The physiological and growth response of sugarcane to the sodium absorption ratio in flowing solution sand culture

Crema, AT
THE PHYSIOLOGICAL AND GROWTH RESPONSE OF SUGARCANE TO THE SODIUM ABSORPTION RATIO IN FLOWING SOLUTION SAND CULTURE

by

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This report was prepared by the author to fulfil B.Ag.Sci. requirements (Subject AG 421) in the Agriculture Department of the University of Queensland, Brisbane. The project was conducted with BSES supervision and facilities at Tully. This report was prepared for limited circulation within the sugar industry and is not to be abstracted, stored in information retrieval systems or cited as a reference, without the prior approval of the Director.
ABSTRACT

The growth of sugarcane variety Q117 in sand culture using nutrient solutions with sodium absorption ratios of 0, 5, 10, 15, 20 and 30, each with a constant electrical conductivity of 1.5 dS/m was determined under glasshouse conditions.

Increasing the SAR of nutrient solutions from 0 to 30 while holding EC and ionic strength constant, was found to have no significant effect on sugarcane grown in coarse sand for 12 weeks. Thus, sugarcane growth was not inhibited by Na\(^+\) concentrations up to 12 mM when Ca\(^{2+}\) and Mg\(^{2+}\) were each present at 76uM.

It can be tentatively concluded from these results that increasing levels of sodium, in the absence of high levels of soluble salts are not toxic to the variety Q117, as long as other major cations are present at concentrations uninhibitive to plant growth. The major growth effect on sugarcane of sodic soils occurs as a result of the physical limitations associated with soil structure deterioration.
DECLARATION OF ORIGINALITY

This report describes the work of the author, except as otherwise stated. It has not been submitted previously for a degree at any university.

ADRIAN T. CREMA
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INTRODUCTION

1.1 General

Saline and sodic soil conditions reduce the value and productivity of soils in the arid and semi-arid regions of the world. Accumulation of soluble salts in the soil solution imposes stress on growing crops that can lead to decreased yields and, in severe cases, complete crop failure.

1.2 Occurrence of salinity and sodicity in Australia

Soil salinity will develop where a source of salt or shallow ground water is available, where annual rainfall is less than approximately 1200 mm, and where evaporation exceeds rainfall for much of the year. In higher rainfall zones, soil and ground water systems are subjected to more leaching and less evaporation; thus, less concentration of salt occurs. Australia is the driest continent in the world. Of the average rainfall of 420 mm, 87% is lost to the atmosphere by evaporation and transpiration (Australian Water Resources Council 1975) and so it is hardly surprising that salts are found in a wide variety of soils.

Saline soils are most common in the more arid parts of the continent accounting for at least 5% of the surface area of Australia (Figure 1.1).

Figure 1.1 A map of saline and sodic soils in Australia (Northcote and Skene 1972)
Secondary or induced salinity is a more important issue for the future of new and existing cropping lands. This form of salinity is caused by the rise of saline or non-saline ground water tables into the crop root zone. Capillary action and evaporation then cause concentration of salt near the soil surface (BSES 1991).

Northcote and Skene (1972) in their detailed study of Australian soils with saline and sodic properties, reported that sodic soils, many of which have appreciably saline subsoils, are widespread throughout both the intensively developed southern and eastern parts of the continent and the sparsely grazed lands of Queensland and Western Australia. They reported that 27.6 % of the total land area in Australia was affected by sodicity (Figure 1.1) and this percentage is increasing steadily.

While the sodicity in subsoils is due to natural processes, the sodicity of both surface and subsoils is increasing insidiously due to the recent use of saline groundwater for irrigation, aggravated by management practices such as cultivation which accelerate structural degradation (Isbell et al. 1983). Hence, secondary salinisation and sodification is increasing rapidly in many parts of Australia as a consequence of irrigation, inappropriate agricultural practices and the clearing of native vegetation, often occurring together.

It should be noted that whereas all the saline soils described by Northcote (1972) are sodic, many of the sodic soils are non-saline.

1.3 Salinity and Sodicity in the Sugar Industry

The sugar industry is placing greater reliance on irrigation to improve and expand production. Sugarcane is a relatively salt sensitive plant, and cane yield response to irrigation can be severely restricted on saline and sodic soils.

In most cane growing districts, primary salting affects soils in small areas which adjoin tidal areas, e.g. the Rocky Point and Moreton Mill areas. However, secondary salinity occurs in the Burdekin, Bundaberg, Isis and Maryborough irrigation areas. As soil salinity increases, soil moisture becomes less available to plant roots because plants rely largely on osmotic forces to move water from soil into roots. In other words, in a non-saline soil, the higher sugar nutrient level (solute) in root tissue tends to absorb fresh soil water (BSES, 1991). Salinity therefore induces water stress over and above that caused by normal drying of the soil. Figure 1.2 displays the yield losses which may occur in saline soils as measured by the electrical conductivity of the soil solution.
Figure 1.2 The effect of saline soils on sugarcane yield in the Burdekin (Source: BSES).

This stress is shown in saline areas by premature wilting and scorching of leaves, restrictions in growth and in severe cases, plant death (Plate 1.1).

Plate 1.1 The effects of salinity on sugarcane growth and land degradation (BSES).

Sodic soils occur in most cane growing districts and in the Burdekin River Irrigation area, these soils have been identified. Research by the BSES has shown that sodic layers which occur deeper than 600 mm in the profile, generally do not restrict growth, but may reduce drainage through the soil profile.
Field trials at Mackay on a strongly sodic soil showed that a 20 per cent yield loss of sugarcane had occurred at an ESP = 15; yield was halved at ESP = 33; and cane growth had failed completely by ESP = 66 (Figure 1.3).

Figure 1.3 Relation between exchangeable sodium percentage and cane yield in Mackay (BSES).

Increasing levels of sodium attached to the clay, in the absence of high levels of soluble salts, are not believed to be toxic to the cane plant. Instead, the effect is through deterioration of soil structure. Increasing levels of ESP cause clay particles to disperse when the soil is wet. This is associated with sealing and crusting in surface soils, and dense subsoil clays which resist penetration by roots. Even if water does penetrate the surface, it is held very strongly in the very small pores formed in the dispersed soil. It is difficult for roots to withdraw this water. The end result of sodicity is similar to that of salinity – water stress. Both water infiltration and water storage are reduced.
1.4 Experimental Objectives

The aim of this investigation was to test current theories that the harmful effect of sodic soils on sugarcane yields is solely due to physical deterioration of soil structure. It is the view of many investigators that, in non-saline sodic soils, other non-soil related effects in combination with physical degradation are responsible for observed growth reductions of sugarcane. This was investigated by determining the plant response of sugarcane variety Q117 in sand culture using nutrient solutions with varying Sodium Absorption Ratios (SAR) at a constant electrical conductivity non-inhibitory to plant growth.
2.0 LITERATURE REVIEW

2.1 DEFINITION OF SALINE AND SODIC SOILS

2.1.1 Introduction

In attempting to define what exactly saline and sodic soils are, it must be remembered that many attempts have been made to set criteria for sodic and saline levels where plant growth is affected, either for individual crops or a specific soil type. However, plant species vary greatly in their sensitivity to saline and sodic conditions. Besides species differences, "plant responses to salt are conditioned by a range of soil and environmental factors: evapotranspiration demand, moisture regime of the soil, the composition of the salts, nutrient status and mechanical composition of the soil profile" (Isbell, et al. 1983). This means that there can be no universal definition of salt-affected soils in precise chemical levels of salinity, alkalinity and sodicity that satisfies all agricultural situations (Northcote and Skene 1972).

2.1.2 Saline soils are those in which "the concentration of soluble salts in soil water is sufficient to restrict plant growth. Figure 2.1(a) demonstrates a saline soil diagrammatically.

