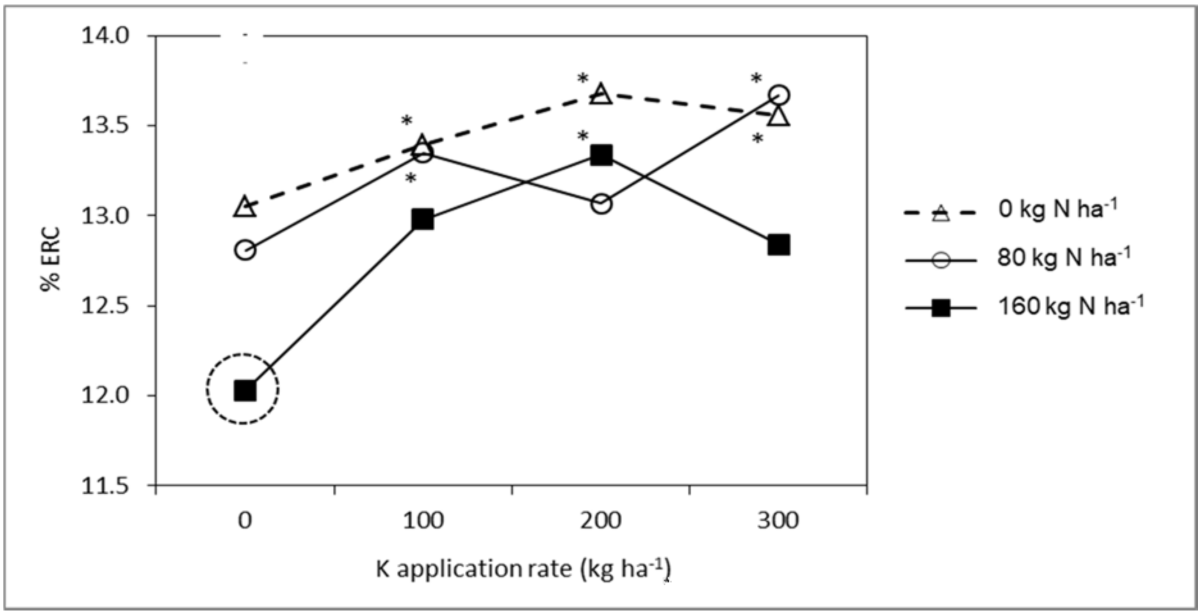


Figure 3.16: Oxisol: Ratoon crops only. The effect of nitrogen (N) and potassium (K) application rates on percent estimated recoverable crystal (%ERC) at 300 kg Si ha^{-1}. All treatment values marked with an asterisk* are significantly higher ($P < 0.05$) than the circled treatment. No other significant differences were found.

3.3.5.2. Inceptisol

On the Inceptisol, there were no significant interactions between any of the applied nutrients in terms of cane yield, cane quality or sucrose yield.

3.4. Conclusions

Different sugarcane crop yield and quality responses were obtained to the nutrients applied to the Oxisol and the Inceptisol. On the Oxisol, K application increased overall sucrose yield, driven by increased %ERC, without affecting stalk yield. This effect has not been widely reported in the industry. On the Inceptisol, however, the increase in sucrose yield with K application was due to increases in cane yield, without affecting %ERC. At both sites, the increased sucrose yields occurred only up to 200 kg K ha^{-1}.

The current K recommendation given by the FAS is linked to the attainable yield and soil clay percent, and would have been 250 kg K ha^{-1} in the plant crop at both sites, while the ratoon recommendations would have been 200 kg K ha^{-1} (Oxisol) and 190 kg K ha^{-1} (Inceptisol). Potassium application rates similar to those recommended by the FAS, significantly increased sucrose yields but were not economically justifiable in the short term (three crops). It is possible, however, that yield response to K would have become greater in later ratoons, particularly on the Oxisol.

Sucrose yield in the ratoons at both sites responded favourably up to intermediate levels of N (80 kg ha^{-1} on the Oxisol, 105 kg ha^{-1} on the Inceptisol). Nitrogen application increased sugarcane yields at both sites in the ratoons, but not in the plant crops. Application of N depressed %ERC in all crops on the Oxisol, but not on the Inceptisol, with its lower organic matter levels.

The current FAS recommendation for N is linked to the attainable yield and soil organic matter and clay contents. Nitrogen recommendations for the Oxisol would have been 70 kg N ha^{-1} in the plant crop, and 110 kg N ha^{-1} in the ratoons; for the Inceptisol 115 kg N ha^{-1} in the plant crop, and 155 kg N ha^{-1} in the ratoons. Application of N at, in general, slightly lower levels than the FAS recommendations, proved economically beneficial, particularly on the Inceptisol. Given the range of environmental and varietal conditions that would affect results at each site, the current FAS recommendations for N appear valid. The exception to this was the plant crop on the Oxisol, where a zero N application would have resulted in the highest sucrose yields. This finding is of importance, given that the FAS currently recommends applying N to every plant crop. The economic analysis conducted in this study indicates that, because N application resulted in reduced sucrose yields on the Oxisol, it was financially detrimental to apply N. Nitrogen application did not significantly reduce sucrose yields on the Inceptisol, probably due to lower organic N reserves. A general recommendation to reduce N application to zero in the plant crop on all soils is thus unlikely to be advisable. Such a recommendation should, however, be considered for humic soils, similar to the Oxisol in this study, and perhaps other soils with a high organic matter content.

On the Oxisol, crops responded very poorly to applied Si, with few significant responses in stalk yield, %ERC or sucrose yield. This may have been due to limited Si uptake on the acidic Oxisol. On the Inceptisol, however, application of 300 kg Si ha^{-1} led to significantly higher sucrose yields. This increase was a result of significantly greater stalk yields, rather than an increase in %ERC. On both soils Si application was not economically justified over the three crops harvested, though it may have become more economically viable in the later ratoons.

While no nutrient interactions were recorded on the Inceptisol, K, N and Si interacted significantly on the Oxisol. In general, the application of siliceous liming materials appeared to increase the amount of N available to the crop, enhancing the depressive effect of N on %ERC. Potassium, however, served to mitigate this effect on this high organic matter soil, likely due to its role in phloem transport of sugars.

CHAPTER 4

The effect of applied potassium, nitrogen and silicon on leaf nutrient concentrations and relationships with sugarcane yield

4.1. Introduction

Characterising the impact of fertiliser applications on plant nutrient concentrations, and the subsequent use of plant sample analyses to establish nutrient requirements of the crop, is key to successful crop production. In sugarcane, leaf samples are routinely analysed to determine crop nutrient status, and this plays an important role in nutrient management (Schroeder *et al*., 1993). In South Africa, approximately 6 000 sugarcane leaf samples are processed annually by the Fertiliser Advisory Service (FAS) laboratory at the South African Sugarcane Research Institute (SASRI).

Two important aspects of leaf analysis interpretation need to be considered. Firstly, the pattern and extent of uptake of applied nutrients needs to be understood in order for leaf analyses to be of reliable diagnostic value. The extent of uptake is complicated by interactions between nutrients, both in the soil and in the plant itself, such as that between nitrogen (N) and potassium (K). Increasing N supply generally results in an increase in K uptake by the plant (De Beaucorps, 1980; Miles, 2010), which can result in significantly higher yields than when either N or K are applied alone (Gething, 1993). Phosphorus (P) availability may also increase with silicon (Si) application (Smyth and Sanchez, 1980), with possible yield implications if P were deficient. Other interactions may be antagonistic. Calcium (Ca), magnesium (Mg) and K tend to exhibit cationic antagonism, and high levels of one or more of these nutrients can result in decreased uptake of another, despite sufficient soil levels (Gosnell and Long, 1971; Marschner, 1995; Garcia *et al*., 1999).

Application of nutrient sources which have a liming effect (e.g. Calmasil®) may induce deficiencies of other nutrients such as zinc (Zn) (Ahmad *et al*., 2012) or copper (Cu) (Nachtigall *et al*., 2007) due to changes in soil pH. These deficiencies may lead to yield reduction. Interpretation of the results of leaf analysis therefore depends on analysing a range of nutrients and not just those applied in trials.

Nutrient interactions need to be taken into account when considering the effects of applied nutrients as they can help to explain yield responses and highlight possible future deficiencies or excesses. The dynamics of nutrient interactions and uptake therefore have a bearing on soil threshold levels and nutrient application rates.

Secondly, results should provide some indication of potential yield (or yield loss) associated with sufficiency (or deficiency) of a particular nutrient. Leaf analysis is therefore only meaningful if reliable nutrient concentration thresholds can be determined, below which some loss of yield or quality can be expected.

This study therefore aimed to determine (i) the effect of various application rates of K, N and Si, along with their interactions, on leaf nutrient concentrations of sugarcane, and (ii) the appropriateness of the current leaf threshold values in determining nutrient sufficiency or deficiency, as determined by corresponding yields. The ultimate goal was to assist in the refinement of industry nutrient recommendations.

4.2. Materials and methods

4.2.1. Trial details

These are given in Sections 3.2.1 to 3.2.4.

4.2.2. Leaf sampling

Leaf samples were collected at both sites when each crop was 4 and 6 months old (Figure 3.2). These crop ages fall within the prescribed range (4-7 months) suitable for leaf sampling in these areas and during the correct time from spring to late summer (Miles and Titshall, 2020), with the exception of two May samplings for the plant and first ratoon crops on the Oxisol. These autumn samplings were included to maintain the 4- and 6-month schedule. The plant crop on the Inceptisol was sampled when the crop was 4 months old only, in April 2010 (Figure 3.2); the 6-month sampling was cancelled due to the extremely dry conditions in winter 2010 (Section 3.2.1.1). While there are currently no rainfall threshold values below which leaf sampling is discouraged, SASRI stipulates that “The crop must have received enough well-distributed rainfall/irrigation to ensure that there is no moisture stress in the crop prior to sampling” (Miles and Titshall, 2020). The rainfall distribution at the trial sites (Figure 3.2) indicates that prior to four of the Oxisol and two of the Inceptisol sampling times rainfall may not have been sufficient to ensure reliable leaf sample results.

At each sampling event, 30 leaves were collected per plot. The third leaf from the top was taken in each case, counting from the first leaf which was more than half unfurled (Miles, 2010). The base and tip of the leaves were cut off, leaving 20-30 cm of the central part of the leaf blade as the sample. The leaf midrib was removed within 15 minutes of sampling and discarded. Blade samples were analysed by the FAS. Nitrogen was determined by near-infrared reflectance (NIR; Bran + Luebbe InfraAlyzer 2000). X-ray fluorescence spectrometry (XRF; PW 2400 PANalytical X-ray) was used to determine Ca, Cu, iron (Fe), K, Mg, manganese (Mn), P, sulphur (S), Si and Zn, and a small subset of samples from each site was analysed colorimetrically for boron (B) (Gaines and Mitchell, 1979). Mean leaf Fe and Mn (data not shown) were within the SASRI-recommended ranges of 75-99 and 15-99 mg kg^{-1}, respectively (Miles and Titshall, 2020), apart from the second ratoon crop on the Inceptisol, where mean Fe was below this range (69 and 54 mg kg^{-1} at 4 and 6 months, respectively). Treatment effects on Fe and Mn were, in most cases, neither significant nor consistent, and are not reported on further. Mean leaf B was 2 and 4 mg kg^{-1} on the Oxisol and the Inceptisol, respectively. Though the current threshold is 10 mg kg^{-1} (Miles and Titshall, 2020), the recommended threshold at the time of the trials was 2 mg kg^{-1} (SASRI, 2013) and so no basal B was applied to the trials.

4.2.3. Statistical analysis

Mean leaf nutrient concentrations per treatment were analysed using analysis of variance (three-way ANOVA) and, in the case of the unbalanced dataset from the Inceptisol second ratoon harvest, residual maximum likelihood (REML) (Genstat, 14th Edition, VSN International, 2011). Data which were not normally distributed were transformed using $\log_{10}(x+1)$ or square root before conducting ANOVA. Where treatments showed significant effects, the Holm Sidak multiple comparison separation or Fisher's protected least significant difference (LSD) test was used to identify where the differences between treatment means lay.

4.3. Results and discussion

4.3.1. Effect of applied potassium on leaf nutrient content

Potassium fertiliser significantly affected leaf Ca, Cu, K, Mg, S and Zn at most sampling times. Leaf sample data from the second ratoon crop on the Inceptisol, at 4 months of age, illustrate the effects of applied K on these nutrients (Table 4.1). They are discussed in the sections below.

Table 4.1: Inceptisol: Effect of applied potassium (K) on mean ± s.e. (n = 24) third leaf K, sulphur (S), calcium (Ca), magnesium (Mg), copper (Cu) and zinc (Zn) in the second ratoon crop, at 4 months' crop age

K applied	**K**	**S**	**Ca**	**Mg**	**Cu**	**Zn**
(kg ha^{-1})	------------------------------ (%) ------------------------------				-------- (mg kg^{-1}) --------	
0	1.08 ± 0.12 a[Ŧ]	0.16 ± 0.00 a	0.23 ± 0.01 a	0.15 ± 0.01 a	5.32 ± 0.13 a	13.86 ± 0.33 a
100	1.31 ± 0.04 b	0.15 ± 0.00 b	0.20 ± 0.01 b	0.12 ± 0.00 b	4.97 ± 0.13 b	12.72 ± 0.20 b
200	1.40 ± 0.08 c	0.14 ± 0.00 b	0.19 ± 0.01 b	0.12 ± 0.00 b	4.95 ± 0.13 b	12.62 ± 0.20 b
300	1.46 ± 0.14 c	0.14 ± 0.00 b	0.18 ± 0.01 b	0.10 ± 0.00 c	4.91 ± 0.12 b	12.58 ± 0.20 b
Sig.	**P<0.001**	**P<0.001**	**P < 0.001**	**P < 0.001**	**P<0.05**	**P<0.001**

[Ŧ]Within columns, values with different letters are significantly different to each other.

4.3.1.1. Potassium

Potassium fertiliser significantly increased leaf K concentrations at all sampling times at each site (Appendix 4.1). On the Oxisol, in the zero K treatment, leaf K was below the SASRI 1.05% threshold at three of the six sampling times (first ratoon, 4 and 6 months; second ratoon, 4 months). At most Oxisol sampling events, leaf K tended to reach a maximum at 100 or 200 kg K ha^{-1}; the highest K application rate (300 kg ha^{-1}) never increased leaf K significantly above that at 200 kg ha^{-1} (Appendix 4.1). On the Inceptisol, leaf K fell below 1.05% at one of the five sampling times (first ratoon, 4 months), in the zero K treatment only. Leaf K on the Inceptisol tended to reach a maximum at 200 or 300 kg K ha^{-1} (as in Table 4.1).

4.3.1.2. Sulphur, zinc and copper

Applied K significantly suppressed S, Zn and Cu uptake at most sampling events (as in Table 4.1). Increasing K rates were associated with significantly reduced leaf S on the Oxisol at 5 out of 6 sampling events, and on the Inceptisol at 4 out of 5 events. Sulphur is taken up by sugarcane roots as SO_4^{2-} (Meyer, 2013). Increased soil and plant concentrations of the K^+ ion might thus be expected, by maintaining charge balance, to facilitate increased uptake of the sulphate anion, or at least not reduce it. The reduction in S with the application of KCl might, however, be linked to the chloride (Cl^-) ions. At high soil concentrations, nonspecific competition for uptake between ions of the same charge can occur (Marschner, 1995). Potassium chloride fertiliser caused *in planta* Cl levels to increase in potatoes (James *et al*., 1970) and tomatoes (Nukaya *et al.,* 1991) and, in sugarcane plants, Cl deficiency can be corrected by the application of KCl (Anderson and Bowen, 1990). Although not measured in the present study, it is probable that application of KCl would have increased leaf Cl. Despite suppression, however, at no sampling time did leaf S fall below the critical threshold level of 0.12% (Miles and Titshall, 2020) at either site.

Both Zn and Cu are taken up by the plant as cations (Zn^{2+}, Cu^{2+}) (Mengel and Kirkby, 2001) and the decrease in leaf Zn (4/6 events on the Oxisol; 3/5 on the Inceptisol) and Cu (3/6 on the Oxisol; 2/5 on the Inceptisol) could have been caused by ionic antagonism with the applied K. Smith (1975) reported a reduction in alfalfa leaf Zn and Cu with K application. Bowen (1969), on the other hand, reported that K stimulated their uptake by sugarcane, though this effect did not occur consistently.

At all sampling times, leaf Cu was greater than the SASRI threshold of 3.0 mg kg^{-1} (Miles and Titshall, 2020). Leaf Zn was generally higher than the threshold of 13.0 mg kg^{-1} (Miles and Titshall, 2020), though it was below this threshold at one of the two sampling events at each site in the second ratoon crop, where K was applied (results not shown).

4.3.1.3. Calcium and magnesium

At both sites, increased leaf K significantly suppressed leaf Ca and Mg at most sampling events. This effect is illustrated, for the second ratoon crop on the Oxisol, in Figure 4.1.

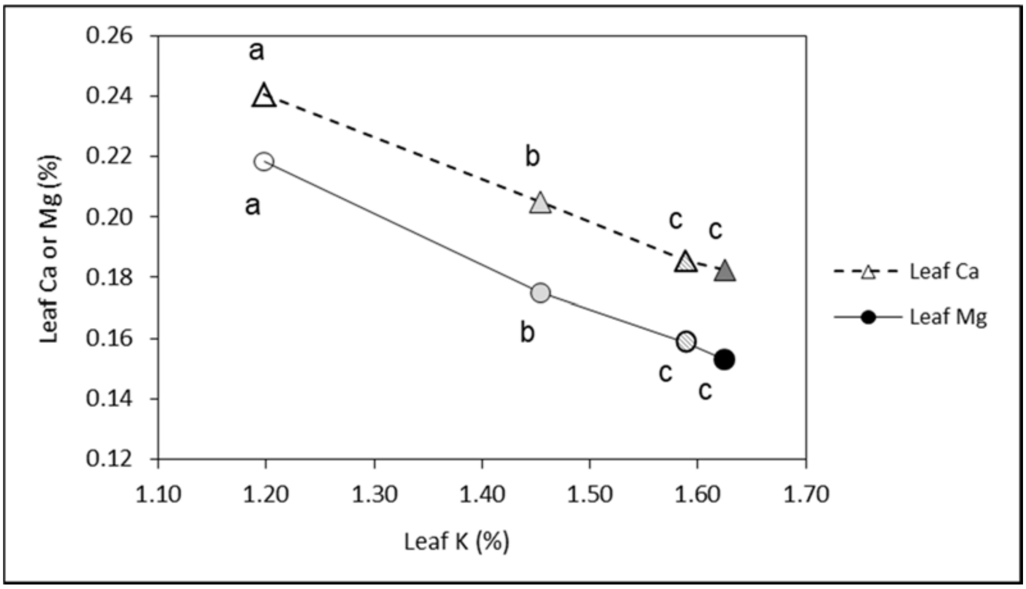


Figure 4.1: Oxisol: Relationship between leaf potassium (K) and calcium (Ca) and magnesium (Mg) in the second ratoon crop. Leaf samples collected at 6 months' crop age. Within nutrients (Ca or Mg), points with different letters are significantly different ($P < 0.001$). Each point represents the mean (n=24), across all replicates, at each of the four K application rates (0 kg K ha^{-1}: clear symbol; 100 kg K ha^{-1}: grey symbol; 200 kg K ha^{-1}: hatched symbol; 300 kg K ha^{-1}: black symbol).

Applied K had a more consistent suppressive effect on Mg on both soils (reduced at every sampling event) than Ca that was reduced at four out of six events and four out of five events on the Oxisol (Table 4.2) and Inceptisol (Table 4.3), respectively.

Table 4.2: Oxisol: Effect of applied potassium (K) on mean ± s.e. (n=24) third-leaf calcium (Ca) and magnesium (Mg), at 4- and 6-months' crop age

K applied (kg ha^{-1})	**Ca and Mg** (%)			
	[a]PC - 4 months		***PC - 6 months***	
	Ca	**Mg**	**Ca**	**Mg**
0	0.308 ± 0.001	0.150 ± 0.002 a[Ŧ]	0.316 ± 0.002	0.167 ± 0.003 a
100	0.308 ± 0.002	0.145 ± 0.001 b	0.310 ± 0.002	0.160 ± 0.002 ab
200	0.305 ± 0.001	0.140 ± 0.001 c	0.313 ± 0.002	0.162 ± 0.002 ab
300	0.306 ± 0.001	0.143 ± 0.002 bc	0.311 ± 0.003	0.158 ± 0.003 b
Sig.	**NS**	**P<0.001**	**NS**	**P<0.05**
	[b]R1 – 4 months		***R1 – 6 months***	
	Ca	**Mg**	**Ca**	**Mg**
0	0.308 ± 0.002 a	0.162 ± 0.003 a	0.314 ± 0.001 a	0.167 ± 0.002 a
100	0.300 ± 0.001 b	0.153 ± 0.003 ab	0.307 ± 0.001 b	0.150 ± 0.002 b
200	0.302 ± 0.001 ab	0.150 ± 0.002 b	0.306 ± 0.001 b	0.147 ± 0.002 bc
300	0.300 ± 0.002 b	0.146 ± 0.002 b	0.303 ± 0.001 b	0.143 ± 0.002 c
Sig.	**P<0.01**	**P<0.001**	**P<0.001**	**P<0.001**
	[c]R2 – 4 months		***R2 – 6 months***	
	Ca	**Mg**	**Ca**	**Mg**
0	0.383 ± 0.010 a	0.293 ± 0.008 a	0.240 ± 0.006 a	0.218 ± 0.004 a
100	0.333 ± 0.009 b	0.235 ± 0.005 b	0.205 ± 0.005 b	0.175 ± 0.004 b
200	0.323 ± 0.010 b	0.217 ± 0.004 bc	0.185 ± 0.004 c	0.159 ± 0.004 c
300	0.290 ± 0.004 c	0.203 ± 0.004 c	0.183 ± 0.004 c	0.153 ± 0.004 c
Significance	**P<0.001**	**P<0.001**	**P<0.001**	**P<0.001**

[a]PC = Plant crop; [b]R1 = First Ratoon crop; [c]R2 = Second Ratoon crop.
[Ŧ]Within sampling events and columns, values with different letters are significantly different to each other.

Table 4.3: Inceptisol: Effect of applied potassium (K) on mean ± s.e. (n=24) third-leaf calcium (Ca) and magnesium (Mg), at 4- and 6-months' crop age

K applied (kg ha^{-1})	**Ca and Mg** (%)			
	aPC - 4 months		***PC - 6 months***	
	Ca	**Mg**	**Ca**	**Mg**
0	0.316 ± 0.002 a[Ŧ]	0.186 ± 0.003 a	nd[#]	nd
100	0.310 ± 0.002 ab	0.170 ± 0.003 b	nd	nd
200	0.308 ± 0.002 bc	0.163 ± 0.002 b	nd	nd
300	0.303 ± 0.001 c	0.162 ± 0.003 b	nd	nd
Sig.	**P < 0.001**	**P < 0.001**	nd	nd
	bR1 - 4 months		***R1 - 6 months***	
	Ca	**Mg**	**Ca**	**Mg**
0	0.340 ± 0.005 a	0.171 ± 0.003 a	0.333 ± 0.003	0.203 ± 0.003 a
100	0.310 ± 0.007 b	0.156 ± 0.003 b	0.329 ± 0.002	0.199 ± 0.003 ab
200	0.316 ± 0.004 b	0.152 ± 0.002 bc	0.331 ± 0.002	0.198 ± 0.002 ab
300	0.309 ± 0.003 b	0.143 ± 0.002 c	0.329 ± 0.002	0.193 ± 0.001 b
Sig.	**P < 0.001**	**P < 0.001**	**NS**	**P < 0.05**
	cR2 - 4 months		***R2 - 6 months***	
	Ca	**Mg**	**Ca**	**Mg**
0	0.227 ± 0.006 a	0.148 ± 0.006 a	0.184 ± 0.004 a	0.141 ± 0.003 b
100	0.198 ± 0.005 b	0.124 ± 0.004 b	0.158 ± 0.003 b	0.122 ± 0.003 b
200	0.189 ± 0.006 b	0.117 ± 0.003 b	0.152 ± 0.003 bc	0.113 ± 0.002 c
300	0.179 ± 0.006 b	0.103 ± 0.003 c	0.144 ± 0.003 c	0.110 ± 0.002 c
Sig.	**P < 0.001**	**P < 0.001**	**P < 0.001**	**P < 0.001**

[a]PC = Plant crop; [b]R1 = First Ratoon crop; [c]R2 = Second Ratoon crop.
[Ŧ]Within sampling events and columns, values with different letters are significantly different to each other.
[#] nd – not determined.

Interactions between K, Ca and Mg as indicated by plant uptake are well documented. Grunes *et al*. (1992) found that concentrations of Mg and Ca in three cool-season grass species were significantly reduced after K fertilisation. Garcia *et al*. (1999) reported a reduction in grapevine leaf K with increased Ca application, and a reduction in leaf Ca and Mg with higher K application rates. Gosnell and Long (1971) attributed decreased sugarcane uptake of Ca and Mg with K fertilisation to cationic antagonism. Potassium depresses root uptake of Mg when rhizosphere K is high (Marschner, 1995) and increased K concentrations in roots have been reported to depress Mg translocation from roots to shoots, leading to low leaf Mg (Karlen *et al*., 1978; Wilkinson *et al*., 2000). Decreases in Ca and Mg have also been attributed to the ‘dilution effect’ caused by higher yields in response to K application (Dibb and Thompson, 1985).

Most studies of K x Ca x Mg interactions have considered a two- or even three-way interaction with increased (or reduced) rates of any of the three nutrients leading to a concurrent reduction (or increase) in the other two, resulting in a more or less stable cationic total (Mengel and Kirkby, 2001). In the present study, however, K fertiliser application consistently reduced leaf Ca and Mg, while increased rates of Ca and Mg (as applied in the Calmasil® / cement treatments) seldom affected leaf K (Section 4.3.3.3). This indicates one-way antagonism between K and Ca or K and Mg. Potassium ions are generally taken up more efficiently than Ca or Mg due to the effective H^+/K^+ symport, and so K uptake may be less affected by a rise in soil Mg concentration (Mengel and Kirkby, 2001). Similar results were reported for alfalfa (Omar and El Kobbia, 1966), where increasing K led to reduced plant Mg, but increasing Mg had little or no effect on plant K. Miles (2010) reached a similar conclusion for sugarcane. Marschner (1995) reports that Ca^{2+} stimulates net uptake of K^+ at low pH, by counteracting the negative effects of high H^+ concentrations on uptake mechanisms.

4.3.1.4. Sum of cations

The sum of cation equivalents within plant tissue often remains nearly constant when the concentration of one cation is increased in the soil (Mengel and Kirkby, 2001), largely due to ionic antagonism. This pattern was shown, to a large extent, in the leaf samples from both sites (Table 4.4). Although the sum of cations (equivalent charge basis) differed between, it remained fairly consistent within, sampling times, across the different K rates (Table 4.4).

Table 4.4: Effect of applied potassium (K) on the mean ± s.e. (n=16) third-leaf sum of potassium, calcium (Ca) and magnesium (Mg), at 4- and 6-months' crop age, on the Oxisol and Inceptisol. Cation sum calculated for the 0 kg Si ha^{-1} and intermediate N rate (80 kg ha^{-1} [Oxisol]; 105 kg ha^{-1} [Inceptisol]) treatments

K applied (kg ha^{-1})	**Sum of K, Ca and Mg** (cmol$_c$ kg^{-1})			
	Oxisol		**Inceptisol**	
	[a]PC - 4 months	***PC - 6 months***	***PC - 4 months***	***PC - 6 months***
0	70.59 ± 0.63	64.51 ± 1.24	61.02 ± 1.10	nd[#]
100	71.42 ± 2.78	63.37 ± 0.49	62.73 ± 0.45	nd
200	72.39 ± 0.34	65.42 ± 1.32	64.34 ± 0.55	nd
300	72.81 ± 0.79	67.05 ± 1.38	64.20 ± 0.72	nd
Significance	**NS**	**NS**	**NS**	nd
	[b]R1 - 4 months	***R1 - 6 months***	***R1 - 4 months***	***R1 - 6 months***
0	54.57 ± 0.49	56.91 ± 0.29	57.47 ± 0.89	66.14 ± 0.74 a[Ŧ]
100	54.77 ± 0.43	57.93 ± 0.35	55.24 ± 2.41	67.98 ± 0.27 b
200	55.61 ± 0.69	58.64 ± 0.56	60.44 ± 0.45	67.93 ± 0.38 b
300	55.65 ± 0.79	58.64 ± 0.60	61.15 ± 0.64	68.21 ± 0.60 b
Significance	**NS**	**NS**	**NS**	**P<0.05**
	[c]R2 - 4 months	***R2 - 6 months***	***R2 - 4 months***	***R2 - 6 months***
0	67.46 ± 1.30	60.38 ± 1.97 a	51.01 ± 0.57 a	51.78 ± 0.65 a
100	67.21 ± 1.45	62.99 ± 0.99 ab	54.32 ± 0.99 ab	53.08 ± 0.35 ab
200	68.52 ± 1.49	62.93 ± 1.32 ab	55.38 ± 1.21 ab	53.60 ± 0.40 ab
300	66.15 ± 0.86	63.93 ± 0.63 b	56.95 ± 1.26 b	55.07 ± 0.80 b
Significance	**NS**	**P<0.05**	**P<0.01**	**P<0.05**

[a]PC = Plant crop; [b]R1 = First Ratoon crop; [c]R2 = Second Ratoon crop.
[#]nd – not determined.
[Ŧ]Within sampling events, values with different letters are significantly different to each other.

While some significant differences in the sum of cations were found between different K rates, the differences themselves were not large (~5-8%), and similar to the range (~4-6%) reported by Mengel and Kirkby (2001). It is possible that inclusion of ammonium and sodium, which were not measured in the leaf at either trial site, might have made the sum of cations even more similar across the K rates. Increasing K supply, therefore, increased leaf K but did not result in greatly increased cation totals, illustrating the suppression of Ca and Mg uptake.

4.3.2. Effect of applied nitrogen on leaf nutrient content

4.3.2.1. Nitrogen

As expected, N application caused a highly significant increase in leaf N at all sampling events at both sites (Appendix 4.2). On the Oxisol, the highest rate of N did not lead to an increase in leaf N above that of the intermediate rate. The highest N rate did, however, increase leaf N further on the Inceptisol at times, even when leaf N was high (>2.0%) (Appendix 4.2).

4.3.2.2. Phosphorus, potassium, sulphur, zinc, copper and silicon

Leaf concentrations of P, K, S, Zn and Cu all increased with N application at most sampling events at both sites. Leaf sample results from one sampling event each on the Oxisol and Inceptisol illustrate typical effects of applied N on nutrient concentrations (Table 4.5).

Nitrogen plays a critical role in increasing plant utilisation of available P, due to mechanisms such as N-induced increases in root growth, and enhanced ability of the roots to absorb and translocate P (Wilkinson *et al*., 2000). Poor uptake of K under conditions of severe N deficiency, despite plentiful soil K resources (as reported by Miles, 2010), was evident at both trial sites. In the zero N treatment, leaf K was always lower than at the highest applied N levels, and this effect was significant at five out of six sampling events on the Oxisol and four out of five events on the Inceptisol.

Nitrogen and S uptake must be balanced for efficient protein synthesis and optimal crop quality (Wilkinson *et al*., 2000). It is evident that the soil organic matter, as well as the gypsum applied at both sites at planting, provided sufficient S to counterbalance the increased N uptake (Table 4.5).

Table 4.5: Effect of applied nitrogen (N) on mean ± s.e. (n = 32) third-leaf nutrient status on the (A) Oxisol and (B) Inceptisol, each at one sampling event

N applied	**A. Oxisol: plant crop, 4 months**					
	P	**K**	**Si**	**S**	**Cu**	**Zn**
(kg ha^{-1})	---------- (%) ----------				------ (mg kg^{-1}) ------	
0	0.207 ±0.001 a[ǂ]	1.603 ±0.017 a	0.519 ±0.012 a	0.298 ±0.003 a	5.75 ±0.02 a	15.96 ±0.08 a
80	0.220 ±0.001 b	1.720 ±0.023 b	0.464 ±0.010 b	0.329 ±0.003 b	5.82 ±0.02 b	16.74 ±0.07 b
160	0.219 ±0.001 b	1.761 ±0.023 b	0.463 ±0.012 b	0.325 ±0.002 b	5.85 ±0.02 b	16.87 ±0.08 b
Sig.	**P<0.001**	**P<0.001**	**P<0.001**	**P<0.001**	**P<0.01**	**P<0.001**
N applied	**B. Inceptisol: second ratoon crop, 4 months**					
	P	**K**	**Si**	**S**	**Cu**	**Zn**
(kg ha^{-1})	---------- (%) ----------				------ (mg kg^{-1}) ------	
0	0.175 ±0.001 a	1.256 ±0.091 a	0.459 ±0.014 a	0.129 ±0.003 a	4.63 ±0.08 a	12.10 ±0.13 a
105	0.182 ±0.001 b	1.326 ±0.182 b	0.383 ±0.018 b	0.153 ±0.003 b	5.13 ±0.09 b	12.88 ±0.21 b
210	0.183 ±0.001 b	1.353 ±0.221 b	0.368 ±0.018 b	0.160 ±0.002 c	5.35 ±0.13 b	13.85 ±0.21 c
Sig.	**P<0.001**	**P<0.001**	**P<0.001**	**P<0.001**	**P<0.001**	**P<0.001**

[ǂ]Within columns and sites, values with different letters are significantly different to each other.

Micronutrient interactions with N often occur as a result of the acidifying effect of applied N (Wilkinson *et al*., 2000), leading to increased solubility of metal micronutrients (Meyer, 2013). Although the pH($CaCl_2$) was already low in both soils (Oxisol: 4.3; Inceptisol: 4.5), it is possible that localised acidification, through the application of urea, could have rendered Zn and Cu more available in the higher N treatments, resulting in their greater plant uptake.

Leaf Si decreased with N application at all six sampling events on the Oxisol, and at two of the five events on the Inceptisol (as in Table 4.5). These reductions may be linked to a decrease in soil pH associated with increasing N application, rendering phytolith Si less soluble (Haynes, 2014). Additionally, N application, especially to N-deficient plants, leads to more efficient water use by the plants, allowing greater dry matter production for each unit of water and Si absorbed (Jones and Handreck, 1967).

