EFFECTS OF IRRIGATION-INDUCED SALINITY AND SODICITY ON SOIL CHEMICAL AND MICROBIAL PROPERTIES AND SUGARCANE YIELD

By

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DECLARATION

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

Signed: ....

Diana N. Rietz

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ABSTRACT

The effects of irrigation-induced salinity and/or sodicity on sugarcane yield, and two growth parameters, namely stalk height and number of nodes per stalk, were investigated on a sugarcane estate in the Zimbabwean lowveld. The effects of soil salinity and/or sodicity on the size, activity and metabolic efficiency of the soil microbial community was also studied. Furrow-irrigated fields which had a gradient in soil salinity and/or sodicity which increased from the upper to lower ends of the fields were selected for this study. This gradient was recognized by decreasing sugarcane growth down from the upper to the lower ends and the appearance of salt on the soil surface at the lower ends of fields. Sugarcane growth was classified as either dead, poor, satisfactory or good; and soil samples (0-0.15 m, 0.15-0.3 m, 0.3-0.6 m and 0.6-0.9 m) were taken from each of these areas. Soils from under adjacent areas of undisturbed veld were also sampled. Sugarcane growth and yields in micro-plots of the various areas of the fields were measured. Foliar samples of sugarcane were taken at 22 weeks of age and analysed for nutrient content. Soil salinity and sodicity were quantified by measuring $pH_{(water)}$, electrical conductivity (EC_e) and cation content of saturation paste extracts and the exchangeable cation content. From this information, the sodium adsorption ratio (SAR_e) and exchangeable sodium percentage (ESP) were also calculated.

The calcareous, vertic soils in the study area under undisturbed veld were found to have high pH values (8 to 9.5), very high exchangeable Ca and Mg concentrations and there was evidence of accumulation of soluble salts in the surface 0.15 m. Under sugarcane production, irrigation-induced salinity and sodicity had developed. Under poor and dead sugarcane, high values for EC_e, SAR_e and ESP were generally encountered in the surface 0-0.3 m of the profile. In addition, the pH values under sugarcane were often between 9 and 10 particularly in profiles where sugarcane grew poorly or had died. As expected, pH was positively related to ESP and SAR_e but negatively related to EC_e.

Measurements of aggregate stability by wet sieving, the Emerson dispersion test and the Loveday dispersion score all showed that soils from the study sited tended to disperse and that dispersion was most apparent where high ESP and SAR_e values occurred in association with elevated pH

values and relatively low EC_e values. These measurements confirmed observations at the sites of low infiltration rates and restricted drainage particularly on the lower ends of fields where sugarcane had died.

In addition to the above measurements it was also observed that there was a rise in the watertable under furrow irrigation and that the watertable was nearest to the surface at the lower ends of the fields. In some cases the watertable was observed to be only 0.2 to 0.3 m from the surface. Thus, death of roots due to anaerobic conditions could be occurring to a greater extent at the lower ends of the fields. Another consequence of the high watertable was that these vertic soils were observed to remain in a permanently swollen state. This limits air and water movement in the soil profile as such soils need to be allowed to dry out and crack regularly so that macroporosity can be restored.

Sugarcane yield, stalk height and number of nodes per stalk were not significantly related to EC_e. Sugarcane yields were, however, significantly correlated with ESP and pH while stalk height and number of nodes were negatively correlated with ESP, SAR_e and pH. These results suggested that sodicity was a more limiting factor for sugarcane growth than salinity. Foliar analysis of leaf tissue did not reveal substantial differences in macro- or micro-nutrient content between good and poorly-growing sugarcane.

It was concluded that the gradient of decreasing sugarcane growth down the furrow-irrigated fields, with crop death at the lower ends, was the result of a combination of factors. That is, the watertable had risen due to over-irrigation and it was nearer the surface at the lower ends of the fields. Due to capillary rise of salts, this resulted in sodic and sometimes saline-sodic conditions in the surface soil. These conditions could limit plant growth through ion toxicities, plant water stress and inhibition of root growth and function and physiological processes. These would be induced by the high pH and high salt, Na^+ and HCO_3^- concentrations in soil solution. Poor physical conditions associated with sodicity and the continually swollen state of the soils presumably limited infiltration and aeration in the surface soil, and probably restricted root growth. In addition, it is likely that the high watertable limited effective crop rooting depth to about 0.2 m at the lower ends of the fields. The net result was that sugarcane died at the lower ends.

A negative effect of soil salinity and/or sodicity was also observed on the soil microbial population. Significant negative correlations were obtained with EC_e SAR_e and ESP with microbial biomass C and microbial activity (as measured by FDA hydrolytic activity or arginine ammonification rate). The activity of enzymes involved in C (β-glucosidase), P (phosphatase) and S (arylsulfatase) mineralization and potential nitrogen mineralization (as determined by aerobic incubation) were also negatively correlated with these factors, with the exception of arylsulfatase activity and ESP. All the above mentioned microbial population measures were also positively correlated with soil organic C content, besides potential nitrogen mineralization. The metabolic quotient, which provides an indication of stress and efficiency of the microbial community, increased considerably with increasing salinity and sodicity and decreased with soil organic C. Thus, increasing salinity and/or sodicity resulted in a smaller, more stressed, less efficient microbial community, while the turnover rate and cycling of C, N, P and S also decreased. It was concluded that salt affected soil not only causes a decline in sugarcane yield through raising the concentration of soluble salts in soil solution, but also has a detrimental effect on microbial activity and on mineralization of soil organic C, N, S and P.

CHAPTER 1
INTRODUCTION

The Zimbabwean lowveld in the south-eastern parts of the country has an almost ideal climate for the production of sugarcane (Clowes and Breakwell, 1998). The area has hot, wet summers and short mild winters with high annual amounts of solar radiation (Clowes and Breakwell, 1998). However, the area receives highly variable, inadequate rainfall (averaging 590 mm per annum) for the production of most crops, including sugarcane, as the evaporative demand is high (Class A pan evaporation averages 1990 mm per annum; Clowes and Breakwell, 1998). Therefore irrigation, mainly by furrow, is necessary (Clowes and Breakwell, 1998). However this, in conjunction with cool winters (that promote natural ripening), results in sugarcane yields that can reach 180 t cane ha^{-1} or 22 t sucrose ha^{-1} (Clowes and Breakwell, 1998).

A sugarcane estate, Hippo Valley Estates (HVE) (Figure 1.1) in the area near the town of Chiredzi was established in 1956 by Sir Raymond Stockil when he purchased 74 500 ha of land. While citrus production was the original intention for the land, only 300 ha was planted before sugarcane production took over. Sugarcane was first planted in 1959, as it's potential as a highly profitable crop was recognised (S. Chidoma *pers comm.*, 2001; Clowes and Breakwell, 1998). Of the cultivated land on the estate, 13 200 ha is under cane, while 25 ha is still planted to citrus (for local consumption).

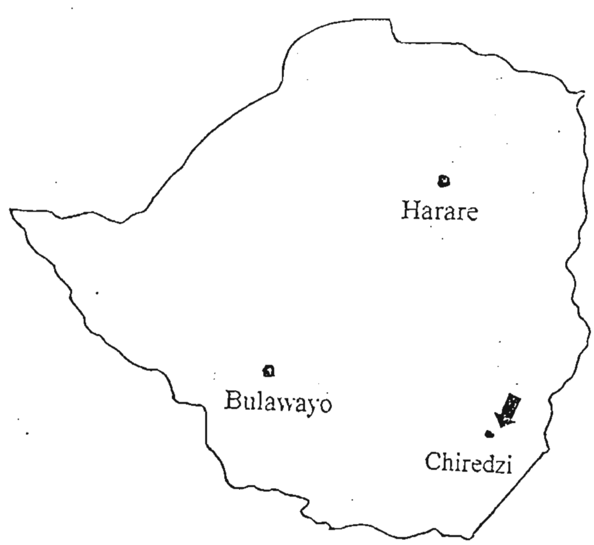


Figure 1.1: Location of the Estate (indicated by the arrow) in Zimbabwe (Peters, 1990).

The geology of the estate is dominated by basalt and gneiss (Clowes and Breakwell, 1998). Soils that have arisen from basalt parent material in the area have high clay contents and have generally been classified as Eutric Vertisols (FAO) or Chisumbanje 3B (Zimbabwean classification system; Nyamaphene, 1984). However, in some areas, Karoo sandstone is overlain by basalt, and soils with lower clay contents have formed (Nyamudeza *et al.*, 1999). The soils in this study generally have clay contents between 25 and 35% and cation exchange capacities (CEC) between 30 and 60 $cmol_c\ kg^{-1}$ (Appendix 1) and have a fairly distinct A and B horizon and have therefore been classified as Bonheim form, Windermere family (Soil Classification Working Group, 1991) or Luvic Phaeozem (FAO) rather than as true Vertisols. The soils often contain visible nodules of $CaCO_3$, found mainly in the top 0.5 m, and cultivation has distributed these evenly throughout this layer. Like the Vertisols found in the surrounding area, these soils generally have a neutral to alkaline pH and if irrigated have the tendency to become saline, sodic or saline-sodic.

Soils arising from gneiss parent materials have been classified as siallitic soils or Chromic Luvisols in the FAO legend (Clowes and Breakwell, 1998; Nyamudeza *et al.*, 1999). These soils are in most cases shallower than Vertisols and usually have a lower clay content, the clay fraction consisting of larger proportions of 1:1 clay minerals, while mica and mixed layer minerals make up the majority of the 2:1 clay mineral fraction. Total exchangeable bases and CEC are just above 30 meq per 100 g clay, while base saturations are usually over 85% (Clowes and Breakwell, 1998).

At present on HVE, approximately 4300 ha of sugarcane is planted on basalt-derived soils, while an additional 7800 ha is on gneiss derived soils (C. Muchehiwa *pers comm.*, 2000). The sugarcane variety NCo376 (the most prominent variety in the lowveld) is currently being grown on both types of soils occurring on the Estate (Clowes and Breakwell, 1998; Muchehiwa *pers comm.*, 2000). Estate records indicate that virgin basalt-derived soils out-yield gneiss-derived soils for the first few years of cropping, but then yields rapidly drop below the industrial average. In addition, basalt derived soils require replanting earlier than gneiss derived soils, often only after the 5th ratoon as yields become poor (Nyamudeza *et al.*, 1999).

The poor performance of sugarcane after several ratoons on basalt-derived soils is thought to be due to the development of salt-affected soils. These have developed as a result of poor irrigation management on these soils, resulting in the development of saline, sodic or saline-sodic conditions. These conditions are primarily due to over-irrigation, as a result of incorrect design or scheduling, of soils with low internal drainage, thus leading to a rise in the water table (Hussein, 1998). This, coupled with the high evaporative demand of the area, leads to water movement by capillary action to the soil surface. The evaporation of this water, which contains dissolved salts, results in the deposition of these salts near or on the soil surface. This results in other problems, such as high salt levels, alkaline pH and poor soil structure (Hussein, 1998).

The aims of this study were to:

(a) measure the extent of yield depressions within the area of irrigated vertic soils

(b) investigate the cause of yield depressions and crop death within irrigated fields with particular reference to irrigation-induced soil salinity and sodicity

(c) investigate the effect of saline-sodic conditions induced within irrigated sugarcane fields on the size and activity of the soil microbial community, and thus on biological soil quality.

CHAPTER 2
REVIEW OF LITERATURE

2.1 Introduction

Sugarcane originated in New Guinea, and the earliest mention of it's growth and use was in about 1400 B.C. in Indian writings (Barnes, 1964). Most cultivated varieties of sugarcane arose from the hybridization of *Saccharum officinarum*, a perennial member of the grass family, *Gramineae*. The amount of land planted to sugarcane has consistently increased over the last century (Bramley *et al.*, 1996). Sugarcane is ideally suited to tropical areas, but has expanded into lower rainfall, sub-tropical areas where irrigation is essential to ensure high yields (Wahid *et al.*, 1997). This is the case in the Zimbabwean lowveld, where approximately 40 000 ha of irrigated sugarcane is grown (Clowes and Breakwell, 1998).