---

Ca = Calcium  Mg = Magnesium

SALINE SOIL
CLAY particles are close together — increased salt in soil water

K = Potassium  Na = Sodium

SODIC SOIL
CLAY particles are dispersed by presence of high sodium levels attached to them — soil water is not saline
These salts can be a combination of $\text{Ca}^{2+}$, $\text{Mg}^{2+}$, $\text{Na}^+$, or $\text{K}^+$ ions in association with $\text{Cl}^-$, $\text{SO}_4^{2-}$, $\text{HCO}_3^-$ or $\text{H}_2\text{CO}_3$ ions (BSES, 1991). The U.S Salinity Laboratory Staff (1954) classifies saline soils as those in which the conductivity of the saturation extract is greater than 4 dS/m. It has been found that the conductivity of the saturation extract of a soil, in the absence of salt accumulation from groundwater, usually ranges from 2 to 10 times the electrical conductivity (EC) of the applied irrigation water. The increase in the salt concentration is the result of continual moisture extraction by plant roots and evaporation. Northcote and Skene (1972) defined saline soils as having more than 0.1 % NaCl in surface sands and loams, more than 0.2 % NaCl in surface clay loams and clays, or more than 0.3 % NaCl in the B horizon.

### 2.1.3 Sodic soils

Sodic soils occur where sodium represents more than a threshold percentage of the cations attached to clay particles and is subject to considerable variation in the applied world. Figure 2.1(b) gives a diagrammatic representation of a sodic soil.

Sodic soils can be formed in a number of ways, (BSES, 1991):

1. From parent materials that contain a high proportion of sodium minerals.
2. In areas previously inundated by sea water, or where saline soils have been leached.
3. By irrigation with poor quality water which contains a high proportion of $\text{Na}^+$ or $\text{HCO}_3^-$ ions. $\text{HCO}_3^-$ causes calcium to precipitate in the soil; this increases the proportion of $\text{Na}^+$ ions on the clay particles.
4. In areas within 40 km of the coast, where rain is enriched with sodium from salt spray, the balance of cations on clay particles is altered over long time periods.

The most widely used index of soil sodicity is the exchangeable sodium percentage (ESP) which is the ratio of sodium to all cations (calcium, magnesium, sodium, potassium and aluminium) held at the cation exchange sites on the clay.

The U.S Salinity Laboratory Staff (1954), after studying many soil samples from the western USA, suggested an ESP of 15 as the critical level above which soil structure could be deleteriously affected. This value was considered to be far too high for Australian soils by McIntyre (1979), who studied the hydraulic conductivity of 71 soil samples. He found that ESP values > 15 are quite rare in soils of arid and semiarid regions and considered that most soils in semiarid and arid regions should be classified as sodic soils if their ESP values were > 5. Northcote and Skene (1972) defined sodic soils as those having an ESP > 6 within the top metre of the profile. The lower ESP for sodicity of Australian soils was attributed to the very low contents of soluble minerals, especially...
2.1.4 Water Quality

Quality of water is an important consideration in any appraisal of salinity conditions in an irrigated area. The measurement of EC is the most commonly used method for determining the quantity of total dissolved ions in irrigation waters. In general, waters with conductivity values below 0.75 dS/m are considered satisfactory for irrigation, in so far as salt content is concerned, by the U.S Dept. of Agriculture, although salt sensitive crops may be adversely affected by the use of irrigation waters having conductivity values in the range 0.25 to 0.75 dS/m. Waters in the range of 0.75 to 2.25 dS/m are widely used, and satisfactory crop growth is obtained under good management and favourable drainage conditions, but saline conditions will develop if leaching and drainage are inadequate. Table 2.1 lists the effects of EC levels on the suitability of irrigation water for sugarcane in the Burdekin.

<table>
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<th>EC (dS/m)</th>
<th>Comments for sugarcane in low rainfall areas</th>
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<tr>
<td>0.6</td>
<td>Lower salt concentrations can cause poor water penetration.</td>
</tr>
<tr>
<td>1.5</td>
<td>Max. recommended for routine use on heavy soils.</td>
</tr>
<tr>
<td>2.2</td>
<td>Max. recommended for routine use on sandy soils.</td>
</tr>
<tr>
<td>3.2</td>
<td>Use only on very sandy soils.</td>
</tr>
</tbody>
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The sodium or alkali hazard involved in the use of a water for irrigation is determined by the absolute and relative concentrations of the cations in the irrigation water concerned.

Sodium Absorption Ratio (SAR) is the relation between soluble Na\(^+\) and soluble divalent cations that can be used to predict the ESP of soil equilibrated with a given solution. The SAR is also determined using the concentrations of Ca\(^{2+}\), Mg\(^{2+}\) and Na\(^+\) from saturated soil paste extracts. Munk (1992) found that soils with SAR's < 10 measured in this way are generally considered to be below the threshold for potential Na\(^+\) hazard.
The importance of the cationic constituents of an irrigation water in relation to the chemical properties of the soil was recognised even before cation exchange reactions were widely understood. Thus, the principal purpose of SAR values has been to characterise the adsorption of sodium by the soil – an index of the sodium or alkali hazard of the water.

The soluble inorganic constituents of irrigation waters react with soils as ions rather than as molecules. The principle cations are Ca$^{2+}$, Mg$^{2+}$, and Na$^{+}$, with small quantities of K$^{+}$ ordinarily present.

Residual alkali represents the amount of sodium bicarbonate and sodium carbonate in the water and is more commonly used as an index for the sodium hazard of irrigation water.

The establishment of water quality classes from the standpoint of the sodium hazard is more complicated than for the salinity hazard. The problem can be approached from the point of view of the probable extent to which the soil will adsorb Na$^{+}$ from the water and the rate at which adsorption will occur as the water is applied. Consider a simple case where a non-alkali soil is leached continuously with a high sodium irrigation water and an increase in concentration of the salts in the solution is prevented by the absence of plant growth and of surface evaporation. Under these conditions, the ESP which the soil will attain when it and the water are in equilibrium can be predicted approximately from the SAR value of the water (U.S Salinity Laboratory Staff 1954). In actual practice, the SAR value of the water increases in the soil, owing to the increase in the concentration of the salts and the possible precipitation of calcium and magnesium salts as the moisture content is decreased by plant extraction and surface evaporation.
2.2 Effect of sodicity and salinity on structurally related soil properties.

2.2.1 Effect on colloidal properties of clays

The amount of interaction between soil solution and the soil particles depends on the types and amounts of the soil clays and on the cationic composition and the free electrolyte concentration in the equilibrium solution.

Clay minerals in the soil are classified according to the way the structural units, silicon tetrahedra and aluminium octahedra sheets are stacked to form a unit layer. Grim (1968) classified clay minerals as follows:

(1) In two layer types, such as kaolinite, the unit layer is composed of one sheet of silica tetrahedra and one sheet of aluminium octahedra strongly bound together; it has a low specific surface area and does not swell.

(2) In three layer types, the unit layers are composed of two sheets of silica tetrahedra with an aluminium octahedral sheet between. Two recognised groups of three-layer clays are an expanding lattice or smectite group, e.g. montmorillonite, and a non-expanding-lattice or illite group, distinguished from the smectites mainly by the absence of an expanding interlayer. When montmorillonite clay is wetted, water molecules penetrate between the unit layers, causing their separation and the lattice expands. The diffuse double layer consists of the lattice charge and the compensating counter ions. The counter ions are subject to two opposing tendencies.