4.3.2.3. Calcium and magnesium

Calcium uptake was seldom affected by N application at either site, decreasing at only two out of six sampling events on the Oxisol, and not at all on the Inceptisol (Table 4.6). On the Inceptisol, Mg uptake was increased by N application at four of the five sampling events (Table 4.6). Nitrogen deficiency can cause marked reductions in uptake of Mg (amongst other nutrients) (Gosnell and Long, 1971), and the significant increases in Mg uptake with N application (Table 4.6) may reflect this. In the zero N treatments, three of the four Inceptisol sampling times with significant Mg effects, had below-threshold N concentrations (Appendix 4.2). This may indicate that N deficiency in the zero N plots had led to reduced Mg uptake. This effect was not consistent, however, on the Oxisol, which showed only two instances of reduction in Mg uptake, of which only one coincided with a below-threshold N concentration in the zero-N treatment (Table 4.6). This soil's inherently higher N status, due to high organic matter, does not explain the fact that at two of the sampling times (plant crop – 6 months and first ratoon – 4 months, Appendix 4.2), below-threshold N concentrations in the zero N treatments did not correspond with a significant reduction in Mg uptake.

Table 4.6: Effect of applied nitrogen (N) on mean ± s.e. (n=32) third-leaf calcium (Ca) and magnesium (Mg), at 4- and 6-months' crop age, on the Oxisol and Inceptisol

N applied (kg ha^{-1})	**Ca** (%)			
	Oxisol		**Inceptisol**	
	[a]PC - 4 months	***PC - 6 months***	***PC - 4 months***	***PC - 6 months***
0	0.311 ± 0.001 a[Ŧ]	0.311 ± 0.002	0.311 ± 0.002	nd[#]
[Φ]80/[Ψ]105	0.306 ± 0.001 b	0.314 ± 0.002	0.309 ± 0.002	nd
[Φ]160/[Ψ]210	0.303 ± 0.001 b	0.313 ± 0.002	0.308 ± 0.002	nd
Significance	**P<0.001**	**NS**	**NS**	nd
	[b]R1 - 4 months	***R1 - 6 months***	***R1 - 4 months***	***R1 - 6 months***
0	0.303 ± 0.002	0.309 ± 0.001 a	0.314 ± 0.004	0.330 ± 0.002
80/105	0.302 ± 0.002	0.306 ± 0.001 b	0.320 ± 0.006	0.329 ± 0.002
160/210	0.303 ± 0.001	0.307 ± 0.001 ab	0.323 ± 0.004	0.333 ± 0.002
Significance	**NS**	**P<0.05**	**NS**	**NS**
	[c]R2 - 4 months	***R2 - 6 months***	***R2 - 4 months***	***R2 - 6 months***
0	0.333 ± 0.009	0.209 ± 0.005	0.204 ± 0.004	0.162 ± 0.004
80/105	0.336 ± 0.011	0.203 ± 0.006	0.199 ± 0.006	0.160 ± 0.004
160/210	0.328 ± 0.008	0.198 ± 0.006	0.192 ± 0.006	0.156 ± 0.004
Significance	**NS**	**NS**	**NS**	**NS**

N applied (kg ha^{-1})	**Mg** (%)			
	Oxisol		**Inceptisol**	
	PC - 4 months	***PC - 6 months***	***PC - 4 months***	***PC - 6 months***
0	0.145 ± 0.001	0.159 ± 0.002	0.174 ± 0.003	nd
[Φ]80/[Ψ]105	0.145 ± 0.002	0.165 ± 0.002	0.168 ± 0.002	nd
[Φ]160/[Ψ]210	0.143 ± 0.002	0.160 ± 0.002	0.168 ± 0.003	nd
Significance	**NS**	**NS**	**NS**	nd
	R1 - 4 months	***R1 - 6 months***	***R1 - 4 months***	***R1 - 6 months***
0	0.156 ± 0.003	0.158 ± 0.002 a	0.149 ± 0.003 a	0.192 ± 0.002 a
80/105	0.151 ± 0.003	0.150 ± 0.002 b	0.158 ± 0.002 b	0.199 ± 0.002 b
160/210	0.152 ± 0.002	0.148 ± 0.003 b	0.159 ± 0.002 b	0.204 ± 0.002 b
Significance	**NS**	**P<0.001**	**P<0.05**	**P<0.001**
	R2 - 4 months	***R2 - 6 months***	***R2 - 4 months***	***R2 - 6 months***
0	0.243 ± 0.009	0.185 ± 0.005 a	0.107 ± 0.003 a	0.111 ± 0.002 a
80/105	0.233 ± 0.007	0.177 ± 0.005 a	0.128 ± 0.004 b	0.126 ± 0.003 b
160/210	0.235 ± 0.007	0.167 ± 0.006 b	0.134 ± 0.004 b	0.128 ± 0.003 b
Significance	**NS**	**P<0.001**	**P<0.001**	**P<0.001**

[a]PC = Plant crop; [b]R1 = First Ratoon crop; [c]R2 = Second Ratoon crop.
[Φ]= rate applied on the Oxisol; [Ψ]= rate applied on the Inceptisol
[#]nd = not determined.
[Ŧ]Within sampling events, values with different letters are significantly different to each other.

4.3.3. Effect of applied silicates on leaf nutrient content

4.3.3.1. Silicon

In the South African sugar industry, a minimum of 0.75% leaf Si is currently considered satisfactory (Miles and Titshall, 2020); this limit was 0.50% at the time of the trials. In Florida, a yield response to Si is likely if leaf Si falls below 1.00%

(Meyer, 2013). An Australian study suggested that 95% of maximum yield could be obtained when Si in the top visible dewlap leaf (usually the third leaf) was 0.55% (Berthelsen *et al*., 2003). In the present study, leaf Si was low on both soils at all sampling times, with minima of about 0.20%, and maxima of only 0.57% (Oxisol) and 0.82% (Inceptisol). Hence, although Calmasil® and cement application caused a significant increase in leaf Si at all sampling events at both sites (Table 4.7), concentrations very seldom increased to above the 'satisfactory' FAS threshold (0.75%) on the Inceptisol, and never on the Oxisol.

Table 4.7: Effect of applied Calmasil® / cement on mean ± s.e. (n=48) third-leaf silicon (Si) content, at 4- and 6-months' crop age, on the Oxisol and Inceptisol

Si applied (kg ha^{-1})	**Si** (%)			
	Oxisol		**Inceptisol**	
	[a]PC - 4 months	***PC - 6 months***	***PC - 4 months***	***PC - 6 months***
0	0.46 ± 0.01 a[Ŧ]	0.19 ± 0.00 a	0.21 ± 0.01 a	nd[#]
300	0.51 ± 0.01 b	0.20 ± 0.00 b	0.25 ± 0.02 b	nd
Significance	**P<0.001**	**P<0.05**	**P<0.05**	nd
	[b]R1 - 4 months	***R1 - 6 months***	***R1 - 4 months***	***R1 - 6 months***
0	0.37 ± 0.01 a	0.48 ± 0.01 a	0.62 ± 0.01 a	0.78 ± 0.01 a
300	0.38 ± 0.00 b	0.50 ± 0.01 b	0.68 ± 0.01 b	0.82 ± 0.01 b
Significance	**P<0.05**	**P<0.001**	**P<0.001**	**P<0.01**
	[c]R2 - 4 months	***R2 - 6 months***	***R2 - 4 months***	***R2 - 6 months***
0	0.50 ± 0.01 a	0.44 ± 0.01 a	0.34 ± 0.01 a	0.26 ± 0.01 a
300	0.57 ± 0.01 b	0.52 ± 0.01 b	0.47 ± 0.02 b	0.33 ± 0.02 b
Significance	**P<0.001**	**P<0.001**	**P<0.001**	**P<0.001**

[a]PC = Plant crop; [b]R1 = First Ratoon crop; [c]R2 = Second Ratoon crop.
[Ŧ]Within sites and sampling months, values with different letters are significantly different to each other.
[#] nd – not determined.

The naturally low soluble Si of acid soils (Section 2.4.2), such as those used for the present trials, resulted in the highly weathered Oxisol being unable to support adequate levels of plant Si, despite additions of this nutrient. On the relatively young Inceptisol, weathering has apparently not advanced sufficiently to break down the Si-containing minerals in the resistant sandstone parent material. Leaching of the applied Si, and adsorption by aluminium (Al) and Fe oxides, may have exacerbated

Si deficiencies at both sites. Keeping *et al*. (2013) similarly reported that sugarcane leaf Si seldom exceeded 0.50% on a rainfed Inceptisol in KwaZulu-Natal.

4.3.3.2. Nitrogen and phosphorus

Silicon application did not affect N uptake at any sampling event on the Oxisol, and significantly reduced it at only one out of five sampling times on the Inceptisol (results not shown). Although Si application has been reported to increase (Cuong *et al*., 2017) and decrease (Greger *et al*., 2018) plant N uptake, its effects in this study were limited.

Phosphorus uptake was improved with Si application at the Oxisol site (3/6 events), and once at the Inceptisol site (results not shown). Obihara and Russell (1972) reported that there is competition between silicate and phosphate for adsorption sites in the soil. Phosphate tends to be displaced by Si from such sites, leading to increased P in the soil solution (Smyth and Sanchez, 1980), facilitating greater uptake of P by the plant. This effect was not consistent but occurred more often on the Oxisol, where a higher concentration of Al and Fe oxides was likely (with a correspondingly greater anion exchange capacity (AEC); Gu and Schulz, 1991). A greater AEC may offer increased scope for replacement of P anions with Si, while the liming effect of Calmasil® and cement would decrease AEC (Gu and Schulz, 1991), possibly leading to release of some P into the soil solution.

4.3.3.3. Calcium, magnesium and potassium

Calcium and Mg uptake was significantly improved by the application of Si at two of the six sampling events on the Oxisol. On the Inceptisol Ca and Mg uptake was increased at three out of five and one out of five events, respectively (Table 4.8). At all sampling events, with or without the Si sources, leaf Ca and Mg were above the ‘satisfactory’ thresholds of 0.15% (Ca) and 0.08% (Mg) (Miles and Titshall, 2020), at both trial sites.

Table 4.8: Effect of applied silicon (Si) as Calmasil® / cement on mean ± s.e. (n=48) third-leaf calcium (Ca), magnesium (Mg) and potassium (K) content, at 4- and 6-months' crop age, on the Oxisol and Inceptisol

Si applied (kg ha^{-1})	Ca, Mg and K (%)					
	Oxisol					
	[a]PC - 4 months			*PC - 6 months*		
	Ca	*Mg*	*K*	*Ca*	*Mg*	*K*
0	0.306±0.001	0.144±0.001	1.714±0.021 a[Ŧ]	0.314±0.002	0.163±0.002	1.394±0.020
300	0.307±0.001	0.144±0.001	1.676±0.019 b	0.311±0.001	0.160±0.002	1.425±0.016
Sig.	**NS**	**NS**	**P<0.05**	**NS**	**NS**	**NS**
	[b]R1 – 4 months			*R1 – 6 months*		
	Ca	*Mg*	*K*	*Ca*	*Mg*	*K*
0	0.302±0.001	0.152±0.002	1.071±0.011	0.307±0.001	0.152±0.002	1.162±0.014
300	0.303±0.001	0.154±0.002	1.064±0.014	0.308±0.001	0.152±0.002	1.147±0.012
Sig.	**NS**	**NS**	**NS**	**NS**	**NS**	**NS**
	[c]R2 – 4 months			*R2 – 6 months*		
	Ca	*Mg*	*K*	*Ca*	*Mg*	*K*
0	0.317±0.006 a	0.231±0.005 a	1.266±0.023	0.200±0.005 a	0.173±0.005 a	1.477±0.032
300	0.348±0.008 b	0.243±0.007 b	1.235±0.030	0.208±0.005 b	0.180±0.004 b	1.455±0.030
Sig.	**P<0.001**	**P<0.05**	**NS**	**P<0.05**	**P<0.05**	**NS**
Si applied (kg ha^{-1})	**Inceptisol**					
	[a]PC - 4 months			*PC - 6 months*		
	Ca	*Mg*	*K*	*Ca*	*Mg*	*K*
0	0.307±0.001 a	0.167±0.002 a	1.317±0.022 a	nd[#]	nd	nd
300	0.312±0.002 b	0.174±0.002 b	1.250±0.022 b	nd	nd	nd
Sig.	**P<0.01**	**P<0.01**	**P<0.001**	nd	nd	nd
	[b]R1 – 4 months			*R1 – 6 months*		
	Ca	*Mg*	*K*	*Ca*	*Mg*	*K*
0	0.314±0.004	0.158±0.002	1.167±0.016	0.329±0.002	0.201±0.002 a	1.359±0.014
300	0.324±0.004	0.154±0.002	1.146±0.018	0.332±0.002	0.196±0.002 b	1.358±0.011
Sig.	**NS**	**NS**	**NS**	**NS**	**P<0.05**	**NS**
	[c]R2 – 4 months			*R2 – 6 months*		
	Ca	*Mg*	*K*	*Ca*	*Mg*	*K*
0	0.188±0.004 a	0.124±0.004	1.322±0.025	0.152±0.003 a	0.122±0.003	1.370±0.018 a
300	0.209±0.005 b	0.122±0.003	1.301±0.026	0.167±0.003 b	0.121±0.002	1.339±0.017 b
Sig.	**P<0.001**	**NS**	**NS**	**P<0.001**	**NS**	**P<0.001**

[a]PC = Plant crop; [b]R1 = First Ratoon crop; [c]R2 = Second Ratoon crop.
[Ŧ]Within sites, sampling months and columns, values with different letters are significantly different to each other.
[#] nd – not determined.

Potassium showed a significant decrease at only three of the 11 sampling times, once on the Oxisol (when there was no corresponding increase in either Ca or Mg) and twice on the Inceptisol (Table 4.8). Those on the Inceptisol both coincided with an increase in Ca; Mg was increased at only one of the times. There was no apparent effect of the sum of Ca and Mg (cation equivalent basis) on the K decrease (results not shown). The data indicate that there was very little antagonistic effect of Ca and Mg on K, but that which did occur appeared to be driven by Ca. It is possible, however, that reduced leaf K may have been caused by a dilution effect following increased growth and yield on the Si treatments (Section 3.3.4.2.1) rather than ionic antagonism.

4.3.4. Leaf potassium, nitrogen and silicon status and crop yield

4.3.4.1. Potassium

Sugarcane yield, sucrose percent (%ERC) and sucrose yield (t ERC ha^{-1}) tended to increase with increasing leaf K, whether this was measured at 4 or 6 months' crop age. This was consistent across trial sites and crops (Figure 4.2A and B), with the exception of the first ratoon crop on the Inceptisol, when increased leaf K associated with the highest K rate resulted in a reduction in sucrose yield (Figure 4.2B). Despite these relatively consistent increases, it would not be possible to use these results to establish a reliable threshold value for K. For instance, on the Oxisol (Figure 4.2A), maximum sucrose yields were obtained at 1.8% K (plant crop), 1.1% K (first ratoon), and 1.4% K (second ratoon). In a later crop, a result of 1.3% would be difficult to interpret as it is not clear whether application of additional K fertiliser would be advisable. It is possible that inadequate moisture status of the crop at some of the sampling times may have contributed to the difficulty in interpreting the leaf sample results.

Similarly, on the Inceptisol (Figure 4.2B), maximum yield was achieved at ~1.4-1.5% K in the plant and second ratoon crops. In the first ratoon crop, however, yield was significantly reduced at 1.3% leaf K. The leaf K threshold used by SASRI is 1.05%, in line with that in many countries (Anderson and Bowen, 1990). In the present trials, maximum yield was unlikely to have been obtained in any of the crops if the leaf K levels were as low as 1.05% (Figure 4.2A and B).

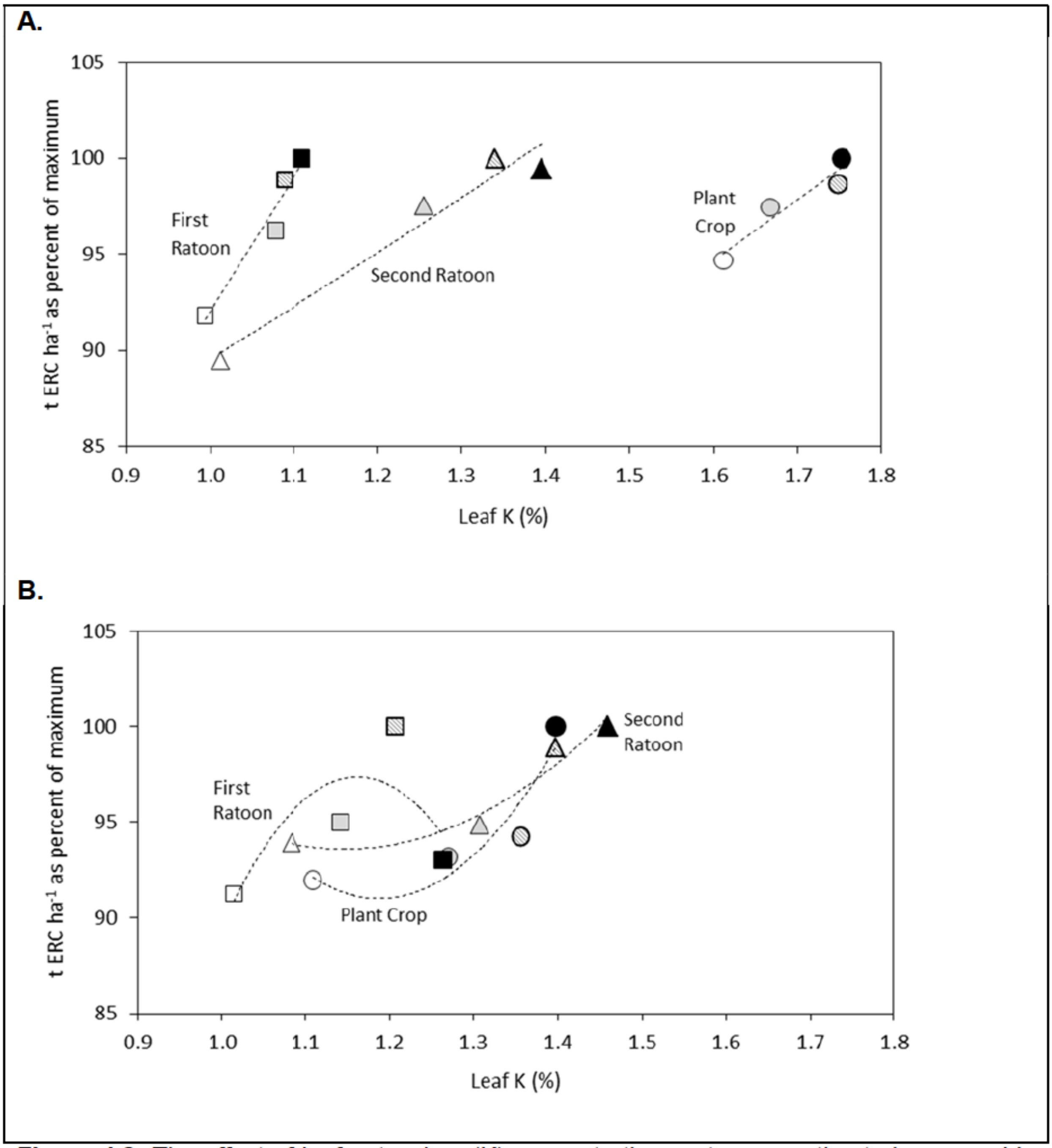


Figure 4.2: The effect of leaf potassium (K) concentration on tonnes estimated recoverable crystal (t ERC ha^{-1}), as a percent of the maximum for each harvest, on the (A) Oxisol; and (B) Inceptisol. Leaf samples were collected at 4 months' crop age. Within soil types and crops, each point represents the mean (n=24), across all replicates, at each of the four K application rates (0 kg K ha^{-1}: clear symbol; 100 kg K ha^{-1}: grey symbol; 200 kg K ha^{-1}: hatched symbol; 300 kg K ha^{-1}: black symbol).

4.3.4.2. Nitrogen

Leaf N and sucrose yield showed a negative association in the Oxisol plant crop (Figure 4.3). As with K, leaf analysis did not provide an accurate estimate of the potential efficacy of applying more N. For example, a leaf N concentration of 2.0% would have been 'too high' in the plant crop indicating reduced sucrose yield. In the second ratoon, 2.0% would have been 'too low', and applying more N would have been advantageous. Current FAS leaf N threshold limits range from 1.6-1.9%, depending on month of sampling, area and crop (plant vs ratoon). In Mauritius, this threshold is 1.95% (at 3-5 months) (Halais, 1962), and in Guyana, thresholds range from 1.9-2.5%, at 2-6 months (Evans, 1965). In Australia, the third leaf N threshold ranges from 1.7-1.9%, depending on the sampling month (Calcino *et al*., 2018). On the Inceptisol, leaf N showed a more predictable pattern of increasing sucrose yield with greater leaf N in the ratoons (data not shown). Again, however, threshold values would be difficult to predict, as yield increases did not level off. Further increases may therefore have occurred beyond the leaf N values recorded (which were as high as 2.3% in the second ratoon crop). Again, moisture status may have impacted these results.

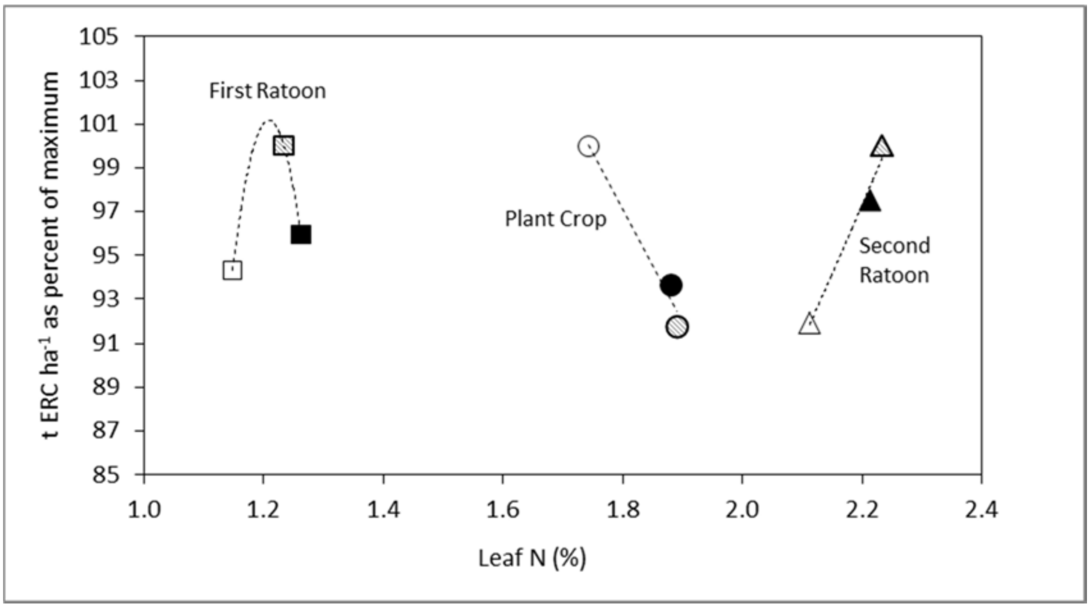


Figure 4.3: Oxisol: The effect of leaf nitrogen (N) concentration on tonnes estimated recoverable crystal (t ERC ha^{-1}), as a percent of the maximum for each harvest. Leaf samples were collected at 4 months' crop age. Within crops, each point represents the mean (n=32), across all replicates, at each of the three N application rates (0 kg N ha^{-1}: clear symbol; 80 kg N ha^{-1}: hatched symbol; 160 kg N ha^{-1}: black symbol).

4.3.4.3. Silicon

Leaf Si levels were not related to %ERC, supporting previous research (Korndörfer and Lepsch, 2001). Increased leaf Si in the ratoon crops coincided with increased stalk (and hence sucrose) yields (Appendix 4.3). As with K and N, leaf analysis could not accurately predict the sufficiency (or otherwise) of measured leaf Si concentrations. The generally low uptake of Si (Section 4.3.3.1) may have contributed to this phenomenon. It is noteworthy, however, that the greatest percentage increases in sucrose yield (t ERC ha^{-1}) were obtained with the greatest percentage increases in leaf Si concentration (Appendix 4.3).

4.4. Conclusions

Increasing rates of applied K suppressed the leaf concentration of Ca, Mg, S, Zn and Cu, with no impact on sugarcane yields. Potassium suppressed Mg uptake more consistently than Ca. Calcium and Mg, on the other hand, seldom suppressed K uptake, and when they did so, Ca appeared to play the dominant role. Cationic antagonism between these three nutrients has been reported in sugarcane, though previous reports have stressed the suppressive effect of Ca and Mg on K. The finding, in this study, that K appears to reduce Ca and Mg uptake far more strongly than *vice versa*, is of considerable significance to the South African sugar industry. Currently, FAS fertiliser K recommendations take soil Ca and Mg into account. For the northern irrigated areas of the industry, when high-clay (>40%) soils have (Ca + Mg) levels greater than 4 000 mg L^{-1}, markedly higher K threshold values are used, as such high Ca and Mg levels are assumed to reduce K uptake (Donaldson *et al*., 1990). Meyer (2013) also refers to reports of leaf K suppression by increased Ca and/or Mg. No allowance is made in the current FAS recommendations, however, for the reverse situation and soil K levels are not taken into account when determining Ca or Mg thresholds, which remain constant. It is therefore recommended that higher Ca and Mg thresholds be implemented where soil K is high. The details of such a change need to be elucidated with further trials.

There was no consistent effect of K application on leaf N or Si at either trial site. Potassium application generally led to a reduction in leaf S, Zn and Cu, but they did not fall below threshold levels. They should nonetheless be monitored regularly to ensure that deficiency (and hence yield reduction) does not occur.

Nitrogen application increased plant uptake of P, K, S, Zn and Cu. In contrast, Si uptake was often suppressed. Application of Si seldom increased leaf Si to above the ‘satisfactory’ level of 0.75%. It is possible that higher rates of Calmasil® could have increased leaf Si to a greater extent, though such rates may not increase yield sufficiently to be economically profitable. Over a longer term, however, more than three crops would likely be produced following a single application of Calmasil®, perhaps leading to improved economic feasibility. Although the required additional cane yield might not be achieved, even over future ratoons, continued soil acidification and depletion of Si reserves would ultimately necessitate applications of these liming sources to allow the continued production of sugarcane.

Relationships between leaf nutrient concentrations and crop yields were poorly defined. Although harvest characteristics showed patterns of increase or decrease with increasing leaf K, N and Si, the leaf data did not allow for the reliable determination of nutrient threshold levels, above which it would not be economic to apply more of a specific nutrient. The data therefore indicated that leaf analysis was not a reliable means of establishing nutrient sufficiency in the crops from the present trials. It is suggested that variable crop moisture status at the time of leaf sampling may have been a major contributor to these poor relationships. The FAS gives instructions to growers of when to collect leaf samples and the analytical reports state that results are only meaningful if the samples were collected under optimal conditions of age, season and rainfall distribution. However, crop moisture status is likely to be variable in the entire rainfed portion of the South African sugarcane industry where seasonal rainfall distribution is often unreliable. Thus, it is likely that a portion of the samples submitted to the laboratory is affected by conditions of limited moisture, as was probably the case from the present trials.

Chapter 5

The effect of potassium, nitrogen and silicon application on relationships between soil nutrient dynamics and yield of sugarcane

5.1. Introduction

Exchangeable or readily-available soil nutrients are supplemented by more slowly-available nutrient reserves. Release of these reserves to the available pool may depend, directly or indirectly, on the amount of the nutrient supplied as fertiliser.

In sugarcane, top- and subsoil samples are routinely analysed to determine soil nutrient status (Schroeder *et al*., 1993). Although readily-available potassium (K) is routinely measured and used for K fertiliser recommendations by many soil laboratories, a number of authors (e.g. Wood and Burrows, 1980; Wood and Schroeder, 1991; Miles and Farina, 2014) have identified the slowly-available K as an important determinant of actual plant K availability. This may represent a considerable source of K, which can become available to the crop over a season or more. Boiling nitric acid has been used to extract this slowly-available soil K (nitric K) (Haysom, 1971). Haysom (1971) concluded that, in the Australian sugarcane industry, soils with nitric K reserves greater than 2.5 $cmol_c\ kg^{-1}$ do not require K fertiliser to maintain high productivity, and Australian recommendations have taken both readily-available and nitric K into account (Moody *et al*., 2007; Schroeder, 2007). Australia's sugarcane soils currently receive a reduced K fertiliser recommendation when nitric K is greater than 0.7 meq 100 g^{-1} (Calcino *et al*., 2018). Miles and Farina (2014) postulated that non-exchangeable K reserves contribute significantly to crop K requirements in many southern African soils.

The availability of applied K is determined by, amongst others, the extent to which it is immobilised by soil minerals. Illite and vermiculite are strongly K-fixing clay minerals that result in reduced availability (Goli-Kalanpa *et al*., 2008), even following K application (Wood and Meyer, 1986). Higher applications of K fertiliser are thus required on soils that contain these minerals in order to supply the crop with sufficient available K (Kingston, 2000). Over time the K from these soil minerals may become available to plants. On the other hand, soils dominated by, for example, hydroxy-aluminium and iron interlayer groups, exhibit low fixation of K, thereby allowing a larger proportion of added K to remain in solution (Rich and Obenshaim, 1955). The presence of only small amounts of 2:1 layer silicate clays influences the supply of K to plants, even in highly weathered soils (Arkcoll *et al*., 1985).

Applied nitrogen (N) and silicon (Si) are affected by different soil, management and environmental conditions. Applied N is typically ephemeral in soil, so its dynamics are difficult to track, and its uptake by plants, and hence effect on crop growth, are challenging to predict. Thus, no attempt was made, in this study, to use soil N data to predict sugarcane yield response to applied N.

Silicon application is recommended in the rainfed areas of the South African sugar industry, as available soil Si is typically below the threshold (15 mg L^{-1}) required by sugarcane (Miles, 2014). However, researchers have reported limited or inconsistent plant uptake of the Si applied in these areas, despite significant increases in soil Si concentrations (Keeping and Meyer, 2002; Berry *et al*., 2011). The possible reasons for such poor Si uptake have been discussed in Section 2.4.2.

In addition to the effect of nutrient applications on the concentration of soil nutrients, the impact of nutrient levels on crop yield and quality needs to be investigated in order for robust fertiliser recommendations to be made. Fertiliser application rates which only raise soil nutrients to below established thresholds will lead to yield loss, while excessive recommendations will be uneconomic and may lead to environmental problems. Further complexity is introduced when subsoil nutrients are also considered.

The aims of this investigation on two different soils of the South African sugarbelt were to determine the effects of (a) applied K, N and Si on soil nutrients and other soil characteristics; (b) varying soil nutrient levels on crop yield and quality; (c) subsoil nutrient levels on crop yield; and (d) the extent to which nitric K contributed to readily-available K.

5.2. Materials and methods

5.2.1. Trial details and pre-trial soil sampling

These are given in Sections 3.2.1 to 3.2.4.

5.2.2. Topsoil and depth sampling

Topsoil samples (0-20 cm) were collected using an auger from each of the four replicates approximately 6 to 8 weeks after application of N fertiliser to each crop. Fifteen samples were collected from each nett plot (central five rows at each trial site), in the middle of the interrows. These samples were bulked per plot and thoroughly mixed prior to being analysed.

Soil samples were also collected from three of the four replicates in 20 cm increments from 0-100 cm (Oxisol) and 0-80 cm (Inceptisol) between 2 and 7 weeks after each harvest. The 0-20 cm samples were collected as before and for the subsoil samples, four cores were collected diagonally across each nett plot from the middle of the interrows. The upper 20 cm of soil was discarded, as this had already been collected, and subsequent 20 cm depth increments were combined across the four core sites within each plot and thoroughly mixed prior to analysis.

5.2.3. Chemical analysis

All soil samples were dried at 40°C, crushed and then sieved to pass a 1 mm mesh. Exchangeable K, calcium (Ca), magnesium (Mg), copper (Cu), iron (Fe), manganese (Mn) and zinc (Zn) were extracted using ‘Ambic 2’ multinutrient extractant (Van der Merwe *et al*., 1984) and phosphorus (P), Si, pH and exchangeable acidity were determined using the methods given in Appendix 3.1. Ammonium and nitrate were extracted with 2 *M* KCl and measured colorimetrically by segmented flow autoanalyser (Seal Analytical Flow Injection Analyser).

5.2.4. Mineralogy and total potassium

At each trial site one soil core was collected with an auger in 20 cm increments to 100 cm (Oxisol) and 80 cm (Inceptisol) from an unfertilised pathway between trial plots. Part of each sample was separated into clay and the (sand + silt) fractions by decanting, using the application of Stokes' Law.

The mineralogical composition of the clay fraction was characterised by X-ray diffraction (XRD) on oriented specimens on glass slides. Prior to preparation of the specimens, half of the separated clay fraction was saturated with Mg^{2+} and the other half with K^{+}. The Mg-saturated specimens were air-dried, treated with ethylene glycol at 60°C overnight, and with glycerol at 85°C overnight, and the K-saturated specimens were air-dried and heated at 550°C for four hours (Bühmann *et al*., 1985). All XRD analyses were carried out on a Philips PW1050 X-ray diffractometer using monochromated CoKα radiation at 40 kV and 40 mA. Oriented specimens were scanned at 1° min^{-1} with a step-scan of 0.02° between 3 and 45° 2Θ. All data were captured by a Sietronics 122D automated micro-processor attached to the diffractometer.

The (sand + silt) samples were dried (110°C for 24 hours), milled and then random powder preparations were examined by XRD using monochromated CoKα radiation from 3 to 90° 2Θ on a PANalytical Empyrean X-ray diffractometer.

The remaining whole soil samples were dried (110°C for 24 hours), milled, formed into a fused bead, and analysed for total K on a PANalytical Axios Max X-ray fluorescence (XRF) spectrometer.

Rock fragments were collected using an auger from the Oxisol at depths between 240 and 300 cm, while decomposing rock was collected at 80 to 100 cm from the Inceptisol. One rock sample from each trial site was dried (110°C for 24 hours), crushed, milled, formed into a fused bead, and analysed for total K by XRF.