A considerable portion of sugarcane grown in the Zimbabwe lowveld is cultivated on heavy clay soils. It is estimated that Zimbabwe has approximately 1.8 million ha of land on soils classified as Dark Clay Soils (FAO, 1965), and these are located in the Zambezi valley and the southern parts of Zimbabwe. In semi-arid areas, these heavy clay soils (often classified as vertisols) are considered very important, as they tend to have a high potential for agricultural production when compared with other soils of this environment. Their potential lies in their stability under extensive use as they are capable of sustaining production for many years. Crop yields, however, are usually low unless they are irrigated (FAO, 1965). In addition, if used for dryland cropping, they have the advantage of deep water storage (Hubble, 1984). However, as a result of their high smectitic clay content and cracking nature, they have a limited moisture range for "safe" cultivation. They also have a "high energy" tillage demand that makes them difficult to manage (Wilding and Puentes, 1988). Despite this, some vertisols have been cropped for centuries, and in some parts of India, they have been cropped for over 1000 years (Hudson, 1984). The unusual physical characteristics of vertisols result in specific management requirements that often prevent the achievement of their production potential (Hubble, 1984 and Virmani *et al.*, 1982 cited by

Probert *et al.*, 1987). A lack of water is usually the main constraint to optimal production on these soils (Probert *et al.*, 1987). Therefore, as in the Zimbabwean lowveld, these soils are irrigated to increase their agricultural potential. For example, sugar yields of over 200 t ha^{-1} have been attained on an irrigated Vertisol in northern Australia (Kingston *et al.*, 1980). However, the irrigation of heavy clay soils in arid areas often results in the development or aggravation of soil salinity and/or sodicity (Probert *et al.*, 1987).

Traditional methods of sugarcane monocropping are known to result in a decline in soil organic matter, soil microbial biomass, nutrient status (in particular K); and to lead to an increase in soil compaction and often an increase in soil acidity (generally in dryland areas). These factors ultimately lead to yield decline. Several researchers have reviewed these aspects of soil degradation under sugarcane monoculture (Hartemink and Kuniata, 1996; Meyer *et al.*, 1996; Garside *et al.*, 1997; Hartemink, 1998a and 1998b; Haynes and Hamilton, 1999). However, only a few of these reviews have considered the development of salinity and/or sodicity under irrigated sugarcane as an important factor (Meyer *et al.*, 1996; Garside *et al.*, 1997; Haynes and Hamilton, 1999). This factor was not even considered in a recent international review (Hartemink, 1998a). Additionally, limited information is available concerning the quantitative effect of salinity in conjunction with sodicity on sugarcane yield (Nelson and Ham, 2000), and on the effect of soil salinity and/or sodicity on soil microbial activity (Oren, 1991, 1999; Szabolcs, 1991). Indeed, several recent comprehensive reviews on the effects of salinity and sodicity on soil properties do not include the effects on soil biological activity (Sumner and Naidu, 1997; Keren, 2000; Levy, 2000).

In the first part of this review, the soil constraints to sugarcane production are outlined and discussed. Where appropriate, particular reference is made to the management of vertic soils. In the second section of the review, the processes of salinisation and sodification, their impact on sugarcane production, and methods to ameliorate salt-affected soils are reviewed and discussed.

2.2 Soil Constraints to Sugarcane Production

2.2.1 Nutrient Supply

Correct nutrition of sugarcane is important for photosynthesis, sugar synthesis and sugar translocation and storage, and like most other crops, certain nutrients are more critical at certain stages of growth than at other stages (Humbert, 1973). Sugarcane requires at least 14 elements for normal growth (Anderson and Bowen, 1990 cited by Wood *et al.*, 1997). Most fertilizer recommendations, except N, are based on soil analyses and are aimed at keeping nutrient levels above values where nutrient deficiencies are seen in the crop, but below values at which no further crop response is seen. Fertilizer N recommendations are, however, normally based on yield responses achieved in each sugarcane growing area (Kingston *et al.*, 1991 cited by Wood *et al.*, 1997).

As a result of removal of a large proportion of the sugarcane plant at harvest, and in many cases burning of sugarcane before harvest, nutrient removal from a sugarcane field is generally relatively large. As a result, large annual applications of N, P and K are common for sugarcane (Wood *et al.*, 1997). Data on the removal of nutrients by sugarcane is shown in Table 2.1. Soil nutrient levels will decline if inadequate fertilization of sugarcane soils occurs, as nutrient removals will exceed nutrient inputs (Haynes and Hamilton, 1999). Losses of nutrients from sugarcane fields via runoff, leaching, gaseous emissions through burning and harvesting mean that nutrient losses may easily exceed nutrient inputs.

Table 2.1. Estimates of nutrient removals (cane, tops and trash) (kg ha^{-1}) by sugarcane made by several different workers.

Nutrient	Calcino (1994) (cited by Wood *et al.*, 1997)	Humbert (1968b)	De Geus (1973)	Fageria *et al.* (1991)
N	136	285	120	240
P	21	31	33	150
K	220	559	125	510
Ca	39	108	-	-
Mg	36	90	-	-
S	34	-	-	-
Cu	0.09	0.40	-	-
Zn	0.47	-	-	-
Fe	7.00	6.1	-	-
Mn	3.81	5.6	-	-
Na	-	5.5	-	-
Al	-	0.83	-	-
B	-	0.33	-	-
Yield (Mg ha^{-1})	92	252	-	150

- no data given

Heavy clay soils tend to limit losses through leaching of nutrients as their cation exchange capacity (CEC) is often relatively high (Hartemink, 1998a). This is mainly as a result of a high content of montmorillonite with it's high permanent charge. In addition, a lack of extensive leaching in heavy clay soils leads to their high base saturation (Hubble, 1984). Base saturation of vertisols varies with pH but is generally between 70 and 100 percent (Young, 1976).

(a) Nitrogen

As in most intensive crops, N fertilizer application is standard practice (Keating *et al.*, 1997). As shown in Table 2.1, estimates of N removals by a sugarcane crop range from 120-240 kg N ha^{-1}. In agreement with this, recommended fertilizer N applications are about 120 kg N ha^{-1} for plant crops and 160 kg N ha^{-1} for ratoon crops (Wood *et al.*, 1997).

Deficiencies in soil N are common in many cultivated soils, including cultivated heavy clay soils (Stephens and Donald, 1958; van Wambeke, 1991) and there is a considerable amount of evidence that crops grown on heavy clay soils respond to applications of N fertilizer especially when other deficiencies (particularly P), have been corrected (Hubble, 1984; Probert *et al.*, 1987). The reason for this is that under arable cultivation there is a characteristic loss of soil organic matter (see section 2.2.3), and thus soil organic N, so there is less potentially mineralizable N available for crop use. Indeed, the availability of mineral N in soils is mostly dependent on mineralization/immobilization, nitrification and denitrification, except where N fertilizers have been added and make a direct short-term contribution to soil N. The high 2:1 clay content of vertisols imparts them with an ability to fix and release NH_4^+-N, this has been confirmed by a number of studies on heavy clay soils (Rodrigues, 1954; Ahmad *et al.*, 1972). The mechanisms responsible for NH_4^+ fixation are similar to those of K fixation because the ionic radius of the NH_4^+ is very similar to that of K^+ (Prasad and Power, 1997a), this is discussed in section 2.2.1 (c) dealing with K fixation. The fertilization of NH_4^+ and K^+ fixing soils with K fertilizer prior to the application of NH_4^+, or NH_4^+ producing fertilizers, reduces NH_4^+ fixation (Prasad and Power, 1997a). Loss of nitrate by leaching is less likely in vertisols than in lighter textured soils (Holford, 1981) due to their high water-holding capacities usually coupled with moderate rainfall. Although vertisols tend to have an alkaline pH, their high CEC lowers the potential loss of N via ammonia volatilization (Waring and Saffigna, 1984).

Gaseous losses of N through denitrification can be high under anaerobic or waterlogged conditions (Skerman and MacRae, 1957 cited by Waring and Saffigna, 1984) which could arise under irrigation, especially in heavy clay soils. The mildly acid to mildly alkaline pH common in heavy clay soils also promotes denitrification (Bremner and Shaw, 1958). There is evidence that denitrification causes substantial losses of applied N fertilizers on cultivated cracking clays, particularly in Australia (Craswell and Martin, 1975; Craswell and Strong, 1976; Craswell, 1979). Therefore, careful irrigation management is essential to prevent waterlogging and the consequent losses of N via denitrification.

(b) Phosphorus

A decline in available P with sugarcane monocropping without P fertilization has been well documented (Bramley *et al.*, 1996; Hartemink and Kuniata, 1996; Hartemink, 1998b; Nyamudeza *et al.*, 1999). This decline can be exacerbated by irrigation, probably as a result of higher crop removal of P (with higher yields), lower soil organic matter levels and precipitation by Ca and Mg in irrigation water as phosphates (van Antwerpen and Meyer, 1996).

In heavy clay soils the fixation of P, and therefore P availability, is affected by:

- Calcium content. In arid and semi-arid regions, calcium carbonate concretions are common in heavy clay soils, resulting in a high Ca content and P precipitates as Ca-phosphates (Webber and Mattingly, 1970).
- pH. With increasingly alkaline pH, P will precipitate as insoluble Ca phosphates and availability will decrease (Burnham and Lopez-Hernandez, 1982).
- Clay content and mineralogy. P is strongly adsorbed in heavy clay soils as a result of their high clay content which is dominated by smectite and illite (Pissarides *et al.*, 1968; Barrow, 1981 cited by Waring and Saffigna, 1984 and Sanchez and Uehara, 1980 cited by Yerima *et al.*, 1988).
- Soil water content. As water content increases, iron is reduced. However, upon drainage, the content of oxalate extractable iron remains high, and these amorphous iron oxides have a high P adsorption capacity. Therefore, previously flooded soils have a higher P buffering capacity than soils that have not been flooded (Willett and Higgins, 1978).

For the above reasons, heavy clay soils have often been reported to be deficient in P (Stephens and Donald, 1958; Donald, 1964 cited by Waring and Saffigna, 1984; Sanchez, 1976 cited by Yerima *et al.*, 1988; Smith, 1977 cited by Waring and Saffigna, 1984). However, little work has been done on this subject in the semi-arid tropics (Ahmad, 1983). To a large extent the size of P reserves are dependent on the P content of the parent material and the degree to which the soil has weathered (Beadle, 1962 cited by Waring and Saffigna, 1984; Hawkins and Kunze, 1965; Ahmad and Jones, 1967; 1969a;b).

The quantity of soil organic P present is another important consideration. As a result of the dependence of P availability on it's reactions with inorganic constituents of the soil, mineralization of P from organic matter is often not considered to make an important short-term contribution to plant available P (Barrow, 1981 cited by Waring and Saffigna, 1984). There is, however, evidence that over longer periods of time, mineralization of organic P may make substantial contributions to P availability. This may be important in the case of continuously cultivated heavy clay soils where it may lead to an increase in available P (Dalal, 1977). Yerima *et al.* (1988) concluded that the management of the soil organic matter pool could effect the quantity of fertilizer P needed.

(c) Potassium

Sugarcane is reputed to be a large K consumer (Yates, 1978 cited by Hartemink, 1998a; Anderson and Bowen, 1990 cited by Hartemink and Kuniata, 1996; Bramley *et al.*, 1996) and luxury uptake of K is known to occur in some varieties of sugarcane, such as N14 (Clowes and Breakwell, 1998). Soil K levels (including non-exchangeable, 'fixed' K) decline rapidly under sugarcane without adequate fertilization (Orlando Filho; 1985 cited by Hartemink, 1998b; Naidu *et al.*, 1995a; Hartemink, 1998a; 1998b; Nyamudeza *et al.*, 1999). There are large discrepancies in the amount of K calculated by authors to be removed by sugarcane (Table 2.1) and some of these are probably attributable to luxury K uptake. Potassium fixation in heavy clay soils is similar to that of ammonium discussed earlier (Ahmad *et al.*, 1972).

Kunze *et al.* (1963) found heavy clay soils to be low in exchangeable K, however Hubble (1984) considered their K status to be moderate to good, although the author did mention the occasional report of deficiency. However both Hubble (1984) and van Wambeke (1991) concluded that K contents of heavy clay soils are adequate for crop production, and are often considered high when compared to other soils. Norrish and Pickering (1977; cited by Hubble, 1984) concluded that it is improbable that soils high in illite are deficient in K, unless removal has been large.

Potassium fixation is a factor that must be taken into account when considering the K nutrition of crops. This is because exchangeable K is transformed into non-exchangeable forms of K; that is, it becomes held between adjacent tetrahedral layers of 2:1 clay minerals (Bühmann *et al.*, 1986; Sparks, 1987; Prasad and Power, 1997b). Although the conversion of exchangeable K (including the portion derived from fertilizers) into fixed K lowers plant-available K, it does decrease leaching of K and luxury K uptake by plants. Fixed K does go into solution when the pool of exchangeable K is depleted through the maintenance of a dynamic equilibrium between the two forms of K (Pearson, 1952). The mechanism of K fixation essentially occurs in three steps: (i) selective adsorption of K into the interlayer space of the clay mineral, (ii) the negatively charged interlayer surface dehydrates the K ion, and , (iii) the K ion moves deeper into the lattice structure of the clay where a strong negative charge tightly holds it (Bühmann *et al.*, 1986). K fixation is increased by:

- type and quantity of clay. Illite, smectite, vermiculite, weathered mica and interstratified minerals all fix K more than other clay minerals. Therefore with increasing clay percentage, especially if it consists of the clay minerals mentioned above, K fixation increases (Prasad and Power, 1997b). Potassium was fixed by clays of vertisols in the West Indies, which lowered the overall CEC and surface area (Ahmad, 1983).
- increasing soil pH. At high pH values, a high OH^- concentration results in the precipitation of Al^{3+}, thus "freeing" K binding sites on clay minerals. In addition, the charge on Fe and Al oxides and hydroxide becomes increasingly negative with increasing pH, thus increasing K adsorption (Bühmann *et al.*, 1986; Prasad and Power, 1997b).
- drying out of the soil. K fixation is substantially greater in dry soils than in wet soils (Sawhney, 1972; Prasad and Power, 1997b). Therefore it could be assumed that irrigation of vertisols without adequate drying off periods may result in luxury uptake of K by plants.
- K fertilization. Since the relationship between exchangeable and fixed K is one of dynamic equilibrium, addition of substantial quantities of exchangeable K to the soil pushes the equilibrium towards fixation (Prasad and Power, 1997b).