The cations are attracted electrostatically to the negatively charged clay surface, and they also tend to diffuse from the surface of the particle, where the concentration is high, into the bulk of the solution where the concentration is lower. The two opposing tendencies result in decreasing counter ion concentration from the clay surface to the bulk solution. Complete descriptions of the diffuse double-layer theory are presented in textbooks (e.g. Bolt, 1979, Bresler et al., 1982).

The swelling and dispersion of clays are affected by the composition of the clays exchangeable cations. Divalent ions are attracted to the surface with a force twice as large as monovalent ions. Therefore, adsorbed Na\(^+\) ions form a diffuse double layer, create high swelling pressures, tending to disperse clay platelets. This swelling and/or dispersion of soil colloids alters the geometry of soil pores and thus affects the soils hydraulic conductivity and permeability.

The low swelling pressure between Ca\(^{2+}\)-clay platelets prevents their dispersion and because of the electrostatic attraction between divalent cations and negative surfaces, the
The dominant clay mineral in the semiarid region is montmorillonite, the most reactive constituent among the soil mineral colloids. In a montmorillonitic soil with a given experimental ESP, the ESP at the external surfaces is higher and the ESP at the internal surfaces lower than the experimental ESP as a result of demixing (sodium ions concentrating on the external surfaces of the tactoids). This phenomenon explains the pronounced effect of sodium, even in clays and soils of low sodicity.

2.2.2 Effect on Hydraulic Conductivity of Soils

The hydraulic conductivity of a soil is usually measured empirically and includes soil properties (tortuosity, pore size distribution etc) and percolating fluid properties (viscosity).

Most definitive data on the effects of sodicity and salinity on soil permeability has been provided from laboratory studies of hydraulic conductivity under conditions where the soil surface is not disturbed; however, relative values for soil permeability should describe relative behaviour in the field under similar conditions. Reductions in soil permeability due to salinity are usually more pronounced for weakly structured soils common to irrigated agriculture and for the regularly tilled surface soils.

In considering the effect of salinity and sodicity on soil permeability, the salt concentration of percolating water, i.e. irrigation water is of equal importance. The permeability of a soil to water has been found to depend on both its ESP and the salt concentration of the percolating solution (Quirk and Schofield, 1955; McNeal et al., 1966, 1968; Yaron and Thomas, 1968). To describe the relationship between hydraulic conductivity and solution composition, Quirk and Schofield (1955) developed the concept of a "threshold concentration" which they defined as the concentration of salts in percolating solutions which decrease soil permeability by 10 – 15 % at a given ESP value. Soil permeability can be maintained at high ESP values if the solution is above the critical (threshold) level. Conversely, at low ESP values where little soil swelling is expected, clay dispersion and a marked reduction in soil permeability occur in very dilute salt solutions. Different soils will respond differently to the same combination of salt concentration and ESP with respect to soil permeability, depending on clay content, clay mineralogy, iron oxide and aluminium oxide content, organic matter content and bulk density.

The two main mechanisms suggested by Quirk and Schofield (1955) to explain the soil permeability decrease are:

(1). The swelling of clay particles, which increases with an increase in clay
(2). Deflocculation and dispersion of clay particles plugging soil pores.

2.2.3 **Effect on hydraulic conductivity of soil surface (crust formation) as determined by the Infiltration Rate (IR).**

Infiltration – or the downward entry of water into soil – is one of the more important processes in the soil phase of the hydrological cycle. The rate of this process relative to the rate of the water supply determines how much water will enter the root zone and how much, if any, will run off. When the infiltration rate is restricted, plants may be denied moisture while the amount of erosion increases. It is also the process most sensitive to the ESP of the soil and the electrolyte concentration in the applied water.

The mechanical impact of raindrops (or the surface stirring and mixing introduced by applied irrigation water) and the relative freedom of particle movement at the soil surface may account for the greater sensitivity of the infiltration rate than of hydraulic conductivity.

Experimental observations suggest that crust formation is due to two complementary mechanisms: a physical breakdown of soil aggregates followed by thin layer compaction caused by impact of the drops and a chemical dispersion dependent on the soil ESP and the electrolyte concentration in the applied water. Stirring of the soil surface by drop impact and irrigation flow enhances the rate of clay dispersion and crust formation.
2.3 Role of essential cations in plant nutrition

2.3.1 Potassium

Plants take up potassium in the form of K⁺. One main feature of K⁺ is the high rate at which it is absorbed by plant roots. It is also the only mineral cation which may be transported against an electro-chemical gradient into plant cells. In other words, K⁺ ions are actively absorbed even if solution concentrations are low. Results of Spear, Asher, and Edwards (1978) strongly support the view that plants can grow vigorously at comparatively low solution concentrations. This study indicated that cassava, sunflower and maize reached maximum growth within the range of 2 – 6 μM K⁺. Wild et al. (1974) showed that four temperate pasture species achieved maximal growth at solution concentrations of 1 – 3 μM in the absence of NH₄ which inhibits K⁺ uptake.

Asher and Ozanne (1967) found that the lowest tissue concentrations of K⁺ corresponding to maximum yield range from 172 to 197 μmol/gram FW for shoots. Their results are summarised in Table 2.2.

TABLE 2.2 Concentrations of K⁺ in the whole shoots of cassava, sunflower, and maize expressed on (a) fresh weight basis (μmol/g fresh weight) and (b) dry weight basis (% dry weight).

<table>
<thead>
<tr>
<th>Species</th>
<th>K⁺ concentrations in solution (μM)</th>
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<tbody>
<tr>
<td></td>
<td>0.5</td>
</tr>
<tr>
<td>Cassava</td>
<td>35</td>
</tr>
<tr>
<td>Sunflower</td>
<td>25</td>
</tr>
<tr>
<td>Maize</td>
<td>22</td>
</tr>
<tr>
<td>Cassava</td>
<td>0.68</td>
</tr>
<tr>
<td>Sunflower</td>
<td>1.04</td>
</tr>
<tr>
<td>Maize</td>
<td>0.89</td>
</tr>
</tbody>
</table>

(Source: Spear, Asher and Edwards, 1978)

There is evidence that K⁺ uptake is active at low K⁺ concentrations in the nutrient solution and passive at high K⁺ solution concentrations, entering the plant by diffusion. Thus, a dual pattern of absorption becomes apparent (Figure 2.2, Welch and Epstein...
At low concentrations, an isotherm is obtained in which for many tissues the rate of absorption levels off at around 0.2 mM $K^+$, (left side of Fig. 2.2) with a wide plateau from 0.2mM to 1mM $K^+$.

At higher concentrations, (1–50mM), (right side of Fig. 2.2) the rate of absorption rises again; the isotherm depicting the relation between external concentrations and rate of uptake has having several characteristic inflections.

The main differences between these two mechanisms are as follows:

1) The first mechanism has a much higher affinity for potassium than the second mechanism which makes little contribution below 1.0mM.

2) The first mechanism is selective for potassium with regard to the effect of $Na^+$ ions. Large excess concentrations of $Na^+$ have almost no effect on $K^+$ absorption, when $K^+$ is at concentrations for which only the first mechanism operates, that is up to 0.2mM.

3) It has been shown that the second mechanism, in which sodium competes with potassium is a mechanism of sodium absorption.

4) $K^+$ absorption by the first mechanism is indifferent to the identity and rate of absorption of the anion. However at the higher concentrations where the second mechanism becomes operative, substitution of sulphate for chloride as the anion greatly diminishes $K^+$ absorption to a rate only slightly higher than can be attributed to the first mechanism.