5.2.5. Slowly-available potassium

Subsoil samples from each depth collected from the zero K, zero N and zero Si treatment plots following the first ratoon crop harvest at each site were extracted with boiling 1 *M* HNO_3 for 30 min (Haysom, 1971). The K was measured using inductively coupled plasma optical emission spectrometry (ICP-OES, Varian 720ES), and the mean nitric K calculated for each soil and soil depth. Reported nitric K values were corrected for readily-available ('Ambic 2') K.

5.2.6. Statistical analysis

Mean results of each determination were subjected to analysis of variance (ANOVA) (Genstat – 14th Edition; VSN International, 2011), where the data sets were balanced (i.e., the topsoil samples). For the unbalanced depth sample data (where four replicates were sampled at 0-20 cm and only three at greater depths), residual maximum likelihood (Genstat – 14th Edition; VSN International, 2011) was used.

Where data were not normally distributed, $\log_{10}$ transformations were performed to normalise the data. Where treatments showed significant effects, values were analysed using the Holm Sidak multiple comparison separation or Fisher's protected least significant difference test to identify where the differences between treatment means lay. Differences were considered to be significant at $P < 0.05$.

5.2.7. Potassium balance

To examine the fate of K in the cropping system, a K balance was calculated for each harvest (Equation 5.1).

K balance (kg ha^{-1}) = (*K in harvested crop* + *Remaining soil K*) –
(*Applied K* + *Initial soil K*) ………………………… *Equation 5.1*

where:

K in harvested crop is the amount of K present in each above-ground plant part, determined within two weeks prior to harvest. Treatments including all rates of K and N with applied Si were sampled for this purpose. At each sampling event, 1 m of one guard row per plot was cut at ground level and partitioned into the stem, dead leaves, green leaf blades and the combined meristem and green leaf sheaths. Each component was weighed fresh, dried (80°C for 48 hours), reweighed and analysed for K by XRF (leaf material) or ashing and ICP-OES (other plant components).

Remaining soil K is the readily-available ('Ambic 2') soil K in the top 100 cm (Oxisol) or 80 cm (Inceptisol), sampled two weeks after crop harvest. This is assumed to reflect the available K which remained in the soil after the crop was removed.

Applied K is the amount of fertiliser K (kg ha^{-1}) applied at the start of each crop.

Initial soil K is the readily-available ('Ambic 2') soil K in the top 100 cm (Oxisol) or 80 cm (Inceptisol), sampled two weeks after harvest of the *previous* crop. This is the amount of K available in the soil at the start of the crop's growth.

Potassium in root tissue, slowly-available K and leaching were not taken into account.

5.3. Results and discussion

5.3.1. Initial soil properties

These are presented in Section 3.3.1 (Table 3.2).

5.3.2. Potassium

5.3.2.1. Mineralogy and total potassium content

The parent material at both sites was sandstone, though there were differences in mineralogy (Table 5.1). The Oxisol sandstone was found at depth (240-300 cm) and was highly weathered. It was chiefly composed of quartz and kaolinite with subsidiary K-feldspar, goethite and hematite. Kaolinite was the dominant mineral in the clay fraction of the Oxisol which also contained some hydroxyl Al interlayered vermiculite (HIV) and illite, along with traces of hematite, quartz and K-feldspar (Table 5.1). In the (sand + silt) fraction, quartz was dominant, with trace amounts of K-feldspar and anatase.

In contrast, the Inceptisol sandstone was more coherent and found at 80-100 cm depth. It was, however, weathered to the extent that some root penetration was possible. The rock was a mixture of quartz, kaolinite, K-feldspar and mica and/or illite, with trace amounts of goethite, hematite and anatase (Table 5.1). Again, kaolinite was the dominant mineral in the clay fraction. Illite and quartz were present as subsidiary components, along with trace amounts of vermiculite, goethite and K-feldspar (Table 5.1). In the (sand + silt) fraction, quartz was dominant, with K-feldspar present, as well as trace amounts of anatase. The Inceptisol, being less weathered, contained more K-feldspar than the Oxisol. The K-feldspars present in both soils could be responsible for some K release (Sadusky *et al.*, 1987; Sanz Scovino and Rowell, 1988; Parker *et al.*, 1989a, b; Pal *et al.*, 2001).

Table 5.1: Mineralogy of the sandstone parent rock, and the clay and (sand + silt) fractions of the Oxisol and Inceptisol topsoils

Fraction	Depth (cm)	Kao	Goe	Hem	Qtz	HIV	Ill / Mca	Vrm	K-Fel	Ant
				Oxisol						
Clay	0-20	+++	-	tr	tr	+++	+	-	tr	-
(Sand + silt)	0-20	-	-	-	++++	-	-	-	tr	tr
Rock	240-300	++	+	+	++++	-	-	-	+	tr
				Inceptisol						
Clay	0-20	++++	tr	-	+	-	+	tr	tr	-
(Sand + silt)	0-20	-	-	-	++++	-	-	-	+	tr
Rock	80-100	+	tr	tr	++++	-	++	-	+	tr

++++ = > 60%; +++ = 40–60%; ++ = 20–40%; + = 5–20%; tr = <5%; - = absent; Kao = kaolinite; Goe = goethite; Hem = hematite; Qtz = quartz; HIV = hydroxyl Al interlayered vermiculite; Ill = illite; Mca = mica; Vrm = vermiculite; K-Fel = K-feldspar; Ant = anatase

The differences in the parent material at the two sites, both in the degree of weathering and the mica present in the Inceptisol, are reflected in the Inceptisol containing an order of magnitude greater total K than the Oxisol at all depths (Table 5.2). The Inceptisol thus has a much larger pool of potentially available K than the Oxisol.

Table 5.2: Total potassium (K) in the whole soil and rock from the Oxisol and Inceptisol

Soil	Sample	Depth (cm)	K (%)
Oxisol	Whole soil	0 – 20	0.096
		20 – 40	0.080
		40 – 60	0.076
		60 – 80	0.078
		80 – 100	0.092
	Rock	240 - 300	0.252
Inceptisol	Whole soil	0 – 20	0.564
		20 – 40	0.592
		40 – 60	0.607
		60 – 80	0.847
	Rock	80 - 100	2.704

5.3.2.2. Effect of potassium application on topsoil (0-20 cm) readily-available potassium

The application of K led to an increase in topsoil readily-available K in both soils (Figure 5.1). At both sites, there was a greater rate of increase in the ratoon crops (where the K was surface-applied) than in the plant crop (when the K was incorporated into the soil).

An increase in topsoil K in the zero plots, between the pre-trial sampling and the plant crop's sampling, was evident at both sites. On the Oxisol, pre-trial analysis returned a value of 55 mg K L^{-1} (Table 3.2), while the zero plots had 125 mg K L^{-1} three months after trial planting (Figure 5.1A). On the Inceptisol, K increased from 44 mg L^{-1} (Table 3.2) to 96 mg L^{-1} (Figure 5.1B) over four months. It is possible that K release from slowly-available pools accounted for this additional K (McLean and Watson, 1985).

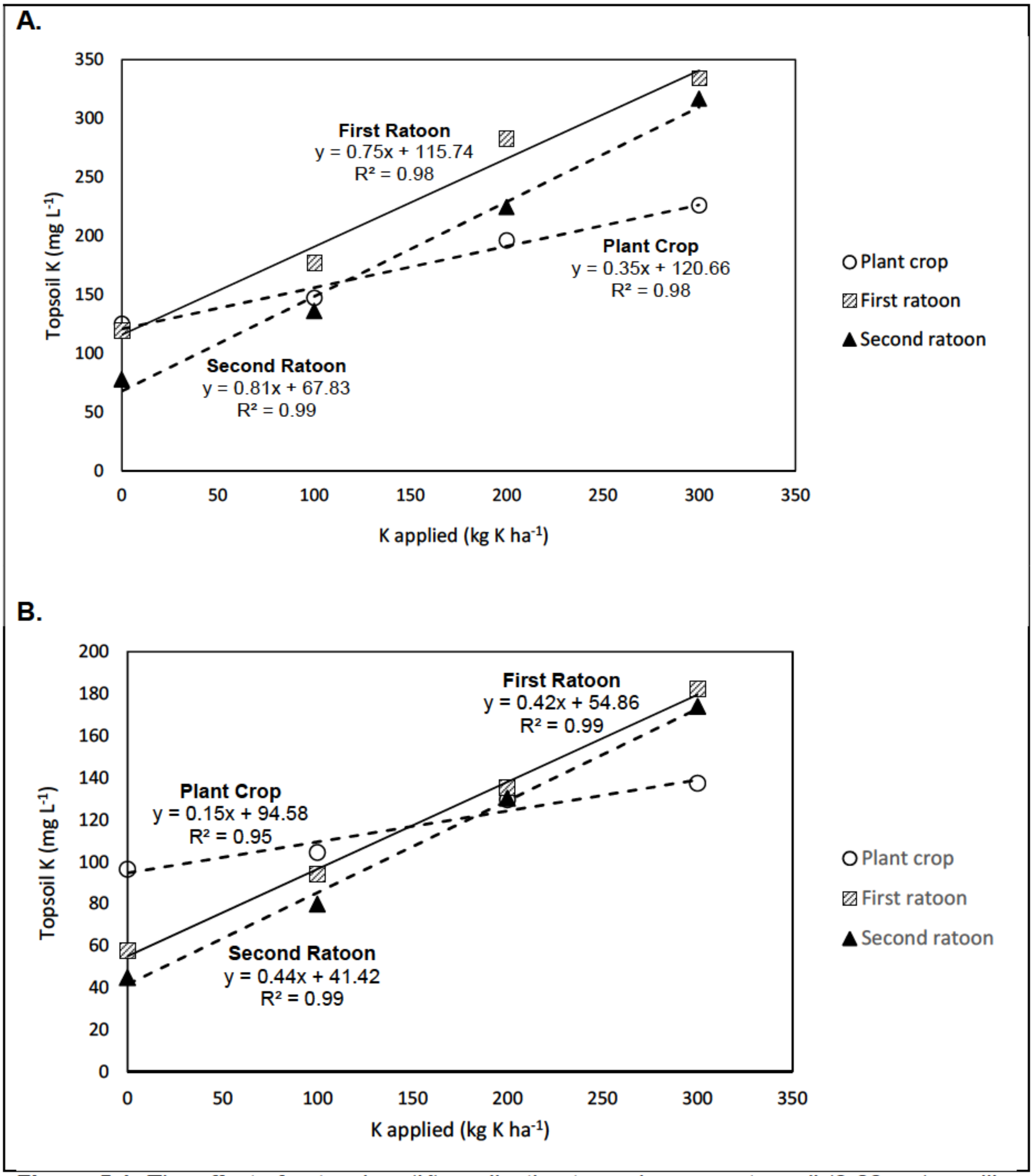


Figure 5.1: The effect of potassium (K) application to each crop on topsoil (0-20 cm) readily-available K in the (A) Oxisol and (B) Inceptisol. Each point represents the mean of 24 plots per K treatment.

Also noteworthy is the extent to which topsoil readily-available K increased in each soil, in response to fertiliser applications. At the plant crop sampling event, the zero plots' topsoil K at the two sites were within 30% of each other. In the plant crop

300 kg K ha^{-1} treatment, however, (where each soil had received the same amount of K), the Oxisol's K concentration (226 mg L^{-1}) was 65% greater than that in the Inceptisol (137 mg L^{-1}) and by the second ratoon, it was 82% greater. There was thus a greater build-up of readily-available K over the duration of the three crops on the Oxisol, where second ratoon soil K concentrations were 40% greater than after the plant crop (at 300 kg K ha^{-1}), compared with 26% greater in the Inceptisol.

The amount of organic matter in the soils (Table 3.2) may have affected the behaviour of applied K. High soil organic matter content may favour the initial fast adsorption of K^+ ions (Wang and Huang, 2001). However, monovalent ions tend to be more loosely held by organic matter than divalent ions (Wang and Huang, 2001), and, depending on the constitution of the organic matter, may be more easily released or exchanged. The higher organic matter in the Oxisol may thus have adsorbed a portion of the applied K, but retained it in a more readily-available form.

The clay mineralogy of the two soils could also have influenced the degree to which applied K became part of the non-exchangeable K pool. Of the major clay minerals responsible for K fixation, vermiculite was present in the Inceptisol in trace amounts, but absent in the Oxisol (Table 5.1) and this may have increased K fixation in the Inceptisol to a limited extent. Hydroxyl-aluminium interlayered vermiculite was an important constituent of the Oxisol's clay mineral fraction, but was absent in the Inceptisol (Table 5.1). This could have been a contributing factor in the reduced fixation of K, and hence build-up of readily-available K, in the Oxisol in comparison with the Inceptisol.

The inverse of the regression slopes in Figure 5.1 represents the K requirement factor (KRF) of each soil, defined as the amount of K (kg ha^{-1}) required to raise the soil K test by 1 mg L^{-1} (Johnston *et al*., 1999). The KRFs of the Oxisol were 2.84, 1.33 and 1.24 kg K ha^{-1} mg^{-1} L^{-1} soil in the plant, first and second ratoon crops, respectively. The corresponding KRF values of the Inceptisol were 6.77, 2.41 and 2.28. These KRF values fall within the range (1.50 to 8.80 kg K ha^{-1} mg^{-1} L^{-1} soil) reported for KwaZulu-Natal soils by Johnston *et al*. (1999). Two Oxisols (Inanda soil forms) reported by Johnston *et al.* (1999) had KRF values of 1.68 and 1.64, within the same range as the Oxisol in the present study; a number of Inceptisols ranged from 2.27 to 3.40. No similar Inceptisols in the Johnston *et al*. (1999) study, however, exhibited KRF values as high as that at the plant crop in the present study. Thus, almost twice the amount of K fertiliser was required to raise the Inceptisol K concentration than that of the Oxisol in the present study.

5.3.2.3. Effect of potassium application on mean soil profile characteristics following harvests

Following each crop of sugarcane, treatments with applied K showed an increase in average soil profile K concentrations, on both soils. Both trial sites responded similarly and showed the same trend as given for the topsoil samples alone (Figure 5.1). Potassium application also, at times, significantly decreased soil pH and significantly increased Zn, exchangeable acidity and acid saturation (results not shown), though these effects did not occur consistently across trial sites or sampling times.

There was, however, a significant decrease in Si, with K application, after two of the three crop cycles on the Inceptisol (Figure 5.2). This was likely due to the higher yield from the plots which had received K, leading to increased Si uptake by the crop. Ashraf *et al.* (2010) reported that Si uptake by sugarcane was significantly increased by the addition of K (in a hydroponic medium), and Tahir *et al*. (2010) found that Si application to wheat seedlings significantly increased K concentration in the shoots. This mutually positive relationship between K and Si was not, however, reflected in the Inceptisol leaf analyses (Chapter 4).

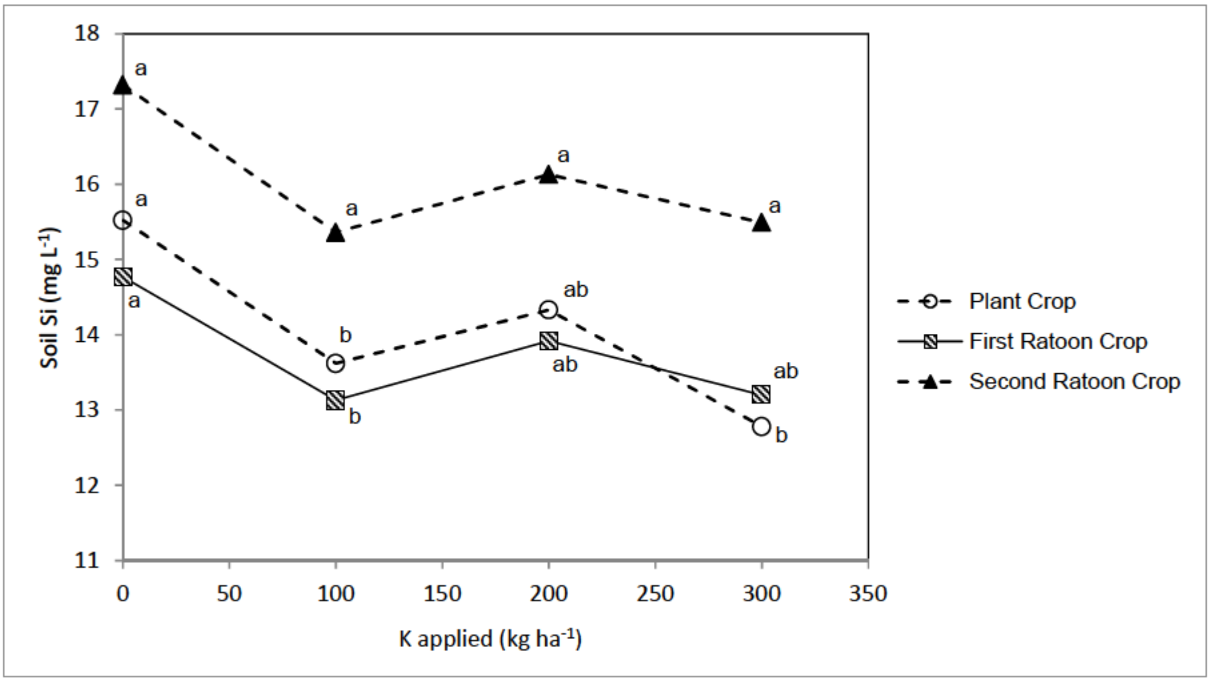


Figure 5.2: Inceptisol: Effect of potassium (K) application on soil profile (0-80 cm) available silicon (Si) after each of the three crops (n=31). Within each crop, points with different letters are significantly different to each other ($P < 0.05$).

5.3.2.4. Potassium movement down the profile

There was some evidence of K movement down the profile at both trial sites. Movement was most marked in the Oxisol (Figure 5.3A, B, C) as shown after the harvest of the second ratoon crop, when there were significant differences between the readily-available soil K at the different K application rates at the 40-60 cm depth interval (Figure 5.3C).

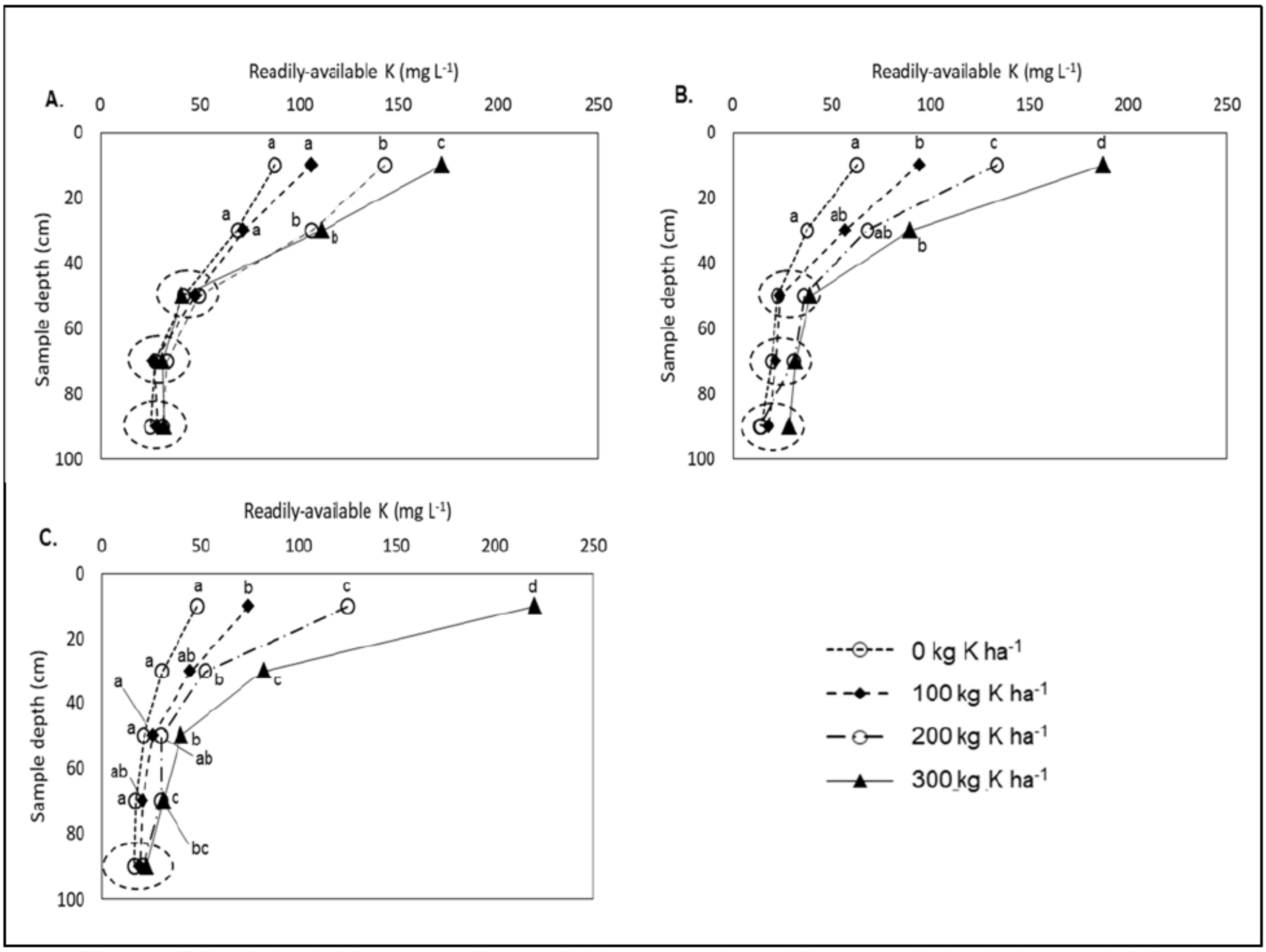


Figure 5.3: Oxisol: Mean readily-available potassium (K) per soil depth interval following (A) plant crop, (B) first ratoon and (C) second ratoon harvests. n=24 (0-20 cm) and n=18 (20-100 cm). Within each crop, points with different letters are significantly different to each other ($P < 0.001$). Where no significant differences occurred between points within a depth interval, the points are circled.

The Inceptisol, however, did not show significant differences between K rates at this depth (Figure 5.4A, B, C), indicating either that K application had not affected the soil to this depth, or that the applied K may have become non-available at depth. Although this might indicate slightly greater leaching of applied K in the Oxisol, K movement may also have been facilitated by the higher rate of gypsum applied to the Oxisol (5 t ha^{-1}) compared to the Inceptisol (3 t ha^{-1}). Gypsum has been reported to cause some leaching of K through the soil profile (Ernani *et al*., 2006).

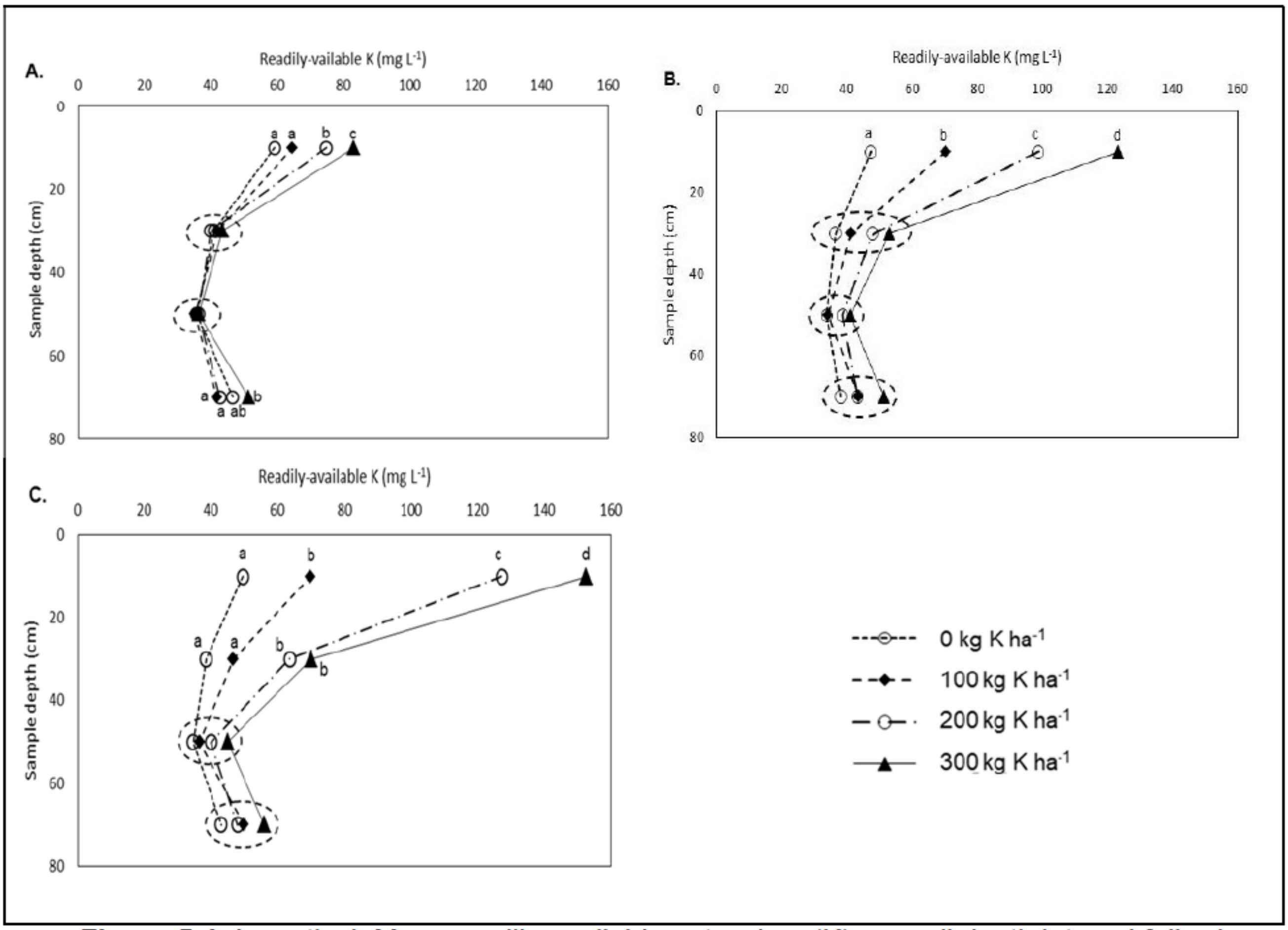


Figure 5.4: Inceptisol: Mean readily-available potassium (K) per soil depth interval following (A) plant crop, (B) first ratoon and (C) second ratoon harvests. n=24 (0-20 cm) and n=18 (20-80 cm). Within each crop, points with different letters are significantly different to each other (P < 0.001). Where no significant differences occurred between points within a depth interval, the points are circled.

5.3.2.5. Slowly-available (nitric) potassium

The nitric K in both soils, at all but two of the sampled soil depths, was < 1 $cmol_c\ kg^{-1}$ (Table 5.3). This corresponds with mean values reported for the KwaZulu-Natal north coast by Miles and Farina (2014) and indicates low slowly-available K reserves (Miles, 2016). The Inceptisol contained between three and five times the amount present in the Oxisol at each depth interval (Table 5.3). This finding and the trends with depth are consistent with the amount of total K found in the soil and parent material at each site (Table 5.2). In the Oxisol, between 7.2 and 9.0% of the total K was made up by nitric K, depending on the sample depth (Table 5.3), while these figures were 4.7-6.7% in the Inceptisol. Corresponding figures in the literature range from 0.7-2.2% on a loamy sand (Sadusky *et al.*, 1987) to 3.6%

on a laterite soil (Lalitha and Dhakshinamoorthy, 2014), illustrating a greater percentage of slowly-available K reserves in the soils of the present study.

Table 5.3: Mean ± s.e. (n=5, Oxisol; n=4, Inceptisol) slowly-available (nitric) potassium (K) per soil depth interval at each trial site, following the first ratoon crop harvest, and as a percentage of total K

Soil	**Depth** (cm)	**Nitric K** ($cmol_c\ kg^{-1}$)	**Nitric K** ($kg\ K\ ha^{-1}$)	**% of Total K made up by nitric K**
Oxisol	0-20	0.22 ± 0.02	189 ± 20	9.03 ± 0.86
	20-40	0.17 ± 0.02	148 ± 14	8.33 ± 0.76
	40-60	0.14 ± 0.01	125 ± 7	7.21 ± 0.39
	60-80	0.16 ± 0.01	143 ± 5	7.97 ± 0.27
	80-100	0.19 ± 0.01	169 ± 8	7.92 ± 0.37
Inceptisol	0-20	0.70 ± 0.13	661 ± 118	4.65 ± 0.87
	20-40	0.97 ± 0.15	976 ± 130	6.54 ± 0.99
	40-60	1.06 ± 0.12	1009 ± 107	6.70 ± 0.75
	60-80	1.29 ± 0.12	1238 ± 103	6.30 ± 0.57

5.3.2.6. Potassium balance

On the Oxisol, between 33 and 112 kg ha^{-1} more K was available at the end of the three crop cycles than at the beginning (Table 5.4). This represents a recovery of 104-129% of the original K. On the Inceptisol, K recovery was even greater, between 110 and 194% of the original K, or 63-202 kg K ha^{-1} more. This recovery was despite the fact that neither K in the crop roots, nor K leaching below the root zone, were taken into account, both of which are likely to have resulted in even greater K recovery. It is, however, not uncommon for more K to be 'recovered' than was present at the start of cropping (e.g. Madaras and Lipavský, 2009).

In each soil there was a greater over-recovery of readily-available K in the lower-K treatments than in those with higher K rates (Table 5.4). Where less fertiliser K was applied, therefore, a larger proportion of K became available from other sources. It is possible that in the low K-input treatments, the sugarcane roots extracted additional K from deeper in the soil profile, while the higher K treated plots had sufficient in the upper portion of the profile.

Table 5.4: Potassium (K) balance for the Oxisol and the Inceptisol soil profiles. Values are mean ± s.e. (kg K ha^{-1}) per crop at each site (n=24). 'K removed by crop' refers to K present in the total above-ground biomass, per crop. Calculated K recovery compares the mean amount of readily-available K remaining at the end of each crop with that at the start

Start of Crop		**End of Crop**		**K Balance**	
K applied	**K originally present in soil profile**	**K remaining in soil profile**	**K removed by crop**	**Difference end-start**	**Calculated K recovery**
------------------------------------- (kg K ha^{-1})				-------------------------------------	(%)
Oxisol profile (0-100 cm)					
0	480 ± 23	361 ± 21	230 ± 39	112 ± 44	129 ± 11
100	557 ± 27	465 ± 31	245 ± 22	53 ± 42	110 ± 6
200	645 ± 20	607 ± 23	271 ± 38	33 ± 41	104 ± 5
300	712 ± 26	791 ± 29	272 ± 24	51 ± 44	106 ± 5
Inceptisol profile (0-80 cm)					
0	331 ± 19	336 ± 10	197 ± 19	202 ± 23	194 ± 26
100	348 ± 18	389 ± 12	213 ± 20	153 ± 24	141 ± 9
200	397 ± 19	469 ± 23	265 ± 25	137 ± 29	125 ± 6
300	418 ± 21	541 ± 24	240 ± 20	63 ± 28	110 ± 5

Another possible explanation for the over-recovery of K may be that greater amounts of slowly-available K became available during the growing season, possibly due in part to efficient root extraction, as well as in response to lower levels of readily-available K. Poss *et al.* (1997) similarly concluded that if K exports exceeded inputs, some K must have been released from the slowly-available soil K pool. Based on the nitric K values (Table 5.3), K could become slowly available to the crop over a period of years. It is feasible that with the low readily-available K in the zero K plots, diffusion dynamics favoured faster release of slowly-available K than in the high K treated plots. The results indicate that despite these soils having 'low' K reserves (Section 5.3.2.5; Haysom, 1971), they may be able to release more K than such a classification suggests. The greater K recovery on the Inceptisol is supported by the greater reservoir of nitric K in this soil than in the Oxisol (Table 5.3).

5.3.2.7. Effect of topsoil potassium on sugarcane yield and quality

There were no significant differences in stalk yield between the different rates of applied K at any harvest on the Oxisol (Section 3.3.2.1.1). Yields did, however, increase slightly with increasing topsoil readily-available K in each harvested crop (Figure 5.5A). Although not statistically significant, the increase in yield between the lowest and highest readily-available soil K values was almost 8 t cane ha^{-1} or 6% in the first ratoon crop, a yield increase significant in practical terms.

Sucrose content (% estimated recoverable crystal, %ERC) of the cane on the Oxisol was significantly increased by increasing K rates only in the second ratoon harvest, and then not by a large amount (Section 3.3.2.1.2). The total sucrose tonnage (t ERC ha^{-1}) was, however, notably increased by increased soil K (Figure 5.5B), with increases in the second ratoon crop being significant.

The readily-available topsoil K threshold currently recommended for this soil appears to be accurate in terms of both stalk and sucrose yield. Figure 5.5 indicates that above approximately 150 mg K L^{-1}, both stalk and sucrose yield response curves begin to flatten off. Above the South African Sugarcane Research Institute's Fertiliser Advisory Service (FAS) threshold of 166 mg K L^{-1} (Miles, 2014), yield responses to further readily-available K were limited, and there would therefore be minimal additional yield benefit of applying more K fertiliser.