(d) Sulphur

Sulphur removal by sugarcane is generally not considered large enough to warrant fertilization with S (Hartemink and Kuniata, 1996; Hartemink, 1998a). However, Clowes and Breakwell (1998) found removal to be between 25 and 45 kg S $ha^{-1}an^{-1}$ and recommend S application, even if in the form of single superphosphate. Sulphur deficiencies in the Zimbabwe lowveld are however rare. Sulphur availability is greatly dependent on the quantity in soil organic matter and the rate of it's mineralization (Williams and Lipsett, 1961 cited by Waring and Saffigna, 1984; Lipsett and Williams, 1971 cited by Waring and Saffigna, 1984). Responses to S applications in Australian heavy clay soils, particularly those developed from basalt, have been recorded (Hilder, 1954 cited by Waring and Saffigna, 1984; Crofts and Blair, 1966 cited by Waring and Saffigna, 1984; Jones, 1970 cited by Waring and Saffigna, 1984).

Characteristics of heavy clay soils that have an effect on S availability are:

- Soil pH. Sulphate adsorption tends to be low in soils with a high pH as a result of minimal positive charge (Barrow, 1975; cited by Waring and Saffigna, 1984). This increases the likelihood of leaching and therefore reduces the size of the plant-available pool of sulphate.
- High clay content, dominated by montmorillonitic clay minerals. Sulphate can be leached in the same manner as nitrate, but the high clay content in the subsoil can result in adsorption of S and it's retention in the rooting zone. Another effect may be that of lower rates of mineralization of S from organic matter caused by the formation of stable clay-organic matter complexes (Waring and Saffigna, 1984).

(e) Calcium and Magnesium

Soil exchangeable Ca and Mg levels generally do not decline substantially under sugarcane monoculture (Maclean, 1975; Hartemink and Kuniata, 1996; Hartemink, 1998b), unless substantial soil acidification has occurred (see section 2.2.2).

The parent material of heavy clay soils determines the relative levels of exchangeable Ca and Mg. Exchangeable Mg levels will be almost as high, if not higher than exchangeable Ca levels if the parent material is a substance such as a basic igneous or metamorphic rock or a marine sediment. However calcareous parent materials give rise to higher exchangeable Ca than Mg levels (Ahmad, 1983). Large quantities of free Ca and gypsum are common in vertisols (van Wambeke, 1991) as carbonates of Ca or Mg, and they occur in a range of forms in heavy clay soils. These vary from very fine particles scattered throughout the soil mass, to horizons comprising indurated pedogenic nodules forming hardpans in some instances (Sehgal and Stoops, 1972; Ahmad, 1983; Hubble, 1984; Mermut and Dasog, 1986). Formation of nodules or concretions of carbonate is dependent on soil age, origin of deposits and climate (Ahmad, 1983). Carbonates may occur either at specific depths or else throughout the entire soil profile (Ahmad, 1983). In moister climates, they are usually found below 40 cm, but in drier climates they may occur anywhere in the profile (Hubble, 1984). Heavy clay soils with their frequently high pH and naturally high levels of exchangeable Ca and Mg are therefore not likely to show deficiencies of these nutrients (Hartemink, 1998a).

(f) Zinc

Bramley *et al.* (1996) found that there was a decline in available Zn with sugarcane monocropping. The availability of Zn is generally dependent on soil pH (Waring and Saffigna, 1984; Naidu and Rengasamy, 1993), with optimum availability occurring between pH values of 5 and 5.7 (Schroeder *et al.*, 1994). With increasing pH the availability of Zn declines (Waring and Saffigna, 1984) due to adsorption/precipitation reactions. Zinc deficiency has been recorded in heavy clay soils (Stephens and Donald, 1958). Soils with a low total Zn content, high clay content, low in organic matter content and those that are highly calcareous (as with many heavy clay soils) tend to show positive crop responses to applied Zn (Radjagukguk, 1975 cited by Waring and Saffigna, 1984; Waring and Saffigna, 1984; van Wambeke, 1991).

(g) Role of Foliar Analyses

Thus far, this discussion on nutrient supply has concentrated on the reactions of nutrients in soils and their consequent availability and uptake by crops. By implication, this reflects the central importance of soil testing in soil fertility management. It is, however, noted here that foliar analysis can also be an important tool for diagnosing nutritional problems in the sugarcane crop.

For foliar analyses to be of relevance in an area, foliar samples must be taken from the same part of the sugarcane plant, at the same growth stage. This is because nutrient levels determined from analyses of foliar samples taken at different stages often vary too much for reliable conclusions to be drawn about the resultant sugarcane yield (Humbert, 1973).

In Zimbabwe, the standard practice is to take foliar samples when the sugarcane is 22 weeks (± 1 week) old. The first fully expanded leaf from the top of the sugarcane plant (usually the third leaf down the stalk) is sampled, the midribs removed, the leaves from each plot bundled and the tops and bottoms chopped off (Clowes and Breakwell, 1998). Correction factors are applied to foliar results to limit the seasonal variation in nutrients when samples are taken at different times of the year. General guidelines to critical foliar nutrient levels in sugarcane are given in Table 2.2.

Table 2.2: Critical levels of foliar nutrients in sugarcane at about 22 weeks of age for the Zimbabwe Sugar Association Experimental Station (ZSAES) and the South African Sugar Association Experimental Station (SASEX)[1].

Nutrient	ZSAES	SASEX
N (%)	1.70	1.7
P (%)	0.18	0.19
K (%)	1.05	1.05
S (%)	-	0.12
Ca (%)	0.18	0.15
Mg (%)	0.08	0.08
Zn (ppm)	-	13
Mn (ppm)	-	15
Cu (ppm)	-	1
Fe (ppm)	-	50
N/S (ppm)	-	<17

- not analysed by ZSAES

[1] Data from Meyer *et al.* (1997) and Clowes and Breakwell (1998).

Although the taking and handling of foliar samples must be done with care, the results obtained can be very useful. For example, they could indicate that although nutrients can be at acceptable levels within the soil; as a result of an adverse soil environment, they may not be taken up by the plant. This was demonstrated by Hartemink (1998b) who found that although soil P and K levels were considered adequate, several foliar samples indicated nutrient deficiencies. He attributed these deficiencies to soil compaction and acidification limiting root growth and nutrient uptake.

2.2.2 Soil acidification

A $pH_{(water)}$ of 6.5 has been considered by some as the optimum for sugarcane (Yates, 1978 cited by Hartemink, 1998a) although sugarcane yield has not been found to be seriously affected by pH values as low as 4 and as high as 9. Nonetheless nutrient status can be affected at extreme pH values (Fageria *et al.*, 1991; Hartemink, 1998a). The ZSAES recommends lime application when soil $pH_{(CaCl2)}$ values are less than 5, and classes these soils as strongly acid. Soil $pH_{(CaCl2)}$ values above 7.5 are considered by the ZSAES to be strongly alkaline, and may be detrimental to sugarcane growth unless found on heavy clay soils (Clowes and Breakwell, 1998). The pH of vertisols is generally weakly acid to weakly alkaline (Young, 1976). However, vertisols have been found to have almost any pH from highly alkaline throughout the soil profile to strongly acid throughout the profile (Hubble, 1984; Hubble and Isbell, 1958).

Soil acidification under sugarcane monocropping is well-documented (Hartemink and Kuniata, 1996; Hartemink, 1998a; 1998b; Wood, 1985, Schroeder *et al.*, 1994). It arises mainly as a result of nitrification of NH_4^+ following the application of N fertilizers containing or producing NH_4^+ but also following mineralization of organic N originating from crop residues or native soil organic matter (Sumner, 1997; Haynes and Hamilton, 1999). During the microbial process of nitrification, NH_4^+ is converted to NO_3^- and there is a release of $2H^+$ ions per molecule of NO_3^- formed (Sumner, 1997, Haynes and Hamilton, 1999). Removal of bases with harvesting of sugarcane has been suggested to be another contributing factor to soil acidification (Hartemink 1998c) With increasing acidity there is:

- an increase in exchange acidity (Bramley *et al.* 1996)
- a rise in exchangeable and extractable Al (Schroeder *et al.*, 1994; Bramley *et al.* 1996; Meyer *et al.*, 1996; Sumner, 1997)
- a decline in exchangeable bases (Wood, 1985; Schroeder *et al.*, 1994; Sumner, 1997; Hartemink, 1998a)
- a decline in CEC (Wood, 1985; Bramley *et al.* 1996; Sumner, 1997, Hartemink, 1998a; 1998b).

An increase in acidity has been linked to sugarcane yield decline (Quinan and Wood, 1989; Bramley *et al.*, 1996; van Antwerpen and Meyer, 1996; Hartemink, 1998a). However, there is evidence that many presently-grown sugarcane varieties are Al-tolerant and therefore tolerant of acidic soil conditions (Hetherington *et al.*, 1986). Schroeder *et al.* (1996) (cited by Wood *et al.*, 1997) suggested that acid tolerant varieties have been inadvertently selected by sugarcane breeders. Although strongly acid vertisols do occur (Hubble, 1984; Hubble and Isbell, 1958), these are not common under arid/semi-arid conditions where irrigated sugarcane is cultivated. Thus, on heavy clay soils, soil acidification is not likely to be a common limitation to sugarcane production.

2.2.3 Loss of soil organic matter

Upon tillage of a virgin soil, soil disruption causes the exposure of previously unavailable organic matter to decomposition and so the organic matter content of the soil decreases (Dalal and Mayer, 1986; Johnston, 1986; Sumner, 1997; Skjemstad *et al.*, 1998). Another important factor leading to this decrease is that organic matter inputs to the soil under arable systems are usually considerably lower than under natural systems (Dalal and Mayer, 1986). Generally an exponential drop in organic matter is seen with continuing cultivation, until a relatively stable level in the soil is reached after 20-50 years of cultivation (Russell, 1981 cited by Probert *et al.*, 1987; Haynes and Beare, 1996). Traditional sugarcane cultivation is no exception, and the resultant decline in soil organic matter is well-documented (Wood, 1985; Hartemink and Kuniata, 1996; van Antwerpen and Meyer, 1996; Hartemink, 1998a). Declines in organic matter content under both dryland and irrigated sugarcane were observed by van Antwerpen and Meyer (1996).

Green cane harvesting rather than the conventional method of burning prior to harvesting has led to an increase in soil organic matter contents in several studies (Wood, 1991; Vallis *et al.*, 1996; van Antwerpen and Meyer, 1996). In relation to this it is important to note that the availability of carbon varies greatly throughout the year in the case of arable crop production where material is removed and crop residues are occasionally incorporated. This directly affects the production pattern of mineral N from the substrate (Chalk and Waring, 1970 cited by Waring and Saffigna, 1984). Nitrogenous fertilizer applications must also be correctly timed as N can be immobilized if applied at the same time as residue incorporation (Saffigna *et al.*, 1984).

In spite of their dark colouration, virgin vertisols generally have low organic matter contents (0.5-3 %), and the level is mainly dependent on the interaction of factors such as vegetation, climate and available soil P (Hubble, 1984). Although the high clay content of these soils generally protects organic matter (due to formation of clay-organic matter complexes; Coulomb *et al.*, 1996, cited by Hartemink, 1998a) a decrease in organic matter levels upon cultivation in heavy clay soils is well-documented (Young, 1976; Ahmad, 1983; Skjemstad *et al.*, 1986).