5) In the presence of $Ca^{2+}$, $K^+$ absorption by the first mechanism proceeds at a higher and more nearly constant rate than in its absence, and inhibitory effects of $Na^+$ and $H^+$ are minimized or eliminated. The rate of $K^+$ absorption by the second mechanism is progressively inhibited by increasing $Ca^{2+}$ concentrations in the solution.
Potassium functions in the activation of enzymes, synthesis of amino acids and in the opening and closing of stomata. Uptake of water in cells and tissues is frequently the consequence of active $K^+$ uptake. Plants well supplied with $K^+$ tend to show a lower water loss and this is due to a reduction in transpiration rate, which not only depends on the osmotic potential of the mesophyll cells but is also controlled to a large extent by the opening and closing of stomata in which the $K^+$ plays a major role.

The activation of some enzymes is inhibited by sodium. When sodium is a dominant cation in saline soils, the sodium—potassium pump provides a means of keeping the concentration of sodium in the cytoplasm as low as possible. Therefore, the sodium—potassium pump is important in salt tolerance in halophytes as high concentrations of $K^+$ and low concentrations of $Na^+$ are necessary for plant cells in most plants to function properly. Figure 2.3 shows how the sodium—potassium pump functions in passing the $Na^+$ ions to the outside of the cell and allowing the $K^+$ ions to enter the cell.

---

**A model of the sodium-potassium pump.**

(a) $Na^+$ is bound to the transport protein;
(b) the protein is phosphorylated; (c) the protein changes form, and the $Na^+$ is released to the cell's exterior; (d) and (e) $K^+$ is bound to the transport protein, which in this form provides a better fit for $K^+$ than for $Na^+$; (f) the protein is dephosphorylated, inducing conversion back to the original form, and $K^+$ is released to the cell's interior.
2.3.2 Calcium

Higher plants often contain Ca\(^{2+}\) in appreciable amounts, generally in the order of 0.5–3.0 % of the plant dry matter. These high Ca\(^{2+}\) concentrations, however, mainly result from the high Ca\(^{2+}\) concentrations in the soil solution rather than the efficiency of the Ca\(^{2+}\) uptake mechanisms of root cells (Rengel and Kirkby 1987).

The nutrient requirement of plant tissues has long been defined (Gerloff, 1963) as "the minimum tissue concentration necessary for plant growth". It should be noted that the critical concentration (Ulrich 1952) as used in deficiency diagnosis is concerned with the concentration of nutrient present in a tissue or organ at maximal yield and is not synonymous with the functional requirement of the plant.

The Ca\(^{2+}\) concentration in plant tops which remained constant while yield increased substantially is believed to indicate the minimal functional requirement of the tops for calcium (Loneragan and Snowball 1969). Figure 2.4 indicates that for herbs and legumes, this requirement was 0.1–0.2% plant DM while the requirement for grasses and cereal crops was 0.05–0.1% plant DM.

![Fig. 2.4](image)

When plants were grown continuously in solutions at constant concentration, the relation between the calcium concentration in tops and the yield generally showed two regions. Increasing Ca\(^{2+}\) concentrations in solution from 0.3–2.5 μM had relatively little effect on the concentration of Ca\(^{2+}\) in the tops and roots of most plants. Increasing solution concentration to 10 μM and beyond increased the concentration of Ca\(^{2+}\) in the tops and roots of plants markedly (Figure 2.5).
Figure 2.5 illustrates how prominently the conditions of Ca$^{2+}$ supply figure in the concentration of Ca$^{2+}$ in plants and hence critical values used by various people to diagnose deficiency in plants.

Islam et al. (1986), investigated solution Ca$^{2+}$ concentration required for the growth of a range of plant species. This revealed that solution concentrations required for 90% of maximum yield were generally for monocotyledons (3–20 µM) than for dicotyledons (7–720 µM) when CaCl$_2$ was used as the calcium source.

Calcium is required for cell elongation and cell division. Calcium is also of fundamental importance for membrane permeability and the maintenance of cell integrity. Impairment of membrane permeability by Ca$^{2+}$ deficiency reduces the retention of diffusible cellular compounds. Membranes become leaky and as the deficiency progresses, there is a general disintegration of membrane structure.

Potassium ions are actively absorbed by plant roots, and the role Ca$^{2+}$ ions play in enhancing the active absorption of K$^+$ appears to be an important mechanism in avoiding Na$^+$ toxicity (Rengel 1992).

Calcium has recently been recognised as a transducer of hormonal and environmental signals to the responsive elements of cell metabolism (Heplar and Wayne 1985; Briars and Williams 1991). The hypothesis of Ca$^{2+}$ being the primary physiological transducer of environmental stress effects has been advanced for chilling injury (Minorsky 1985) and Al toxicity (Bennet and Breen 1991) as well as for salt stress (Cramer, Lauchli and Polito 1985; Lynch, Polito and Lauchli 1989). Therefore, it appears that disturbance of the cell Ca$^{2+}$ homeostasis may be the primary response to a variety of environmental...
2.3.3 Magnesium

Magnesium is required in relatively large amounts by plants and commonly varies from 0.2 - 0.6% of the plant dry matter. Magnesium is absorbed as the divalent magnesium ion (Mg$^{2+}$). The Mg$^{2+}$ concentration in the soil solution is present in fairly high concentrations often between 0.1–5 mM. Both K$^+$ and NH$_4^+$ ions are strong inhibitors of Mg$^{2+}$ absorption by plant roots and may lead to the development of secondarily induced Mg$^{2+}$ deficiency in field-grown plants. Aluminium is also a strong of Mg$^{2+}$ absorption, which can have deleterious consequences on plant growth in acid soils.

A major role of Mg$^{2+}$ in plants is its occurrence at the centre of the chlorophyll molecule. However, the major part of cell Mg$^{2+}$ (70% or more) is freely diffusible within the cytoplasm. It is also required as a co-factor in almost all enzymes involved in the phosphorylation processes.

2.4 The Role of Sodium in Plant Nutrition

2.4.1 Introduction

As early as the beginning of the 18th century, Duhamel De Monceau identified sodium as a component of certain plants growing along seashores. It was not for another 100 years or more that the first investigations into the importance of sodium for the development of plants were carried out. In 1880, it was well known that sodium was a very common constituent of the ash of plants, leading scientists to question whether the element might not be capable of replacing in part other similar plant constituents. Atterburg (1881), experimenting with Black Tartarian oats grown in pots filled with coarse sand, showed that sodium may fill a very important function in case of a deficiency in potassium, and suggested that it is therefore not to be regarded as an altogether useless plant constituent. Holt and Volk (1945), working with several crops, reported that plants vary in their need for and capacity to utilise sodium. Sodium may be essential for maximum growth, or it may substitute for potassium to a variable extent, depending on the kind of plant.
2.4.2 Sodium: A beneficial or an essential element

At present, several categories of plants are believed to exist with respect to sodium (Glass 1989):

(1). Species for which Na is essential.

Certain halophytes, plants indigenous to saline soils, not only tolerate the high concentrations of NaCl in such soils, but actually require Na⁺. Atriplex vesicaria is a perennial shrub species of inland Australia. Although not a typical halophyte (it is not usually found on highly saline soils), it is very tolerant of high concentrations of salt. Brownell (1965) showed that this species requires sodium as a micronutrient element. Several other species of Atriplex also have a Na⁺ requirement (Brownwell 1968).

(2). Species which demonstrate beneficial responses to high sodium application even when all other required elements are available.

Members of the Chenopodiaceae e.g. beet (Beta vulgaris), many of which are restricted to salty habitats. Halophytes characteristically utilise the controlled accumulation and sequestration of inorganic ions, chiefly Na⁺ and K⁺ balanced by Cl⁻, as the basic mechanism by which they adjust the osmotic potential of their internal tissues to external salinity (Flowers and Yeo 1986; Cheeseman 1988).

(3). Species which demonstrate little or no response to sodium even when elements such as K are limiting growth, e.g. cucumber, potato and sunflower.