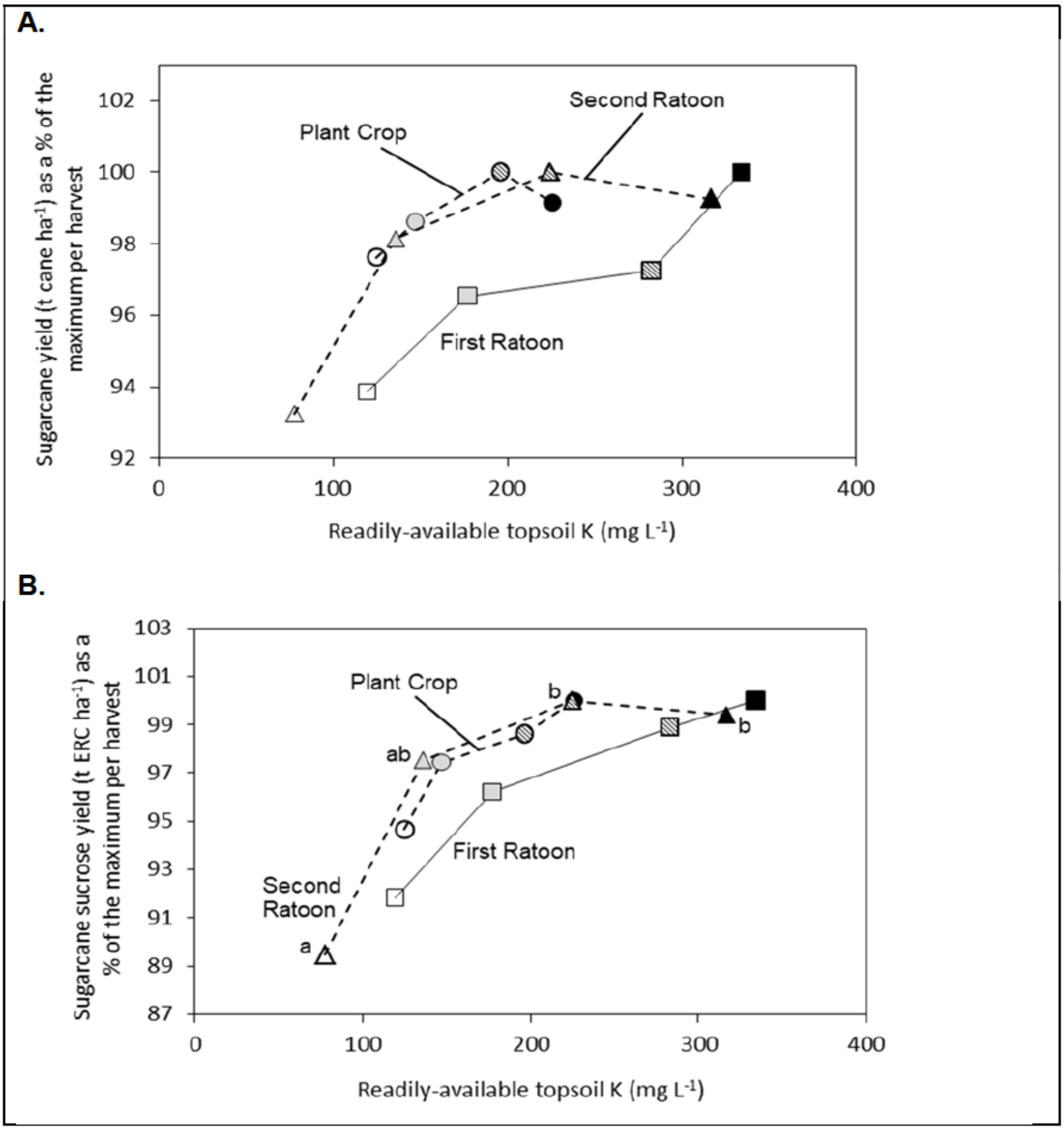


Figure 5.5: Oxisol: Mean (n=24) sugarcane (A) stalk and (B) sucrose yield, as a percentage of the maximum yield per harvest in relation to readily-available topsoil potassium (K). For the second ratoon crop in B, points with different letters are significantly different to each other ($P < 0.05$). Each point is shaded to represent one of the four K application rates (0 kg K ha^{-1}: clear symbol; 100 kg K ha^{-1}: grey symbol; 200 kg K ha^{-1}: hatched symbol; 300 kg K ha^{-1}: black symbol).

Only the first ratoon crop on the Inceptisol showed significant yield differences between different K application rates (Section 3.3.2.2.1). However, a general pattern of yield increase was evident with increasing topsoil readily-available K, with, for example, a difference of 7 t cane ha^{-1} (7%) between the lowest and highest amounts of soil K in the plant crop (Table 5.5). No significant differences were evident in the %ERC between different K rates on the Inceptisol (Table 5.5). The t ERC ha^{-1} was, however, significantly increased by increased topsoil K in both the plant and first ratoon crops (Table 5.5).

Table 5.5: Inceptisol: Mean (n=24) sugarcane stalk yield, sucrose percent and sucrose yield, as a percentage of the maximum yield per harvest in relation to readily-available topsoil potassium (K)

K applied (kg ha^{-1})	**Readily-available K** (mg L^{-1})	**Stalk yield** (t cane ha^{-1})	**Sucrose percent** (%ERC)	**Sucrose yield** (t ERC ha^{-1})
		------ (as % of the maximum yield per harvest) ------		
			Plant crop	
0	96	93.3	98.6	92.0 a [ŧ]
100	104	94.4	98.7	93.2 a
200	129	94.4	99.9	94.2 a
300	137	100.0	100.0	100.0 b
	Significance	**NS**	**NS**	**P<0.05**
			First ratoon crop	
0	57	91.2 a	99.3	91.3 a
100	94	94.1 ab	100.0	95.0 ab
200	135	100.0 b	98.8	100.0 b
300	182	93.7 ab	98.5	93.0 ab
	Significance	**P<0.05**	**NS**	**P<0.05**
			Second ratoon crop	
0	45	94.7	99.5	93.9
100	80	98.0	97.1	94.9
200	130	100.0	99.4	98.9
300	174	99.9	100.0	100.0
	Significance	**NS**	**NS**	**NS**

[ŧ] Within each harvest and yield component, values with different letters are significantly different to each other.

The topsoil readily-available K threshold recommended for the Inceptisol (average stalk yields obtained ~90 t cane ha^{-1} over the three crops), was 135 mg K L^{-1}. Statistically, with no significant differences between the stalk yields associated with the three highest topsoil K values in the first ratoon crop, and no differences in either of the other two crops, this threshold could have been reduced to 94 mg L^{-1}, the amount associated with the 100 kg K ha^{-1} application rate (Table 5.5, stalk yield, first ratoon crop). However, from the total sucrose tonnage (Table 5.5), sucrose yield would have been significantly reduced below 137 mg L^{-1} topsoil K in the plant crop, and by approximately 1 t ERC ha^{-1} (though not significant) in the first and second ratoon crops. Given that sugarcane payments are based on sucrose yield, the current recommended local threshold appears appropriate for this soil.

Mean sugarcane stalk yields over the three harvests were greater on the Inceptisol than on the Oxisol (Table 5.6). In contrast, the Inceptisol had lower readily-available topsoil K over the duration of the trial, and lower stalk K concentrations. This may suggest luxury uptake of K on the Oxisol, which had more topsoil (0-20 cm) readily-available K, and lower cane yields, but greater stalk K. Luxury uptake is less evident on the Inceptisol, where stalk K percent values did not increase substantially upon addition of fertiliser K (Table 5.6). Wood and Schroeder (2004) reported luxury uptake of K in sugarcane, though a variety x K rate interaction was evident. It is also possible that the lower stalk K on the Inceptisol (in comparison with the Oxisol) was due to dilution following greater crop growth.

Table 5.6: Mean readily-available topsoil (0-20 cm) potassium (K) (n=27), mean yield (n=27) in harvested stalks and mean K percent in stalks (n=27) per season, and total K removed (n=36), as a sum over the three crops at each trial site

K applied (kg ha^{-1})	**Mean readily-available soil K** (mg L^{-1})		**Mean stalk yield** (t cane ha^{-1})		**Mean percent K in stalks** (%)		**Total K removed in the harvested stalks** (kg ha^{-1})	
	Oxisol	*Inceptisol*	*Oxisol*	*Inceptisol*	*Oxisol*	*Inceptisol*	*Oxisol*	*Inceptisol*
0	107	66	81.9	90.7	0.32	0.26	270	298
100	153	93	84.5	93.0	0.34	0.36	285	317
200	234	132	85.5	95.4	0.44	0.35	378	446
300	292	164	86.4	95.5	0.46	0.33	369	332

Also notable is the large amount of K removed in the harvested stalks at both sites (Table 5.6). Even with a low concentration (66 mg L^{-1}) of readily-available K, stalks on the Inceptisol removed almost 300 kg K ha^{-1} in the zero K treatment. Potassium removal on the Oxisol was also high, albeit with a larger pool of readily-available soil K. This indicates that, in the absence of high available K, less available sources of soil K supplied sufficient K to support high uptake, particularly on the Inceptisol (Section 5.3.2.6).

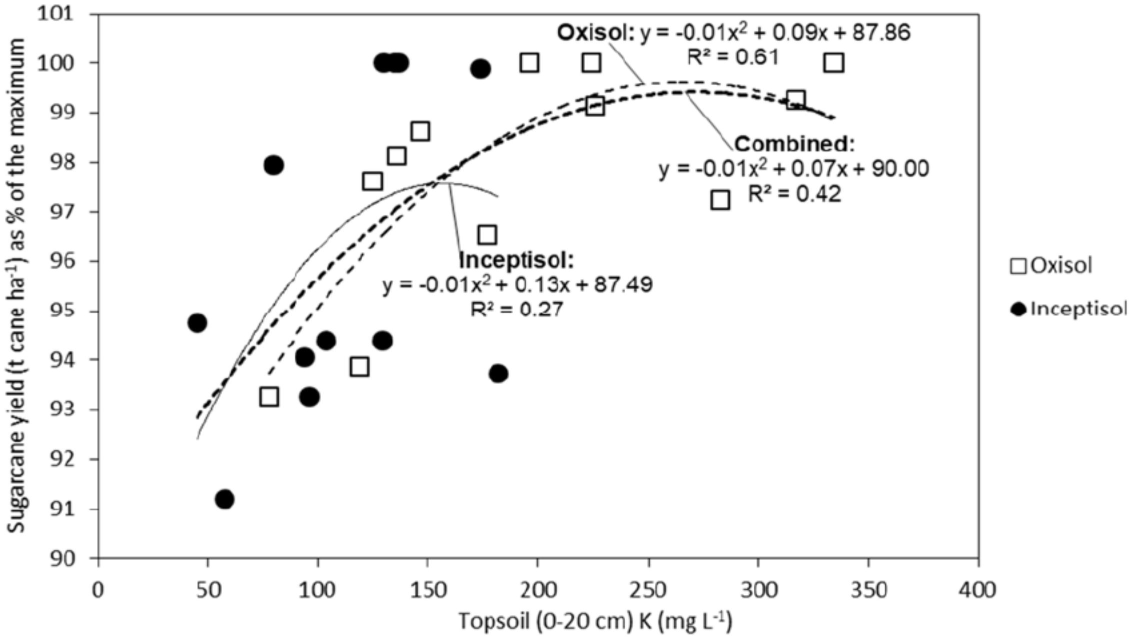
5.3.2.8. Inclusion of subsoil potassium data into topsoil calibration

In order to ascertain the extent to which subsoil (>20 cm) K affected sugarcane yields, subsoil K concentrations were included with the topsoil regressions against harvest yields (t cane ha^{-1}). Although samples were collected to 80 cm (Inceptisol) and 100 cm (Oxisol), sugarcane growers do not have standardised procedures for depth sampling, and hence sample to varying depths. If subsoil data are to be included in routine advisory calibrations, it may be most useful to include only two subsoil depths (20-40 cm and 40-60 cm), since in practice samples are likely to be taken only to these depths. Mean soil K from 0-60 cm was thus plotted against sugarcane stalk yield (Figure 5.6).

When only topsoil (0-20 cm) K concentrations were plotted against stalk yield (Figure 5.6A), an R^2 value of 0.42 was obtained when the soils were combined. When the Oxisol and Inceptisol values were separated, R^2 values of 0.61 and 0.27 were obtained, respectively (Figure 5.6A). Including the subsoil values improved the relationships (R^2 = 0.59, 0.78 and 0.48 for the combined, Oxisol and Inceptisol soils, respectively) (Figure 5.6B). The threshold used by a laboratory to make fertiliser recommendations would depend upon the targeted yield. While the topsoil threshold, based on the maximum value of the trendlines in Figure 5.6A, would range from 145-250 mg K L^{-1} (depending on the threshold curve chosen), the profile (0-60 cm) threshold K for these soils (Figure 5.6B), would be approximately 78-95 mg L^{-1}. If 95% of maximum yield is considered satisfactory, then these thresholds could be considerably reduced to approximately 100 mg K L^{-1} (for topsoils, Figure 5.6A), and 45 mg K L^{-1} (for soil profiles, Figure 5.7). Regardless of which soil's curve and yield threshold are used, the results indicate that inclusion of subsoil K values into the recommendation package would improve the accuracy of the soil K threshold curve, ultimately leading to more precise fertiliser recommendations. However, the responses to K in these trials were small; even the lowest yields were, in all cases, > 90% of the maximum (Figure 5.6A and B). More precise response curves would need to be determined on soils where the K response is greater.

The better relationship between readily-available soil K and sugarcane stalk yield obtained for the Oxisol (R^2 = 0.61) than the Inceptisol (R^2 = 0.27) may have been due to the greater amounts of nitric K present in the Inceptisol (Table 5.3). Release of K from this pool may have rendered the relationship between yield and readily-available K less consistent.

A.



B.

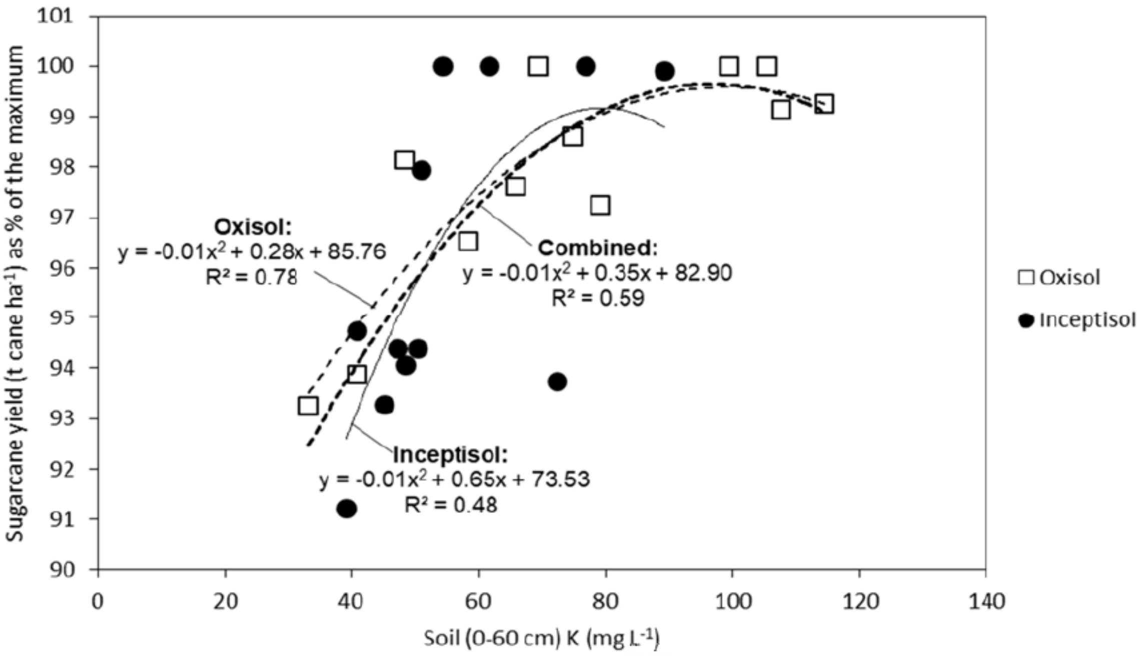


Figure 5.6: Mean sugarcane stalk yield, as a percentage of the maximum yields obtained at each harvest, in relation to (A) topsoil (0-20 cm) and (B) top- and subsoil (0-60 cm) readily-available potassium (K) in the Oxisol and Inceptisol. The trendlines are also plotted for the two soils combined. Each point comprises a mean of 24 (0-20 cm) or 18 (0-60 cm) plot yields and soil K values.

5.3.3. Nitrogen

Results from these measurements and analyses showed few significant findings and so are not included here but for completeness are given in Appendix 5.1 - 5.4.

5.3.4. Silicon

5.3.4.1. Effect of silicate application on topsoil (0-20 cm) properties

Similar results were obtained at all sampling events on both soils; the significant results from one sampling time at each trial site are thus used to illustrate these effects (Table 5.7). The application of Calmasil® and cement led to an increase in pH, and a concomitant decrease in acid saturation and exchangeable acidity and, at a number of sampling events, decreases in some micronutrients such as Zn and Cu (Table 5.7). Total cations were significantly increased by the addition of the siliceous materials, a phenomenon associated with the increase in variable charge on colloids resulting from pH increases (Wooldridge, 1989; Lemire *et al*., 2006).

Table 5.7: Effect of applied silicates (Calmasil® and blastfurnace cement) on selected topsoil (0-20 cm) properties in the second ratoon crop, 6 weeks (Oxisol) and 8 weeks (Inceptisol) after application of cement. Data are presented as mean ± s.e. (n=48)

Si applied	**Ca**		**Mg**		**Si***	
	(mg L^{-1})					
(kg ha^{-1})	**Oxisol**	**Inceptisol**	**Oxisol**	**Inceptisol**	**Oxisol**	**Inceptisol**
0	1246 ± 34 a[Ŧ]	582 ± 21 a	159 ± 6 a	134 ± 5 a	15 ± 0 a	15 ± 1 a
300	1740 ± 35 b	894 ± 59 b	189 ± 5 b	156 ± 7 b	27 ± 1 b	27 ± 2 b
Sig.	**P<0.001**	**P<0.001**	**P<0.001**	**P<0.01**	**P<0.001**	**P<0.001**
Si applied	**pH ($CaCl_2$)**		**Zn**		**Cu**	
			(mg L^{-1})			
(kg ha^{-1})	**Oxisol**	**Inceptisol**	**Oxisol**	**Inceptisol**	**Oxisol**	**Inceptisol**
0	4.35 ± 0.02 a	4.07 ± 0.02 a	6.8 ± 0.3 a	3.0 ± 0.1	1.8 ± 0.0 a	0.7 ± 0.0
300	4.60 ± 0.02 b	4.48 ± 0.06 b	5.8 ± 0.2 b	2.7 ± 0.1	1.7 ± 0.0 b	0.7 ± 0.0
Sig.	**P<0.001**	**P<0.001**	**P<0.001**	**NS**	**P<0.001**	**NS**
Si applied	**Exchangeable acidity** ($cmol_c$ L^{-1})		**Acid saturation** (%)		**Total cations** ($cmol_c$ L^{-1})	
(kg ha^{-1})	**Oxisol**	**Inceptisol**	**Oxisol**	**Inceptisol**	**Oxisol**	**Inceptisol**
0	2.75 ± 0.11 a	1.26 ± 0.06 a	25.7 ± 1.2 a	23.1 ± 1.2 a	10.9 ± 0.1 a	5.6 ± 0.1 a
300	1.44 ± 0.09 b	0.68 ± 0.08 b	12.1 ± 0.8 b	11.7 ± 1.4 b	12.3 ± 0.2 b	6.8 ± 0.3 b
Sig.	**P<0.001**	**P<0.001**	**P<0.001**	**P<0.001**	**P<0.001**	**P<0.001**

*Local recommended threshold is 15 mg L^{-1}.

Ŧ Within soils and columns, values with different letters are significantly different to each other.

5.3.4.2. Effect of silicate application on mean soil profile characteristics following harvest

The effects of silicate application on soil profile properties were similar at each site and sampling time, and only those for the Oxisol (second ratoon) are presented (Table 5.8). The application of Calmasil® and cement led to significant increases in soil Ca throughout both profiles at all sampling times, along with increases in Mg, Si and pH at almost every sampling time. Exchangeable acidity and acid saturation decreased at two out of three sampling times at each site, while Cu, Zn and Fe were sometimes reduced, presumably also due to the increased pH (Meyer, 2013). The application of silicates significantly increased soil profile K (P<0.05) at only one sampling time (second ratoon) on the Inceptisol, and never on the Oxisol. Even non-significant effects of silicates on K at both sites were inconsistent, with K being slightly increased at times, and decreased at others (data not shown).

Table 5.8: Oxisol: Effect of applied silicates (Calmasil® and blastfurnace cement) on selected soil profile (0-100 cm) properties following the second ratoon crop harvest. Data are presented as mean ± s.e. (n=36)

Si rate	**Ca**	**Mg**	**Si**	**Zn**
(kg ha^{-1})	--------------------------------	(mg L^{-1})	--------------------------------	
0	650 ± 23 a[Ŧ]	121 ± 3 a	16 ± 0 a	3.0 ± 0.2 a
300	856 ± 23 b	132 ± 3 b	19 ± 0 b	2.6 ± 0.2 b
Sig.	**P<0.001**	**P<0.01**	**P<0.001**	**P<0.05**
Si rate	**pH ($CaCl_2$)**	**[a]Exch. acidity**	**[b]Acid sat.**	
(kg ha^{-1})		(cmol$_c$ L^{-1})	(%)	
0	4.33 ± 0.01 a	2.84 ± 0.06 a	40.72 ± 0.98 a	
300	4.46 ± 0.01 b	2.20 ± 0.07 b	32.19 ± 1.29 b	
Sig.	**P<0.001**	**P<0.001**	**P<0.001**	

[a]Exch. acidity = exchangeable acidity

[b]Acid sat. = acid saturation

[Ŧ] Within columns, values with different letters are significantly different to each other

5.3.4.3. Silicon, calcium and magnesium movement down the profile

There was some movement of Si down the soil profile at both trial sites. Though Si had not moved deeper than 20 cm following the first ratoon harvest, by the second ratoon harvest, both soils had significantly more Si to a depth of 60 cm in the 300 kg Si ha^{-1} treatment than in the 0 kg Si ha^{-1} treatment (Figure 5.7). Increases in available Si in both the top- and subsoil, and Si movement were more pronounced in the lower-clay Inceptisol than in the Oxisol (Figure 5.7). Lower acid saturation in the Inceptisol (Table 3.2) may also have been partially responsible for the increased Si availability.

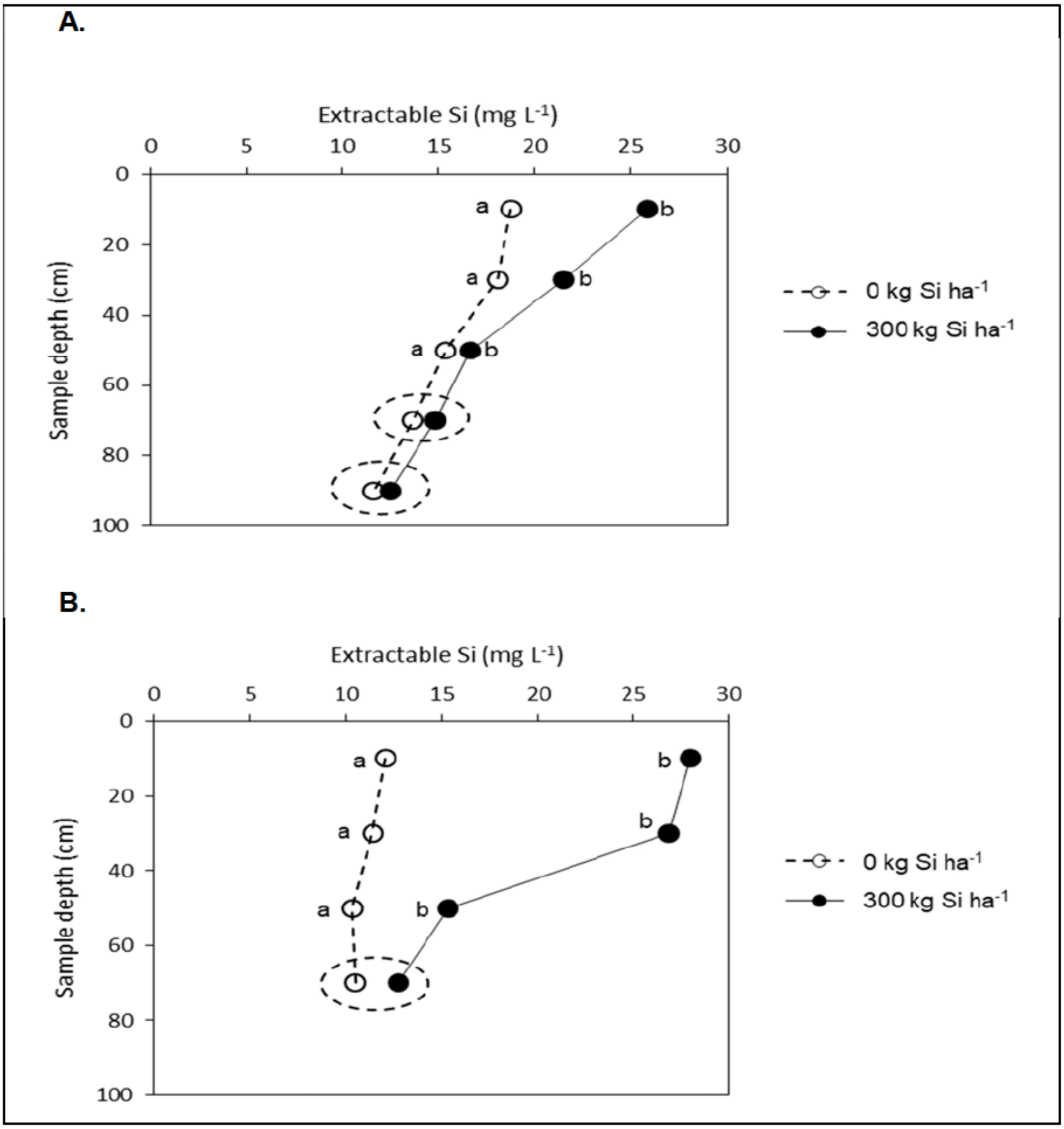


Figure 5.7: Mean extractable silicon (Si) per soil depth interval following the second ratoon crop in the (A) Oxisol and (B) Inceptisol. n=24 (0-20 cm) and n=18 (>20 cm). Within each trial site and depth interval, points with different letters are significantly different to each other ($P < 0.001$). Where no significant differences occurred between points within a depth interval, the points are circled.

Calcium movement down the soil profiles was limited, as expected. In both soils, Ca was significantly increased by silicate application for the first two crops in only the 0-20 cm soil layer. By the second ratoon harvest, this difference had extended to the 20-40 cm layer (Appendix 5.5).

Significant differences in Mg in the Oxisol between the two Si rates only extended to 20 cm (plant crop), 40 cm (first ratoon) and 20 cm (second ratoon; Appendix 5.6A). More movement of Mg occurred in the Inceptisol (Appendix 5.6B). This downward movement was most likely in response to the gypsum applied at the start of the trial (Alva *et al*., 1998; Ernani *et al*., 2006; Blum *et al.*, 2011). Magnesium leaching is generally greater on sandier soils (Ernani *et al*., 2006), and thus the Inceptisol experienced greater Mg leaching than the Oxisol, despite a lower rate of gypsum application.

5.3.4.4. Effect of topsoil silicon on sugarcane yield and quality

Sugarcane sucrose yields were consistently highest where Si was applied. In four of the total six harvests across the two trial sites (all three on the Inceptisol and one on the Oxisol), these increases were significant (Section 3.3.4). Although the FAS recommended threshold for soil Si (across all soils) is 15 mg L^{-1}, increases above this level at the two trial sites always resulted in greater stalk and sucrose yields (Table 5.9), indicating that this threshold may be too low for these soils. In the Australian sugarcane industry, on soils with low Si reserves (H_2SO_4-extractable Si), a response to Si application is considered “possible” when available ($CaCl_2$-extractable) Si is between 10 and 20 mg kg^{-1} (Calcino *et al*., 2018). A response is considered “unlikely” when available Si is > 20 mg kg^{-1}.

Table 5.9: Mean (n=48) sugarcane stalk yield (t cane ha^{-1}) and sucrose yield (t ERC ha^{-1}), as a percentage of the maximum yields obtained in the second ratoon harvests, in relation to available silicon (Si) (mean ± s.e.) in the Oxisol and Inceptisol topsoil (0-20 cm)

Oxisol			*Inceptisol*		
Available Si	**Stalk yield**	**Sucrose yield**	**Available Si**	**Stalk yield**	**Sucrose yield**
(mg L^{-1})	----------- (%) -----------		(mg L^{-1})	----------- (%) -----------	
15 ± 0	95 aŦ	95 a	15 ± 1	94 a	94 a
27 ± 1	100 b	100 b	27 ± 2	100 b	100. b
Significance	**P<0.05**	**P<0.05**		**P<0.05**	**P<0.05**

Ŧ Within columns, values with different letters are significantly different to each other.

For the Inceptisol, raising soil Si to 27 mg L^{-1} would have been economically beneficial in terms of the extra sucrose yields realised. On the Oxisol, however, significant yield increases were only obtained in the second ratoon crop (Table 5.9). Inconsistent yield increases, therefore, would not make application of 600 kg Si ha^{-1} (over the three crops) economically beneficial on the Oxisol, though future ratoons may affect this conclusion.

5.3.4.5. Inclusion of subsoil silicon data into topsoil calibration

Stalk yield plotted against topsoil (0-20 cm) Si concentration measured after three harvests gives a strong (R^2=0.95) relationship across the two soils (Figure 5.8). This indicates that a topsoil Si concentration of approximately 20 mg L^{-1} would be an improvement on the current 15 mg L^{-1} threshold. Inclusion of the subsoil (20-60 cm) data weakened the relationship (R^2 = 0.23; results not shown), possibly due to roots accessing Si, Ca and Mg at depths greater than 60 cm.

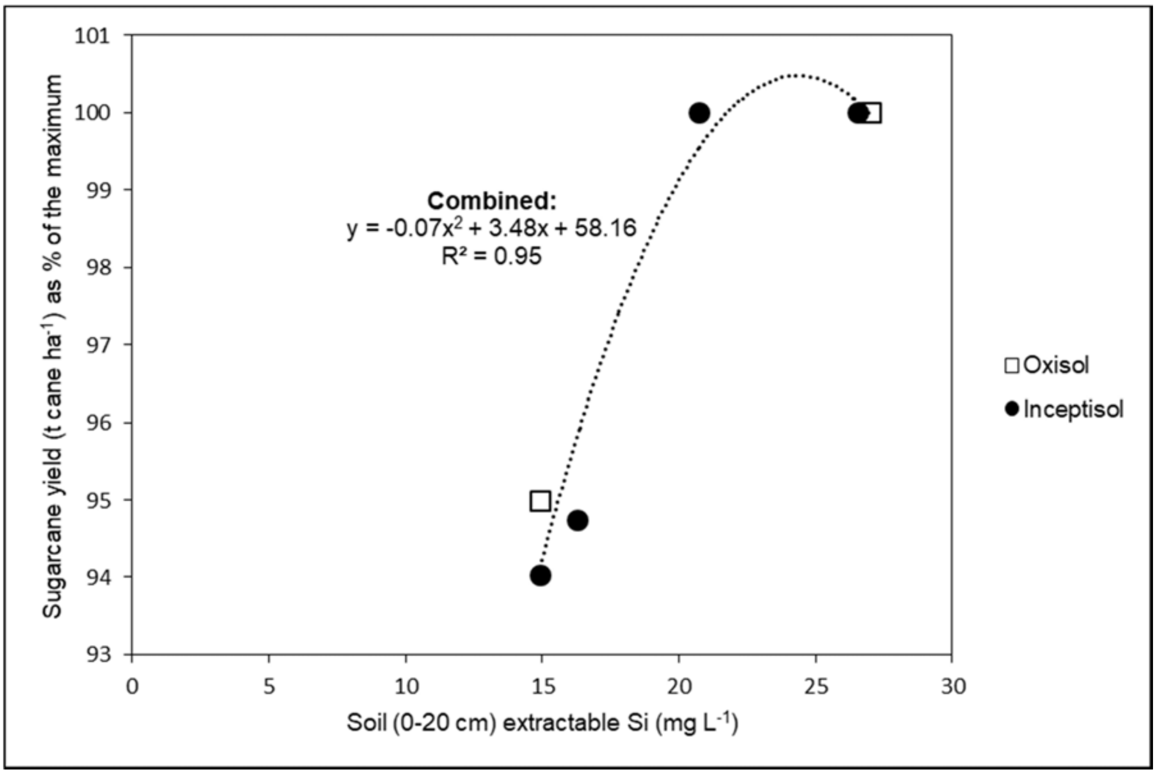


Figure 5.8: Mean sugarcane stalk yield, as a percentage of the maximum yield in each harvest, in relation to topsoil (0-20 cm) extractable silicon (Si) in the Oxisol (second ratoon harvest) and Inceptisol (first and second ratoon harvests). Each point comprises a mean of 48 plot yields and soil Si values.

5.4. Conclusions

5.4.1. Potassium

There were low concentrations (<1 $cmol_c\ kg^{-1}$) of slowly-available K (nitric K) in both soils and yet K release contributed substantially to readily-available soil K. Two findings illustrate this point. Firstly, readily-available K increased considerably, in both soils, between pre-trial sampling and the first sampling event following plant crop fertiliser application, in the zero-K plots. Secondly, the K balance over all of the crops at each site showed that, on average, more K was accounted for at the end of each crop, than was present at the start. It was noteworthy that the zero-K plots gave a higher percentage of K recovery than the treatments which received K. This may have been due to release of more slowly-available K, or K release from organic matter, in response to reduced readily-available K levels. Based on these results, it is possible that nitric K values do not present a true picture of the amount of slowly-available K in these soils, and that more K may become available to a crop than this measure suggests.

Readily-available soil K increased more and there was greater build-up of K over the duration of the study in the Oxisol than in the Inceptisol. As both soils received the same amount of K fertiliser, the increased readily-available K in the Oxisol may have been the result of greater quantities of organic matter in this soil retaining K in a form more readily available for exchange and thus measurement than in the Inceptisol. In addition, greater K fixation by the 2:1 clay minerals present in the Inceptisol may have limited readily-available K following K fertiliser application.

In the Oxisol, increasing topsoil K did not translate into statistically significant stalk yield increases. The total tonnes of sucrose obtained were, however, increased by increasing topsoil K, significantly so in some cases. Similar results were obtained on the Inceptisol, and though lower mean readily-available K, stalk and sucrose yield increases were measured, they were more often significant than on the Oxisol. Importantly, while much reliance is placed on statistical significance, in this study small increases in yield (and hence profitability) may prove economically significant to the farmer, even when not statistically significant. The results obtained confirmed that the local recommended threshold values used for both soils were appropriate.

The inclusion of subsoil K values improved the strength of the relationship between soil K and yield. The FAS recommendations should take this finding into account, and growers should be encouraged to have subsoil samples analysed in order to improve the accuracy of K fertiliser recommendations.

Potassium application significantly decreased topsoil Si in the Inceptisol at times. This was possibly due to increased plant uptake following higher yields in the higher K treatments on this soil.

5.4.2. Nitrogen

Conclusions are presented in Appendix 5.4.