There is evidence that losses in organic matter may contribute to sugarcane yield decline (Wood, 1985; Yadav and Prasad, 1992). This may be as a result of the influence organic matter has on many important soil properties. A loss of soil organic matter results in a decrease in the following:

- CEC and thus the capacity of the soil to retain exchangeable cations (Ca, Mg, K and Na) (Vaughan and Ord, 1984; Sumner, 1997)
- the supply of plant nutrients both as a result of there being less mineralizable organic material, and leaching of exchangeable cations because of the lowered CEC (Vaughan and Ord, 1984; Wood, 1991; Sumner, 1997). The C:N ratio of organic matter can also be altered thus affecting mineralization/immobilization of N (Alexander, 1961; Black, 1968; Hubble, 1984; Hartemink, 1998a).
- soil biological activity and diversity. This has implications for: nutrient turnover (mineralization and immobilization), soil physical properties (aggregation and water retention) and the multiplication of soil-borne plant pathogens (Vaughan and Ord, 1984)
- soil aggregation and increase in bulk density which negatively effects soil aeration, water infiltration, drainage and root penetration (Vaughan and Ord, 1984; Ekwue, 1990; Schjønning *et al.*, 1994; Sumner, 1997)
- soil water holding capacity (Vaughan and Ord, 1984; Ekwue, 1990)
- soil physical conditions at the soil surface, such as surface seals which reduce infiltration, increase runoff and therefore erosion and decrease seedling emergence (Vaughan and Ord, 1984; Sumner, 1997), although this may not be substantial in high clay-containing soils (Warkentin, 1982).

With the serious implications of losses of soil organic matter in mind, efforts should be made to, at least, minimise this loss as much as possible.

2.2.4 Bulk density and compaction

An increase in bulk density usually occurs in the soil in the sugarcane inter-rows as a result of wheeled traffic from field operations (Swinford and Boevey, 1984; Wood, 1985; Hartemink and Kuniata, 1996; Braunack, 1997; Hartemink, 1998a). This is aggravated when the soils are wet (Maud, 1959; Meyer *et al.*, 1996), a factor which cannot always be avoided as essential operations may need to take place. In addition, losses of soil organic matter (Schjønning *et al.*, 1994) and sodicity can lead to clay dispersion (Johnston, 1981) and this may contribute significantly to increasing bulk density. Increases in bulk density lead to:

- increases in soil strength (Swinford and Boevey, 1984)
- decreases in air-filled porosity (Humbert, 1968b; Swinford and Boevey, 1984)
- lowered water infiltration (Hartemink, 1988a; Hussein, 1998) and an increased risk of erosion.

These processes ultimately lead to a drop in cane yield as root penetration is lowered in areas of high bulk density as a result of the large amount of energy required to penetrate a more massive soil (Trouse and Humbert, 1961; Humbert, 1968b; Wood, 1985; Torres and Villegas, 1993; Hartemink and Kuniata, 1996). In addition, lower water infiltration rates (particularly prevalent on vertisols) of inter-rows lower irrigation efficiencies, thus contributing to lowered yields (Hartemink, 1998a).

Heavy clay soils are very prone to structural degradation (Probert *et al.*, 1987). Heavy machinery often compacts vertisols, while plough pans are formed beneath the tilth, so increasing the bulk density of these soils (FAO, 1965). Tillage of wet heavy clay soils leads to structural damage, changes in pore size distribution (a loss of larger pores giving a greater proportion of finer pores) and increases in bulk density (possibly to the extent that a plough pan is formed) (Smith *et al.*, 1984 cited by Probert *et al.*, 1987; Puentes *et al.*, 1988). These then lead to slower drainage, which then may result in increased anaerobosis, denitrification, surface runoff and erosion (Puentes *et al.*, 1988). However Warkentin (1982) found that the effect of cultivation on the soil structure of heavy clay soils is less than that of cultivation on medium-textured soils. This is because of the self-mulching effect of alternate wetting and drying which creates macroporosity in vertic soils.

This was reflected in a study by Hartemink (1998a), who found that below 0.3 m the inter-row bulk density of the vertisols he studied was no different to that within the row. In other non-vertic soils he studied, the bulk density was higher in the inter-row area than within the row even at depths below 0.3 m.

2.2.5 Clay mineralogy and water retention

Sugarcane can survive extreme soil moisture conditions. For instance in Hawaii in 1958, some sugarcane survived for four months without water, and revived itself once water was applied (Humbert, 1968b). In Mexico, it has been recorded that sugarcane survived flooding for several weeks under 0.9-1.2 m water (Humbert, 1968b). These characteristics are an advantage when growing sugarcane in heavy clay soils. This is because heavy clay soils are sticky, cohesive, plastic and virtually impermeable when wet; and hard and massive, hard and blocky or prismatic (with cracks) when dry (Young, 1976; van Wambeke, 1991).

Over 80 % of the clay content of vertisols can consist of fine clay (< 0.2 μm) , resulting in vertisols being exceptionally fine-textured. Fine clay content in carbonate-containing vertisols tends to be more variable, with carbonate particles usually falling into the coarse clay (0.2-2 μm) fraction (Ahmad, 1983). Smectites (2:1 expanding clays) tend to predominate in the clay fraction, a factor which gives these soils their characteristic ability to shrink and swell greatly with drying and wetting. As a result of their mineralogy, the structure of heavy clay soils varies greatly with moisture content. This is because moisture content affects the size, shape, grade and consistence of the structural elements of the soil (Dudal and Eswaran, 1988).

The variation in exchangeable Ca and Mg has a great effect on structure, consistence and physical behaviour. Calcium dominated heavy clay soils (which usually have low exchangeable Na levels) tend to have good structure and have a self-mulching surface. In cases where Mg is codominant with Ca, Na levels tend to be higher, and Mg and Na levels increase with depth, resulting in poorer structured heavy clay soils (Hubble, 1984).

Dry vertisols have high initial water infiltration rates (approximately 100 mm h^{-1}) mainly as a result of their cracks. With increasing water content, this decreases as saturated hydraulic conductivities are low (as low as 0.05 mm h^{-1}) when the soil is wet (Zein El Abedine *et al.*, 1969 and Young, 1976). This is because the cracks that conduct large quantities of water close as the soil swells, and the low sand contents of heavy clay soils results in low numbers of large macro-pores (van Wambeke, 1991). Hydraulic conductivity is not only affected by structure, but also by adsorbed cations. Increasing exchangeable sodium percentage (ESP) lowers saturated hydraulic conductivity (Hubble, 1984). Hydraulic conductivity however, is not greatly affected by clay mineral type (McIntyre and Loveday, 1979 cited by Hubble, 1984).

The amount of water held in the subsoil is relatively dependent on the initial wetting of the dry soil. Intense storms with large quantities of rainfall (or equivalent irrigation practices) on dry vertisols leads to moist subsoils as water drains into the cracks and is conducted to depth. On the other hand, gentle, low rainfall on dry vertisols leads to closure of surface cracks without water being conducted to the subsoil. Subsequent rainfall on this moistened, swelled surface soil leads to not only to runoff, but results in the subsoil is not being moistened (van Wambeke, 1991).

The high clay content and montmorillonite mineralogy characteristic of vertisols gives them high water holding capacities (van Wambeke, 1991) as water is held in the inter-layers of montmorillonite, adsorbed on the clay surfaces (as a result of the clay's high surface area) and retained in the very fine packing voids within peds (Ahmad, 1983). The majority of the water responsible for large volume changes with varying water contents is inter-particle water (van Wambeke, 1991). Even when high suction is applied to these soils, they retain much of their water, indicating that although they hold large quantities of water only a small proportion is plant available (Ahmad, 1983). Zein El Abedine *et al.* (1969) working on vertisols in Sudan found that in many cases less than one third of total pore space was occupied by air between pressures of 0.1 and 15 bars, indicating that aeration is a potential problem.

As a result of their unusual water retention properties, heavy clay soils have unique tillage problems and needs. When dry, they are hard and may be massive and require large amounts of energy to be tilled. Tillage of these soils when wet leads to compaction (as a result of compression), soil shearing and smearing (as a result of plastic flow) and puddling (as a result of compaction; Hubble, 1984; Probert *et al.*, 1987). Therefore, the soil moisture content range at which vertisols can be cultivated is relatively narrow (Ahmad, 1983).

2.3 Soil Salinity and Sodicity

Irrigation-induced salinity and/or sodicity under sugarcane has been reported in many parts of the world (Maud, 1959; Bernstein *et al.*, 1966; von der Meden, 1966; Sehgal *et al.*, 1980; Workman *et al.*, 1986; Nour *et al.*, 1989; Ham *et al.*, 1997; Tiwari *et al.*, 1997; Hussein, 1998; Nelson and Ham, 1998; Nyamudeza, 1999). Salinity and/or sodicity has been regarded as the most significant soil chemical property leading to soil degradation under irrigated sugarcane cropping (van Antwerpen and Meyer, 1996).

The cations Na, Ca and Mg and anions Cl and SO_4^- are some of the main soluble salts that accumulate in soils. Ions such as K, CO_3^-, HCO_3^- and NO_3^- usually occur in smaller concentrations (Shainberg, 1975). A saline soil is traditionally classified as a soil with a saturated soil paste extract electrical conductivity (EC_e) of 4dS m^{-1} or more, while a sodic soil has a Na adsorption ratio (SAR_e) greater than 13 or an exchangeable sodium percentage (ESP) over 15% and a pH higher than 8.3 (USSL Staff, 1954a; Gupta and Abrol, 1990; Sumner, 1995). Saline-sodic soils have high salinity and sodicity levels. Sodic and saline-sodic soils generally have soil solutions dominated by Cl^- and SO_4^- ions. By contrast sodic soils, with pH values greater than eight, (i.e. alkaline sodic soils) have soil solutions dominated by CO_3^{2-} and HCO_3^- (Rengasamy and Ollson, 1991).

The total soluble salt (TSS) content of heavy clay soils is highly variable both between clay soils and within soil profiles; the dominant salt is normally NaCl (40-80 % of TSS), unless large quantities of gypsum are present within the soil (Hubble, 1984). Hubble (1984), Abdulla (1985; (cited by Probert *et al.*, 1987), and El-Swaify *et al.* (1985; cited by Probert *et al.*, 1987) reported that large areas of vertisols, although low in soluble salts in the surface layers, have significant concentrations below 50 cm depth in the soil profile. The accumulated neutral soluble salts alter the soil's physical, chemical and biological properties thereby impeding soil fertility (Sarig and Steinberger, 1994) and plant growth (Zahran, 1989; cited by Zahran, 1997) since the ions hinder water uptake and may also be phytotoxic (Zahran, 1997).

Sodicity is more common than salinity (Probert *et al.*, 1987). There is no agreement on critical levels of sodicity. For example some authors (such as Northcote and Skene, 1972 cited by Probert *et al.*, 1987; Gupta and Verma, 1984 cited by Probert *et al.*, 1987; Venkateswarlu, 1984, cited by Probert *et al.*, 1987) suggest varying ESP's between 6 and 10 per cent in soils with low soluble salts are detrimental. However ESP's between 8 and 16 per cent have been measured in African heavy clay soils with good surface structure (van Wambeke, 1991). The effect of high ESP is a breakdown in surface structure (Probert *et al.*, 1987), often leading to the formation of a surface crust (van Wambeke, 1991) and a decrease in consistence and hydraulic conductivity (Hubble, 1984).

2.3.1 Development of Salinity and/or Sodicity

Salinity and sodicity are prevalent in soils under irrigated sugarcane, especially in areas of low rainfall and high evaporative demand (Haynes and Hamilton, 1999). Poor irrigation and drainage management are normally the main causes of salinisation and as the water table rises, salts dissolved in the groundwater, reach the soil surface by capillary movement. This is, in turn, is aggravated if the area has high temperatures which increase the rate of evaporation, leaving salt crystals or crusts on the surface or in the top few centimetres of soil (Humbert, 1968a; Carter, 1975; Shainberg, 1975). In addition, soils of high pH can accumulate bicarbonate (Brown, 1976). The formation of bicarbonate is favoured in moist, calcareous soils containing decomposing organic matter (Brown, 1976).

Irrigation of heavy clay soils must therefore be managed carefully. Low slope gradients and the low hydraulic conductivity of moist heavy clay soils may lead to ponding of water on the surface once the profile is already waterlogged. This can be detrimental to crops that are sensitive to waterlogging and poor aeration, such as cotton (Probert *et al.*, 1987). The effectiveness of subsequent irrigations may be largely dependent on the extent to which the soils have dried out and cracked prior to water applications. Another problem is that of salinisation as a result of poor quality irrigation water and/or upward movement of salts through unsaturated flow of rising ground waters. This is especially a problem with salt-sensitive crops. The low drainage rate of an irrigated heavy clay soil may prevent the attainment of a desired leaching ratio that would prevent salinisation (Probert *et al.*, 1987). Once the groundwater table rises, the only viable option is to install artificial drainage. The type of drainage is mainly dependent on the economics of the crop, but usually only surface drainage has been considered for heavy clay soils (Probert *et al.*, 1987).

The general move towards decreased cultivation (i.e. conservation tillage or no-till) is difficult to achieve on furrow irrigated heavy clay soils. This is because the soil must be worked in order to form ridges and furrows. There is evidence that this tillage may worsen soil structure, especially if performed at incorrect water contents (Probert *et al.*, 1987). Tillage of irrigated heavy clay soils at their optimal water content may be difficult as although the surface soil may be at optimal moisture content, the subsoil may still be too wet (Probert *et al.*, 1987).