(4). Species which respond to high levels of Na application only when K⁺ is limiting growth, e.g. barley, wheat and oats.

These categories are not always clearly distinguishable and some overlapping does occur. For example, some species may demonstrate a response to Na⁺ irrespective of the availability of K⁺. Smith (1974) demonstrated the ability of Rhodes grass (Chloris gayana) to maintain maximum yield with less applied K⁺ as the level of applied Na⁺ was increased. Chemical analysis of the plant tops indicate that Rhodes grass have the capacity to use other cations such as Na⁺ in place of K⁺ for some physiological and metabolic functions. Figure 2.6 shows that the concentration of K⁺ in the tops of plants growing at 95% maximum yield decreased progressively from 2.7% to 0.5% DM yield, as the level of applied Na⁺ was increased from 0–400 mg/pot.
A critical value (Ulrich 1943) assessed as the K\(^+\) concentration in the tissue at 95% maximum yield cannot be used for these plants. Diagnostic criteria which also account for the concentrations of those elements that at least partially replace K\(^+\) in its role of maintaining the ionic balance in the tissues are required.

Although K\(^+\) concentrations in the plant tops increased as the rate of application of K\(_2\)SO\(_4\) increased, there was a marked K\(^+\)—Na\(^+\) interaction. Increasing rates of Na\(_2\)SO\(_4\) reduced in the K\(^+\) concentration in plants grown at the higher levels of K\(_2\)SO\(_4\) than in those grown at the lower rates. This relationship corresponds to the dual pattern of K\(^+\) absorption described previously (Section 2.3.1).

2.4.4 The influence of Na\(^+\) upon the water economy of plants

Plants require large amounts of water which once taken up are mostly lost to the atmosphere through evapotranspiration. The water balance of the plant is governed by the factors which control water uptake through the roots, the water holding capacity of the plant and the transpiration. The difference between the suction tension of the roots and the soil, which is partly determined by the salt concentration in the soil solution is of great importance for water uptake. An increase in the osmotic pressure of the soil solution, results in a decrease in the physiological availability of water to the plant. Therefore, many investigators attribute the toxicity of salts largely to osmotic effects.
2.4.5 Influence of Na⁺ ions upon the permeability of plant cells

Wybenga (1957) reported that the presence of salts results, in general, in an increase in permeability. Monovalent cations, such as Na⁺ and K⁺, pass the cytoplasmic membranes more easily than the divalent and trivalent cations. The investigations with *Laminaria* carried out by Osterhout (1922) indicate that monovalent cations all promote permeability, whilst divalent and trivalent cations in combination with the monovalent anions suppress the permeability of membranes to the absorption of monovalent cations.

Thus, if sufficient Ca²⁺ was present in a solution of NaCl, it would cause the suppression of the effect of Na⁺ upon the permeability. These early observations can be supported by recent investigations into the role of Ca²⁺ upon salt toxicity (Rengel, 1992).

Extending our knowledge on physiological mechanisms of salt tolerance is of the utmost importance in developing plants better adapted to saline and sodic soils. Understanding the relationship between Na⁺ and Ca²⁺ may represent one of the crucial links in such a pursuit.

Rengel (1992) reported that uptake of Na⁺ across the plasma membrane is very fast and results in physiological effects on extracellular as well as intracellular sites. Sodium reduces binding of Ca²⁺ to the plasma membrane, inhibits influx while increasing efflux of Ca²⁺, and depletes the internal stores of Ca²⁺ from endomembranes. These changes in the cell Ca²⁺ homeostasis are suggested by Rengel (1992) to be the primary responses to salt stress that are perceived by root cells. Salt would almost instantly reduce the amount of Ca²⁺ being transferred to the leaf cells, with Ca²⁺ activity dropping and Na⁺ activity rising in the apoplasm of leaf cells. This Ca²⁺ signal would be transported to leaves together with, if not preceding, the signal of limited water supply. Ameliorative effects of supplemental Ca²⁺ on salt stress are exerted through preventing Na⁺ related changes in the cell Ca²⁺ homeostasis.

2.5 Management of sodic and saline soils

The saline soils indicated on Figure 1.1 occur mainly in the more arid interior, where extensive grazing of native vegetation is the main form of land use, and soil management *per se* is not generally feasible. On the other hand, sodic soils, many of which have saline subsoils, are especially common in areas where a significant part of the nation's mixed farming and irrigation is practised. Considerable disturbance of the natural ecosystems has usually resulted, with consequent changes to hydrological regimes; salt formerly distributed in deeper subsoil and substrate layers in the catchments and alluvial plains has become mobilised and concentrated in certain vulnerable parts of the landscape;
Our problems have counterparts elsewhere in the world, but the emphasis is
different, especially in relation to northern hemisphere soils. In the case of irrigated soils,
this arises because much of Australia's irrigation water is applied to relatively
impermeable clays and duplex (texture contrast) soils, rather than the more permeable silty
and sandy soils as commonly used in India, China, Central Asia, Eastern Europe, and the
U.S (Isbell et al. 1983)

In the dryland context, the widespread use of sodic duplex soils for farming
operations in Australia has resulted in hillside seepage, valley salting, tunnel erosion and
scalding.

The broad management options available for saline and sodic soils fall into two
categories:

(1) Treatments aimed at directly changing the level of salinity or sodicity of the
soil itself, and

(2) Measures to change the hydrology of the soil or the landscape in which the
salt-affected soil occurs and so to indirectly manage salinity.

Prevention is in most cases better than the cure. The identification of areas where
there is a subsoil store of salt waiting to be mobilised by a rising water table is an
important step in expanding production areas.

Technology is now available to recognise areas where salinity is likely to prevent
sustainable economic production and cause land degradation. To avoid development of
these areas for cropping should be the first step in the future management of salinity. In
existing saline areas, management should be directed towards leaching salt from the root
zone while minimising watertable rise. This can be achieved through a combination of
subsurface drainage to lower watertables and an efficient irrigation program which
supplies only crop requirements plus a small amount of water to allow for leaching.

In sodic soils, with poor hydraulic conductivity, the problem is one of ameliorating
existing undesirable physical properties. Affected surface soils are poorly structured, are
difficult to prepare as seed beds, easily form crusts that cause poor emergence of seedlings
and have low infiltration and hence low water storage. In texture differentiated profiles
(duplex soils), sodic subsoils of low permeability can cause waterlogging of surface
horizons, restricted root development and proneness to erosion. Sodic soils are probably
the most expensive soils to reclaim.

In the management of sodic soils under irrigation, the first step is to have the
irrigation water analysed to determine the sodicity hazard. If a high watertable is present,
it must be lowered by subsurface drainage or groundwater pumping as the water table will
exchangeable sodium by calcium and removal of the sodium and any other soluble salts. To do this, sodium must be leached away and replaced with calcium. Subsurface drainage is necessary to allow sodium to leach from the soil. Gypsum is most commonly used as a calcium source. The chemical reaction involved in the use of gypsum in sodic soil is as follows:

\[
2\text{Na}^+ + \text{CaSO}_4 \rightleftharpoons \text{Ca}^{2+} + \text{Na}_2\text{SO}_4
\]

In the Burdekin, the technique of mixing gypsum with irrigation water has been adopted successfully through the use of a dissolvenator. This technique has been responsible for major sugarcane yield responses.

2.6 Conclusion

Soluble salts can have two types of effects on the growing plant: specific effects due to particular ions they contain being harmful to the crop, and a general effect due to the raising of the osmotic pressure of the solution around the roots of the crops. There is evidence that, in saline, sodic soils, crop damage may be caused by a cation imbalance.