5.4.3. Silicon

Application of silicate products led to the expected significant increases in soil pH, Ca, Mg, Si and total cations, along with significant decreases in exchangeable acidity and acid saturation. Zinc, Fe and Cu were also decreased at some sampling times. Silicate application significantly increased soil profile K once, on the Inceptisol. The effects of silicate application on K were non-significant at all other times. Downward Si movement through the soil profile was more pronounced on the Inceptisol than on the Oxisol. Downward Ca movement was limited in both soils, while Mg leaching occurred, especially in the Inceptisol. Increased soil Si was generally associated with increased stalk (and hence sucrose) yield. Inclusion of subsoil Si values weakened the relationship with yield. The results indicate that the current local recommended threshold of 15 mg L^{-1} is too low for both soils and a higher threshold of approximately 20 mg L^{-1} should be considered.

CHAPTER 6

Stratification of potassium and silicon in two sugarcane soils and the effect of sampling depth on fertiliser recommendations and costs

6.1. Introduction

Sugarcane soils undergo relatively little tillage in comparison with some other crops. In South Africa, sugarcane is replanted, on average, every eight cropping seasons (Lecler and Tweddle, 2010), which total between eight and sixteen years, depending on the climate of the area. Many sugarcane growers also use minimum tillage at replanting, whereby the old crop is sprayed with herbicide, and new rows are drawn using a ridging implement, without full ploughing (Meyer and van Antwerpen, 2010). Conventional tillage is illegal in South Africa on slopes steeper than 12-20%, depending on the soils' erodibility (Anonymous, 1983; McFarlane and Maher, 1993), rendering minimum tillage the only means of replanting on such slopes. Lime is incorporated, typically to a depth of 20 cm, and fertiliser applied in the furrows, at planting only. For each ratoon crop, fertiliser is generally applied to the soil surface.

Infrequent tillage, coupled with surface or topsoil nutrient application, may lead to stratification of nutrients in the soil, with implications for nutrient retrieval by crop roots. Organic matter (Franzluebbers, 2002; Sá and Lal, 2009) and less mobile nutrients such as potassium (K), phosphorus (P) and zinc (Zn) are most likely to become concentrated at or near the soil surface (Wright *et al*., 2007; Fernández *et al*., 2012; Cade-Menun *et al*., 2015), especially in clay soils where downward movement of nutrients is more restricted (Askegaard *et al*., 2004). Under certain conditions, where sugarcane surface feeder roots are absent or limited (due to management and environmental conditions), or if the surface soil should dry, these nutrients will be largely unavailable to the crop.

In Chapter 5, both the topsoil and the whole soil profile (down to 100 cm (Oxisol) or 80 cm (Inceptisol)) were studied, and movement of nutrients down the soil profile was discussed with a focus on the consequences for nutrient management and soil sampling decisions. However, nutrient stratification can also occur at a finer scale, such as within the 'topsoil'. Most routine analytical laboratories make nutrient recommendations based on a certain standardised sampling depth. The Fertiliser Advisory Service (FAS) at the South African Sugarcane Research Institute (SASRI), for example, gives recommendations based on an assumed sampling depth of 0-20 cm (SASRI, 2004), as this is the depth at which samples have been collected in crop nutrition trials. Collecting samples at different depths from within the 'topsoil', in soils where nutrients are markedly stratified, may affect nutrient and lime recommendations. Samples collected from shallower depths, where soil is nutrient-rich, may result in recommendations lower than those required for good crop performance, leading to reduced yields. Samples collected from too deep, on the other hand, where nutrients are less concentrated (unless leaching and redeposition have occurred), will result in recommendations higher than required, leading to excessive expenditure and possible environmental pollution.

This chapter, therefore, reports on an investigation to determine (a) the extent to which K and silicon (Si) are stratified within the upper part of two contrasting soil profiles, and (b) the effect this stratification has on K and Si recommendations and costs based on samples collected at different depths.

6.2. Materials and methods

6.2.1. Trial details

These are given in Sections 3.2.1 to 3.2.3.

6.2.2. Incremental soil depth and topsoil (0-20 cm) sampling

Incremental soil samples were collected following application of fertiliser to the second ratoon crop at each site. This crop on the Oxisol started to grow in winter. Potassium and Si (cement) were applied 5 and 13 weeks, respectively, into the crop's cycle, while nitrogen (N) was applied when spring regrowth started, 17 weeks into the crop's cycle. Incremental soil sampling was conducted in October 2012, 3, 4 and 7 weeks after N, Si and K application, respectively.

On the Inceptisol (which started to grow in summer), N and K were applied 7 weeks into the crop's cycle, and Si, 10 weeks. Sampling was carried out in February 2013, 8 weeks after Si application and 11 weeks after K and N were applied.

Due to the intensity of sampling, not all plots were sampled. The first three replicates were sampled from plots including all four K rates, both Si rates and one (intermediate) N rate (80 kg N ha^{-1} and 105 kg N ha^{-1} on the Oxisol and Inceptisol, respectively) giving a total of 24 plots at each trial site. The soil samples were collected using four Beater augers (Beater, 1955), each with a hollow tubular metal tip that was inserted into the soil to depths of 2.5, 7.5, 15 and 28 cm. The first (2.5 cm) auger was used to collect 3-4 soil cores per row, in the middle of each interrow and a total of approximately 18-20 cores were collected from each plot. The 7.5 cm auger followed directly behind the first auger, collecting samples from the same holes, so that the depth increment 2.5-7.5 cm was collected. The 15 cm auger followed immediately, collecting soil from 7.5 to 15 cm, and finally the 28 cm auger collected soil from the 15 to 28 cm depth increment from the same holes as the previous augers. Samples from each depth were bulked per plot, thoroughly mixed, and analysed for exchangeable K, calcium (Ca), magnesium (Mg) and Si, and pH and exchangeable acidity at the FAS (Appendix 3.1).

Within one day of the incremental sampling, topsoil (0-20 cm) samples were collected using a Beater auger from the middle three interrows of each plot, with five soil cores collected from each. The fifteen cores from each plot were bulked, thoroughly mixed, and analysed, as for the incremental depth samples, at the FAS.

6.2.3. Statistical analysis

Differences within the mean determinants for each sampled depth interval were determined using analysis of variance (ANOVA) (Genstat – 14th Edition, VSN International, 2011). Where treatments showed significant effects, values were analysed using the Holm Sidak multiple comparison separation or Fisher's protected least significant difference test to identify where the differences between treatment means lay. Differences were considered to be significant at $P < 0.05$. Mean K, acid saturation, organic matter and clay were determined for each soil depth interval, and for the depths 0-7.5 cm, 0-15 cm, 0-28 cm and 0-20 cm.

6.2.4. Fertiliser recommendations

Using the current FAS crop nutrition guidelines, fertiliser recommendations were calculated for the 0-7.5, 0-15, 0-28 and 0-20 cm depths. The K fertiliser requirement is calculated at the FAS by subtracting the soil test value (readily-available K) from a threshold value (based on the clay content, base status and predicted yield), and multiplied by a K requirement factor (the amount of fertiliser K required to raise the soil test value by 1 mg L^{-1}). This value is then modified according to whether the crop is burnt or not, and adjusted according to the nitric K value.

Recommended Si rates are not usually calculated based on soil Si concentrations. The amount of Calmasil® is determined by the lime recommendation, with Calmasil® being substituted in a 1:1 ratio for dolomitic lime. Each ton of Calmasil® contains approximately 100 kg Si. The Ca, Mg, exchangeable acidity and total cations in each depth interval (Appendix 6.1) were used to calculate lime (and hence Calmasil®) requirements for the same depth intervals as for K. Lime requirements are calculated at the FAS using a factor that takes into account lime quality and depth of incorporation, along with threshold acid saturation (usually 20%), exchangeable acidity and effective cation exchange capacity (Miles, 2014). In situations where no lime is required but extractable soil Si is < 15 mg L^{-1}, Calmasil® may be recommended by sugarcane extension specialists (Miles, 2014), often at a rate of 3 t ha^{-1}. Although blastfurnace cement was applied to supply Si during the field trial, it is too expensive for commercial farm use and recommendations for this product were therefore not calculated. Current prices of potassium chloride (KCl) and Calmasil® were used to establish fertiliser costs and partial budgets calculated (Section 3.2.6).

6.3. Results and discussion

6.3.1. Stratification of potassium and silicon

6.3.1.1. Potassium

Potassium exhibited marked stratification within the upper 28 cm of both soils. The surface layers (0-2.5 and 2.5-7.5 cm) of all the plots, including the zero K treatments, contained the greatest amounts of readily-available K (Figure 6.1). This stratification was particularly evident in the Oxisol (Figure 6.1A), where differences between depth intervals were significant even in the zero K plots where no K had been applied for the preceding three years. This was likely a residual effect from pre-trial fertiliser applications, together with returns of K from leaf material and K deposition during burning. In the Inceptisol, treatment differences became less marked at 7.5-15 cm, and non-significant at 15-28 cm (Figure 6.1B). Potassium is typically not very mobile in soil (McKenzie and Pauly, 2013), and remained near the soil surface even in the sandy Inceptisol. By the time the second ratoon crops were harvested, 11 months (Oxisol) and 14 months (Inceptisol) after this incremental sampling was conducted, readily-available K had shown some movement to 40-60 cm (Oxisol, Figure 5.3C) and 20-40 cm (Inceptisol, Figure 5.4C).

There was greater build-up of readily-available K in the Oxisol than in the Inceptisol, with over 600 mg K L^{-1} measured in the top 2.5 cm of the Oxisol at the highest K rate, and only 312 mg L^{-1} in the Inceptisol (Figure 6.1). As discussed in Chapter 5, this may be accounted for by the presence of vermiculite in the Inceptisol, and its absence in the Oxisol. Higher organic matter content in the Oxisol is also likely to have played a role in K retention.

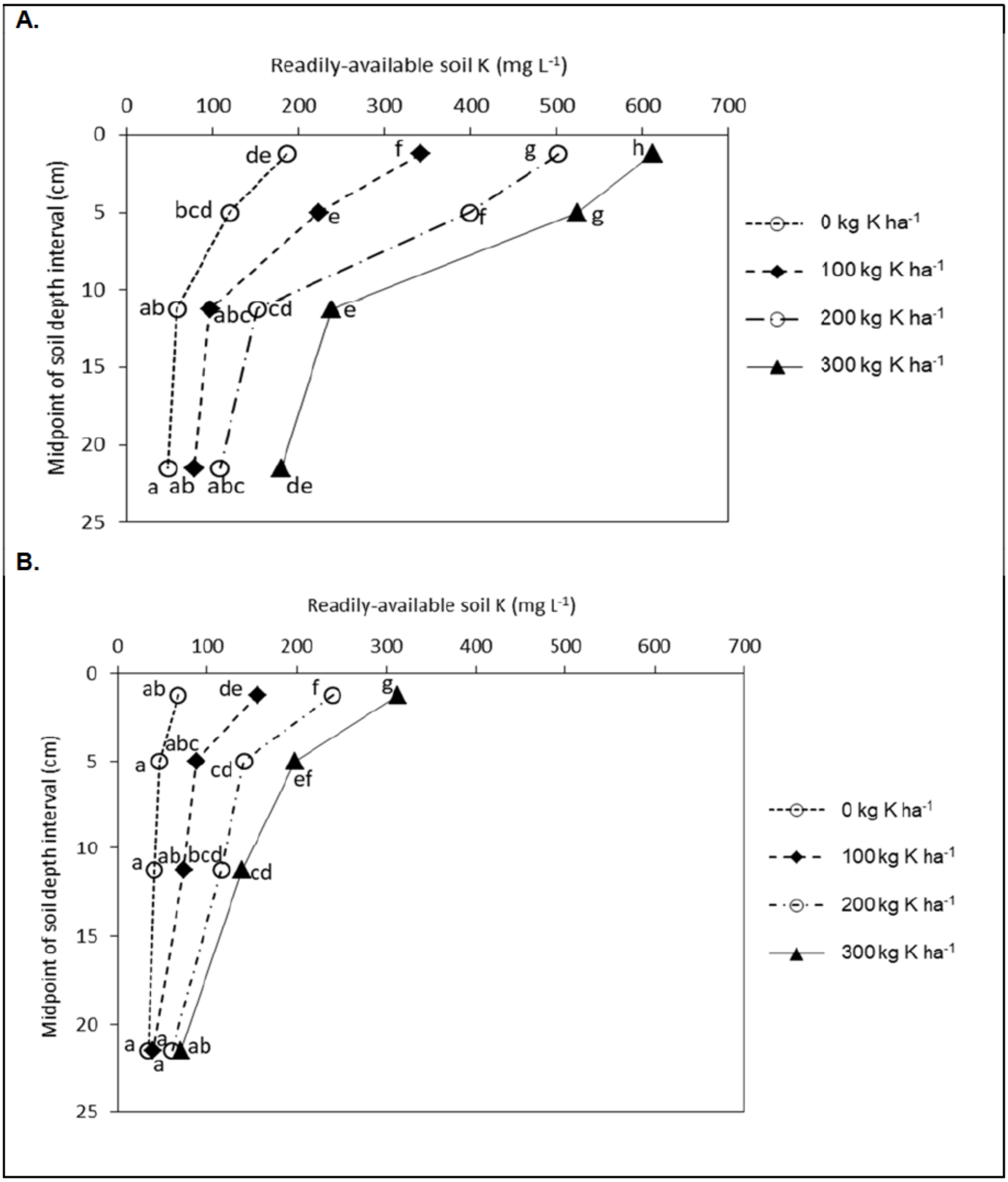


Figure 6.1: Readily-available soil potassium (K) across both rates of applied silicon (0 and 300 kg ha^{-1}), in the (A) Oxisol and (B) Inceptisol, at four K application rates, following fertiliser application at the start of the second ratoon crop. Within each soil, points with different letters are significantly different to each other (P < 0.001).

6.3.1.2. *Silicon*

Stratification of Si was far less marked than that of K. In the Oxisol, there were significant differences between the zero Si and 300 kg Si ha^{-1} treatments at all depths (Figure 6.2), indicating downward movement of Si through the soil. While available Si was highest in the shallowest depth intervals (in the 300 kg Si ha^{-1} treatment), it was only significantly greater than at one other depth in this treatment. The blastfurnace cement was incorporated to a depth of approximately 3 cm (Section 3.2.3) but the Si did not remain at this depth, and downward movement was evident despite the cement being applied only 4 weeks before sampling. Movement may have been promoted by the above-average rainfall experienced during September and October 2012 (Figure 3.2), between application and sampling. Leaching is an important process determining soil Si concentration (Berthelsen and Korndörfer, 2005; Tubana *et al.*, 2016) and may have occurred to a sufficient extent to move applied Si into the deepest depths sampled.

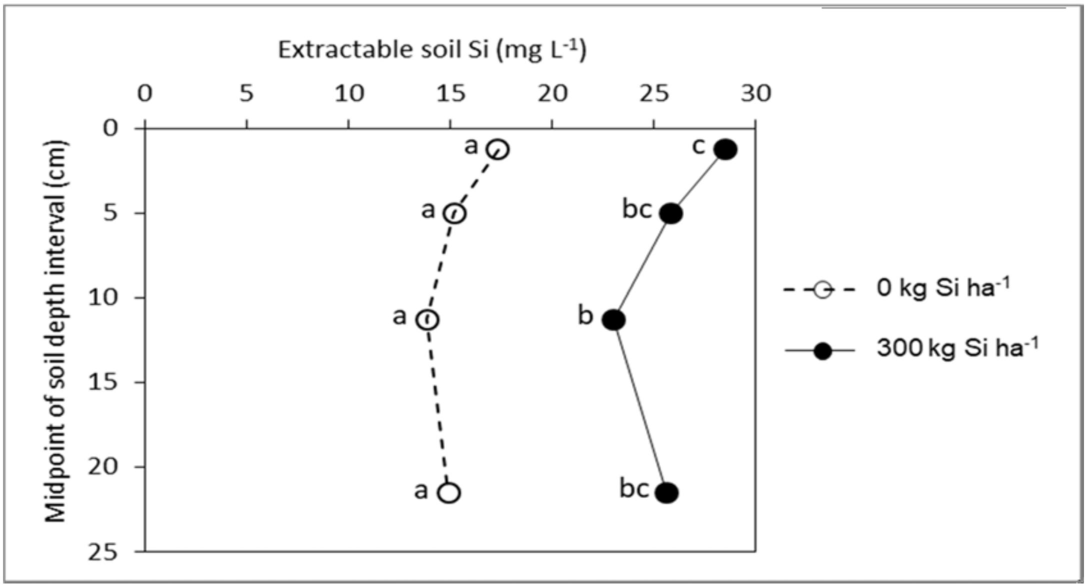


Figure 6.2: Oxisol: Extractable soil silicon (Si) at two Si application rates following fertiliser application at the start of the second ratoon crop (n=4). Points with different letters are significantly different to each other (P = 0.001).

On the Inceptisol, Si from the Calmasil® had not reached a depth of 15-28 cm by the second ratoon, 3 years after application (Figure 6.3). There had been some downward movement of Si, however, as indicated by significant differences between the zero and 300 kg Si ha^{-1} treatments to a depth of 7.5-15 cm. The trends in Figure 6.3 appear to indicate considerable movement over a relatively short period, as indicated by the sharp increase in Si at 7.5-15 cm (but no deeper). It is possible that this Si 'bulge' could have been Si from the Calmasil®, but a more likely cause was movement of Si from the blastfurnace cement, applied 8 weeks before sampling. Downward movement of this Si may have been greater than that from Calmasil® due to its smaller particle size enhancing solubility. Approximately 33% of Calmasil® particles are greater than 200 μm (Keeping, 2017), while less than 5% of cement particles are typically larger than 90 μm (Thomas and Jennings, 2014).

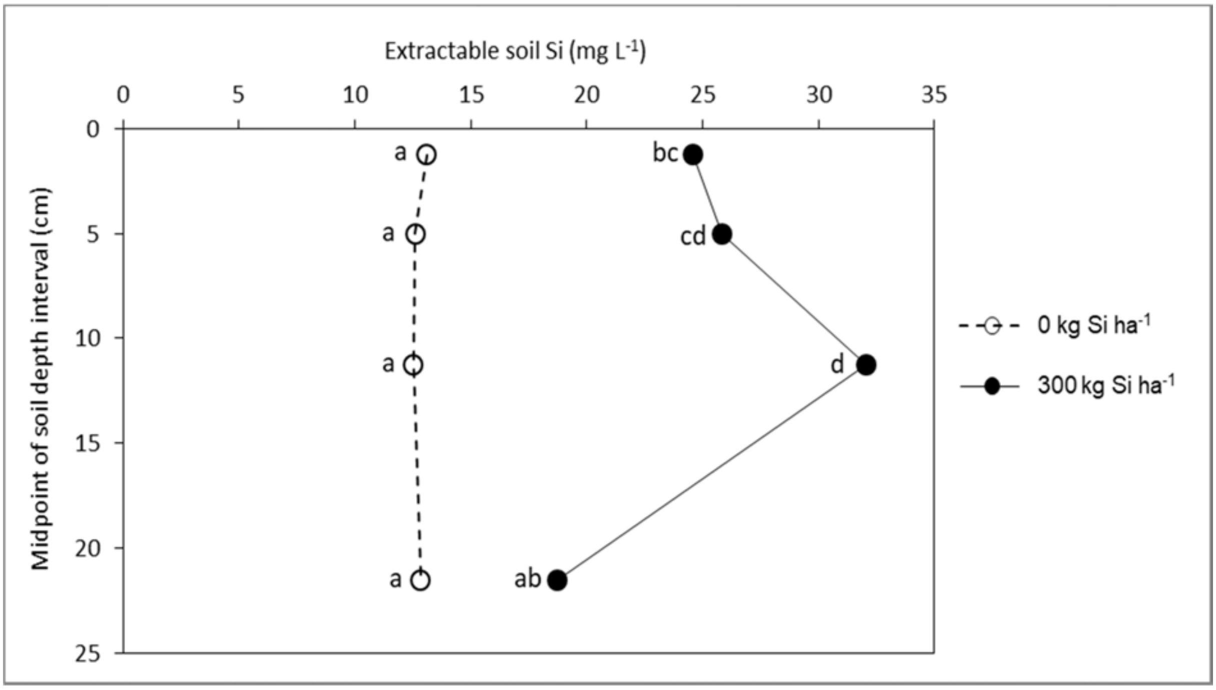


Figure 6.3: Inceptisol: Extractable soil silicon (Si) at two Si application rates following fertiliser application at the start of the second ratoon crop (n=4). Points with different letters are significantly different to each other (P = 0.001).

6.3.2. Fertiliser recommendations based on sampling depth

6.3.2.1. Potassium

Increasing sampling depth significantly affected K fertiliser recommendations and costs (Figure 6.4). Comparison of the 0-20 cm K recommendation (from the 100 kg K ha^{-1} treatments) with those from the other depth increments illustrated different points at the two trial sites.

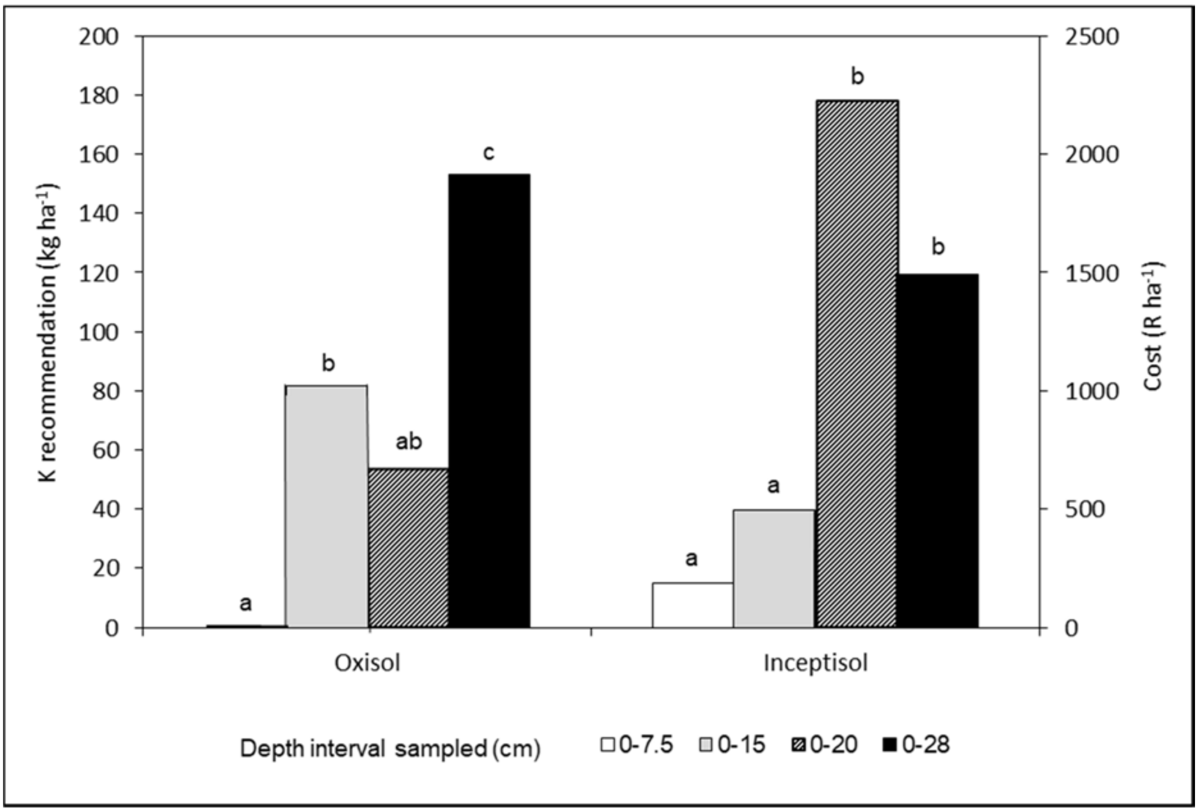


Figure 6.4: The Fertiliser Advisory Service potassium (K) recommendation and K fertiliser purchase cost, based on samples collected at different depths from the 100 kg K ha^{-1} plots (n=6) during the second ratoon crop on the Oxisol and Inceptisol. Within each soil, columns with different letters are significantly different to each other ($P < 0.05$).

On the Oxisol, the standard 0-20 cm sample K recommendation was not significantly different to those for 0-7.5 and 0-15 cm. The 0-28 cm recommendation was, however, significantly higher than that for any other depth (Figure 6.4). Fertiliser costs were R0, R978, R644 and R1 838 ha^{-1} for the 0-7.5, 0-15, 0-20 and 0-28 cm depths, respectively (Figure 6.4). Sampling to 28 cm instead of 20 cm would, therefore, result in fertiliser costs being almost trebled. Increasing the K application above 100 kg K ha^{-1} led to no further (statistical) increase in yield (Figure 3.4). Thus applying 150 kg K ha^{-1} (the recommended amount based upon the 0-28 cm sample) would have caused unnecessary expenditure of approximately R600 ha^{-1}, with no extra income likely (Table 6.1).

Table 6.1: Partial budget: Economic effect of basing potassium (K) fertiliser application rate on soil samples collected at 0-28 cm instead of 0-20 cm (recommended depth) in the second ratoon crop on the Oxisol

Added income due to change:	**(R ha^{-1})**	**Added costs due to change:**	**(R ha^{-1})**
No additional yield for > 100 kg K ha^{-1} application		*Cost of extra K fertiliser (50 kg K ha^{-1} @ R12 kg^{-1} K)	600
		*Cost of extra K fertiliser application (€R0.26 kg^{-1} KCl)	26
Reduced costs due to change:	**(R ha^{-1})**	**Reduced income due to change:**	**(R ha^{-1})**
None		None	
Subtotal	0	**Subtotal**	626
Net change: R0 – R626 = -R626 ha^{-1}			

*Though the FAS recommendation for 0-20 cm was 53 kg K ha^{-1}, this study did not include this K rate, so the 'extra' K fertiliser for 0-28 cm sampling was based on the difference between 100 kg K ha^{-1} (closest treatment to the 0-20 cm recommendation) and 150 kg K ha^{-1} (0-28 cm).
€'Tin and string' method (see Glossary)

On the Inceptisol, the 0-20 cm recommendation was not significantly different to that from 0-28 cm, while the two shallowest depths returned K recommendations about 8% and 22% of that from 0-20 cm (Figure 6.4). In this soil, too little K would have been recommended had the sample been taken at a shallower depth than the calibrated 0-20 cm. Assuming linear interpolation between yield points in Figure 3.6, a loss of approximately R1 200 ha^{-1} would have been incurred if fertiliser recommendations were based on 0-15 cm samples rather than the recommended 0-20 cm samples (Table 6.2).

Table 6.2: Partial budget: Economic effect of basing potassium (K) fertiliser application rate on soil samples collected at 0-15 cm instead of 0-20 cm (recommended depth) in the second ratoon crop on the Inceptisol

Added income due to change:	**(R ha^{-1})**	**Added costs due to change:**	**(R ha^{-1})**
None		None	
Reduced costs due to change:	**(R ha^{-1})**	**Reduced income due to change:**	**(R ha^{-1})**
*Reduction in K fertiliser (78 kg K ha^{-1} @ R12 kg^{-1} K)	936	0.5 t sucrose ha^{-1} yield reduction (R4 450 t^{-1} ERC)	2 250
*Cost of extra K fertiliser application ([€]R0.26 kg^{-1} KCl)	41		
Subtotal	977	**Subtotal**	2 250
Net change: R977 – R2 250 = -R1 273 ha^{-1}			

*Though the FAS recommendation for 0-15 cm was 40 kg K ha^{-1}, this study did not include this K rate, so the reduction in K fertiliser for 0-15 cm sampling was based on the difference between 100 kg K ha^{-1} (closest treatment to the 0-15 cm recommendation, rounding up) and 178 kg K ha^{-1} (0-20 cm).
[€]Tin and string' method

6.3.2.2. Silicon / Lime

There were no significant differences between the lime recommendations (based on a threshold of 20% acid saturation) for any of the depths on the Oxisol (Figure 6.5). On average, on this soil, Calmasil®/cement application did not affect yield (Section 3.3.4.1.1).

On the Inceptisol, sampling to 28 cm would have returned a significantly greater recommendation than that of the 0-20 cm depth (Figure 6.5). This would come at a significantly higher cost to the grower. For instance, the 0-20 cm sample returned a lime recommendation of 1.3 t ha^{-1}, at a cost of R1 297 ha^{-1} (applied) (Calmasil®), while the recommendation for a 0-28 cm sample was 2.8 t ha^{-1}, at a cost of R4 020 ha^{-1} (applied), a 148% increase in cost. However, results in Chapter 3 (Figure 3.14B) showed that application of 3 t ha^{-1} lime (300 kg Si ha^{-1}) resulted in a significant increase in sucrose yield over the 0 t ha^{-1} treatment. The data do not indicate whether application of 1.3 t ha^{-1} lime (based on the 0-20 cm depth sample) would have been sufficient to increase sucrose yield.

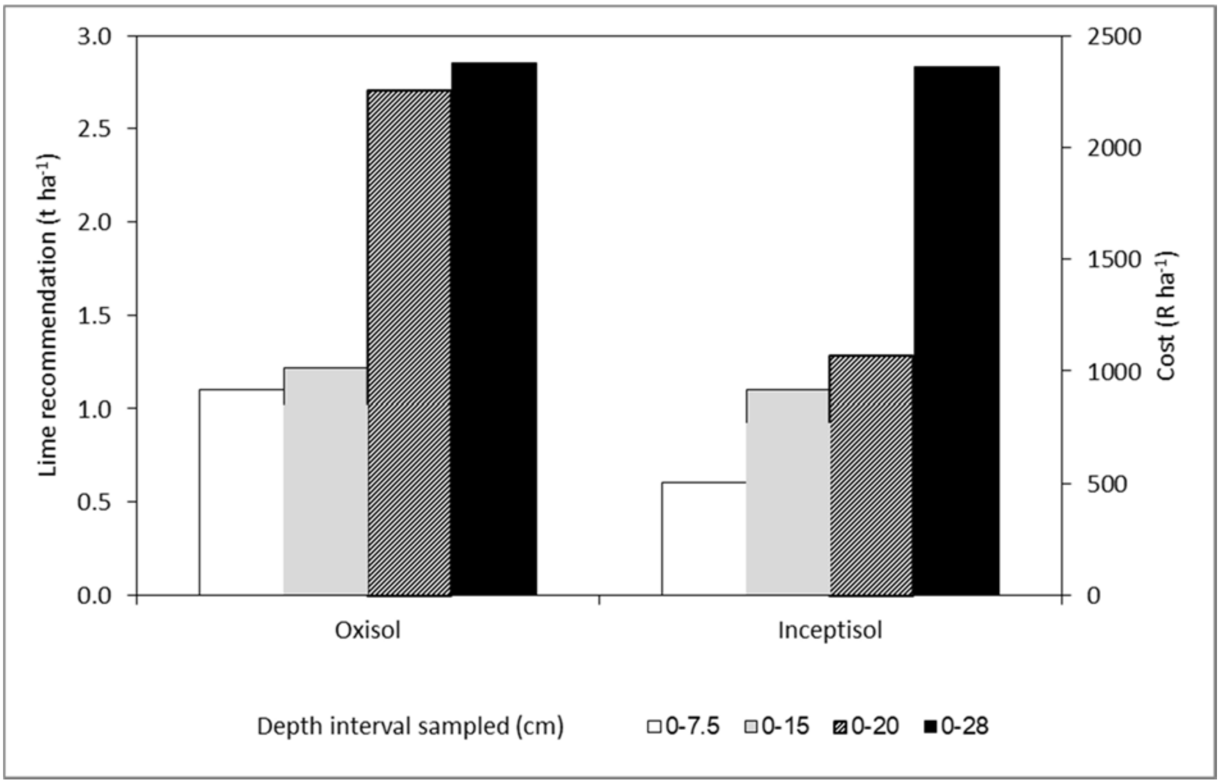


Figure 6.5: The Fertiliser Advisory Service lime recommendation and lime purchase cost, based on samples collected at different depths from the zero silicon plots (n=12) during the second ratoon crop on the Oxisol and Inceptisol. Within each soil, columns with different letters are significantly different to each other (P < 0.05).

6.4. Conclusions

Potassium exhibited marked stratification within the upper 28 cm of both soils. Readily-available K was greatest at the surface and decreased with depth. This stratification was particularly evident on the Oxisol that had higher clay and organic matter than the Inceptisol. As a result, soil samples collected at different depths resulted in different K fertiliser recommendations. Samples collected from close to the soil surface indicated that little K fertiliser was required, possibly leading to reduced yields. Samples collected deeper than the 20 cm recommended by the FAS resulted in recommendations that were likely to be too high, and therefore significantly more expensive.

Although Si stratification was less marked than that of K, lime recommendations were nonetheless significantly affected by sampling depth on the Inceptisol. When samples were collected at a depth greater than that recommended by the FAS, lime recommendations were substantially higher than for samples collected from the recommended depth.

These results highlight important management considerations. Although deep rooting systems are important, especially for accessing water and nutrients, surface rooting should be encouraged on both soils to take advantage of the nutrient-rich topsoil layers. This can be done by mulching in the form of a cover crop, or the retention of the crop residue after sugarcane harvest. These findings underline the importance of the recommended best management practice of maintaining a surface cover.

Secondly, soil samples for nutrient recommendations must be collected at the depth specified by the advisory service to which the samples are sent. Collecting samples at other depths will likely lead to either under- or over-fertilisation, with considerable yield and economic consequences.

CHAPTER 7

The effect of potassium and silicon application on sugarcane root distribution in two soils

7.1. Introduction

In the South African sugarcane industry, there is concern that sugarcane roots are often stunted, blackened and unhealthy, and apparently not reaching the depths reported in earlier studies (6 m, Evans, 1936; 5 ft / 1.52 m, Wood and Wood, 1967). Consequently, research at the South African Sugarcane Research Institute (SASRI) includes investigations into the extent and possible causes of this phenomenon. The present research project therefore included a study of root distribution as part of the field study (Sections 1.3.2, 2.6.1 and 2.6.3).

Potassium (K) encourages healthy root development and reduces susceptibility to root rots (Melis and Farina, 1984). Cavalcante *et al*. (2015) reported a 53% decrease in root density and reduced root dry matter production in sugarcane grown in a K-deficient nutrient solution, compared with a K-replete solution.