2.3.2 Consequences for Soil Chemical Properties and Processes

The effect of salinity on soil chemical properties is not considered as severe as the effect of sodicity since the latter leads to unbalanced soil fertility (Mortvedt, 1976). Chloride, CO_3^-, HCO_3^-, SO_4^-, Mg^{2+} and Na^+ are generally the predominant ions in soil solution in sodic soils (USSL Staff, 1954b; Naidu *et al.*, 1995b). Calcium is usually present in low concentrations and is often the limiting factor to both plant nutrition and soil structural stability. Potassium is also often found in low proportions, but a constant supply of K is assured in many sodic soils because their mineralogy is dominated by smectites (Naidu and Rengasamy, 1995).

Under sodic conditions, soil pH typically rises to between 8.5 and 10 because of hydrolysis of exchangeable Na (Shainberg, 1975). This in turn, markedly reduces the solubility and plant availability of Zn, Fe, Cu and Mn due to the adsorption/precipitation reactions (Mortvedt, 1976; van Wambeke, 1991; Naidu and Rengasamy, 1995). However, it is noted here that solubilization of organic matter at high pH may mobilize elements such as Cu and Zn (i.e. by formation of soluble complexes), thus providing adequate Cu and Zn nutrition to plants (Jeffery and Uren, 1983). The solubility of B and Mo increases with increasing soil pH, and B toxicity therefore becomes a potential problem in sodic soils (Naidu and Rengasamy, 1995).

Phosphorus availability is generally increased under sodic soil conditions. This is because the soil solution P concentration increases (Sharpley *et al.*, 1988). When Na replaces Ca, Mg and Al on the exchange sites, surface negative potential is increased leading to desorption of P (Naidu and Rengasamy, 1995).

In high pH, calcareous, sodic soils N availability can be decreased by increased N losses. These can occur particularly where NH_4^+ fertilizers are used through the process of NH_3 volatilization and precipitation of $(NH_4)_2CO_3$ (Dalal and Clarke, 1984).

Waterlogging can be a serious problem in soil profiles with sodic horizons. As noted in section 2.3.3, Na-induced dispersion results in soils with low infiltration capacities and lowered hydraulic conductivities. Due to reduction reactions under anaerobic conditions, ions such as Zn^{2+}, Co^{2+}, Cu^{2+}, Fe^{2+} and Mn^{2+} become more soluble and therefore more plant-available (Ponnamperuma, 1984, cited in Naidu and Rengasamy, 1995). Nonetheless, in alkaline sodic soils, the high pH means that the solubilized ions are rapidly removed from soil solution by adsorption/precipitation reactions (Naidu and Rengasamy, 1995). Phosphorus availability is also generally enhanced under anaerobic conditions as a result of reduction of ferric phosphates and hydrolytic dissolution of other phosphates (Ponnamperuma, 1984, cited in Naidu and Rengasamy, 1995). However, the high pH will favour precipitation of the solubilized P as calcium phosphates. The availability of N is also affected by reducing conditions which favour the gaseous loss of N as N_2O and N_2 through the process of denitrification (Curtin and Naidu, 1998, cited in Nelson and Ham, 2000).

2.3.3 Consequences for Soil Physical Properties

The effect of soil salinity and/or sodicity on soil physical properties has been well documented (Humbert, 1968a; Bakker *et al.*, 1973; Shainberg, 1975; Johnston, 1978; Levy *et al.*, 1997; Haynes and Hamilton, 1999). Dispersion/flocculation phenomena are important factors determining soil physical properties (Rengasamy and Olsson, 1991; Sumner, 1995). Cations near the negatively charged clay surfaces are subject to an electrostatic attraction toward the surface as well as a tendency to diffuse into bulk solution. As a result, the concentration of cations diminishes exponentially as a function of distance from the clay surfaces. The partition of cations between surface sorption in the diffuse layer and solution is termed the electrical double layer. The formation of the double layer leads to mutual repulsion of opposing clay surfaces in dilute electrolyte solutions (Shainberg *et al.*, 1989). As the valency of the cations and/or solution ionic strength increases, the diffuse layer is compressed and the repulsive force decreases.

Attractive forces also exist between clay particles and these are dominated by Van der Waals forces. These attractive forces diminish with increasing separation distance. Thus, as the double layer is compressed attractive forces become more important. Where the net force is attractive, the clay particles remain close together and are described as flocculated (Shainberg *et al.*, 1989). Conversely, if the net force is repulsive the particles move further apart and may exist as separate entities in a dispersed state.

Thus, dispersion is favoured by factors that promote the formation of negative electric fields, and therefore repulsive forces, around clay particles (Shainberg *et al.*, 1989). Important factors include a dominance of monovalent cations, such as Na and low ionic strength (i.e. sodic conditions), and a high soil pH (Shainberg *et al.*, 1989). A high soil pH increases the net negative charge on soil surfaces resulting in an increased ratio of negative to positive charges (Arora and Coleman, 1979; Suarez *et al.*, 1984; Shainberg *et al.*, 1989).

Salinity reduces the effect of sodicity on soil physical properties in saline-sodic soils through flocculation of clay particles. The presence of free electrolytes causes an increase in the ionic strength of the soil solution which in turn, counteracts the dispersion of clay particles initially caused by repulsive forces as a result of the hydration of Na and net negative charge on the clay surfaces (Shainberg, 1975; Rengasamy, 1998). The EC_e level at which the clay particles flocculate at different levels of sodicity is known as the threshold electrolyte concentration (TEC) level. The dispersion of clays in relation to salinity and sodicity has been studied by many workers (Quirk and Schofield, 1955; Frenkel *et al.*, 1978; Rengasamy *et al.*, 1984; Greene *et al.*, 1998) and the relationship is demonstrated in Figure 2.1. Quirk and Schofield (1955) and Rengasamy and Olsson (1991) also found that salinity negated the effect of sodicity on dispersion.

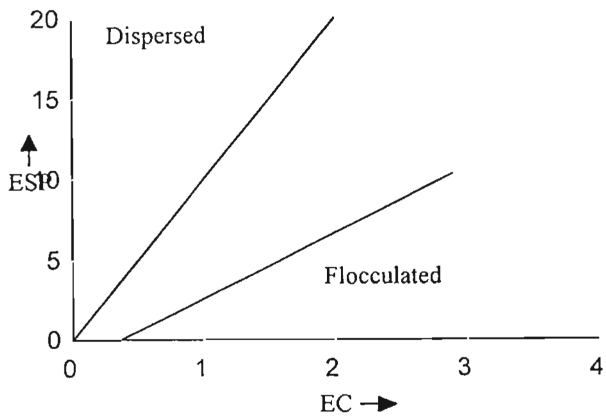


Figure 2.1: Diagrammatic illustration of the dispersive behaviour of clays as related to EC and ESP (Sumner, 1993).

Where soils have been limed, the increased electrolyte concentration and the cementing actions of $CaCO_3$ interact with the effect of increased pH in influencing dispersion/flocculation. That is, increasing levels of $CaCO_3$ have been found to decrease clay dispersion (Gupta *et al.*, 1984a) while increasing pH tends to promote clay dispersion (Suarez *et al.*, 1984). The flocculating effect of $CaCO_3$ can sometimes override the dispersive effect of high pH (Gupta *et al.*, 1984b). Calcite is present in many sodic soils as a natural secondary mineral and its presence may sometimes temper the dispersing effect of high Na concentrations (Gupta and Abrol, 1990).

The flocculated state of saline soils results in soil water infiltration and permeability rivalling or out-competing those of similar non-saline soils (Shainberg, 1975). This, however, is not the case in sodic soils that have poor water infiltration, hydraulic conductivity and low aeration. This arises as a result of increased exchangeable Na, leading to dispersion of clay particles that swell, lowering pore size and causing blockage of pores (Humbert, 1968a; Shainberg, 1975). Wet sodic soils have poor movement of air and water, while dry sodic soils often have a soil surface crust and when tilled breaks into hard clods (Humbert, 1968a). The physical properties of saline-sodic soils are comparable to those of saline soils if the concentration of the salt in the soil solution is high for reasons already discussed. If, however, the soil solution salt levels are lowered (possibly as a result of leaching), the soil pH will rise, dispersion of clay will occur, and the physical properties of the soil will resemble those of a sodic soil (Shainberg, 1975).

2.3.4 Consequences for Soil Biological Properties

Whilst the effects of salinity/sodicity on soil chemical and physical properties are well known (Haynes and Hamilton, 1999) their effects on the soil microbial community and microbiological processes remain relatively unstudied (Oren, 1991, 1999; Szabolcs, 1991). Indeed, several recent comprehensive reviews on the effects of salinity and sodicity on soil properties do not include effects on soil microbial activity (Sumner and Naidu, 1997; Keren, 2000; Levy, 2000). Since organic matter is a substrate for soil microbiota, and is typically concentrated in the top few centimetres of soil, (Murphy *et al.*, 1998) changes in the chemistry of the surface soil (such as an increase in soil salinity) could greatly affect the size, composition and activity of the soil microbial community. In addition, salinity and/or sodicity decreases the availability of water to microorganisms. Therefore microbes may be desiccated under these conditions, and the medium in which many catalytic reactions are performed (the soil solution) is substantially altered (Galinski, 1995; Gianfreda and Bollag, 1996; Oren, 1999). Zahran (1997) also suggested that toxic levels of ions such as Na and Cl may inhibit microbial growth directly.

Many studies have shown that in naturally saline soils, the size of the microbial community has been found to be negatively correlated with total soluble salts (Ragab, 1993; García *et al.*, 1994) but positively correlated with organic C contents (Dick *et al.*, 1988; Zahran *et al.*, 1992; Ragab, 1993; Haynes, 1999). Additionally, measures of the activity of the microbial community have also been found to be negatively correlated with increasing salinity and/or sodicity (Laura, 1974; García *et al.*, 1994; Sarig and Steinberger, 1994). The rise in pH which accompanies sodicity could also have a negative effect on some agriculturally important microorganisms. For instance the optimal pH range for several bacteria species (such as *Nitrosomonas* spp. and *Nitrobacter* spp.) is below pH values of 8.8 (Burges and Raw, 1967, cited in Rengasamy and Olsson, 1991).

Thus, it seems possible that increasing salinity and/or sodicity induced by irrigation could reduce soil microbial activity, therefore reducing the turnover rate of nutrients held by the soil organic matter (i.e. N, S and P) as well as the rate of decomposition of organic residues added to soils (Naidu and Rengasamy, 1995). Additionally, a reduction in soil microbial activity could adversely affect soil physical properties since microbial polysaccharides and fungal hyphae are intimately involved in soil aggregation (Tisdall and Oades, 1982; Haynes and Francis, 1983). This could be of particular concern in sodic soils where soil physical conditions are already characteristically poor. These aspects of the effect of salinity and/or sodicity on soil conditions are worthy of future study.

2.3.5 Consequences for Crop Growth

(a) Symptoms

The symptoms of excessive salinity have been fairly well-documented in sugarcane. Many of these are also the symptoms of drought stress (Wahid *et al.*, 1997). Symptoms include water stress, premature wilting, a deep pinkish colour of emerging shoots, deep blue-green leaves, stem waxiness (which possibly lowers water loss), scorching of leaves, and at high salinity levels, plant death (USSL Staff, 1954b; Wahid *et al.*, 1997; Culverwell, 2000). Wahid *et al.* (1997) also listed chlorosis, tip burning, arrested growth, thinning of stems and reduced foliage as symptoms of NaCl salinity. Humbert (1968a) found that excessive soil salinity caused the burning of tips of young leaves and of the edges in older leaves, and that leaves tended to be rolled up. The distance between inter-nodes is short, reflecting low growth rates (Humbert, 1968a). Chlorosis is commonly seen in plants growing on calcareous salt-affected soils (USSL Staff, 1954b). As a result of these effects of salinity on sugarcane growth, yield is depressed. Culverwell (2000) suggested salinity hazard ratings for sugarcane in South Africa (Table 2.3).

Table 2.3: Soil salinity (EC_e in the 0-0.6 m soil layer) hazard ratings for sugarcane.

EC_e (mS/m)	Rating	Effects on Sugarcane Growth
0-200	Non-saline	None
200-400	Slightly saline	Slight
400-600	Moderately saline	Severe
>600	Strongly saline	Very severe

From: Culverwell (2000)

It should, however, be noted that sugarcane varieties differ in their tolerance of sodicity. It has been suggested that both saline- and sodic-tolerant varieties of sugarcane decrease or prevent the reduction of photosynthetic area by diluting ion toxicity, either through faster growth or by compartmentalizing superfluous ions into physiologically less active, older leaves (Chavan and Karadge, 1986; Schachtman and Munns, 1992; Wahid, 1994, cited by Wahid *et al.*, 1997; Gupta and Abrol, 1990). In addition to producing low yields, sugarcane harvested from saline soils is often pithy, has poor quality juice and a high salt content (Humbert, 1968a).