While salinity levels in soils are high, it appears to be the dominant problem reducing plant growth. Sodicity problems associated with soil structure degradation only appear once soluble salts have been leached out of the profile. Accumulation of dispersive cations such as sodium and potassium in the soil solution and the exchange phase affects soil physical properties such as structural stability, hydraulic conductivity and infiltration rate, which consequently affects crop production. Sodic soils exhibit poor soil–water and soil–air relations; these properties adversely affect root growth restricting plant production.
3.0 MATERIALS AND METHODS

3.1 Cultural Details

A pot experiment was established at the Tully Bureau of Sugar Experiment Station under glasshouse conditions in early April, 1993 (Plate 3.1).

Plate 3.1 Outlay of the experiment, shortly after plants were established in the glasshouse

The sugarcane variety Q117 was chosen for this experiment. Although sensitivity of sugarcane to sodicity may vary between varieties, Q117 was chosen as it is a dominant variety in the Burdekin where the potential sodicity of soils is a serious management problem in the industry.

Coarse river sand collected from the Tully river was used as the cultural medium in all treatments. Sand was rinsed through with distilled water to remove most of the silt and sediment and acid washed using 10% HCl acid. The sand was rinsed through again with distilled water after acid treatment to remove all acid residue which might affect...
transplanting of setts and shown to be about 6.

Single-eyed setts were heat treated (i.e. dipped in water at 50°C for 30 minutes), dipped in the fungicide, CANE SETT TREATMENT, and pregerminated in trays of vermiculite. All setts were taken from plant material free from infestation with ratoon stunting disease which might bias yield results.

Germinating setts were sorted on the day of planting (March 24) into 6 groups according to their stage of germination. These groups of plants formed the plant source for each of the six blocks used. 4 setts were transplanted into each pot and the surface of each pot was covered with reflective sisalation paper to reduce evaporation of water.

Chemical control of aphids and grubs was required initially to curb these pest populations. All plants were sprayed with ROGOR on Day 6 and 17 of the experiment.

Plant growth was observed to be abnormally slow during the first 2 weeks of the experiment. At Day 14, many plants had failed to show any sign of growth. A nitrogen (N) deficiency was suspected and hence N solution concentrations were increased from 25µM to 250 µM on Day 21. Plant growth improved immediately and the problem appeared to have been alleviated. Symptoms of an unknown disorder were also observed on older leaves (Plate 3.2) of some plants, particularly those grown in the higher SAR treatments at this time. These symptoms also vanished, however, once active plant growth had resumed.

Plate 3.2: The visual symptoms of the unknown disorder observed 1 week after
3.2 Treatment Application

Treatments were imposed on the 13th of April and continued for 12 weeks when the final plant harvest was taken on 9 August 1993.

Treatments involved the irrigation of plants with a nutrient solution containing all essential elements and a specified Sodium Absorption Ratio (SAR). SAR's of 0, 5, 10, 15, 20 and 30 were used and calculated for a constant EC of approximately 1.5 dS/m to avoid an osmotic effect as induced in saline soils. Figure 3.1 shows the relationship between concentrations of the single salt solutions MgCl₂, CaCl₂, and NaCl and EC. These are the salts which were used to make up the SAR solutions as they are readily soluble.

Figure 3.1 The relationship between concentrations of single salt solutions of MgCl₂, CaCl₂ and NaCl and EC

The Ca²⁺, Mg²⁺ and Na⁺ concentrations in the nutrient solutions corresponding to the SAR values of 0, 5, 10, 15, 20 and 30 are presented in Table 3.1.
These concentrations were calculated using the equation:

\[
SAR = \frac{[Na^+]^2}{\sqrt{[Ca^{2+}] + [Mg^{2+}]}}
\]

in which \(Na^+, Ca^{2+}, \) and \(Mg^{2+}\) represent the solution concentrations of the 3 ions (meq/l). The constraint that the EC of each solution should not exceed 1.5 dS/m meant that the sum of the concentrations of \(Na^+, Ca^{2+}\) and \(Mg^{2+}\) should not exceed 12 meq/l (Figure 3.1). A further constraint was equality of the solution \(Ca^{2+}\) and \(Mg^{2+}\) concentrations at all SAR values. Refer to Appendix 1 for details of these concentrations were calculated.

<table>
<thead>
<tr>
<th>[Cation]</th>
<th>Sol (^a) concentrations of (Ca^{2+}), (Mg^{2+}) and (Na^+) for SAR treatments (meq/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SAR 0  5   10  15   20  30</td>
</tr>
<tr>
<td>(Ca^{2+})</td>
<td>6.000 2.250 1.000 0.532 0.322 0.152</td>
</tr>
<tr>
<td>(Mg^{2+})</td>
<td>6.000 2.250 1.000 0.532 0.322 0.152</td>
</tr>
<tr>
<td>(Na^+)</td>
<td>0.000 7.500 10.000 10.937 11.355 11.696</td>
</tr>
</tbody>
</table>

Treatments were applied at a sufficient rate to replace the nutrient solution in each pot on a daily basis and thus prevent the build up of residual NaCl in the profile. When filled with coarse river sand, each pot had a water holding capacity of approximately 600 ml. On the basis that between 100 and 300 mL of water per day, depending on plant size and atmospheric conditions would be transpired from each pot (J.R Reghanzani, pers. comm.) throughputs of between 700 and 900 mL of solution per day were used in each pot. All pots were flushed with deionised water every 2 weeks; the treatments were re-applied on that same day.

As other basal nutrients were also applied continuously in the SAR solutions, concentrations of these elements to be used were calculated on the basis of nutrient demand in pot trials run previously at the Tully Research Station. In these pot trials, nutrients are applied once at the beginning to supply adequate nutrient for at least 12 weeks. These concentrations were then checked with the literature to make sure that no nutrient deficiencies would occur. Table 3.2 displays the concentration of basal nutrients.
TABLE 3.2. Concentrations of all basal essential elements (µM) in the nutrient solutions.

<table>
<thead>
<tr>
<th>Element</th>
<th>Concentration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sulphur (Na₂SO₄)</td>
<td>7.7</td>
</tr>
<tr>
<td>Boron (Na₂B₄O₁₇·10H₂O)</td>
<td>0.7</td>
</tr>
<tr>
<td>Iron (C₁₀H₁₂O₈N₂FeNa·H₂O)</td>
<td>1.2</td>
</tr>
<tr>
<td>Manganese (MnCl₂·H₂O)</td>
<td>2.2</td>
</tr>
<tr>
<td>Zinc (ZnCl₂)</td>
<td>1.5</td>
</tr>
<tr>
<td>Copper (CuCl₂·2H₂O)</td>
<td>1.5</td>
</tr>
<tr>
<td>Molybdenum (Na₂MoO₄·2H₂O)</td>
<td>0.08</td>
</tr>
<tr>
<td>Cobalt (CoCl₂·6H₂O)</td>
<td>0.03</td>
</tr>
<tr>
<td>Nitrogen (NH₄NO₃)</td>
<td>246.0</td>
</tr>
<tr>
<td>Phosphorus (K₂HPO₄)</td>
<td>12.6</td>
</tr>
<tr>
<td>Potassium (K₂HPO₄)</td>
<td>25.2</td>
</tr>
</tbody>
</table>

3.3 **Experimental Design**

The six treatments were arranged in a randomised complete block design (RCBD) with 6 replications. The pots within each block were relocated randomly at fortnightly intervals to reduce positional effects within the glasshouse.