Silicon (Si) application has been reported to improve water use efficiency and plant performance under conditions of drought stress in a range of plants, including sorghum (Hattori *et al*., 2005; Ahmed *et al*., 2011), maize (Gao *et al*., 2004), wheat (Gong *et al*., 2005), soybean (Shen *et al*., 2010), rye (Hattori *et al*., 2009), and sugarcane (Savant *et al*., 1999). Sonobe *et al*. (2011) investigated the root responses of sorghum to Si application with and without drought stress. They found that the reduction in seedling dry weight due to water stress was alleviated by Si application, and water uptake was increased. Silicon nutrition, therefore, may also play a role in root development.

Due to the arduous nature of root sampling and observation, however, information on the effects of nutrition on root growth and density in the field is limited. This study was therefore conducted to (a) determine the effects of K and Si on sugarcane total root length and distribution, and (b) establish whether different rates of these nutrients affect root growth.

7.2. Materials and methods

7.2.1. Trial details

These are given in Sections 3.2.1 to 3.2.4.

7.2.2. Root sampling

Root samples were collected 5.5 months (Inceptisol) and 6 months (Oxisol) after harvest of the first ratoon crop, i.e., during the growth of the second ratoon crop. A sampling date between 5 and 6 months after harvest was selected to coincide with sufficient maturity of the new crop's root system, at a time when the old root system would have died off (considered to be within approximately 4 months of harvest; Smith *et al*., 2005). Samples were collected during the summer months, in a period of favourable growth conditions. On the Oxisol, sampling occurred 6 weeks after nitrogen (N) application, 2.5 months after blastfurnace cement (Si) application and 4.5 months after application of K and phosphorus (P). On the Inceptisol, sampling occurred 3 months after cement application, and 4 months after application of N and K. Roots were sampled from intermediate N treatments (80 kg N ha^{-1} on the Oxisol; 105 kg N ha^{-1} on the Inceptisol), on both Si treatments (0 and 300 kg Si ha^{-1}), and on three of the K treatments (0, 100 and 300 kg K ha^{-1}). All four replicates were sampled, resulting in a total of 24 plots being sampled at each trial site.

Corers (stainless steel pipes, 3.8 cm internal diameter and approximately 1.2 m in length) were constructed in-house at SASRI and used to collect bulk soil and root samples. The end of the pipe inserted into the soil was tapered slightly to assist soil penetration, and the other end was reinforced to allow it to be hammered into the soil using a heavy mallet. The sampling pipes were marked at 20 cm increments, to 100 cm. In each sampled plot, eight holes were made between the stools (clumps) of sugarcane, within the five nett rows. Each depth core (0-20, 20-40, 40-60 and 60-80 cm and, on the Oxisol only, 80-100 cm) from each hole was placed in a separate plastic sampling bag. Practical difficulties, including extremely hard soil at depth and soil getting stuck in the corers, resulted in some plots being sampled to only 60 or 80 cm on the Oxisol.

To separate the roots, the samples were placed into a 1.5 L bucket and soaked in tap water for 30 minutes before being poured through a 1 mm sieve and all soil washed off. The roots remaining on the sieve were collected with tweezers, placed into an airtight 50 mL container and scanned on a flatbed document scanner (HP Scanjet 4570c). The scanned images were analysed using APS Assess 2.0 software (Lamari, 2008), yielding total root length per sample.

7.2.3. Statistical analysis

The total root length per depth interval dataset was unbalanced due to the fact that some holes had been sampled to only 60 cm, while others were sampled to greater depth. The effect of soil type and depth interval on the mean total root length per depth interval was therefore analysed using Residual Maximum Likelihood (REML) (Genstat – 14th Edition, VSN International, 2011). Total root length per hole to 60 cm was calculated. Differences in total root length between K and Si treatments, and soil type, were established using three-way analysis of variance (ANOVA) (Genstat – 14th Edition, VSN International, 2011). For both REML and ANOVA, where treatments showed significant effects, values were analysed using the Holm Sidak multiple comparison separation test to identify where the differences between treatment means lay. Differences were considered to be significant at $P < 0.05$.

7.3. Results and discussion

7.3.1. Profile root distribution

In the Oxisol, 46% of the total root length per sample hole (0-100 cm) was found in the top 20 cm, and 69% in the top 40 cm. In the Inceptisol, which was sampled to 80 cm, 49% of total root length was found in the top 20 cm, and 73% in the top 40 cm (Figure 7.1). Most sugarcane root biomass is typically found close to the surface, declining, approximately exponentially, with increasing depth (Smith *et al*., 2005). Root length density follows a similar pattern (Smith *et al*., 2005). Blackburn (1984) reported that approximately 50% of sugarcane root biomass is found in the top 20 cm of soil, and 85% in the top 60 cm. This equates to an 'extinction coefficient' for root distribution, *b*, of ~0.967, where the cumulative proportion of roots (Y) to a certain depth, d (cm), can be calculated as $Y = 1 - b^d$ (Gale and Grigal, 1987). Using this relationship, approximately 74% of the roots should have been found in the top 40 cm of soil, which is very close to the value found in both soils.

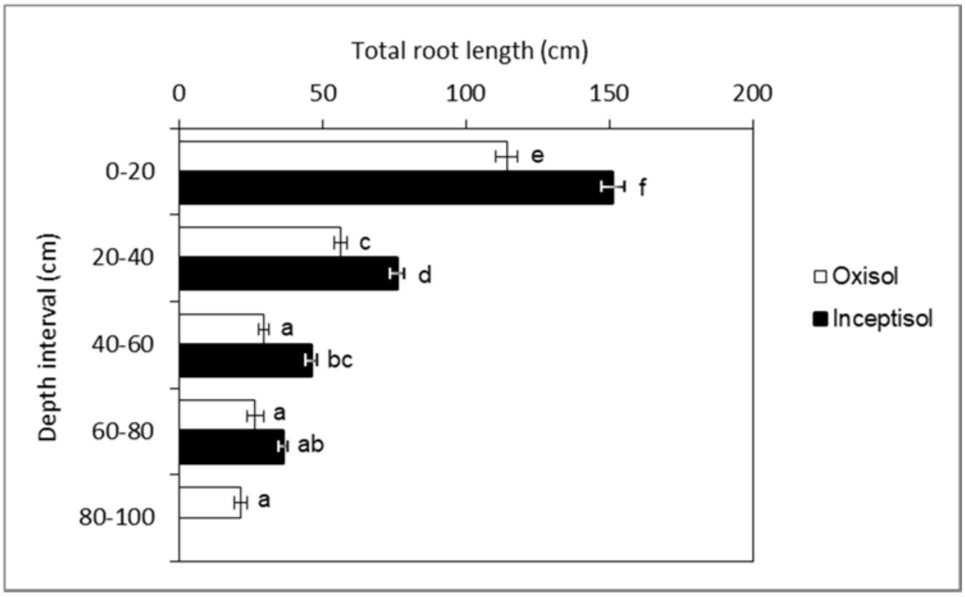


Figure 7.1: Mean (± s.e.) total length of roots per sampled depth interval in the Oxisol (n = 24) and Inceptisol (n = 24), across all potassium and silicon treatments sampled. Bars with different letters are significantly different to each other ($P < 0.001$).

Van Antwerpen (1999) reported that 57% of total sugarcane roots (sampled to 195 cm) were found in the top 45 cm of a non-irrigated clay soil (32-44% clay), while in a sandy soil (12% clay), this figure was 38%. The lower percentage of roots in the latter was due to the need for more roots to access the subsoil to obtain water (Van Antwerpen, 1999). This distribution was not evident in the present study, where a greater proportion of measured roots was found in both topsoils. It is probable that some roots in the current study were not sampled due to growth being below the lowest sampling depth leading to some overestimation of the proportion found in the topsoil. The lithocutanic B horizon (Soil Classification Working Group, 1991) of the Inceptisol may also have restricted downward root growth, in contrast to the deep sands in the Van Antwerpen (1999) study. The higher proportion of roots found in the Oxisol topsoil than that found in the high clay soil of the Van Antwerpen study may have been due to variations in root growth under dryland (non-irrigated) conditions.

Van Antwerpen (1999) lists rainfall as an important determinant of root growth. At the Oxisol site, above-average rainfall was recorded in the 3 months prior to root sampling, which may have led to slightly lower rates of root extension into the subsoil as the roots had access to sufficient moisture in the topsoil.

Root density in the top 20 cm ranged from 0.08 to 1.25 cm cm^{-3} in the Oxisol, and from 0.05 to 1.39 cm cm^{-3} in the Inceptisol. These values are within and below the lower range of the root density reported by Van Antwerpen (1998), of 0.5 to 2.7 cm cm^{-3}. Again, above-average rainfall during the months prior to root sampling on both the Oxisol and Inceptisol may have resulted in less need for root proliferation.

7.3.2. Effect of soil type and applied nutrients on total root length

In both soils the amount of K applied had no effect on the total root length to a depth of 60 cm (Table 7.1). While deficiencies in P or N tend to foster preferential partitioning of photosynthetic carbon to the roots, leading to an increase in the root : shoot dry weight ratio (Cakmak *et al*., 1994), the opposite is true for K and magnesium (Mg) deficiencies (Marschner *et al*., 1996).

Table 7.1: Mean (± s.e.) total root length in samples collected from 0-60 cm, 6 months (Oxisol) and 5.5 months (Inceptisol), after harvest of the first ratoon crop from potassium (K) and silicon (Si) treatments. n=8 (K rates) and n=12 (Si rates) at each site

Treatment (kg ha^{-1})	**Soil**	
	Oxisol	**Inceptisol**
K	**Root length** (cm)	
0	ƚ 200.2 ± 9.1	316.1 ± 11.3
100	213.0 ± 10.4	306.7 ± 9.5
300	187.4 ± 9.6	306.2 ± 12.7
Significance	**NS**	**NS**
Si		
0	204.7 ± 8.4	327.3 ± 8.4 a
300	195.7 ± 7.5	292.0 ± 9.5 b
Significance	**NS**	**P<0.01**
Soil	**Mean (± s.e.) total root length (cm) per soil type, over all treatments**	
Oxisol	200.2 ± 5.6 a	
Inceptisol	273.5 ± 5.9 b	
Significance	**P<0.001**	

ƚ Within soils and treatments, values with different letters are significantly different at the P level specified.

Potassium concentrations in the 0-20 cm depth of the 0 kg K ha^{-1} treatments were 63 mg L^{-1} and 47 mg L^{-1} in the Oxisol and Inceptisol, respectively (Table 7.2), both well below the SASRI Fertiliser Advisory Service's 90 t cane ha^{-1} thresholds of 155 mg L^{-1} and 93 mg L^{-1}, respectively (Miles, 2014). In the 300 kg K ha^{-1} treatment, 188 mg K L^{-1} and 123 mg K L^{-1} were present in the Oxisol and Inceptisol, respectively (Table 7.2). In this treatment, K status of the soils was well above the K thresholds, yet root length was not greater than that on the zero-K treatments.

Table 7.2: Readily-available potassium (K) and extractable silicon (Si) to 100 cm (Oxisol) and 80 cm (Inceptisol), in the 0, 100 and 300 kg K ha^{-1} and the 0 and 300 kg Si ha^{-1} treatments, in samples collected 4 weeks (Oxisol) and 6 weeks (Inceptisol) after harvest of the first ratoon crop. n=8 (K rates) and n=12 (Si rates) on each soil

Nutrient	Application rate (kg ha^{-1})	Sample depth (cm)	Readily-available K and extractable Si (mg L^{-1}) ŧ Oxisol	Inceptisol
Potassium	0	0-20	63 de	47 ab
		20-40	37 abc	37 ab
		40-60	23 a	34 a
		60-80	20 a	38 ab
		80-100	14 a	
	100	0-20	94 f	70 c
		20-40	57 bcde	41 ab
		40-60	24 ab	34 a
		60-80	22 a	44 ab
		80-100	18 ab	
	300	0-20	188 g	123 e
		20-40	90 ef	53 b
		40-60	39 abcd	41 ab
		60-80	31 ab	51 b
		80-100	28 abc	
	Significance		**P<0.001**	**P<0.001**
Silicon	0	0-20	15 e	14 abc
		20-40	13 d	13 abc
		40-60	10 c	12 ab
		60-80	8 b	12 a
		80-100	6 a	
	300	0-20	19 f	16 c
		20-40	14 de	15 bc
		40-60	10 c	14 abc
		60-80	8 b	13 abc
		80-100	7 ab	
	Significance		**P<0.001**	**P<0.001**

ŧWithin soils and nutrients, values with different letters are significantly different at the P level specified.

It is possible that the sugarcane roots may have obtained some K from depths below those measured. In the Inceptisol, for instance, mean readily-available K from 80-420 cm (i.e., below the depths routinely measured in this study) was 30 mg L^{-1} (data not shown), with some depth layers up to 57 mg K L^{-1}. This may explain the fact that the zero-K plots did not show a significant reduction in root length in comparison with the K-treated plots. Less readily-available K pools may also have contributed towards supplying the K required to maintain rooting in the zero-K treatments. Other results indicated that less readily-available K became available during the growing season, possibly providing more K than that indicated by the nitric K measurements (Section 5.3.2.6).

Silicon application on the Inceptisol led to a significant decrease in total root length (0-60 cm), in comparison to the zero-Si treatment (Table 7.1). Silicon was significantly higher in the topsoil of the 300 kg Si ha^{-1} treatment than in the zero-Si treatment (Table 7.2). Application of Si may affect sugarcane rooting in a number of ways. Firstly, the application of Calmasil® and cement led to a significant increase in soil pH and a decrease in exchangeable acidity and acid saturation (Section 5.3.4.1; Table 5.7). Application of such siliceous materials should, therefore, encourage root growth (Sumner, 2011). Secondly, their application led to slight decreases in leaf N, this decrease being significant at one sampling time (data not shown). A model (Thornley, 1972) predicts increased biomass partitioning towards the shoot under conditions of increased N concentration. Decreased plant N, with Si application, would therefore be predicted to decrease shoot biomass, favouring root growth instead. Thirdly, the silicate materials applied contained Mg (Section 3.2.3), raising the soil's Mg status (Section 5.3.4.2; Table 5.8). This would overcome any Mg deficiency, and should therefore increase biomass partitioning to the roots. None of these effects, however, explain the measured decrease in root length following Si application. This may, however, be a result of the improved water use efficiency reported following Si application that reduces the need for the crop to establish an extensive root system. Sugarcane plants subjected to water deficit tend to grow deeper root systems (Smith *et al*., 2005), with rainfed plants typically having deeper root systems than irrigated crops (Van Antwerpen, 1998). In general, grasses subjected to water stress tend to prioritise root growth and in sugarcane an increase in root dry matter has been reported (Queiroz *et al*., 2011). It is possible, therefore, that the plants' reaction to water stress in the zero-Si treatments may have led to an increase in biomass accumulation in the roots, whereas the applied Si reduced the plants' stress reaction in the 300 kg Si ha^{-1} treatment. It is also possible that application of Calmasil® and cement could have raised the soil electrical conductivity (not measured in this study), possibly restricting root growth to some extent.

The Inceptisol had significantly greater total root length than the Oxisol (Table 7.1). The Oxisol had better water-holding characteristics than the Inceptisol, including higher clay and organic matter contents (41% and 3.9%, respectively, at 0-20 cm in the Oxisol; 24% and 1.4% in the Inceptisol; Table 3.2). In addition, the Oxisol site had received higher rainfall (approximately 1 110 mm) during the second ratoon crop (from harvest of the previous crop to root sampling), than the Inceptisol (approximately 770 mm). It is therefore likely that the second ratoon crop (and possibly all crops) on the Inceptisol experienced greater water stress than on the Oxisol, leading to greater root extension in the Inceptisol. Soil strength can also inhibit root growth and clay soils may have significantly reduced root systems compared with their sandy or loam counterparts (Smith *et al*., 2005). The higher clay percentage in the Oxisol may therefore have inhibited root growth. As mentioned in Section 7.2.2, difficulties were encountered during root sampling to depth on the Oxisol, highlighting the possibility of soil strength reducing root growth.

7.4. Conclusions

Approximately 70% of the roots sampled were found in the top 40 cm of the soil at each site. The concern within the South African sugar industry of roots not reaching depths reported by earlier workers does not seem to apply to the two trial soils where the root distribution appears to be normal according to the proportion of roots expected to be in the upper part of the soil (Blackburn, 1984; Gale and Grigal, 1987).

Unexpectedly, K application had no effect on total root length. It is possible that roots may have obtained some K from deeper in the soil profile, and also from less readily-available K pools, to maintain root growth in the zero-K treatment. Application of Si, on the other hand, decreased total root length to a depth of 60 cm, significantly so in the Inceptisol. In addition, total root length in the Oxisol was less than in the Inceptisol. Water stress may be implicated in both responses, with the effect of increasing total root length where water was limited, or where plants experienced water stress for other reasons such as soil texture. The lower total root length (in the Inceptisol) in the 300 kg Si ha^{-1} treatment suggests that the reported amelioration of drought stress following Si application is likely not due to an increased root system, but rather to other mechanisms such as, amongst others, increased water uptake by the roots or decreased water loss from the leaves (Zhu and Gong, 2014).

CHAPTER 8

Potassium exhaustion study of an Oxisol and an Inceptisol, using Italian ryegrass (*Lolium multiflorum* L.)

8.1. Introduction

As with most crops, sugarcane responds to a shortage of essential nutrients through a reduction in crop performance or yield. Low readily-available (exchangeable) potassium (K) can inhibit sugarcane germination (Anderson and Bowen, 1990), and lead to a decrease in cane yield and quality (Wood and Schroeder, 2004). Soil K thresholds have been established in many countries (Anderson and Bowen, 1990) and when soil K is below this threshold, sugarcane yields will be compromised, unless fertiliser K is applied.

For some soils, measures of readily-available K provide an accurate estimate of their K-supplying power. In other soils, however, less available (non-exchangeable) K may become available to crops, sometimes within a single growing season (Adamo *et al*., 2016). High crop yields can then be maintained even where readily-available soil K is below the accepted threshold. In the present field trials, sugarcane did not show a marked yield response to K application, even on the Inceptisol, where the pre-trial readily-available K was below threshold. A K balance (Section 5.3.2.6) indicated that more K was taken up by the crop than was originally present in readily-available form in the soils. To examine this further a K 'exhaustion' pot trial, using soil from the two trial sites, was established. Italian ryegrass (*Lolium multiflorum*) was grown. It is commonly used in K exhaustion trials because it has a very high K requirement per unit dry matter produced, re-grows rapidly after harvest, has an intensive root system, can be planted densely, and can be grown in small containers (Wood and Burrows, 1980; Samadi, 2011). The objectives of this pot trial were to determine a) whether K could be exhausted in these soils, as evidenced by a marked reduction in ryegrass yield and K content; b) if the K was not exhausted, whether more K was being released, and taken up by the plants, than was originally readily available in the soil; and c) information regarding the K-supply potential of the two soils.

8.2. Materials and methods

8.2.1. Pot trial procedure

Topsoil (0-10 cm) was collected with a spade at four locations in two replications from the 0 kg K ha^{-1}, 300 kg Si ha^{-1}, 80 kg N ha^{-1} (Oxisol) or 105 kg N ha^{-1} (Inceptisol) treatment plots. The soil was collected following harvest of the second ratoon crop on the Oxisol, and 12 months into the growth of the second ratoon crop on the Inceptisol. The soils were bulked at each site, air-dried for 8 days at room temperature, milled and passed through a 1 mm sieve.

The mass of 500 mL of each soil was determined and used to calculate the amount of each nutrient to apply to the pots, assuming a plough depth of 20 cm. The equivalent of 5 t ha^{-1} dolomitic lime (ryegrass is acid-sensitive) and 100 kg P ha^{-1} (as calcium phosphate) were thoroughly mixed into each topsoil. Six 500 mL plastic pots, each with four 5 – 6 mm diameter drain holes were filled with each treated topsoil, to within 1.5 cm of the top. Filter paper was placed inside each pot before filling with soil, in order to prevent soil loss. Sub-samples of the potting soils were analysed by the South African Sugarcane Research Institute's Fertiliser Advisory Service (FAS) for pH, clay, organic carbon, P, K, calcium (Ca) and magnesium (Mg) (Appendix 3.1).

Twenty-five long-duration Italian ryegrass (*Lolium multiflorum* L., cv. Feast II) seeds were spread evenly over the soil in each pot, and covered with a further 0.5 cm of the fertilised soils. Ten millilitres of the trace element mixture Trelmix® was added to 2 L of distilled water, the rate recommended by the suppliers. Undiluted Trelmix® contains boron (1.0 g L^{-1}), copper (3.0 g L^{-1}), iron (21.3 g L^{-1}), manganese (2.7 g L^{-1}), Mg (0.3 g L^{-1}), molybdenum (0.3 g L^{-1}) and zinc (2.3 g L^{-1}).

Mottram *et al*. (1981) and Van Antwerpen *et al*. (1994) derived equations to relate field capacity to topsoil clay percent, and the mean value of these equations was used to calculate the volume of water required to bring each soil to field capacity. The appropriate volumes of the Trelmix® solution were applied to each pot, and any seeds exposed during watering were gently pushed back into the soil, to a depth of 0.5 cm.

The pots were randomly placed into two 43 cm x 30.5 cm x 8.8 cm plastic trays. At one end of each tray, a 7.2 cm length of 7.6 cm diameter PVC pipe was placed vertically. At the top and bottom of each of these pipes, four slots, each 1.0 cm x 0.3 cm wide, had been cut, one in each quadrant of the circular pipe. This allowed a 1.75 L bottle to be filled with distilled water, turned upside down and placed so that the neck of the bottle rested on the top of the PVC pipe, while the slots in the pipe allowed a depth of 1 cm of water to be maintained within the trays at all times. This method of irrigation followed that outlined by Portch and Hunter (2002) and allowed capillary action and root demand to regulate the uptake of water by the plants. The trays were placed in a glasshouse, where minimum and maximum temperatures were recorded for the duration of the trial. Temperatures ranged from 17.0 to 33.0°C in summer, and 14.5 to 28.0°C in winter.

Initial germination of the ryegrass was poor due to crusting of the soils. The soil surfaces were therefore disturbed and the pots reseeded at a rate of 50 seeds pot^{-1}, and removed from the water trays for all but 10 to 15 minutes per day. Subsequent germination was favourable and a dense stand was obtained in each pot. Plants were not thinned. One month after the initial planting, limestone ammonium nitrate (LAN, 28% N) was crushed and broadcast over the surface of each pot at an equivalent rate of 100 kg N ha^{-1}. The Trelmix® solution was applied, at the same rates as before, to the newly fertilised pots. For the remainder of the trial, LAN was applied at the same rate every 21 days and the Trelmix® solution every 42 days.

Sixty days after sowing, the ryegrass was harvested by cutting at 5 cm above the soil surface. At harvest, the grass was at the ‘three-leaf stage’, where three leaves had grown on the primary tiller of each plant. Because the amount of ryegrass harvested per pot was insufficient for analysis, all replicates were combined at each harvest event. The material was weighed immediately (data not shown) and then dried at 70°C for 48 hours. The material was re-weighed, ground and stored. Harvests were again conducted each time the primary tillers reached the three-leaf stage (112, 161, 207, 249, 291 and 340 days after sowing), and the material treated as before. At the last harvest, the stubble (the 5 cm of aerial plant material remaining after harvest) was cut at ground level and treated in the same way as the leaf samples. A sub-sample of soil (± 50g) from each pot was analysed at the FAS as before. To separate the roots, the remaining soil from each pot was placed into a plastic beaker and covered with tap water to soak for 4 hours before being washed under running tap water over a 1 mm sieve. The clean roots were dried at 70ºC for 72 hours, weighed and stored for analysis. The root, stubble and leaf samples from all harvests were analysed at the FAS for total K by inductively coupled plasma-OES spectrometry (Varian ICP 720-ES) following acid digestion.

8.2.2. Data analysis

The total amount of K removed by the plants for the duration of the pot trial was calculated. This total included the cumulative total K in the leaves from each harvest, as well as the stubble and root K measured after the final destructive harvest. Combining the replicates to obtain enough plant material for analysis precluded statistical analysis of the data.

8.3. Results and discussion

The Oxisol and Inceptisol differed in texture and nutritional status. The Oxisol had higher clay, organic carbon, P and Ca contents and readily-available K was 60% higher than in the Inceptisol (Table 8.1). However, both soils were below the soil K threshold for Italian ryegrass of 100 mg kg^{-1} (0.26 cmol$_c$ kg^{-1}) (Manson, 1995).

Table 8.1: Initial properties of soils used in the ryegrass pot trial (following the application of dolomitic lime and calcium phosphate basal treatments)

Soil	pH ($CaCl_2$)	Clay	Organic carbon	P	Readily-available K	Exch. Ca	Exch. Mg
		---- (g kg^{-1}) ----		(mg kg^{-1})	---------- (cmol$_c$ kg^{-1}) ----------		
Oxisol	5.2	340	51	59	0.24	10.00	1.37
Inceptisol	4.9	190	21	36	0.15	5.12	1.39

8.3.1. Ryegrass uptake of potassium and potassium balance

With the exception of the first harvest, the ryegrass grown on the Inceptisol had a higher leaf K content than that on the Oxisol (Figure 8.1). Leaf K was above 3% at the first harvest on each soil, but dropped to below 2% from the second harvest. By the final harvest, leaf K was 0.43% (Oxisol) and 0.90% (Inceptisol) (Figure 8.1).

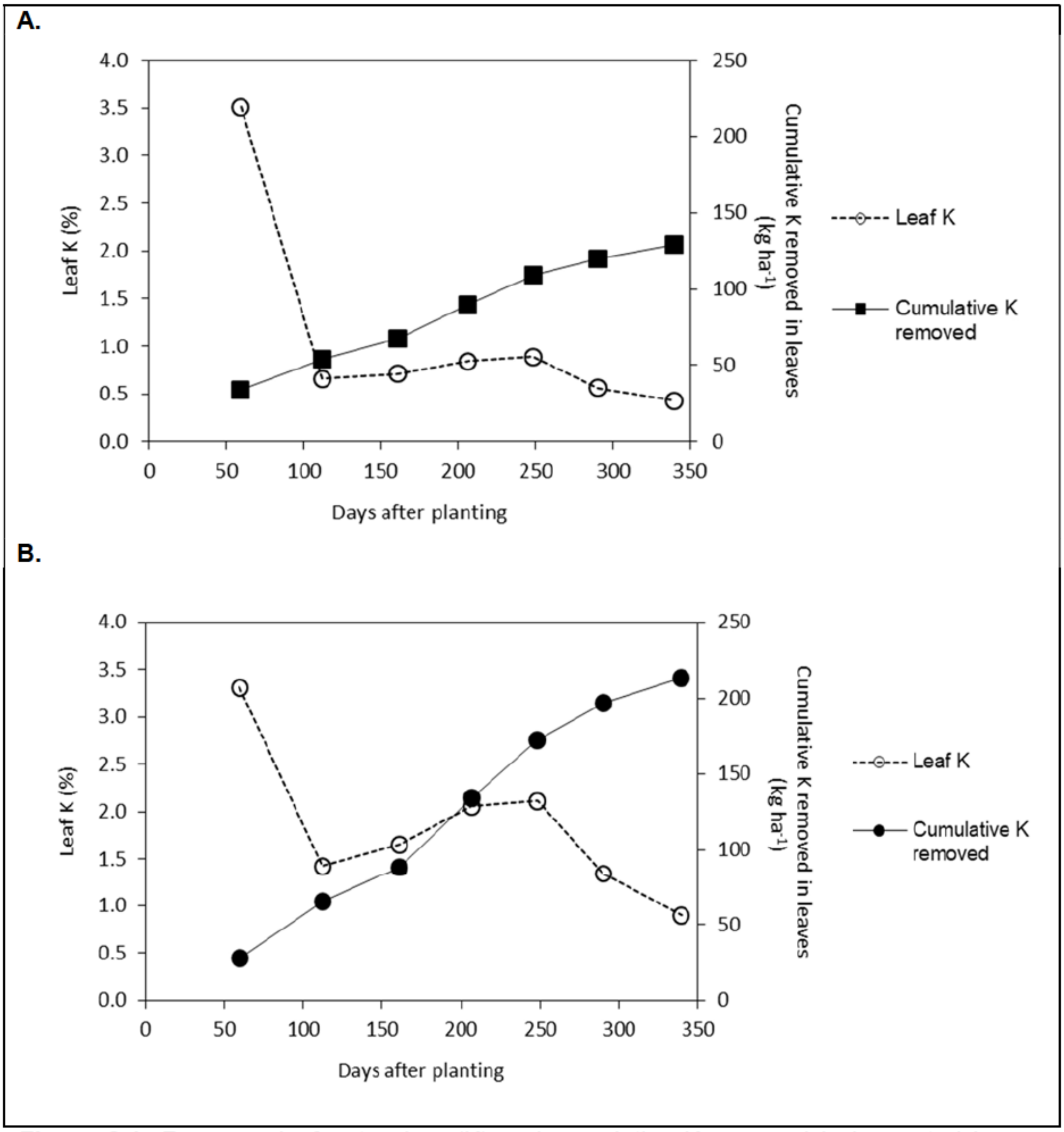


Figure 8.1: Ryegrass leaf potassium (K) and cumulative K removed in harvested leaves over time on the (A) Oxisol and (B) Inceptisol.

Manson (1995) and Miles *et al*. (1986, cited in Manson, 1995) reported a critical leaf

K threshold of 3.0% for optimal ryegrass production in KwaZulu-Natal, South Africa, while McDonnell *et al*. (2018) gave a satisfactory range of 1.6 - 2.0% K in south-western Australia, the higher concentration targeting the first two ryegrass harvests. Both soils, therefore, provided sufficient K for the first harvest, but leaf K dropped below the sufficiency level of 1.6% for the second harvest. For the remainder of the pot trial, leaf K in the ryegrass grown on the Oxisol was below 1% (Figure 8.1A), while that on the Inceptisol exceeded 1.6% for the third, fourth and fifth harvests, before dropping below this for the last two harvests (Figure 8.1B). Cumulative leaf K removal appeared to be leveling off in both soils (Figure 8.1A and B) – more particularly so in the Oxisol. This, coupled with the declining leaf K concentration, indicates that the soils may have been nearing K exhaustion.

Although the Oxisol ryegrass leaf (Table 8.2) and stubble (Table 8.3) had a higher dry mass than that grown on the Inceptisol (possibly due to higher N mineralisation on the higher organic matter Oxisol), the K concentration (K%) was greater on the Inceptisol (Table 8.3). The net result was that a greater amount of K was removed by the ryegrass from the Inceptisol (269 kg K ha^{-1}) than from the Oxisol (155 kg K ha^{-1}) (Table 8.3). Figure 8.1A and B, where only leaf K is shown, illustrates a similar pattern. A considerable amount of K was thus removed from these soils. Interestingly, root mass was greater in the Inceptisol than the Oxisol (Table 8.3). The same pattern was found with sugarcane root length (Table 7.1) and may be a function of soil texture and consequent water or nutrient availability.

Table 8.2: Ryegrass leaf dry matter at each harvest on the Oxisol and Inceptisol

Days after planting	**Dry mass of harvested leaf material** (g pot^{-1})	
	Oxisol	**Inceptisol**
60	0.57	0.49
112	1.76	1.54
161	1.13	0.81
207	1.58	1.33
249	1.27	1.05
291	1.14	1.07
340	1.27	1.08
TOTAL	**8.72**	**7.37**

Table 8.3: Ryegrass stubble and root dry matter and potassium (K) content at final harvest (340 days after planting) and total K removed by leaf, stubble and roots

Soil	**Plant part**	**Dry mass of harvested plant material** (g pot^{-1})	**K content** (%)	(kg ha^{-1})
Oxisol	Stubble	4.82	0.21	17.04
	Roots	5.98	0.09	8.98
Inceptisol	Stubble	4.15	0.60	42.62
	Roots	9.68	0.08	12.57
TOTAL: kg K ha^{-1} equivalent, over all plant parts, at final harvest				
			Oxisol:	**155.2**
			Inceptisol:	**268.6**

At the end of the pot trial, almost 94% of the original readily-available K in the Oxisol was accounted for, with almost 76% taken up by the ryegrass and 18% remaining in the soil (Table 8.4). By contrast, the ryegrass grown on the Inceptisol took up 181% (269 kg K ha^{-1}) of the original readily-available soil K (149 kg K ha^{-1}), while 41% (61 kg K ha^{-1}) remained in the soil after the pot trial. A total of 330 kg K ha^{-1}, or 222% of the original amount, was thus taken up by the ryegrass or remained in the soil after the pot trial.

Table 8.4: Potassium balance in the ryegrass pot trial on the Oxisol and Inceptisol

Property	**Oxisol**	**Inceptisol**
Pre-trial: readily-available K in soil (kg ha^{-1})	205.54	148.56
Post-trial: readily-available K in soil (kg ha^{-1})	36.68	61.15
Difference: readily-available K (pre-trial) – readily-available K (post trial) (kg ha^{-1})	168.86	87.41
% of pre-trial K remaining in soil after the trial	17.85	41.16
Readily-available K removed by ryegrass (kg ha^{-1})	155.21	268.63
% of original readily-available soil K removed by ryegrass	75.51	180.82
% readily-available K unaccounted for by ryegrass removal and remaining soil K	6.64	-121.98

More K was therefore taken up from the Inceptisol, despite having approximately 60 kg ha^{-1} less readily-available K than the Oxisol before the trial started. This apparent inconsistency may be explained by the mineralogy of the soils. The Inceptisol topsoil contained six times more total K and the parent material approximately ten times that of the Oxisol (Table 5.2). Slowly-available (nitric) K was also greater in the Inceptisol than in the Oxisol (Table 5.3). In the topsoil (0-20 cm), the Inceptisol contained 661 kg ha^{-1} nitric K, approximately 3.5 times more than the Oxisol (Table 5.3). If the total potentially available pool of K is assumed to be the sum of the readily-available and nitric K fractions, the Oxisol had 395 kg K ha^{-1} and the Inceptisol 810 kg K ha^{-1}. The ryegrass took up 39% of this total on the Oxisol, and 33% on the Inceptisol. All of the K taken up by the ryegrass on the Oxisol could be accounted for by the readily-available K (Table 8.4), while two thirds of the Inceptisol ryegrass K removal was supplied by the nitric K pool. This indicates that more K became available for slow release to the crop in the Inceptisol than in the Oxisol.