(b) Physiological Mechanisms

Sugarcane yield is decreased in salt-affected soils because of the effect of salinity and/or sodicity directly on the plant and indirectly on the soil physical, chemical and biological properties (discussed above). Plants growing under saline and/or sodic soil conditions have lowered yields as a result of:

- increased plant water stress and poor root development. Saline soils lower the water potential of the soil solution, thus impairing the ability of plants to absorb water. This leads to water stress in the plant (von der Meden, 1967; Humbert, 1968a; Flach, 1976; Naidu *et al.*, 1995b; Keren, 2000; Nelson and Ham, 2000). In addition, under saline conditions, as plants extract water from the soil, the remaining soil solution becomes more concentrated until new less concentrated water is introduced to the system by rainfall or irrigation. This then results in fluctuating levels of soil salinity, which can cause plants considerable stress (Humbert, 1968a; Mass, 1986 cited by Sarig and Steinberger, 1994).

- increased levels of the hormone abscissic acid. Abscissic acid is involved in stomatal closure, thereby lowering transpiration. This, in turn, decreases passive uptake of salt and increases the water content of the tissue which results in a reduction in the ionic concentration within the plant. Disadvantages of stomatal closure are lowered CO_2 uptake and therefore a diminished rate of photosynthesis and growth (Gale, 1975a).
- leaf chlorosis, and eventually leaf necrosis, leading to a lowered photosynthetic rate per unit leaf area. This occurs primarily as a result of deterioration of the photosynthetic apparatus due to excessive levels of soil salinity and/or growth in saline soils for extended periods of time (Gale, 1975a).
- reduced production and expansion of leaves under saline conditions (Rawson *et al.*, 1988; Kumar *et al.*, 1994 cited by Wahid *et al.*, 1997). This directly lowers growth rate and ultimately crop yield (Wahid *et al.*, 1997).
- increased respiration. Energy from respiration, is needed for the pumping of ions against an electro-chemical gradient and for maintenance of turgor pressure. The resulting increased rate of respiration results in reduced plant growth. Respiration is, however, eventually reduced at very high levels of salinity (Gale, 1975a).
- nutrient deficiencies. As noted in section 2.3.2, the high pH of sodic soils can lead to deficiencies of Fe, Mn, Zn and Cu (van Wambeke, 1991; Naidu and Rengasamy, 1995). In addition, deficiencies of N and S are often encountered in crops grown in sodic soils (Oades, 1988 cited by Naidu *et al.*, 1995b; Naidu and Rengasamy, 1995; Nelson and Ham, 2000) and this has been attributed to reduced mineralization rates.
- sodium-calcium imbalance. Many sodic soils have low concentrations of Ca in soil solution and high Na/Ca ratios which cause a nutritional imbalance. In addition, high concentrations of solution Na reduce Ca uptake by plants, and Ca deficiency is common in plants growing in sodic soils (Sumner, 1997). The decreased Ca uptake effects the permeability of plant membranes which, in turn, can decrease the uptake and transport of other essential nutrients (Levitt, 1980 cited by Naidu and Rengasamy, 1995). Indeed, high Na uptake can lead to deficiencies of K, Zn, Cu and Mn (Levitt, 1980 cited by Levy, 2000). Nonetheless, the low concentrations of Ca in solution can lead to enhanced uptake and hence toxicities of elements like Zn, Ni, Mg, Pb, Se and Al (Levitt, 1980 cited by Naidu and Rengasamy, 1995).

- nutrient toxicities. High concentrations of B, Na and Cl in soil solution are often encountered in sodic soils (van Wambeke, 1991; Naidu and Rengasamy, 1995). Plant metabolism is negatively affected by the increased uptake of these toxic ions (Naidu and Rengasamy, 1993; Naidu *et al.*, 1995a; Keren, 2000). In soils of very high pH (i.e. >8.5) concentrations of HCO_3^- in solution may reach toxic levels and affect nutrient uptake and plant metabolism (USSL Staff, 1954b; Brown, 1976; Mortvedt, 1976; Gupta and Abrol, 1990).

In addition, the effect of salinity on plant growth has been observed to be exacerbated by the following climatic conditions:

- high temperatures
- high radiation intensity
- low air humidity (Gale, 1975b).

2.3.6 Prevention of Development or Aggravation of Salinity and/or Sodicity

Improvements in the efficiency of water application can be made by altering irrigation methods. For instance, drip irrigation is considerably more efficient than furrow irrigation. However, economic (Lee *et al.*, 1985 cited in Robertson *et al.*, 1997) and practical constraints often prevent the change from one irrigation system to another. Improvements must therefore often be made within the existing irrigation system. For example with furrow irrigation, these improvements can be made through better design, by matching factors such as furrow length to the soil type (Raine and Bakker, 1996; Hussein, 1998) and management. Furthermore, the timing of irrigation events, and the amounts of water applied per event can be altered so that the proportion of applied water held in the root zone is maximised and losses are minimised (Robertson *et al.*, 1997).

In the case of heavy textured soils containing 2:1 clay minerals, "drying off" periods are necessary to facilitate the formation of deep cracks that improve drainage. These cracks are further promoted if the soil is not ploughed during this "drying off" period, as ploughing destroys cracks in the surface soil, forming a mulch that will decrease subsoil drying (Hussein, 1998). Ramdial (1974) suggested that the aggravation of salinity in swelling clay soils can be prevented by the maintenance of soil surface cracks. He found that salts accumulated on crack edges and irrigation leached these salts down into cracks and this saline water was then transported down furrows into drains.

2.3.7 Methods of Amelioration

The methods used to ameliorate saline and/or sodic soils are well documented (Sharma, 1971; Johnston, 1978; Sumner, 1995; Hartemink, 1998a; Culverwell, 2000), and below they are broadly discussed with particular reference to sugarcane production.

(a) Saline Soils

Desalinization of saline soils can only be achieved through leaching of the soil profile with non-saline water (Sumner, 1997). This was demonstrated by Johnston (1977), who found that amelioration of saline soils by application of gypsum or S only resulted in small decreases in EC_e when compared to simply leaching with water, although there were benefits to sodic soils. Continuous ponding of a saline soil with a volume of water equivalent to the bulk volume of soil to be ameliorated generally results in the leaching of 60 % or more of the total salts (Sumner, 1997). Oster *et al.* (1996; cited by Sumner, 1997) concluded that the efficiency of leaching was increased with intermittent ponding or sprinkler application of water. Leaching of saline soils with non-saline water may lead to the development of sodic behaviour once most of the salts have been removed (Sumner, 1997). To prevent this, gypsum must be applied to the soil or slightly saline water must be used for leaching (Sumner, 1997). In practice, leaching the profile of some soils can be a problem. For example, van Wambeke (1991) found that deep vertisols are very poorly drained, making leaching of these profiles for the amelioration of salinity problematic.

(b) Sodic Soils

The application of gypsum is the generally accepted method of amelioration of sodic soils (Sharma, 1971; Szabolcs, 1971 cited by Johnston, 1977; Johnston, 1978; Sumner, 1997; Nelson and Ham, 1998). This is because it not only decreases the dispersion of clay and the formation of surface crusts through providing adequate levels of electrolyte, but also decreases ESP and improves hydraulic conductivity by supplying Ca^{2+} ions which displace Na^+ on exchange sites (Sumner, 1997). Traditionally, in American literature, it is only necessary to apply gypsum to soils with an ESP of more than 15%. Other authors have, however, found that yield responses occurred at ESP's below 6% (Birch and Adriaans, 1984) or even below 1% (Bridge, 1968 cited by Birch and Adriaans, 1984) Bridge (1968; cited by Birch and Adriaans, 1984) proposed that factors besides ESP, such as soil texture contribute to a soil's gypsum responsiveness. Bakker *et al.* (1973) found that clay dispersion was caused by exchangeable Mg and Grierson (1978) (cited by Birch and Adriaans, 1984) found that an exchangeable magnesium percentage (EmgP) above 20 % induces clay dispersion. However other authors such as Brooks *et al.* (1956) did not find that exchangeable Mg had any effect on soil structure.

Culverwell (2000) investigated the use of not only gypsum, but also elemental S and filtercake on sodic soils under sugarcane. He found that gypsum reduced the SAR faster than the other two ameliorants (for instance, it was four times faster than filtercake). Johnston (1975), however, found that S was almost as effective as gypsum at reducing the SAR (measured in saturated paste). Sulphur and filtercake do have benefits that do not accrue from gypsum applications. For example, soil acidification induced by ammonium sulfate (van Antwerpen and Meyer, 1996) or sulphuric acid (Johnston, 1977; Rengasamy and Olsson, 1991) may be preferable in instances of high pH (i.e. alkaline sodic soils); while the use of filtercake will increase soil organic matter levels (Culverwell, 2000). Increases in the buffering capacity of the soil and it's resistance to compaction are additional benefits that can occur due to increases in soil organic matter (Hartemink, 1998a). The application of filtercake (a waste product of sugar mills) can be practical in areas close to mills. However, unless filtercake can be incorporated to depth, the ameliorative effects are confined to the surface layers of sodic soils (Levy, 2000). In addition, some authors recommend the application of a calcium-based amendment prior to the application of organic materials to sodic soils so that Na is replaced by Ca, to allow stable organic matter linkages to form between particles (Gupta *et al.*, 1984b). It must be noted, however, that several authors (Aylmore and Sills, 1982; Gupta *et al.*, 1984b; Rengasamy and Olsson, 1991) found organic matter to either have no effect or a negative effect on the soil physical conditions of alkali-sodic soils (as it increased the dispersion of clay). It was therefore recommended by Gupta *et al.* (1984b) that soil sodicity and alkalinity must be lowered prior to applications of organic matter. Johnston (1977) concluded that gypsum was slightly better than S at ameliorating sodic soils from the point of view of soil physical and chemical properties and sugarcane yield. Other ameliorants suggested by Gupta and Abrol (1990) such as calcite, iron, and aluminium sulfates and pyrite may also be considered depending on factors such as amelioration capacity, cost and availability.

Results presented in Table 2.4 demonstrate the positive effect that phosphogypsum application can have on sugarcane yields in a slightly sodic soil in Swaziland. Yield increases were substantial four to seven years after its' application. Although the application of gypsum increased EC_e, it reduced ESP markedly to a depth of 1.2 m. Probert *et al.* (1987) found that even in poorly drained sodic vertisols, the application of gypsum in conjunction with increased drainage improved infiltration, lowered crusting and increased crop yields.

Table 2.4: Effect of the application of phosphogypsum to a soil on sugarcane yield over seven seasons and the resultant exchangeable sodium percentage (ESP) and electrical conductivity in a saturated soil paste (EC_e) of that soil and the control.

Crop	**Sugarcane yield (t ha^{-1})**	
	Control	**Gypsum**
Plant	120	126
First ratoon	84	102
Second ratoon	95	97
Third ratoon	96	132
Fourth ratoon	94	122
Fifth ratoon	72	123
Sixth ratoon	77	124
Average	91	118
Soil Property		
ESP (%) (0-30cm)	8.5	2.0
ESP (%) (90-120cm)	16.2	7.0
EC_e (mS m^{-1}) (0-30cm)	500	800
EC_e (mS m^{-1}) (90-120cm)	700	1200

Adapted from: Sumner (1997).

(c) Saline-sodic Soils

In the case of saline-sodic soils, the general consensus is that a combination of the strategies for the amelioration of both saline and sodic soils should be used (von der Meden, 1967; Workman *et al.*, 1986; Sumner, 1997). Many authors (von der Meden, 1967; Workman *et al.*, 1986) suggest leaching, possibly with the prior installation of drains, to lower salinity; and the application of gypsum to decrease sodicity. For example, furrow irrigation of soils under sugarcane in Swaziland resulted in a decline in yields attributed to salinity and sodicity and waterlogging (Workman *et al.*, 1986). Drains (both open ditches and salt-glazed tile layouts) were installed in areas that had salinity values greater than 1 dS m^{-1} in the top 60 cm, water logging and poor growth. Gypsum was applied to soils with an excess of Na salts. The combination of water control and gypsum application resulted in sugarcane yields being almost restored to those that were obtained prior to the development of saline-sodic conditions. Yield increases were also observed where additions of organic matter (in the form of filter cake or a summer crop of sunnhemp, *Crotalaria juncea*, during a fallow) were made, especially in fields that could not be further improved by drainage (Workman *et al.*, 1986).

Improvements to soil conditions using these methods have been seen in saline-sodic vertic soils. For instance, Ahmad and Webster (1988; cited by van Wambeke, 1991) found improvements in soil structure, saturated hydraulic conductivity and penetration of soil by sugarcane roots in vertisols in Barbados. This was achieved through the application of gypsum (which reduced sodicity), while salts on the soil surface were removed by surface runoff. However, the low drainage rates of heavy clay soils means that amelioration may take many years (Hussein, 1998). For instance, the poor hydraulic conductivity resulted in little effluent being removed through the subsurface drains in a study performed by Greene and Snow (1939).