3.4 **Plant Measurements**

Growth was measured at weekly intervals using height to the top visible dewlap. Roots were weighed at the conclusion of the experiment. It was not possible to separate out the root system of each plant at the end of the trial so the total root mass in each pot was weighed. Treatments were also photographed at this time.
tissue analysis from the germination trays for an indication of the initial nutrient status of plants. At harvest 1 and 2, Day 30 and Day 56 respectively, a plant from each pot was cut at ground level, weighed and oven–dried at 70°C. Dry weights of individual plants were then determined and the whole tops ground for tissue analysis. A complete nutrient assay was conducted for each plant harvested. At the final harvest, the harvesting procedure was as for the first two harvests with the exception that two plants were harvested and analysed instead of one. Third leaf samples were also taken at this time. At harvests 1 and 2, there was not sufficient plant material for tissue analysis via this method. Even at harvest 3, treatment replicates had to be combined to gain enough plant material for third leaf analysis.
4.0 RESULTS

4.1 Plant growth

Plant growth as determined by the parameter of plant height did not vary significantly with the SAR treatment imposed at any stage of the experiment.

Analysis of plant dry matter yield at each harvest also failed to reveal a significant difference in plant growth between any treatments at harvest 1, 2 and 3. (Table 4.1). Plant height data presented below also fails to reveal any significant differences between treatments.

TABLE 4.1 The effect of the SAR treatment on total plant dry matter and plant height at the final harvest (Day 87).

| Plant Parameter | 0    | 5    | 10   | 15   | 20   | 30   | LSD  
|----------------|------|------|------|------|------|------|------
| Total Plant DM | 7.65 | 8.41 | 9.38 | 7.56 | 8.07 | 7.24 | 1.73 |
| (g/plant)      |      |      |      |      |      |      | (5%) |
| Plant Height   | 25.21| 26.21| 26.40| 26.60| 27.77| 27.90| 3.98 |
| (cm)           |      |      |      |      |      |      |      |

4.2 Tissue analysis

Analysis of the 3rd youngest expanded leaf blade (sampling technique used by the BSES) at the final harvest was particularly useful in determining whether nutrient levels in plants were adequate (Table 4.2).
Table 4.2  Nutrient concentrations in the third youngest expanded leaf blade of sugarcane cv. Q117 grown in sand culture watered with nutrient solutions varying in SAR from 0 to 30

<table>
<thead>
<tr>
<th>Nutrient</th>
<th>Units</th>
<th>SAR</th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>0</td>
<td>5</td>
<td>10</td>
<td>15</td>
<td>20</td>
</tr>
<tr>
<td>[K]</td>
<td>%</td>
<td>0.79</td>
<td>0.99</td>
<td>0.88</td>
<td>0.98</td>
<td>1.04</td>
</tr>
<tr>
<td>[P]</td>
<td>%</td>
<td>0.29</td>
<td>0.32</td>
<td>0.29</td>
<td>0.29</td>
<td>0.25</td>
</tr>
<tr>
<td>[Ca]</td>
<td>%</td>
<td>0.48</td>
<td>0.46</td>
<td>0.59</td>
<td>0.52</td>
<td>0.36</td>
</tr>
<tr>
<td>[Mg]</td>
<td>%</td>
<td>0.51</td>
<td>0.51</td>
<td>0.39</td>
<td>0.30</td>
<td>0.21</td>
</tr>
<tr>
<td>[Na]</td>
<td>%</td>
<td>&lt;.01</td>
<td>&lt;.01</td>
<td>&lt;.01</td>
<td>&lt;.01</td>
<td>&lt;.01</td>
</tr>
<tr>
<td>[S]</td>
<td>%</td>
<td>0.14</td>
<td>0.14</td>
<td>0.15</td>
<td>0.15</td>
<td>0.15</td>
</tr>
<tr>
<td>[B]</td>
<td>ug/g</td>
<td>27</td>
<td>19</td>
<td>17</td>
<td>19</td>
<td>15</td>
</tr>
<tr>
<td>[Cu]</td>
<td>ug/g</td>
<td>8</td>
<td>9</td>
<td>13</td>
<td>12</td>
<td>13</td>
</tr>
<tr>
<td>[Zn]</td>
<td>ug/g</td>
<td>34</td>
<td>38</td>
<td>38</td>
<td>41</td>
<td>35</td>
</tr>
<tr>
<td>[Mn]</td>
<td>ug/g</td>
<td>210</td>
<td>227</td>
<td>274</td>
<td>345</td>
<td>297</td>
</tr>
<tr>
<td>[Fe]</td>
<td>ug/g</td>
<td>66</td>
<td>74</td>
<td>68</td>
<td>303</td>
<td>68</td>
</tr>
</tbody>
</table>

These concentrations compared favourably with optimum nutrient ranges (Appendix 2). The only exceptions were K\(^+\) concentrations which appeared to be deficient in all treatments and the Mg\(^2+\) concentration in Treatment 6 which was bordering a deficient status. As the SAR ratio increased, Ca\(^2+\) and Mg\(^2+\) concentration declined significantly. Na\(^+\) concentrations were very low for all treatments and did not vary significantly between treatments.
4.3 Plant cation uptake

The concentrations of Ca\(^{2+}\), Mg\(^{2+}\) and K\(^{+}\) in the whole tops of sugarcane at 3 days (H1), 56 days (H2) and 87 days (H3) are presented in Table 4.3.

At harvest 1, plant Ca\(^{2+}\) concentrations in the whole tops generally decreased with increase in SAR. The only exception was treatment 2 which had a significantly higher Ca\(^{2+}\) concentration than treatment 1. At harvest 2, the trend was similar to that observed at the first harvest. At harvest 3, the Ca\(^{2+}\) concentration in the whole tops increased with increase in SAR from 0 to 10; thereafter, further increase in SAR strongly depressed Ca\(^{2+}\) concentration in the plant tops. The highest plant Ca\(^{2+}\) concentration in the whole tops at Day 87 occurred in the same treatment (SAR = 10) which resulted in the highest dry matter yield.

Mg\(^{2+}\) concentration in the whole tops of plants grown at an SAR of 5 was significantly greater than that in the whole tops of plants grown at an SAR of 0 at all three harvests (Table 4.3). At higher SAR values, the Mg\(^{2+}\) concentration in the whole tops decreased with increase in SAR.

K\(^{+}\) concentrations in the whole tops of sugarcane were less affected by variation in SAR than either Ca\(^{2+}\) and Mg\(^{2+}\) concentrations. At harvest 1, the only treatment effect was a higher K\(^{+}\) concentration in plants grown at an SAR of 20 than in plants grown at an SAR of 5. At harvest 2, the K\(^{+}\) concentration in plants at an SAR of 30 was was significantly higher than SAR's of 5 and 10. (Table 4.3). At harvest 3, the K\(^{+}\) concentration of whole tops at an SAR of 30 was greater than SAR treatments 0, 5 and 15.

Na\(^{+}\) concentrations in whole tops increased from < 0.01\% in SAR's 0 to 10 to 0.04\% in an SAR of 30. These plant concentrations were very low in comparison to those of Ca\(^{2+}\), Mg\(^{2+}\) and K\(^{+}\) which were present in the SAR solutions at much lower concentrations with the exception of the SAR of 0. Na\(^{+}\) was not significantly different between treatments.

The total Ca\(^{2+}\) content was significantly greater at an SAR value of 10 than in all other treatments, and was strongly depressed by a further increase in SAR from 10 to 30. The total Mg\(^{2+}\) uptake was independant of SAR values from 0 to 10, and declined strongly with further increase in SAR.
Table 4.3  Concentrations (%DM) of Mg$^{2+}$, Ca$^{2+}$ and K$^+$ in whole tops at harvests 1 (H1), 2 (H2) and 3 (H3) for each SAR treatment.