It has been shown that K^+ ions can be extracted by plants from, particularly, illitic and smectitic clay minerals, within a single growing season (Adamo *et al*., 2016). Illite was present in the clay fraction of both topsoils, while vermiculite was present in the Inceptisol, but not the Oxisol (Table 5.1). The extent of the release from the Inceptisol may have been due to the large amount of total K in the topsoil, as well as the presence of illite, vermiculite and K-feldspars that facilitated the slow release of K. These results also raise the possibility that even though the Oxisol contained more organic matter than the Inceptisol, its ability to supply K was less than that of the minerals (and perhaps the organic matter) in the Inceptisol. The organic matter in humic soils is considered to be very stable (due, at least in part, to the presence of aluminium-organic matter complexes), inhibiting its activity with regard to K release. Roberts (1968) reported annual patterns of K release from soil organic matter and retention by the microbial fraction, indicating that the various organic matter fractions have different K dynamics. Although not analysed, it is possible that the organic matter in the Inceptisol – perhaps with a greater labile proportion - may have released more K than the Oxisol.

8.3.2. Soil potassium release: comparison between pot and field potassium balances

Direct comparison of the absolute amounts of K release and uptake between the pot and field trials is not possible, due to the very different trial conditions. However, patterns of supply and uptake by the ryegrass and sugarcane can be examined.

In the pot trial, 94% of the original, readily-available soil K in the Oxisol was recovered in the final soil and plant parts. The 6% that was not accounted for may have been leached, or lost in small amounts of root material that were not recovered during the harvesting and root-washing procedure. In the field K balance conducted on the Oxisol (Section 5.3.2.6), an average of 129% of the original, readily-available soil K was recovered after harvest in the plant parts and that remaining in the soil (Table 5.4). Considering that the field trial K balance did not take the K in crop roots into account, 129% was a conservative measure, likely under-estimating the actual K uptake. Both field and pot trials indicated that pre-trial readily-available soil K supplied a large proportion of the crop's needs and that only a limited amount of K was used from slowly-available sources.

In the Inceptisol, 222% of the original readily-available soil K was recovered in the plant and that remaining in the soil after the pot trial. A large amount of K was therefore taken up by the ryegrass which was not readily available at the start of the trial. In the field K balance, 194% of the original soil K was recovered in the plants and remaining soil K. Again, as root K was not taken into account in the field K balance, 194% underestimates the K recovery. Smith *et al*. (2005) reported that sugarcane root dry mass was approximately 15% of the aerial dry matter at 200 days after planting, though this proportion declines with age. At even half of this figure (7.5%), more than 200% of original soil K would likely have been recovered in the field trial had root K been measured. The recovery values obtained from both pot and field trials further indicate that K which was not initially readily-available, had become available to the crop, and to a much greater extent than in the Oxisol. These data confirm the results reported in Chapter 5 and again may explain the relatively limited sugarcane yield responses to K application (Chapter 3).

The rate (as opposed to just the total amount) of K release was also evidently greater in the Inceptisol than that in the Oxisol. The pot trial (11.2 months) appeared to give sufficient time for the Inceptisol to release slowly-available K, while this was not the case on the Oxisol.

8.3.3. Long-term potassium supply

While it is evident that the K supply had not been exhausted by the end of the pot trial, the data indicate that the soils were nearing this point. Figure 8.1A, in particular, shows a flattening of the cumulative K uptake curve on the Oxisol, and, to a lesser degree, Figure 8.1B indicates a similar trend for the Inceptisol. Although ryegrass leaf K concentration naturally decreases with increasing maturity (McDonnell *et al.*, 2018), two facts indicate that K supply was becoming limited in the Oxisol, in particular, and possibly in the Inceptisol. Firstly, above-ground dry matter decreased by 17% (Oxisol) and 12% (Inceptisol) between the first half of the trial (mean of harvests two, three and four) and the second half (harvests five, six and seven). Harvested ryegrass yields were, therefore, not sustained to the same extent in the second half of the trial, though this may be partly explained by the season – Italian ryegrass thrives in winter, while the trial ended in mid-summer. Secondly, readily-available pre-trial K was 206 mg L^{-1} in the Oxisol and 149 mg L^{-1} in the Inceptisol; at the end of the pot trial, it was 37 and 61 mg L^{-1}, respectively (Table 8.4). Both soils, but particularly the Oxisol, therefore showed a marked reduction in readily-available K over the duration of the trial.

In considering the long-term K supplying power of the two soils, neither the field nor the pot trials ran for long enough to reach K exhaustion, but the percentage K removals in the trials give an indication of when this might theoretically occur. Approximately a third of the total potentially available (readily-available + nitric) K was taken up by the ryegrass on each soil (Section 8.3.1). If a new ryegrass crop were planted, as would typically be the case with annual (Italian) cultivars, and if it is assumed that similar K use would occur, it would take 869 days (2.4 years) for topsoil K to become completely exhausted in the Oxisol, and 1 017 days (2.8 years) in the Inceptisol. On both soils, however, the rate of nitric K release could prove a limiting factor in terms of K supply for crop growth.

In the pot trial, the Oxisol supplied sufficient K, in addition to other nutrients such as N, to sustain yields above those on the Inceptisol. On the other hand, K concentration in the Inceptisol ryegrass was much higher than that on the Oxisol (Figure 8.1), apparently made possible by faster K release from slowly-available pools in this soil. This may then lead to faster K exhaustion on the Inceptisol although it could be more than counterbalanced by the much greater total K present in this soil (Table 5.2).

It is perhaps instructive, in light of the evidence from both the field and pot trials, to consider apparent total K reserves to rooting depth for the ryegrass and sugarcane. In the pots, the soil depth available for the ryegrass roots to exploit provided approximately 395 kg K ha^{-1} in the Oxisol, and 810 kg K ha^{-1} in the Inceptisol (total of readily-available and nitric K). Ryegrass roots can reach depths of over 100 cm when stressed (Steynberg *et al*., 1994), but most are commonly found within 30-60 cm (Fessehazion *et al*., 2012). To a depth of 60 cm, 766 kg K ha^{-1} would be potentially available on the Oxisol, and 2 943 kg K ha^{-1} on the Inceptisol. This amount of K would, in theory, take about 5 years and 11 years, respectively, for the ryegrass to use to exhaustion on each soil. Such estimates are very strongly influenced by the nitric K value in both soils.

A similar calculation for the field trials using total potentially-available soil profile K and sugarcane K removal data results in times to reach K exhaustion of about 17 years on the Oxisol and 63 years on the Inceptisol. If only the readily-available K values are used then these times reduce to about 7 years on the Oxisol and 5 years on the Inceptisol. Practical experience renders all these potential exhaustion times purely theoretical as over such extended periods K would need to be added in order to ensure adequate yields. Significantly, by the ratoon crops in the present field trials, both soils showed indications of yield reduction in the zero-K control treatments.

A portion of the potentially available K (readily-available + nitric K) would not be accessible to the plant, at least within a practically significant timeframe. There are a number of possible reasons for this:

- Potassium depletion will likely continue until a certain soil-specific minimum K level is reached, after which only very small amounts of K will be released (Øgaard *et al*., 2002; Løes and Øgaard, 2003).

- The measurements of soil K, both readily-available and, especially, nitric K, may not be sufficiently sensitive to predict either its availability or accessibility to plants due to differences in the inorganic and organic fractions between soils, the ability of different plants to access the various K pools or incomplete exploitation of soil by the roots.
- If plants are unable to extract nitric K directly from its source, the replenishment of the readily-available pool from the slowly-available pool may be too slow to ensure adequate growth.

The calculations and discussion above indicate that the importance of nitric K is as an indicator of the relative size of the slowly-available K pool. In the Australian sugarcane industry, K recommendations are reduced by varying amounts (depending on soil texture) where nitric K exceeds 0.7 $cmol_c\ kg^{-1}$ (Calcino *et al.*, 2018). Interestingly, the Inceptisol topsoil had 0.7 $cmol_c\ kg^{-1}$ nitric K (Table 5.3), increasing into the subsoil. Its K release was markedly greater in both the pot and field trials than that in the Oxisol, with a topsoil nitric K of 0.22 $cmol_c\ kg^{-1}$, decreasing into the subsoil.

In South Africa, a minimum threshold value of 1.8 $cmol_c\ kg^{-1}$ is used, above which K fertiliser recommendations are reduced (Miles, 2016). As the nitric K value increases, K recommendations are reduced further. The various (conservative) thresholds were calculated by adding the standard error of estimation in the mid infra-red calibration (0.9) to the thresholds proposed by Haysom (1971). When the slowly-available K measure was introduced by the FAS in 2016, it was anticipated that as more data became available, this figure could be amended. Evidence from both the pot and the field trials in the present study suggest that these current FAS limits should be reconsidered, with there being an urgent need for further field trial work on a range of soil types in order to obtain more definitive criteria for the interpretation of the nitric K test.

8.4. Conclusions

A greater amount of K was removed by the ryegrass from the Inceptisol than from the Oxisol, despite higher original levels of readily-available K and, at most harvests, higher ryegrass dry matter on the Oxisol. Most of the original K in the Oxisol could be accounted for at the end of the pot trial. On the Inceptisol, however, an extra 122%, over the original readily-available K, was present in the combination of the ryegrass dry matter and the soil. Thus, a large amount of K was released from 'non-exchangeable' sources in the Inceptisol during the course of the pot trial. This finding supports the differences in amounts of total K and slowly-available (nitric) K (Chapter 5) between the two soils. Furthermore, the indication from the pot trial is that considerable amounts of this K could be released within a single growing season in the field.

The field trials showed that the application of K fertiliser would have resulted in a financial loss on both soils, as it was evident that both soils contained sufficient K to support at least three harvested sugarcane crops (though there was some evidence of yield decline in the zero-K treatments in the ratoons). The pot trial results support the field trial findings, indicating that, particularly in the Inceptisol, a significant amount of K was released from the soil and used by the crop.

Both soils, however, were able to release sufficient K to allow continuous growth of ryegrass without reaching K exhaustion, although there was evidence to indicate that K supply was becoming more limited. The reasons for this may be found in differences in both the mineral and possibly, organic, fractions of the two soils. It is possible that the more stable and base-depleted organic matter present in the Oxisol was associated with reduced availability of K, compared to the situation in the Inceptisol. Although the mineralogy of the two soils was similar, as both contained illite and K-feldspars which are able to supply slowly-available K, the latter were more abundant in the Inceptisol. The presence of small amounts of vermiculite in the Inceptisol may also have facilitated greater K release. The indication is, therefore, that a better understanding of, firstly, the properties of the organic material in the different soils and, secondly, their mineralogy, would further aid in predicting the potential extent of K release, and hence the formulation of K fertiliser recommendations and the prevention of K mining.

CHAPTER 9

A summary conceptual model, general discussion, conclusions and future work

9.1. Introduction

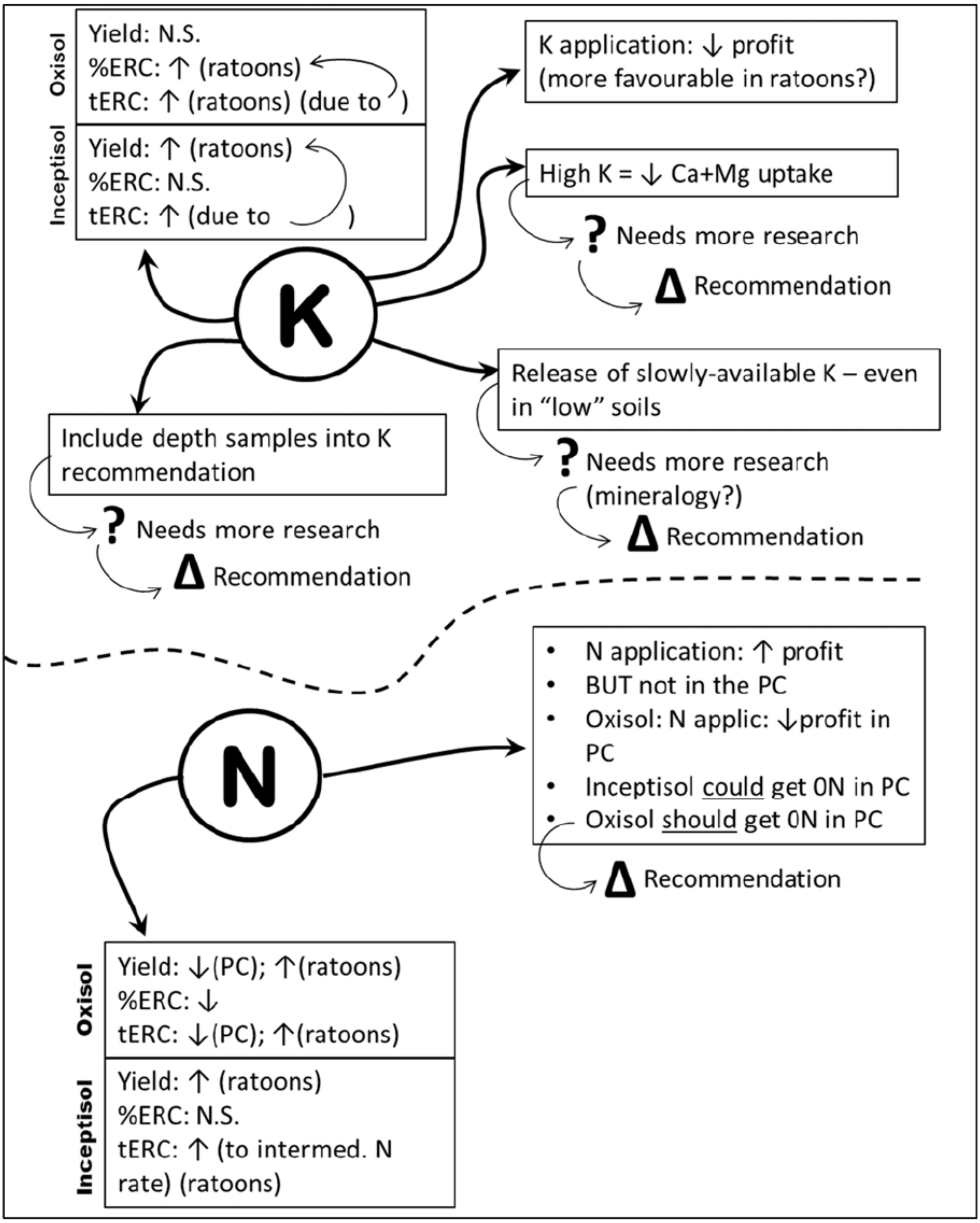
As outlined in Sections 1.3 and 2.6, this study was undertaken to assist in the improvement of potassium (K), nitrogen (N) and silicon (Si) recommendations given by the Fertiliser Advisory Service (FAS) at the South African Sugarcane Research Institute (SASRI). This work resulted from an identified need at SASRI for more research into K and Si in particular. To achieve this the project proposal structure included factorial K x N x Si field trials, established on two contrasting soils, an Oxisol and an Inceptisol, to examine the effects of these applied nutrients and their interactions on sugarcane yield parameters and soil, leaf and rooting characteristics. Pot trial(s) were envisaged in the proposal to allow investigation into factors identified in the field trials which might require further elucidation.

The conclusions in each chapter have highlighted a number of aspects which may be used to improve the recommendations given by the FAS. This chapter presents a summary conceptual model and outlines the major findings of both the field trials and the pot trial and suggests where further work is necessary to either support recommendations or to increase understanding of the processes involved.

9.2. Conceptual model: Effects of potassium, nitrogen and slag-based silicate fertiliser on sugarcane yield and quality

A conceptual model was developed to summarise the possible effects of K, N and Si (slag-based) fertilisers on sugarcane yield and quality (Figure 9.1A and B). It includes suggestions for possible changes to nutrient recommendations for the South African sugar industry (pending, in some cases, further study). The following sections discuss further the aspects outlined in the model.

A.


Oxisol
Yield: N.S.
%ERC: ↑ (ratoons)
tERC: ↑ (ratoons) (due to)
Inceptisol
Yield: ↑ (ratoons)
%ERC: N.S.
tERC: ↑ (due to)
K application: ↓ profit
(more favourable in ratoons?)
High K = ↓ Ca+Mg uptake
? Needs more research
Δ Recommendation
K
Release of slowly-available K – even in "low" soils
? Needs more research (mineralogy?)
Δ Recommendation
Include depth samples into K recommendation
? Needs more research
Δ Recommendation
N
N application: ↑ profit
BUT not in the PC
Oxisol: N applic: ↓profit in PC
Inceptisol could get 0N in PC
Oxisol should get 0N in PC
Δ Recommendation
Oxisol
Yield: ↓(PC); ↑(ratoons)
%ERC: ↓
tERC: ↓(PC); ↑(ratoons)
Inceptisol
Yield: ↑ (ratoons)
%ERC: N.S.
tERC: ↑ (to intermed. N rate) (ratoons)

B.

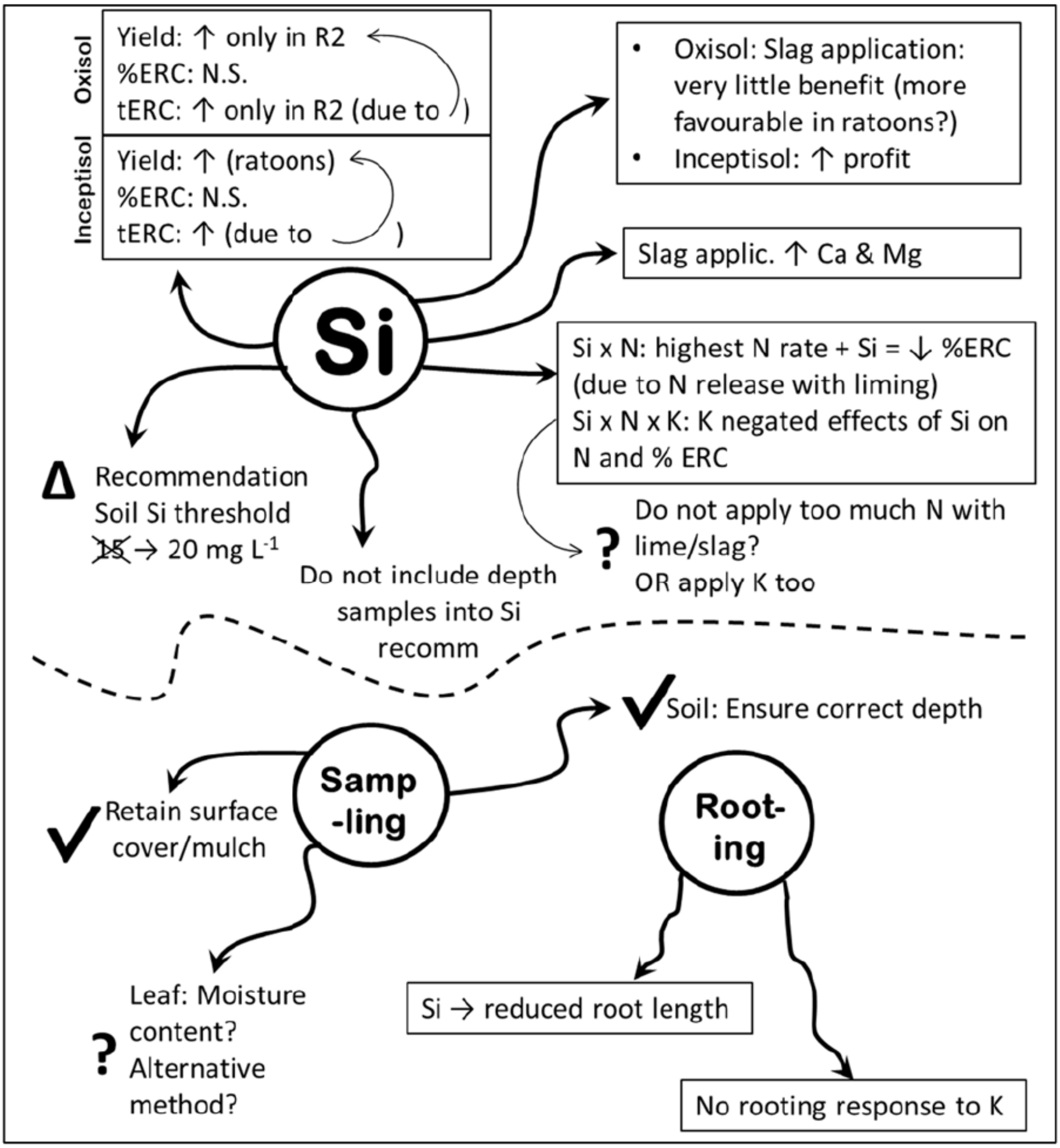


Figure 9.1: Conceptual model summarising possible effects of (A) potassium (K) and nitrogen (N), and (B) silicon (Si) (slag-based) fertilisers on sugarcane yield and quality, along with recommendations for soil sampling and management. Included are suggestions for possible changes to nutrient recommendations. %ERC = percent estimated recoverable crystal; t ERC = tonnes ERC; PC = plant crop; R2 = second ratoon crop; N.S. = non-significant differences; ↓= decrease; ↑= increase; Δ=change; ? = requires further research.

9.3. Nutrient recommendations

9.3.1. Potassium

In general, the K thresholds and recommendations currently used by the FAS appear appropriate for the Oxisol and Inceptisol under study. Sucrose yields were significantly increased by the application of 200 or 300 kg K ha^{-1} in three of the six harvests. Depending upon the amount of K initially present in each soil, the FAS recommendations would have been 250 kg K ha^{-1} for both soils' plant crops, and approximately 200 kg K ha^{-1} for the ratoons. Despite the sucrose yield increases in some crops, at current fertiliser and sucrose prices, an application rate of 200 kg K ha^{-1} was not economically justifiable over the first three crops at each site, but it is possible that the economics might have become more favourable in later ratoons, where response to K is usually more marked. This study also found that combining subsoil (20-60 cm) K data with those from the topsoil (0-20 cm) improved the relationship between soil K and crop yield.

Although K application led to a significant increase in sucrose yields in half of the harvests, the other three crops did not respond to K. This indicates that, at least in some seasons, soil K release was able to supply much of the crop's requirement. This K release was clearly seen in the field trial K balance analysis where, especially in the zero-K plots, large amounts of K were measured at the end of the crop cycle which were not accounted for by either fertiliser or original, readily-available soil K. The ryegrass pot trial showed a very similar effect, especially on the Inceptisol, supporting the field trial results.

In the K balance calculations from both the field and pot trials the Inceptisol showed greater K release than the Oxisol. Despite this, however, the nitric K reserves in both soils were low (< 1 $cmol_c\ kg^{-1}$). This may suggest that the K released was neither initially readily-available nor nitric extractable. This then focuses attention on the soil mineralogy as a major driver of K supply to the crop and points to the possibility of the nitric K test being relatively insensitive to the availability of the K reserves in some clay minerals and perhaps also from within primary minerals such as feldspars. In the context of routine soil testing, the characterisation of mineralogy in each grower sample is currently not an option. The findings in this study, however, indicate a need for a re-evaluation of the currently-used nitric K soil test thresholds at the FAS to ensure appropriate advice is given on crop K requirements.

9.3.2. Nitrogen

This study confirmed the depressive effects of excess N on sucrose percent and that plant crops respond less to N than ratoon crops. Plant crop yields, sucrose percent and total sucrose yield did not respond positively to applied N and, on the humic Oxisol, N application served to significantly decrease sucrose yield in the plant crop. Reduced N application rates, as are currently recommended by the FAS on humic soils and in plant crops, were therefore confirmed by this study. However, the evidence also suggested that plant crops grown on humic soils, and perhaps other soils with a high organic matter content, may not require any N fertiliser at all. The economic analysis conducted in this study confirmed that on the Oxisol, it would be financially detrimental to apply N in the plant crop. This finding is of importance, given that the FAS currently recommends N application in every plant crop, on all soil types.

Nitrogen recommendations for the Oxisol would have been 70 kg N ha^{-1} in the plant crop, and 110 kg N ha^{-1} in the ratoons; for the Inceptisol 115 kg N ha^{-1} in the plant crop, and 155 kg N ha^{-1} in the ratoons. Application of N at, in general, slightly lower levels than the FAS recommendations, proved economically beneficial, particularly on the Inceptisol. The exception to this was, as stated above, the plant crop on the Oxisol, where zero N would have resulted in the highest sucrose yields.

9.3.3. Silicon

The results suggest that the current soil Si threshold of 15 mg L^{-1} is too low to promote optimal yield. It is recommended that the FAS increase this threshold to an interim value of 20 mg L^{-1} (pending confirmation), particularly in light of the fact that results from this study (and others) indicate poor uptake of Si by sugarcane. In contrast to K, inclusion of subsoil Si when calculating nutrient recommendations was not beneficial.

Application of Calmasil® at the rates used in this trial were uneconomic over the three crops measured. Over a longer term, however, continued soil acidification and depletion of Si reserves would ultimately necessitate applications of these liming sources to allow the continued production of sugarcane.

The finding that high soil K may limit calcium (Ca) and magnesium (Mg) uptake by the plant is of considerable significance to the South African sugar industry and has implications for lime recommendations. Although this cationic antagonism is not directly related to Si application, when soil Si is below the threshold, it is recommended at present that a calcium silicate slag (such as Calmasil®) be used in place of the dolomitic lime requirement of the soil, as it similarly provides Ca and Mg (as well as Si) and raises soil pH. Currently, high soil exchangeable Ca and Mg lead to increased FAS K recommendations. Based on the outcomes of this study, it is necessary to consider the reverse situation and to increase Ca and Mg (and hence lime or Calmasil®) recommendations in soils with high available K.

Sugarcane grown on the Oxisol responded poorly to applied Si; on the Inceptisol, however, application of 300 kg Si ha^{-1} led to significantly higher sucrose yields. This increase was a result of significantly greater stalk yields, rather than an increase in sucrose percent.

9.3.4. Nutrient interactions

There were generally few consistent interactions between the three main nutrients applied, though a few notable exceptions were found.

9.3.4.1. Nitrogen and silicon

On the second ratoon crop on the Oxisol, increasing N had no effect on sucrose percent, when zero Si was applied. Where Si was applied, however, increasing N caused a significant decrease in sucrose percent. This interaction was most likely an effect of the Si-containing liming material, leading to increased soil N release, rather than the Si itself.

Nitrogen application led to a significant increase in soil profile Si following each ratoon crop harvest on the Oxisol. This may have been linked to reduced crop removal of Si on these treatments.

9.3.4.2. Potassium and silicon

Potassium application significantly decreased topsoil Si in the Inceptisol at times, possibly due to increased plant uptake following higher yields in the higher K treatments on this soil.

Silicon application increased soil profile K only once, on the Inceptisol. The effects of silicate application on K were non-significant at all other times.

9.3.4.3. Nitrogen, silicon and potassium

There was a significant interaction between the effect of K, N and Si on sucrose percent in the combined ratoon crops on the Oxisol. Under certain conditions, the deleterious effect of high N rates on sucrose percent (exacerbated by high Si/lime rates) were mitigated by the application of sufficient K.

9.3.5. Sampling and crop nutrition

There was poor correlation between leaf nutrient levels and crop yields such that low leaf nutrient concentrations did not necessarily correspond with reduced sugarcane or sucrose yields. Moisture stress during the field trials probably led to this disparity, with insufficient moisture having been shown to render leaf sample results unreliable in terms of predicting sugarcane yields.

This study showed that the soil sampling depth recommended by the FAS should be strictly adhered to. Collection of samples at a shallower or deeper depth than that calibrated for in the laboratory will lead to incorrect recommendations, resulting in too little or too much of each nutrient being applied. Of the three nutrients studied, K and Si recommendations were affected to a greater extent by sampling depth than N. The stratification of nutrients, with higher concentrations of K (in particular) and Si in the upper few centimetres of soil, underlines the importance of encouraging surface rooting (along with the deep rooting system required), in order to take advantage of this nutrient-rich layer.

9.3.6. Rooting

The concern within the South African sugar industry about shallow rooting did not apply to the two trial soils, where the root distribution appeared normal. Unexpectedly, K application did not affect root length, indicating that roots may have obtained some K from deeper in the soil profile and perhaps from less readily-available K pools, to maintain root growth in the zero-K treatment. Silicate application decreased total root length to a depth of 60 cm. In addition, root length in the Oxisol was less than in the Inceptisol. Texture and water stress may be implicated in both responses, with the effect of increasing total root length where water was limited, or where plants experienced water stress for other reasons.

9.4. Future work

9.4.1. Potassium

To improve the K recommendations currently made by the FAS, the current study has highlighted the following two main areas that warrant consideration.

9.4.1.1. Subsoil

At present, the FAS uses only topsoil K results to formulate recommendations. Inclusion of subsoil K data improved the strength of the correlation between readily-available soil K and crop yield. Further trial work is necessary to refine this relationship and to determine optimal recommendations for different soil types.

Stratification of K (particularly in clay soils), along with utilisation of subsoil K by roots, may lead to high concentrations of K in the upper soil layers, and a corresponding lack of K at depth. If stunted, shallow rooting continues to be seen as a problem within the South African sugar industry, it may be necessary to increase subsoil K concentrations. Although incorporation of K to depth may pose practical difficulties, the downward movement of K following gypsum application may assist in this regard. Further investigation could elucidate a possible K requirement factor (KRF) for subsoils, based on mineralogy, clay percent or other soil characteristics, which could indicate the amount of K fertiliser required to raise the subsoil K test by one unit.

9.4.1.2. *Non-exchangeable potassium release*

Both the field and pot trials indicated that a substantial amount of K was released from non-exchangeable pools within a single growing season, even though the soils were classified as having ‘low’ K-supplying capability. These results and those from other work at SASRI (Miles and Farina, 2014; and work leading to the publication of Elephant *et al*., 2018) resulted in ‘reserve K’ (determined by mid infra-red spectrometry (MIR)) being included in 2016 in the routine FAS suite of analyses. The MIR reserve K is a direct measure of nitric K and, at present, a value greater than 1.8 $cmol_c\ L^{-1}$ results in a reduction in the recommended K fertiliser rate, with higher reserve K values leading to further reductions. Inclusion of MIR reserve K has thus improved the value and accuracy of the FAS K recommendations by taking this release into account.

Further work should continue to include not only the nitric K test (or a proxy for it such as using infra-red technology), but also incubation tests and pot trials to investigate the amount of K released by soils within each range of nitric K results, as well as KRFs. Clay mineralogy has been shown in this study and others to have a marked effect on soil K reserves and KRFs (Elephant and Miles, 2016), and an indication of mineralogy, and its routine measurement, would further aid in prediction of the potential extent of K release, and hence the formulation of K fertiliser recommendations.

Findings reported in this study point to a definite need for the nitric K thresholds currently used by the FAS to be re-evaluated, and also that more accurate KRFs be established. Such work is likely to lead to K fertiliser recommendations being substantially reduced on some soil types, leading to cost savings without sacrificing yield. It should always be kept in mind, however, that longer-term vision is required to ensure sustainability, such that K reserves are not exhausted. Continued depletion of soil K reserves is unsustainable in the long term (Kingston, 2000) and it is not possible to continue “mining‟ soil K without eventually decreasing crop production (Askegaard *et al*., 2004).

The results of the present study suggest that the occurrence of vermiculite in the Inceptisol facilitated greater release of slowly-available K than that from the Oxisol, even though the latter soil contained more organic matter, which is also a source of K (Al-Kanani *et al*., 1984). Metson *et al*. (1956, cited in Haysom, 1971) concluded that K released during boiling with nitric acid is released from primary minerals, especially from the more inaccessible surfaces of hydrous mica, while Al-Kanani *et al*. (1984) indicated chlorite and vermiculite. Further research is warranted into the reasons for this release and the factors that control it.

9.4.2. Nitrogen

Results from this study indicated that N recommendations for plant crops grown on humic soils could be reduced to zero without negatively affecting yield. In many cases, a zero-N recommendation may even increase plant crop yields on these soils, where N application may sometimes significantly reduce yield due to, it appears, high N release from the soil. The applicability of this recommendation should be investigated to determine whether it should be a general recommendation for humic soils and possibly others with a high organic matter content. The reason for the depressed plant crop cane yield is also a topic of interest for future research.

9.4.3. Silicon

9.4.3.1. Silicon uptake

Silicon uptake from Calmasil® and cement was poor. This is in line with the findings of other sugarcane researchers, and this aspect should continue to form part of future work, given the importance of Si in promoting crop protection, health and yield.

Researchers have suggested that poor plant uptake of applied Si on weathered (desilicated) soils might be linked to elevated soil acidity and available aluminium (Tavakkoli *et al*., 2011b). The yield response to Si on the Inceptisol may have been linked to slightly improved Si uptake by the plant facilitated by lower acid saturation in the Inceptisol than the Oxisol. In research by Keeping (2017), Calmasil® application led to the highest plant Si uptake of the six Si carriers tested, apparently due to its alkaline nature. Application of lime prior to Si application did not, however, improve Si uptake (Keeping *et al*., 2017). The quest for effective and affordable methods of increasing sugarcane uptake of Si continues, though research suggests that the currently used Si carrier (Calmasil®) is the best one available at present (Keeping, 2017; Keeping *et al*., 2017).

9.4.3.2. Silicon thresholds

Increased soil Si was generally associated with increased stalk (and hence sucrose) yield. However, the current local recommended threshold of 15 mg L^{-1} soil Si was too low for both soil types. A more appropriate threshold would appear to be closer to 20 mg Si L^{-1}, but this would need to be confirmed in further trial work.

Poor plant uptake of Si meant that leaf Si seldom reached even marginal levels. It is noteworthy, however, that the greatest percentage increases in sucrose yield were obtained with the greatest percentage increases in leaf Si concentration. On the Oxisol, where measured leaf Si never exceeded 0.58%, a significant stalk yield increase was obtained only in the second ratoon crop, where both the greatest absolute leaf Si increase, and the highest leaf Si percentage, were obtained (Section 4.3.3.1). The use of a single 'ideal' leaf Si threshold across the whole industry may be unrealistic, given the poor uptake of Si in the rainfed areas of the industry. Future research into the adoption of different leaf Si thresholds in different areas may be warranted. Under conditions where plant uptake is low, Si application should be encouraged, regardless of whether a (possibly unrealistic) minimum threshold can be obtained.