2.3.8 Alternative Uses for Saline and/or Sodic Soils

Other land uses could be considered for salt-affected soils under sugarcane. For instance, the planting of more salt-tolerant crops such as cotton, bermuda grass (for livestock production), barley or sorghum might be viable options. Aronson (1985; cited by Zahran, 1997) compiled a review of agriculturally and horticulturally significant halophytes, and this information could be used to develop alternative crops. Zahran (1997) suggested the use of N_2 fixing bacteria in conjunction with salt tolerant legumes or halophytes, so increasing the N fertility of saline areas. Saline and/or sodic areas still under virgin vegetation should probably not be converted to cultivation, but rather incorporated into areas used for livestock production or game farming.

2.4 Conclusions

It is evident that decreased nutrient status, loss of soil organic matter, soil acidification, degradation of soil structure and compaction can all contribute to soil degradation under sugarcane production. Strategies such as the return of organic matter to the soil (through green cane harvesting rather than pre-harvest burning, addition of bulky organic manures and the use of green crops), avoiding working the soil when it is too wet and regular applications of lime and fertilizer can, however, arrest or prevent these problems.

Specific problems associated with the management of vertisols are primarily related to their high content of smectitic clays which imparts them with their capacity to swell when wet. If they are allowed to dry periodically, they crack and macroporosity is restored. However, if they are continuously moist, they have a low infiltration capacity and hydraulic conductivity.

Irrigation-induced salinity and sodicity are common problems in many arid parts of the world under a range of different crops, including sugarcane. Substantial losses of crop production can accrue. Although the effects of salinity and sodicity on soil physical and chemical properties are well documented, little is known about their effects on soil biological properties. Appropriate methods of ameliorating salt-affected soils are well-known, although in practice they may often be difficult and expensive to implement. Prevention of these problems developing under irrigated crop production is certainly a prudent management strategy.

CHAPTER 3

IRRIGATION-INDUCED SALINITY AND SODICITY AND ITS EFFECT ON SUGARCANE YIELD

3.1 Introduction

As world food demand escalates and agricultural land area decreases, the need to obtain greater yields per unit area increases. One way of achieving this is to irrigate areas that naturally do not have enough rainfall to adequately supply the water requirements of certain crops. Between the mid 1980's and mid 1990's, irrigated crops generated over 50% of the increases in world food production, and this will probably continue (Oster, 2000 cited in Culverwell, 2000). The irrigation of increased areas of arid land, has in many cases, led to a concomitant rise in the area of land affected by a shallow water table. This, in conjunction with a high evaporative demand, poor quality irrigation water and possible increases in fertilizer application has led to the intensification and expansion of saline and/or sodic areas (Oster, 2000 cited in Culverwell, 2000). Steps need to be taken to arrest, or at least decrease, the rate of formation of this type of land degradation. The scale of soil degradation attributed to salinity/sodicity can be judged from the estimation that in 1990, 33% of the world's potentially arable land area was salt-affected (Gupta and Abrol, 1990).

Although small quantities of soluble salts in the soil are often considered beneficial to soil physical properties (through flocculation of clay particles), large quantities are detrimental to most crops (Sumner, 1997). Soluble salts originate from the irrigation water or from within the soil profile via weathering of minerals during soil formation. The majority of these salts are the chlorides of Ca, Mg and Na (Rengasamy and Olsson, 1991). Salinity and/or sodicity usually arises in irrigated agricultural soils as a result of the increased inputs of water to the soil which cause the water table to rise closer to the soil surface. Once this occurs, capillary action and evaporation cause the salts to concentrate near the soil surface. This, in turn, alters the soil's physical, chemical and biological properties. The processes that lead to the formation of salt-affected soils, their resultant properties, as well as their management and amelioration have been described in several reviews (Bresler *et al.*, 1982b cited in Sumner, 1995; Shainberg and Letey, 1984 cited in Sumner, 1995; Gupta and Abrol, 1990; Oster, 1993 cited in Sumner, 1995). In addition, in arid areas, sodicity is often associated with alkalinity (i.e. high levels of dissolved carbonate and bicarbonate in soil solution resulting in a high soil pH; Suarez *et al.*, 1984). The creation of alkalinity is dependent on clay mineral type, exchangeable Na levels and the concentration of the soil solution. It develops as a result of ion exchange of Na and Ca in soils and hydrolysis of Na-rich exchangers (Mashhady and Rowell, 1978).

The amount of land planted to sugarcane has consistently increased over the last century (Bramley *et al.*, 1996). Sugarcane is ideally suited to tropical areas, but has expanded into lower rainfall, sub-tropical areas where irrigation is essential to ensure high yields (Wahid *et al.*, 1997). Irrigation-induced salinity and/or sodicity under sugarcane has been reported in Australia (Ham *et al.*, 1997; Nelson and Ham, 1998), Egypt (Nour *et al.*, 1989), Iraq (Sehgal *et al.*, 1980), United States (Bernstein *et al.*, 1966), India (Tiwari *et al.*, 1997), Pakistan (Anonymous, 1994 cited in Wahid *et al.*, 1997), Swaziland (Workman *et al.*, 1986), South Africa (Maud, 1959; von der Meden, 1966) and Zimbabwe (Hussein, 1998; Nyamudeza, 1999). In the more arid, irrigated areas of the world, soil salinity and sodicity are considered to greatly limit sugarcane yield (Blackburn, 1984 cited in Nelson and Ham, 2000; Ham *et al.*, 1997; M'Ba Minko and Valet, 1998 cited in Nelson and Ham, 2000; Rozeff, 1998). In fact, van Antwerpen and Meyer (1996) considered increasing soil salinity and/or sodicity to be the most significant soil chemical processes leading to soil degradation under irrigated sugarcane.

The negative effect of salinity and/or sodicity on sugarcane yield has been confirmed by a number of workers (Bernstein *et al.*, 1966; Sehgal *et al.*, 1980; Culverwell and Swinford, 1986; Nour *et al.*, 1989; Ham *et al.*, 1997; Nelson and Ham, 1998). Generally, sugarcane is considered to be moderately sensitive to salinity, and sensitive to sodicity (Bower, 1959 cited in Nelson and Ham, 2000; Maas and Hoffman, 1977; Landon, 1984 cited in Nelson and Ham, 2000). Salinity generally causes water stress through osmotic effects while sodicity results in an increased pH, nutrient imbalances and clay dispersion which results in poor penetration of water, air and roots, low readily-available water holding capacity and difficulties in timely and effective tillage (Gupta and Abrol, 1990; Nelson and Ham, 2000).

On the vertic soils of the study area in the Zimbabwean lowveld, sugarcane yield decline is a major problem. In particular, yields of ratoon crops decline rapidly so that normally after only three or four ratoon crops the fields are replanted. The major factors leading to this yield decline are believed to be soil salinity and/or sodicity which have been induced by over-irrigation (Hussein, 1998). Visual observations have revealed that yields decline from high to low ends of the furrow irrigated fields and that crop death at the lower end is associated with accumulation of salts at the soil surface and/or dispersion and loss of soil structure. The aim of this study was to investigate the cause of yield depressions and crop death in these fields with particular reference to irrigation-induced soil salinity and sodicity.

3.2 Materials and Methods

The study was conducted on Hippo Valley sugarcane estate situated in the Zimbabwean lowveld close to the town of Chiredzi (approximately 31°30′ longitude, 21°10′ latitude). The altitude on the estate varies between 320 and 600 m above sea level, although most of the cane is grown between altitudes of 320 and 400 m above sea level. The area receives between 400 and 600 mm rainfall per annum (mainly during summer months), while the temperature ranges between 9 and 38°C (mean of 24°C). As a result of the relatively low annual rainfall combined with high temperatures, evaporative demand is high in this area. Clowes and Breakwell (1998) estimated that an annual precipitation deficit of about 1400 mm, making irrigation essential for the adequate production of many crops. The study sites were on vertic soils which were classified as Bonheim form, Windermere family (Soil Classification Working Group, 1991) or Luvic Phaeozem (FAO). Soils have a clay content of 25 to 35% and their mineralogy was dominated by smectite, in particular montmorillonite with some accessory vermiculite and kaolinite present.

Four furrow irrigated fields, with a slope of less than five per cent, no subsurface drainage and an area of approximately 12 ha, were chosen. These fields were observed to have a gradient of salinity and/or sodicity from apparently unaffected sugarcane at the upper ends of the fields (where irrigation water is applied) to extremely poor or dead sugarcane at the lower ends where salt accumulation at the soil surface was evident. Crops were all at least in their second ratoon at each site.

In each field, four areas of cane were visually identified down the gradient and characterised as (i) dead and dying cane, (ii) poor cane growth, (iii) satisfactory cane growth and (iv) good cane growth. A plot 2 rows by 2 metres (row spacing = 1.5 m) was pegged out at each area. Soil samples (0-0.15 m, 0.15-0.3 m, 0.3-0.6 m and 0.6-0.9 m) were taken randomly (both within and between sugarcane rows) in an area of 2 metres radius around the plots in July 1999 (just prior to harvest). Ten samples were taken and then were bulked for each layer of each area. Soil samples were air-dried and sieved (<2 mm).

Plate 1: A field (site 3) showing the change in sugarcane growth from the low lying areas of the field to the upper ends of the field.

During July, plant growth parameters (mean sugarcane stalk height and mean number of nodes per stalk) were recorded for each study area. Just prior to commercial harvest, the areas were hand-harvested and yields were recorded. All sites were burned prior to harvest. The crop cultivar at each site was NCo376 and the ratoon was harvested at approximately 12 months of age.

Foliar samples of the sugarcane in these plots was taken when the cane was about 22 weeks old in the following ratoon. This is the recommended stage of growth at which foliar samples of sugarcane are taken in Zimbabwe (Clowes and Breakwell, 1998). The first fully expanded leaf from the top of the cane plants (usually the third leaf down the stalk) was collected, the midribs removed, the leaves from each plot bundled and the tops and bottoms chopped off (Clowes and Breakwell, 1998). Foliar samples were oven-dried at 95°C for 24 hours and ground (<0.5 mm).

Soil pH was measured in a 1:2.5 soil:water slurry using a glass electrode. Saturation paste extracts were prepared, the electrical conductivity (EC_e) of extracts was measured and the Ca, Mg and Na content was analysed by atomic absorption spectrophotometry. The sodium adsorption ratio of the extracts (SAR_e) was calculated as:

$$SAR_e\ (cmol_c\ L^{-1}) = \frac{[Na^+]}{\surd 0.5\ ([Ca^{2+}] + [Mg^{2+}])} \qquad (i)$$

The cations Ca, Mg, K and Na were extracted with 1N ammonium acetate and were determined by atomic absorption spectrophotometry (Beater, 1962). Exchangeable cations were calculated as ammonium acetate-extractable cations less the soluble (saturation extract) cations.

The effective cation exchange capacity (ECEC) was assumed to be equal to the sum of exchangeable bases. Since all of the soils had a $pH_{(water)}$ of above 8.0, exchange acidity was not measured. Exchangeable Na percentage (ESP) was calculated as:

$$ESP = \frac{\text{Exch. } Na^+}{\text{Exch. } (Ca^{2+} + Mg^{2+} + K^+ + Na^+)} \times \frac{100}{1} \qquad (ii)$$

During routine analysis of saturation paste extracts, the CO_3^{2-} and HCO_3^- content was unfortunately not measured. Since soils generally had pH values ranging from 8 to 10, the CO_3^{2-} and HCO_3^- contents were considered important. For that reason, and for ease of extraction, 1:5

soil:water extracts were prepared for samples of the 0-0.15 m layer of each plot and these were titrated with 0.025N H_2SO_4 to pH values of 8.2, for CO_3^{2-} determination, and 4.5 for HCO_3^- determination, (USSL Staff, 1954c; Mashhady and Rowell, 1978). Alkalinity of extracts was then calculated. Between pH 6 and 10 $[OH^-]$ and $[H^+]$ are negligible if CO_2 is present (Mashhady and Rowell, 1978) and alkalinity ($Alk_{1:5}$) was calculated as:

$$Alk_{1:5}\ (cmol_c\ kg^{-1}) = [HCO_3^-] + 2[CO_3^{2-}] \qquad \text{(iii)}$$

Aggregate stability was described by three methods. For all methods field-moist soil was sieved through a 6.25 mm and 2 mm sieve, and the aggregates between these sieves were collected and air dried.

The conventional method of Emerson (1967) and that modified by Loveday (1974) were used to assess aggregate dispersion. The method of Emerson (1967) involves two steps:

(i) air-dry aggregates are immersed into distilled water and are left undisturbed. Observations are made 2 hours and 20 hours after immersion. Slaking and the degree of dispersion is recorded at each time interval and aggregates are classed according to Emerson's procedure, with the modified inclusion of subclasses.