<table>
<thead>
<tr>
<th></th>
<th>0</th>
<th>5</th>
<th>10</th>
<th>15</th>
<th>20</th>
<th>30</th>
<th>LSD</th>
</tr>
</thead>
<tbody>
<tr>
<td>[Ca$^{2+}$]</td>
<td>H1</td>
<td>0.438</td>
<td>0.490</td>
<td>0.338</td>
<td>0.313</td>
<td>0.265</td>
<td>0.208</td>
</tr>
<tr>
<td></td>
<td>H2</td>
<td>0.515</td>
<td>0.575</td>
<td>0.498</td>
<td>0.410</td>
<td>0.320</td>
<td>0.238</td>
</tr>
<tr>
<td></td>
<td>H3</td>
<td>0.560</td>
<td>0.593</td>
<td>0.627</td>
<td>0.543</td>
<td>0.415</td>
<td>0.282</td>
</tr>
<tr>
<td>[Mg$^{2+}$]</td>
<td>H1</td>
<td>0.268</td>
<td>0.325</td>
<td>0.262</td>
<td>0.257</td>
<td>0.200</td>
<td>0.165</td>
</tr>
<tr>
<td></td>
<td>H2</td>
<td>0.420</td>
<td>0.460</td>
<td>0.417</td>
<td>0.342</td>
<td>0.255</td>
<td>0.195</td>
</tr>
<tr>
<td></td>
<td>H3</td>
<td>0.615</td>
<td>0.652</td>
<td>0.518</td>
<td>0.422</td>
<td>0.310</td>
<td>0.222</td>
</tr>
<tr>
<td>[K$^+$]</td>
<td>H1</td>
<td>1.65</td>
<td>1.63</td>
<td>1.67</td>
<td>1.74</td>
<td>1.84</td>
<td>1.81</td>
</tr>
<tr>
<td></td>
<td>H2</td>
<td>1.65</td>
<td>1.56</td>
<td>1.49</td>
<td>1.68</td>
<td>1.72</td>
<td>1.76</td>
</tr>
<tr>
<td></td>
<td>H3</td>
<td>1.40</td>
<td>1.40</td>
<td>1.46</td>
<td>1.35</td>
<td>1.51</td>
<td>1.53</td>
</tr>
</tbody>
</table>
5.0 DISCUSSION

Increasing the SAR of nutrient solutions from 0 to 30 while holding the EC and ionic strength constant, was found to have no effect on sugarcane grown for 12 weeks in a coarse sand. Thus, sugarcane growth was not inhibited by Na+ concentrations up to 12 mM when Ca2+ and Mg2+ were each present at 76 uM.

Analysis of index leaves at harvest 3, indicated a possible K+ deficiency in all treatments. Only at an SAR of 30 did the potassium concentration of index leaves fall between an optimum level of 1.11 – 2.50 % plant DM. Although significant plant K+ concentration differences between treatments did occur, these did not conform to a trend which may have been caused by a variation of treatment Na+ concentration. Sodium concentrations in plants were almost negligible in all treatments. Therefore the most probable reason for below optimal K+ levels, if they exist, is directly related to the low solution concentration of 25uM used in all treatments. Sodium appears to have had little effect on absorption of K+ which conforms to Epstein's theory of a dual mechanism of K+ uptake. The first mechanism which operated at low solution concentrations of K+ as were present in this investigation has a very high affinity for K+ and absorption is little affected by large excess concentrations of Na+.

Ca2+ ions is thought to play a major role in avoiding Na+ toxicity in plants through maintenance of the integrity of the plasmalemma of the root cortical cells and through maintenance of selectivity of the first mechanism of K+ absorption. However, despite the decreasing plant Ca2+ concentrations observed with the increasing SAR ratio and hence Na+ ions, K+ uptake remains unchanged. Hence, even in treatment 6 where Ca2+ concentrations are very low, Ca2+ supply was adequate for the plant to function normally. Lazaroff and Pitman (1966), showed that, at higher concentrations of Na+ and K+, the uptake of Ca2+ and Mg2+ can be depressed, but the effect was small and possibly due to reduced transpiration at the higher concentration of Na+ and K+. Loneragan and Snowball (1968) established that increasing solution concentrations of Ca2+ to 10 uM and beyond increased the concentration of tops and roots markedly. This supply effect on uptake was observed for both Ca2+ and Mg2+ up to relatively low concentrations, but did not hold up when concentrations exceeded 250 – 500 uM. As Ca2+ and Mg2+ concentrations rose, each element began to inhibit the uptake of the other. This inhibition was most apparent for Ca2+. Here, competitive inhibition by Mg2+ in treatments 1 and 2 has had a more detrimental effect on Ca2+ uptake than decreasing Ca2+ concentrations to 500uM.

The results of this trial indicated that sugarcane yield was not significantly
saline soil, physical deterioration of soil structure appears to be the major cause of yield reduction of sugarcane.
6.0 ACKNOWLEDGMENTS

I would like to thank BSES for allowing me to use facilities at Tully for the experiment. To John Reghenzani, my supervisor at Tully, and to Marty Phillips and other BSES technical staff, thank you for taking me on and for your complete cooperation and assistance throughout the development and duration of the experimental work. I also wish to thank Gary Ham and other BSES staff at Ayr for suggesting this work and who, together with Graham Kingston of BSES Bundaberg, provided helpful advice towards development of the proposal. Thanks go to David Edwards for overseeing the experiment from Brisbane and for generous assistance in preparation of this report. I would like to thank my family for their encouragement and support throughout this time.
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Appendix 1 Calculation of Na\(^+\), Ca\(^{2+}\) and Mg\(^{2+}\) concentrations for SAR treatments

If the conductivity of each SAR solution is to remain constant and not exceed 1.5 dS/m, then the average concentration of Na\(^+\), Ca\(^{2+}\) plus Mg\(^{2+}\) shall not exceed 0.4 meq\%, according to Figure 3.1.

Therefore:

\[
[Na^+] + [Ca^{2+}] + [Mg^{2+}] = 12 \text{ meq/L} \quad (1)
\]

For the purpose of these calculations, let \([Na^+] = x \text{ meq/L}\), and let \(Ca^{2+}\) and \(Mg^{2+}\) = \(y \text{ meq/L}\).

Thus Eqn 1 becomes:

\[
x + 2y = 12 \text{ meq/L} \quad (2)
\]

And

\[
y = 6 - \frac{x}{2} \text{ meq/L} \quad (3)
\]

Sodium-adsorption ratio (SAR) is defined on page 27 as follows:

\[
SAR = \frac{[Na^+]}{\sqrt{\frac{[Ca^{2+}]+[Mg^{2+}]}{2}}} \quad (4)
\]

Where concentrations in Eqn 4 are expressed in meq/L. Substituting the concentrations \(x\) and \(y\) defined above, Eqn 4 becomes:

\[
SAR = \frac{x}{\sqrt{y}} \quad (5)
\]
Substituting for $y$ in Eqn 5, using Eqn 3.

$$SAR = \frac{x}{\sqrt{6 - \frac{x}{2}}} \quad \cdots \cdots \cdots \cdots \quad (6)$$

Eqn 6 can be solved for $x$ using a value for SAR. For example, for $SAR = 5$, Eqn 6 becomes:

$$5 = \frac{x}{\sqrt{6 - \frac{x}{2}}} \quad \cdots \cdots \cdots \cdots \quad (7)$$

Eqn 7 can be rearranged to the quadratic form, $ax^2 + bx + c$ as follows:

$$5 \sqrt{6 - \frac{x}{2}} = x \quad \cdots \cdots \cdots \cdots \quad (8)$$

$$\sqrt{150 - 12.5x} = x \quad \cdots \cdots \cdots \cdots \quad (9)$$

$$x^2 + 12.5x - 150 = 0 \quad \cdots \cdots \cdots \cdots \quad (10)$$

The roots of the quadratic are:

$$x = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a} \quad \cdots \cdots \cdots \cdots \quad (11)$$