9.4.3.3. Cationic antagonism

The very marked reduction in Ca and Mg uptake by the plant under conditions of high soil K has not been widely reported in sugarcane. These antagonistic effects raise the possibility of Ca and Mg deficiencies being induced under conditions of excess soil K supply. It is suggested that Ca and Mg recommendations be amended so that, when soil K is above a certain threshold, Ca and Mg (and hence lime or Calmasil®) application rates be increased in order to overcome this antagonism. Future work should establish a robust threshold value/values which apply to different sugarcane varieties and soil types.

9.4.4. Nutrient interactions

Two of the nutrient interactions warrant further investigation. In one ratoon crop on the Oxisol, Si application led to increased N release and therefore decreased sucrose percent. Although it is likely that this was a liming effect rather than an effect of Si itself, Calmasil® - a liming agent – is currently the most affordable and effective means of Si application for South African sugarcane farmers. This interaction may have relevance for eldana (*Eldana saccharina*) control. Damage inflicted by this stalk borer is reported to increase with increasing N application, and Si application is recommended as a means to reduce eldana numbers without reducing N (Keeping *et al*., 2014). If sucrose percent is lowered by this practice, however, grower revenue may be negatively affected. Future investigations into N x Si interactions on eldana damage should therefore include measures of crop yield and sucrose percent.

Related to the above interaction is the finding that, in the ratoon crops on the Oxisol, K negated the decrease in sucrose percent with concurrent Si and N application. This effect has bearing on the eldana question as a possible means of reducing any negative effects of Si application on sucrose content, and warrants further research.

9.4.5. General

9.4.5.1. Inclusion of subsoil data into nutrient recommendations

It is evident from the current data that inclusion of subsoil nutrient concentrations would improve soil : yield relationships for some, but not all, nutrients. Further elucidation of this point is required to establish appropriate soil profile (0-60 cm) threshold values for each nutrient for which subsoil data are considered useful.

9.4.5.2. Leaf sampling

It was not possible from the results obtained in the present study to state, definitively, that a certain leaf nutrient level was high enough to support optimal yield. Future work should determine the extent to which moisture stress can affect the analytical results of leaf samples sent to the FAS, and possibly whether a different approach should be followed for leaf sampling. Miles (2010) suggested improvements to the procedure and techniques to strengthen the overall efficacy of leaf sampling, and so improve the establishment of nutrient sufficiency values of the crop. In particular, a modeling approach, taking into account decreases in the leaf N threshold with increasing biomass, was recommended (Miles, 2010). Studies are currently underway at SASRI to investigate such improvements.

9.4.5.3. Rooting

The effect of Si application on the decrease in root length that was significant in the Inceptisol requires further investigation, given the widespread use of Si products in the South African sugarcane industry and the general impression of poor rooting. In addition, understanding the lack of a rooting response to K application and the origin of the K used by the crop is necessary. Further work should ascertain whether these results are widespread and frequent occurrences or a feature of the specific conditions at the trial sites.

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APPENDICES

CHAPTER 3

Appendix 3.1: Laboratory methods used for soil analysis at the South African Sugarcane Research Institute's Fertiliser Advisory Service

Determination	Method	Reference
Clay	Hydrometer	Day (1965)
Organic carbon	Modified Walkley-Black	Walkley and Black (1934)
pH	1:2.5 v/v soil:0.01*M* $CaCl_2$	Peech (1965)
$^{\alpha}$Available phosphorus	Truog	Truog (1930)
$^{€}$Available phosphorus	Anion Exchange Resin	Nuernberg *et al*. (1998)
Exchangeable potassium, calcium and magnesium	Multi-extractant Ambic-2; ICP-OES$^{\Psi}$	Van der Merwe *et al*. (1984)
Silicon (0.01 *M* $CaCl_2$-exchangeable)	Colorimetric	Miles *et al*. (2014)
Exchangeable acidity (Al+H)	10 min extraction with 1M KCl followed by titration with 0.1M NaOH	Farina and Channon (1991)

$^{\alpha}$Truog method used during and after the plant and immediately following the first ratoon crops (Oxisol); the plant crop (Inceptisol); and the pot trial (Chapter 8)

$^{€}$Anion Exchange Resin used during and after the second ratoon crop (Oxisol) and first and second ratoon crops (Inceptisol).

$^{\Psi}$Inductively coupled plasma optical emission spectrometry (Varian 720ES)

Appendix 3.2: Application dates and nutrients applied following the plant crop and first ratoon crop harvests at the Oxisol and Inceptisol trial sites. Nutrient rates for all crops are provided in the text (Section 3.2.3)

Soil	Applied following	Nutrient applied	Application date	Time elapsed since harvest	Application method
Oxisol	Plant crop harvest	N K	11 Feb 2011	2.5 months	Broadcast
	First ratoon harvest	K P	26 Jun 2012	1 month	Broadcast
		Si (cement)	29 Aug 2012	3 months	Broadcast, raked in
		N	26 Sep 2012	[1]4 months	Broadcast
Inceptisol	Plant crop harvest	N K	6 Oct 2011	2 months	Broadcast
	First ratoon harvest	Si (cement)	13 Dec 2012	2 months	Broadcast, raked in
		N K	22 Dec 2012	2.5 months	Broadcast

[1]N applied late to avoid period of poor N uptake in winter.

Appendix 3.3: Harvest date and sugarcane age at harvest for the plant, first and second ratoon crops at the Oxisol and Inceptisol trial sites

Soil	Plant crop	First ratoon	Second ratoon
	-------------------- Age at harvest; harvest dates		--------------------
Oxisol	12 months; 29 Nov – 2 Dec 2010	18 months; 21-25 May 2012	15 months; 2-4 Sep 2013
Inceptisol	20 months; 1-3 Aug 2011	14 months; 1-4 Oct 2012	19 months; 29-30 April 2014

CHAPTER 4

Appendix 4.1: Effect of applied potassium (K) on mean (n=24) third-leaf K, at 4- and 6-months' crop age, on the Oxisol and the Inceptisol

K applied (kg ha^{-1})	**K** (%) Oxisol		Inceptisol	
	[a]PC - 4 months	***PC - 6 months***	***PC - 4 months***	***PC - 6 months***
0	1.611 ± 0.024 a[Ŧ]	1.332 ± 0.026 a	1.109 ± 0.021 a	nd[#]
100	1.667 ± 0.032 a	1.414 ± 0.023 b	1.270 ± 0.023 b	nd
200	1.748 ± 0.024 b	1.427 ± 0.022 b	1.356 ± 0.019 c	
300	1.753 ± 0.022 b	1.464 ± 0.025 b	1.397 ± 0.025 c	nd
Sig.	**P < 0.001**	**P < 0.001**	**P < 0.001**	nd
	[b]R1 - 4 months	***R1 - 6 months***	***R1 - 4 months***	***R1 - 6 months***
0	0.994 ± 0.016 a	1.046 ± 0.013 a	1.014 ± 0.016 a	1.304 ± 0.017 a
100	1.078 ± 0.016 b	1.147 ± 0.012 b	1.142 ± 0.018 b	1.358 ± 0.012 b
200	1.089 ± 0.014 b	1.199 ± 0.011 c	1.207 ± 0.011 c	1.375 ± 0.015 b
300	1.109 ± 0.016 b	1.225 ± 0.012 c	1.263 ± 0.014 d	1.397 ± 0.011 b
Sig.	**P < 0.001**	**P < 0.001**	**P < 0.001**	**P < 0.001**
	[c]R2 - 4 months	***R2 - 6 months***	***R2 - 4 months***	***R2 - 6 months***
0	1.012 ± 0.024 a	1.198 ± 0.027 a	1.083 ± 0.122 a	1.181 ± 0.010 a
100	1.255 ± 0.021 b	1.454 ± 0.025 b	1.307 ± 0.044 b	1.361 ± 0.010 b
200	1.340 ± 0.023 c	1.589 ± 0.025 c	1.397 ± 0.081 c	1.422 ± 0.013 c
300	1.395 ± 0.026 c	1.625 ± 0.033 c	1.459 ± 0.141 c	1.454 ± 0.015 d
Sig.	**P < 0.001**	**P < 0.001**	**P < 0.001**	**P < 0.001**

[a]PC = Plant crop; [b]R1 = First Ratoon crop; [c]R2 = Second Ratoon crop.

[#]nd = not determined.

[Ŧ]Within sampling events, values with different letters are significantly different to each other.

Appendix 4.2: Effect of applied nitrogen (N) on mean (n=32) third-leaf N, at 4- and 6-months' crop age, on the Oxisol and the Inceptisol

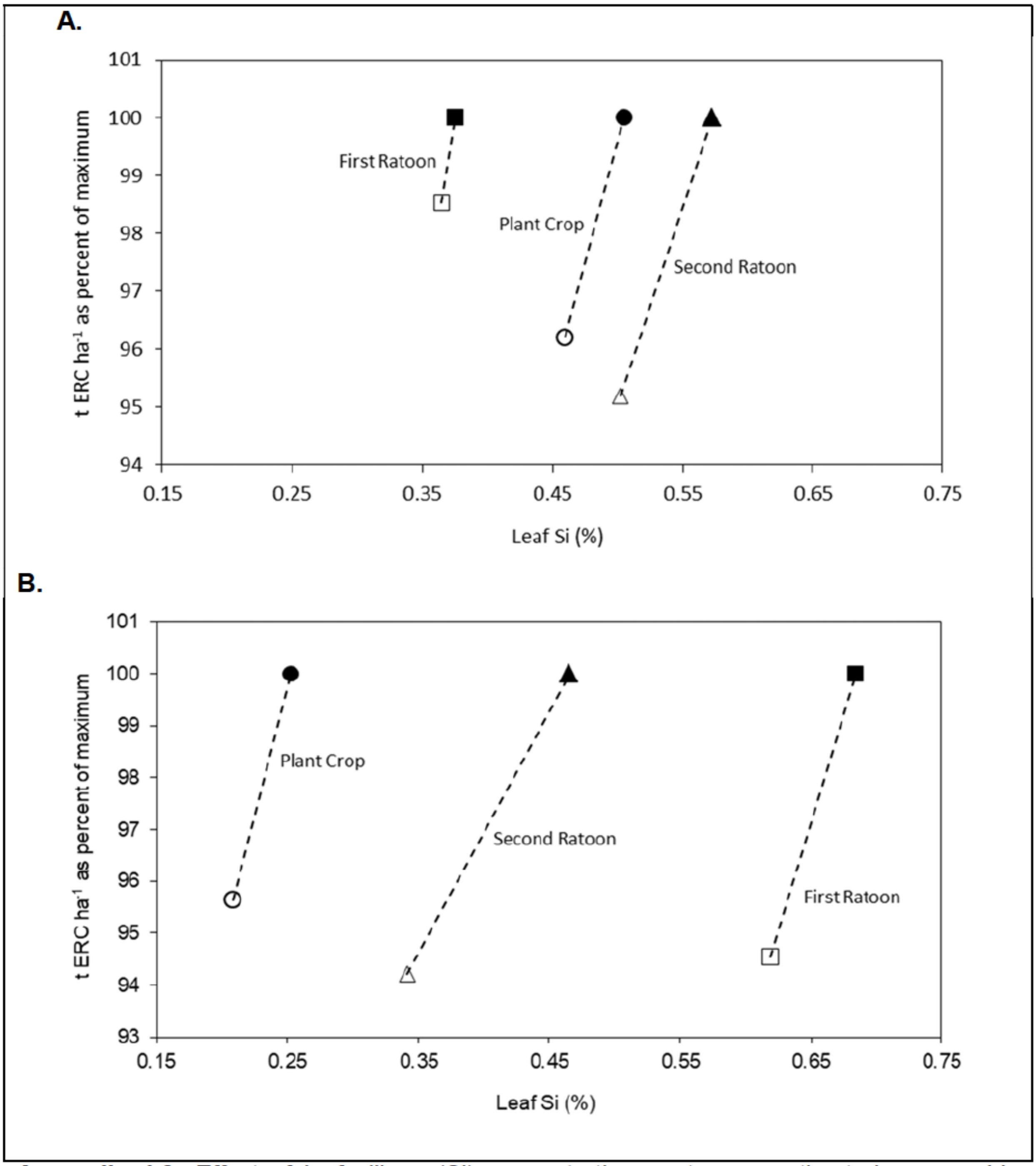
N applied (kg ha^{-1})	**N** (%)			
	Oxisol		**Inceptisol**	
	[a]***PC - 4 months***	***PC - 6 months***	***PC - 4 months***	***PC - 6 months***
0	1.743 ± 0.015 a[ǂ]	1.435 ± 0.016 a	2.031 ± 0.026 a	nd[#]
[ϕ]80/[Ψ]105	1.891 ± 0.018 b	1.572 ± 0.020 b	2.137 ± 0.024 b	nd
[ϕ]160/[Ψ]210	1.881 ± 0.019 b	1.622 ± 0.020 b	2.169 ± 0.018 b	nd
Significance	**P<0.001**	**P<0.001**	**P<0.001**	nd
	[b]***R1 - 4 months***	***R1 - 6 months***	***R1 - 4 months***	***R1 - 6 months***
0	1.148 ± 0.017 a	1.480 ± 0.012 a	1.364 ± 0.033 a	1.262 ± 0.018 a
80/105	1.234 ± 0.018 b	1.561 ± 0.013 b	1.729 ± 0.039 b	1.372 ± 0.022 b
160/210	1.262 ± 0.022 b	1.583 ± 0.010 b	1.845 ± 0.032 b	1.470 ± 0.025 c
Significance	**P<0.001**	**P<0.001**	**P<0.001**	**P<0.001**
	[c]***R2 - 4 months***	***R2 - 6 months***	***R2 - 4 months***	***R2 - 6 months***
0	2.112 ± 0.018 a	2.081 ± 0.023 a	1.854 ± 0.018 a	1.516 ± 0.013 a
80/105	2.234 ± 0.032 b	2.224 ± 0.019 b	2.141 ± 0.025 b	1.675 ± 0.015 b
160/210	2.213 ± 0.015 b	2.243 ± 0.015 b	2.269 ± 0.022 c	1.759 ± 0.014 c
Significance	**P<0.001**	**P<0.001**	**P<0.001**	**P<0.001**

[a]PC = Plant crop; [b]R1 = First Ratoon crop; [c]R2 = Second Ratoon crop.

[ϕ]= rate applied on the Oxisol; [Ψ]= rate applied on the Inceptisol

[#]nd = not determined.

[ǂ]Within sampling events, values with different letters are significantly different to each other.



Appendix 4.3: Effect of leaf silicon (Si) concentration on tonnes estimated recoverable crystal (t ERC ha^{-1}), as a percent of the maximum for each harvest on the (A) Oxisol and (B) Inceptisol. Leaf samples were collected at 4 months' crop age. Within soil types and crops, each point represents the mean (n=48), across all replicates, at each of the two Si application rates (0 kg Si ha^{-1}: clear symbol; 300 kg Si ha^{-1}: black symbol).

CHAPTER 5

Appendix 5.1: Effect of nitrogen application on topsoil (0-20 cm) properties

Although applied N tended to have little effect on either soil, some evidence, and effects, of soil acidification could be found at both trial sites, examples of which are given in Table A5.1. Topsoil pH was significantly decreased by N application at one of the three sampling events on the Oxisol, and two on the Inceptisol. Exchangeable acidity was increased at one sampling event at each site, while acid saturation was increased at one event on the Oxisol. Increases in available Fe (at one sampling event on the Oxisol) and Mn (at one sampling event at each trial site) may be linked to the acidification of these soils by the addition of N.

Table A5.1: Oxisol: Effects of applied nitrogen (N) on mean (n=32) selected topsoil (0-20 cm) properties in the second ratoon crop six weeks after application of fertiliser. Only significant effects are shown

N applied	**Fe**	**Mn**	**pH ($CaCl_2$)**	**Exchangeable acidity**	**Acid saturation**
(kg ha^{-1})	------- (mg L^{-1}) -------			(cmol$_c$ L^{-1})	(%)
0	247.9 a[ŧ]	2.4 a	4.53 a	1.82 a	16.45 a
80	259.2 ab	2.5 a	4.49 a	2.11 ab	19.09 ab
160	273.3 b	2.8 b	4.41 b	2.35 b	21.18 b
Significance	**P<0.05**	**P<0.001**	**P<0.001**	**P<0.001**	**P=0.01**

[ŧ] Within columns, values with different letters are significantly different to each other.

Appendix 5.2: Effect of nitrogen application on mean soil profile characteristics following harvest

Samples were collected and analysed for nitrate-N following the harvest of each crop. Nitrogen application significantly increased soil profile nitrate-N each time it was measured, at both trial sites, even 12-20 months after application. An example of this increase is shown in Figure A5.1. Post-harvest soil profile ammonium levels were not affected by the N rate applied at the start of each crop (results not shown).

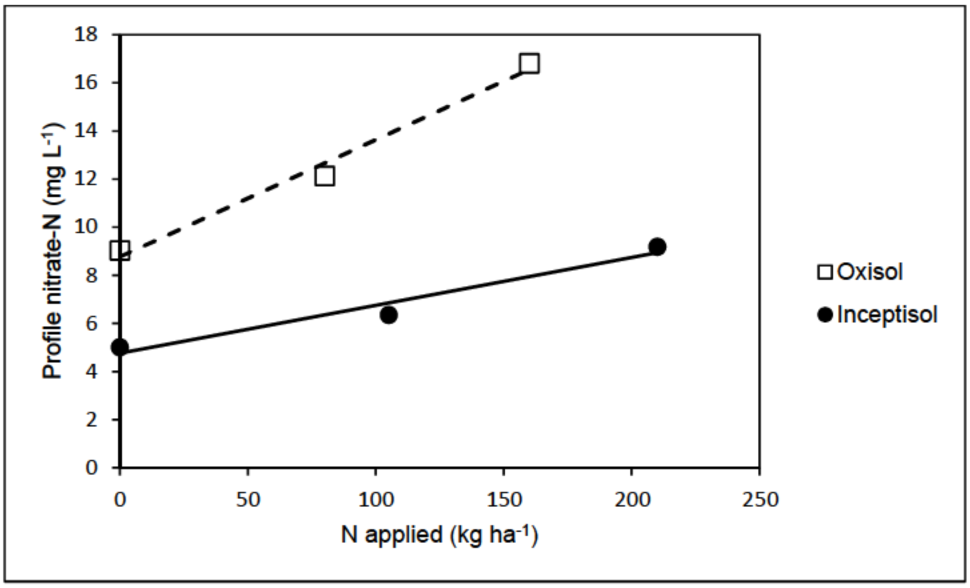


Figure A5.1: Effect of nitrogen (N) application on mean (n=24) soil profile (Oxisol 0-100 cm; Inceptisol 0-80 cm) nitrate-N, following the plant crop harvests.

Soil profile pH was significantly reduced after two crops on the Oxisol, a finding similar to that in the topsoil samples alone (Table A5.1). Nitrogen application did not, however, affect soil profile pH on the Inceptisol, in contrast with its effect on topsoil pH (Appendix 5.1).

Application of N led to a significant increase in soil profile Si following each harvest of the ratoon crops on the Oxisol (Table A5.2). This may be linked to crop removal since application of N led to a reduction in plant Si at all six leaf sampling events on the Oxisol (Section 4.3.2.2). Reduced Si uptake by the crop would result in greater amounts of Si remaining in the soil. On the Inceptisol there were no significant differences between soil Si concentrations across the N rates on this soil.

Table A5.2: Oxisol: Effect of applied nitrogen (N) application on mean ± standard error (n=32) soil profile (0-100 cm) silicon (Si) following ratoon crop harvests

N application rate (kg ha^{-1})	**First ratoon crop**	**Second ratoon crop**
0	16.7 ± 0.4 a	11.0 ± 0.4 a
80	17.3 ± 0.5 ab	11.3 ± 0.4 ab
160	17.7 ± 0.4 b	11.6 ± 0.4 b
Sig.	**P<0.01**	**P<0.05**

Ŧ Within columns, values with different letters are significantly different to each other.

Nitrogen application did not have consistent effects on any of the other soil properties measured at either trial site.

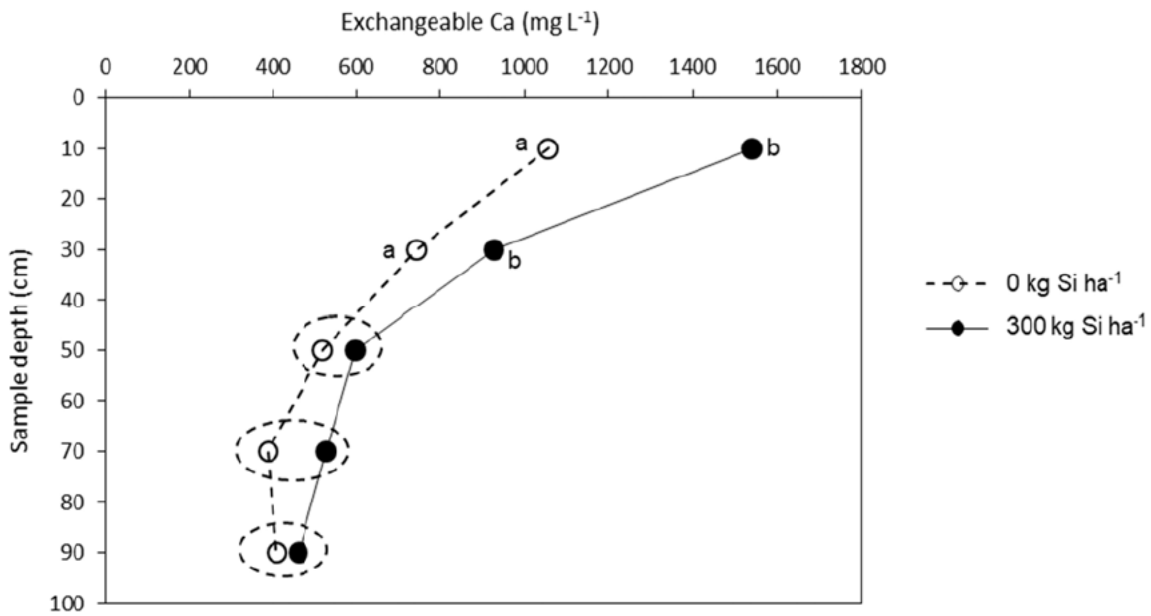
Appendix 5.3: Nitrogen movement down the profile

Ammonium and nitrate showed no consistent pattern down the soil profile, following crop harvests. The Oxisol tended to have higher nitrate-N levels, with an average of 9.5 mg L^{-1} over all N rates at 0-80 cm (9.3 mg L^{-1} over 0-100 cm) following the three crops, compared to 4.9 mg L^{-1} on the Inceptisol (0-80 cm). On both soils, profile nitrate-N concentrations were higher following the plant crop than the ratoons. Mean ammonium following the crops was similar in the two soils, at 7.9 mg L^{-1} (Oxisol) and 7.7 mg L^{-1} (Inceptisol) (0-80 cm).

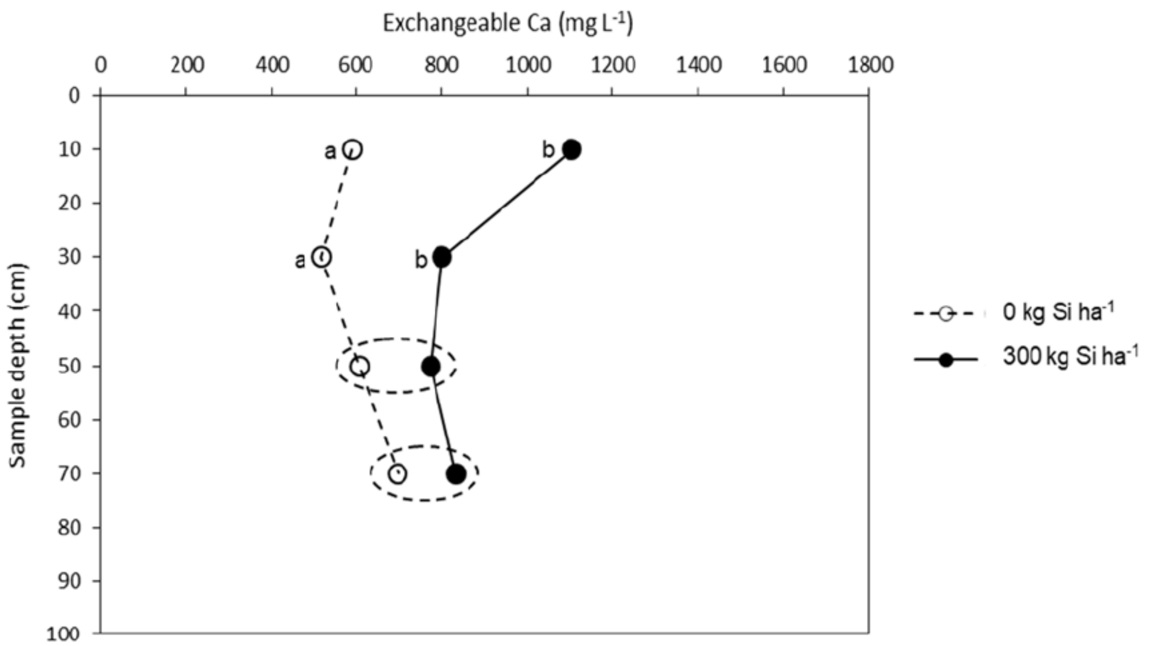
Appendix 5.4: Nitrogen: Conclusions

As expected, N application was associated with a significant decrease in topsoil pH, along with increased acid saturation, exchangeable acidity, Fe and Mn and, in some instances, non-significant increases in Cu and Zn. Within the whole soil profile, N application significantly increased soil nitrate-N at all sampling times where mineral N was measured, at each trial site, with concentrations remaining elevated 12-20 months after N application. This effect was not evident for soil ammonium. Nitrogen application led to a significant increase in soil profile Si following each ratoon crop harvest on the Oxisol. This effect may have been linked to reduced crop removal of Si on these treatments.

A.

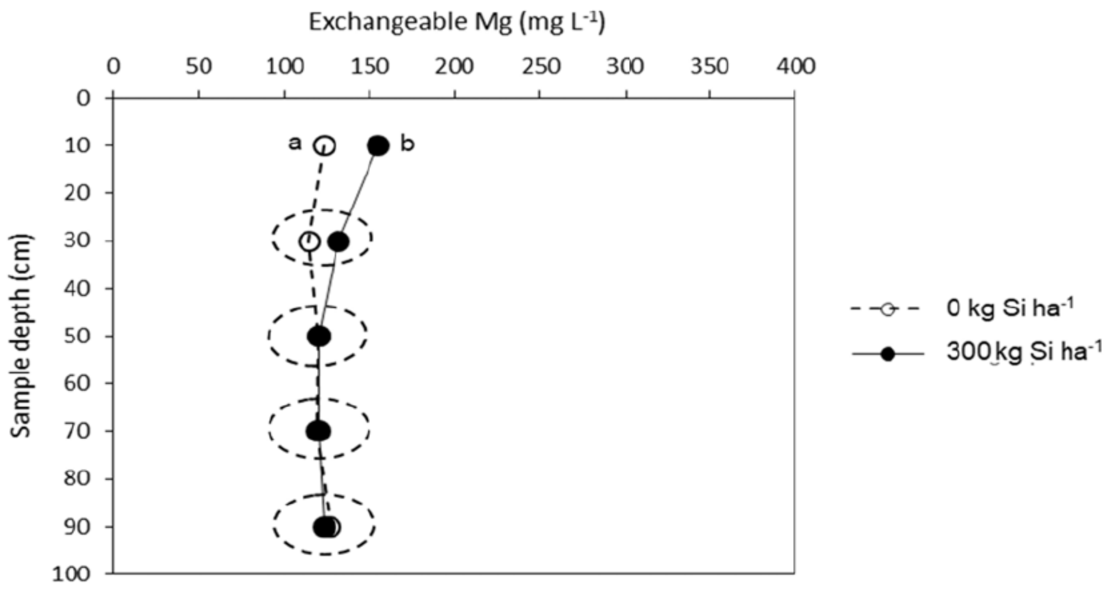


B.

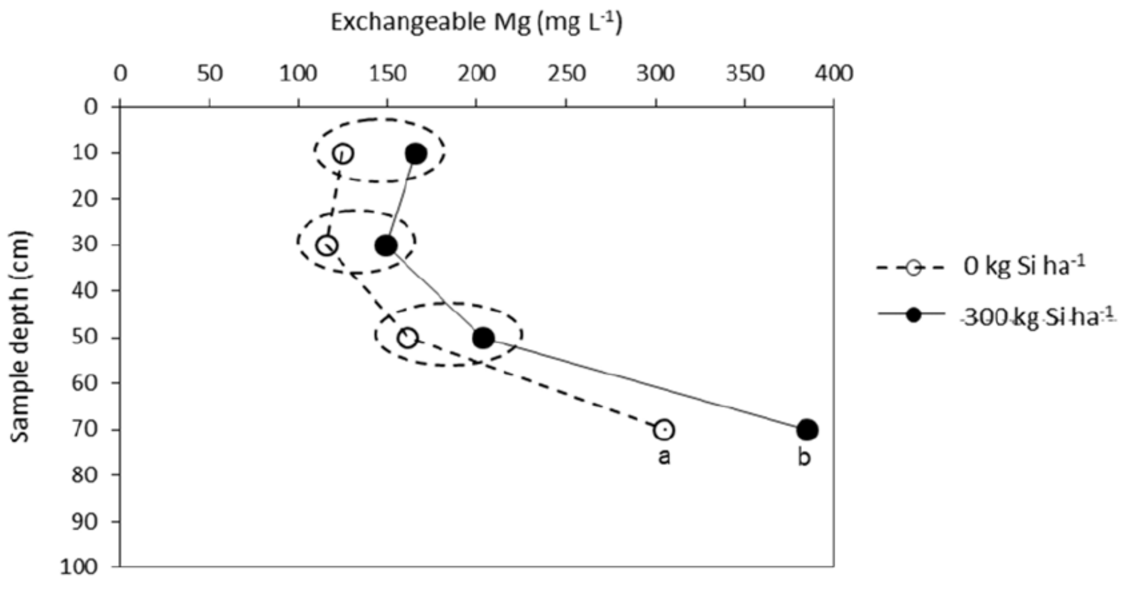


Appendix 5.5: Mean exchangeable calcium (Ca) per soil depth interval following the second ratoon crop in the (A) Oxisol (n=48, 0-20 cm; n=36, >20 cm at both Si rates) and (B) (Inceptisol (n=30, 0 kg Si ha^{-1}; n=32, 300 kg Si ha^{-1} at all depths). Within each depth interval, points with different letters are significantly different to each other (P<0.01). Where no significant difference occurred between points within a depth interval, the points are circled.

A.



B.



Appendix 5.6: Mean exchangeable magnesium (Mg) per soil depth interval following the second ratoon crop on the (A) Oxisol (n=48, 0-20 cm; n=36, >20cm at both Si rates) and (B) Inceptisol (n=30, 0 kg Si ha^{-1}; n=32, 300 kg Si ha^{-1} at all depths). Within each trial site and depth interval, points with different letters are significantly different to each other (P < 0.01). Where no significant difference occurred between points within a depth interval, the points are circled.

CHAPTER 6

Appendix 6.1: Selected soil characteristics in the silicate treatments (Calmasil® (3 t ha^{-1}) and cement (6 t ha^{-1}), each equivalent to 300 kg Si ha^{-1}) at each soil depth interval

OXISOL						
	Calcium --- (mg L^{-1}) ---		**Magnesium** --- (mg L^{-1}) ---		**Total Cations** --- (cmol$_c$ L^{-1}) ---	
Depth (cm)	---------------- **Si applied** (kg ha^{-1}) ----------------					
	0	300	0	300	0	300
0-2.5	1101 a	2 237 d	169 abc	204 c	10.04 ab	14.20 d
2.5-7.5	1 445 bc	2 096 d	175 bc	207 c	11.30 bc	13.52 d
7.5-15	1 312 ab	1 676 bc	146 ab	188 bc	10.20 ab	11.62 c
15-28	1 039 a	1 332 ab	131 a	174 bc	9.61 a	10.47 abc
Significance	**P<0.001**		**P<0.001**		**P<0.001**	
	pH --- ($CaCl_2$) ---		**Exch. Acidity** --- (cmol$_c$ L^{-1}) ---		**Acid Sat.** --- (%) ---	
Depth (cm)	---------------- **Si applied** (kg ha^{-1}) ----------------					
	0	300	0	300	0	300
0-2.5	4.43 ab	5.13 e	2.04 bc	0.22 a	20.61 d	1.61 a
2.5-7.5	4.53 bc	4.93 d	1.82 bc	0.41 a	16.83 cd	3.18 ab
7.5-15	4.43 ab	4.62 c	2.40 c	1.25 b	20.38 d	11.00 bc
15-28	4.28 a	4.47 bc	3.03 d	2.03 bc	32.42 e	19.61 cd
Significance	**P<0.001**		**P=0.018**		**P<0.001**	
INCEPTISOL						
	Calcium --- (mg L^{-1}) ---		**Magnesium** --- (mg L^{-1}) ---		**Total Cations** --- (cmol$_c$ L^{-1}) ---	
Depth (cm)	---------------- **Si applied** (kg ha^{-1}) ----------------					
	0	300	0	300	0	300
0-2.5	1101 a	2 237 d	169 abc	204 c	5.61 a	9.31 b
2.5-7.5	1 445 bc	2 096 d	175 bc	207 c	5.42 a	7.43 ab
7.5-15	1 312 ab	1 676 bc	146 ab	188 bc	5.33 a	7.06 ab
15-28	1 039 a	1 332 ab	131 a	174 bc	5.01 a	6.75 ab
Significance	**P<0.001**		**P<0.001**		**P<0.001**	
	pH --- ($CaCl_2$) ---		**Exch. Acidity** --- (cmol$_c$ L^{-1}) ---		**Acid Sat.** --- (%) ---	
Depth	---------------- **Si applied** (kg ha^{-1}) ----------------					
(cm)	0	300	0	300	0	300
0-2.5	4.15 b	5.04 d	0.86 bc	0.06 a	15.67 bcd	0.73 a
2.5-7.5	4.07 ab	4.49 c	1.16 c	0.42 ab	21.78 cd	6.77 ab
7.5-15	4.04 ab	4.43 c	1.27 c	0.69 abc	24.11 d	11.32 abc
15-28	3.89 b	4.13 ab	1.91 d	1.30 cd	38.47 e	25.15 d
Significance	**P<0.001**		**P<0.001**		**P<0.001**	

ǂ Within each soil type and characteristic, values with different letters are significantly different at the P level specified.