(ii) soil samples (<2 mm) of soils that slake but do not disperse in (i) are moistened and equilibrated to a suction water content of -10 kPa overnight. This soil is then reworked and moulded to form a cube. These are also immersed in distilled water and the amount of dispersion noted after 2 and 20 hours. The soil is again classed according to Emerson's procedure and the modified subclasses. If dispersion does not occur, the soil is tested for the presence of $CaCO_3$ with HCl.

Therefore aggregates falling into classes 1 and 2 suffer from slaking and dispersion of air dry aggregates, class 1 being the most dispersed followed by class 2 and its' subclasses in descending order. Subclasses of class 2 and 3 are determined by the proportion of the aggregate that has dispersed, i.e. the subclass increases from 1 (slight dispersion) to 4 (total dispersion). Class 3 indicates dispersion of the remoulded aggregates, increasing with increasing subclass value, while class 4 indicates the presence of $CaCO_3$. Classes 5 and 6 apply to acid soils with low ESP, while classes 7 and 8 indicate a high organic matter content.

The second method is similar to the above method and was described by Loveday (1974). However the aggregates are rated according to a dispersion index (DI) rather than classed. Aggregates (both air dry and remoulded) are scored at 2 and 20 hours according to their level of dispersion (0 being no dispersion through to 4 being complete dispersion). These scores are then added together. An additional eight units are added to the total scores of soils which have air dry aggregates that disperse. Therefore highly dispersive soils have a possible DI of 16, which decreases with a decreasing rates and degrees of dispersion.

The third method involved taking an oven dry equivalent soil mass of 30 g of aggregates which were then wet sieved by a modified method of that described by Yoder (1936). The aggregates were transferred to the uppermost of a set of three sieves of 1 mm, 0.5 mm and 0.21 mm mesh size and sieved for 15 minutes. Results were calculated as the mean weight diameter (MWD) as follows:

$$\text{MWD (mm)} = \sum(\text{fraction of sample on sieve} \times \text{mean inter-sieve aperture}) \qquad \text{(iv)}$$

The upper and lower limits of MWD are 3.625 mm and 0.105 mm respectively.

Sugarcane leaf samples were analysed for P, K, Ca, Mg, S, Zn, Fe, Mn and Cu by X-ray fluorescence spectrometry and N by near infra-red reflectance (Wood *et al.*, 1985).

Data relating selected soil chemical and physical properties to one another were fitted to linear, quadratic, cubic and exponential regression functions using the Genstat Release 4.1, Fourth edition statistical package. Regression functions of best fit are presented in the chapter along with the lines of best fit and the statistical significance of the relationships.

In order to relate various soil chemical properties to sugarcane yield, average stalk height and average number of nodes per stalk, the zero-yield data was first discarded. This was done because zero yields were distributed over a wide range of values (i.e. above certain "critical" levels sugarcane death occurs regardless of how large the values become). Soil chemical properties were calculated on a 0-0.15, 0-0.3, 0-0.6 and 0-0.9 m depth basis and sugarcane yield and growth data were then fitted to soil chemical data using linear regression functions. For the most part, linear functions gave equal or better fits than quadratic or cubic functions. Originally, it was planned to use two-years of yield data but the unsettled political situation in Zimbabwe at the time prevented collection of the second years' data. Multiple regression analysis was not attempted because of the limited data set and because the main factors found to be negatively related to yield and growth were ESP and pH. These are highly dependent, rather than independent variables and this would compromise the validity of such an analysis.

3.3 Results and Discussion

3.3.1 Soil Chemical Properties

The alkalinity in the top soil layer (0-0.15 m) and the EC_e, SAR_e, ESP and $pH_{(water)}$ of the four soil layers sampled at the five positions at each experimental site are presented in Table 3.1. In order to provide an indication of the exchangeable cation status of the soil profiles, the mean concentrations 0-0.9 m are presented in Table 3.2. Concentrations of exchangeable cations, ECEC and concentrations of Ca, Mg and Na in saturated paste extracts for each layer at each site are presented in Appendix 1.

The high pH values, between 8 and 9.5 (Table 3.1) of soils under undisturbed veld were not unexpected as concretions were observed within the profiles of these calcareous soils. Indeed, the very high concentrations of exchangeable Ca and Mg present in these soil profiles (Table 3.2) are a reflection of the presence of Ca and Mg carbonates in these soils. Some accumulation of soluble salts at the soil surface of the soils under undisturbed veld was evident by the highest EC_e values being recorded in the 0-0.15 m soil layers (Table 3.1). Surface accumulation of Na is also evident in the undisturbed soil under veld at site 1 (Table 3.1, Appendix 1.1).

At the study sites, irrigation-induced salinity and sodicity had developed. Visual observations were made that the watertable has risen to as close as 0.2-0.3 m from the soil surface in low lying areas. Upward movement of salts had resulted in a visible accumulation of salts on the soil surface particularly at the lower ends of many fields. The salts evidently have a high Na content, as confirmed by the SAR_e and ESP values for these soils (Table 3.1). The relatively high values for EC_e, SAR_e and ESP generally encountered in the surface of profiles of soils under satisfactory, poor and dead and dying sugarcane growth (Table 3.1) demonstrate the negative effect that over-irrigation on these soils has had on their condition. The accumulation of exchangeable Na in the soil profiles under dead, poor, and to a lesser extent, satisfactory sugarcane growth is clearly evident from the data presented in Table 3.2.

Table 3.1: Electrical conductivity (EC_e in mS m^{-1}), sodium adsorption ratio (SAR_e) (mmol $L^{-½}$), exchangeable sodium percentage (ESP in %) and $pH_{(water)}$ at different depths of soils and alkalinity ($Alk_{1:5}$ in $cmol_c$ kg^{-1}) in the 0-0.15 m soil layer from four sugarcane fields. Depth weighted mean values of these soil analyses are given in Appendix 2. Sugarcane growth was identified within each field as being either dead and dying (D), poor (P), satisfactory (S) or good (G). Soil samples were also taken from adjacent undisturbed veld (V).

Depth:		0-0.15 m					0.15-0.3 m				0.3-0.6 m				0.6-0.9 m			
Field	Growth	EC_e	SAR_e	ESP	pH	$Alk_{1:5}$	EC_e	SAR_e	ESP	pH	EC_e	SAR_e	ESP	pH	EC_e	SAR_e	ESP	pH
1	D	2480	22.6	44.9	8.17	0.64	483	45.7	48.1	10.16	166	15.8	43.5	10.30	78	10.9	33.9	10.10
	P	390	33.4	34.9	9.16	4.55	181	17.8	28.5	9.38	86	8.9	27.9	9.51	71	7.9	19.7	9.76
	S	278	29.3	0.3	8.89	5.48	160	1.7	1.8	7.96	77	8.9	13.2	9.64	62	10.9	10.4	9.83
	G	177	12.8	14.4	9.17	2.10	121	7.1	7.4	8.06	49	3.3	3.2	8.23	35	2.8	3.3	8.51
	V	108	15.1	15.0	9.14	0.86	105	5.9	8.1	8.55	18	0.4	0.7	7.79	30	1.3	2.0	8.15
2	D	1795	66.9	52.2	9.61	5.38	1518	104.0	64.1	10.30	765	90.0	60.0	10.40	318	40.0	52.8	10.50
	P	78	5.8	5.3	8.50	1.41	128	13.6	16.4	8.74	327	32.1	40.6	10.10	302	32.8	54.9	10.60
	S	54	4.0	3.7	8.48	0.80	83	7.2	9.9	8.71	147	14.2	31.4	10.20	201	20.2	32.6	10.00
	G	77	2.6	2.3	8.47	0.67	33	1.9	2.0	7.92	65	9.1	15.1	10.00	65	8.4	25.6	10.00
	V	129	9.7	7.2	8.50	0.99	91	7.0	10.8	9.08	26	0.7	0.6	8.80	40	2.7	3.1	8.57
3	D	195	21.8	25.1	9.44	8.53	190	13.3	17.7	8.96	62	8.4	22.5	9.85	64	9.1	20.9	9.74
	P	151	20.7	31.4	9.39	6.01	167	18.5	20.2	9.15	44	9.1	15.3	9.25	49	6.3	12.1	9.27
	S	220	0.6	1.0	7.57	3.43	146	20.7	21.5	8.96	117	10.3	22.2	9.52	39	2.4	2.2	8.53
	G	45	2.9	3.1	8.32	0.72	59	7.1	5.6	8.76	41	3.2	3.6	8.48	52	3.2	3.6	8.35
	V	89	3.7	2.7	8.33	0.72	36	3.7	5.5	8.42	158	5.2	6.3	8.40	74	8.5	13.4	9.50
4	D	435	39.1	36.4	8.93	5.13	260	23.4	24.0	8.89	83	10.1	21.1	9.32	64	7.9	20.8	9.96
	P	298	26.3	30.0	9.81	5.40	196	24.0	27.4	9.19	66	8.4	16.4	9.52	59	8.4	14.0	9.45
	S	195	22.9	32.7	9.41	3.37	1.67	11.1	9.3	8.27	65	5.3	9.4	8.91	36	3.6	4.7	8.59
	G	56	2.1	1.8	8.32	1.05	46	5.8	5.1	8.79	59	4.2	3.2	8.66	50	3.5	2.3	8.75
	V	95	3.6	2.6	8.27	0.53	43	3.5	3.9	8.37	162	5.0	5.5	8.30	79	8.4	13.2	9.30

Table 3.2: Depth weighted means (0-0.9 m) of $pH_{(water)}$, exchangeable cations ($cmol_c\ kg^{-1}$) and effective cation exchange capacity (ECEC) ($cmol_c\ kg^{-1}$) of soils from four sugarcane fields. Sugarcane growth was identified within each field as being either dead and dying (D), poor (P), satisfactory (S) or good (G). Soil samples were also taken from adjacent undisturbed veld (V).

			Exchangeable cations				
Field	Growth	pH	K	Ca	Mg	Na	ECEC
1	D	9.86	0.46	8.01	14.85	16.70	39.98
	P	9.51	0.44	8.82	21.50	11.27	42.02
	S	9.30	0.68	21.40	16.46	3.52	42.00
	G	8.45	0.31	30.70	16.90	2.64	50.50
	V	8.26	0.40	25.36	13.43	2.14	41.32
2	D	10.29	0.92	14.74	3.23	25.10	43.95
	P	9.77	0.70	21.91	8.07	16.43	47.07
	S	9.60	0.67	21.60	14.47	11.35	48.02
	G	9.40	0.50	22.96	16.91	6.14	46.45
	V	8.72	0.54	35.18	15.52	2.05	53.25
3	D	9.29	1.32	27.29	17.72	10.50	56.82
	P	9.27	0.93	29.28	18.15	9.45	57.77
	S	9.08	1.11	29.02	15.19	9.30	54.57
	G	8.46	0.52	31.33	8.04	1.63	41.47
	V	8.76	1.03	27.67	15.44	3.78	48.07
4	D	9.40	1.40	24.53	18.00	13.79	57.67
	P	9.49	0.92	26.24	15.29	9.97	52.38
	S	8.78	1.04	28.37	15.94	5.68	50.97
	G	8.66	0.37	31.23	7.47	1.22	40.25
	V	8.64	1.07	28.25	16.08	3.55	48.90

Soils are generally classified as saline when they have an EC_e of 400 mS m^{-1} or more (USSL Staff, 1954a) and sodic when they have an SAR_e greater than 13 or an ESP higher than 15% (USSL Staff, 1954a). Such classifications are somewhat arbitrary and, in many countries lower critical values of sodicity are used to classify sodic soils. For example in Australia the critical ESP value used is only 6% (Northcote and Skene, 1972, cited in Gupta and Abrol, 1990; Shanmuganathan and Oades, 1983).

Salinity was concentrated in the surface layers (0-0.3 m) of soils particularly at sites 1 and 2 under dead and poor sugarcane and under satisfactory sugarcane at site 1 (0-0.15 m). Using a critical SAR_e value of 13%, all these layers were, in fact saline-sodic. Soils under veld or with good sugarcane growth had high pH values (>8) but would not be classified as saline or sodic (except perhaps the 0-0.15 m layer at site 1 under veld which had an SAR_e of 15.1). By contrast in the 0-0.15 m and 0.15-0.3 m layers under poor or dead sugarcane, 56% of the samples were classified as sodic and 38% as saline-sodic (Table 3.3). In Table 3.3 the soil layers at each site have been classified as saline, sodic and saline-sodic. It is evident that at sites 1, 2 and 4, salinity and sodicity generally occurred together while at site 3 non-saline, sodic soil conditions predominated. Site 2 differed from the other sites in that saline-sodic conditions tended to persist down the profile to 0.9 m.

Particularly below 0.3 m depth ESP values were unusually high (Table 3.1) and sometimes they were more than twice the values for SAR_e. This was initially considered highly unusual since ESP can be estimated by the following formula (Levy, 2000):

$$\text{ESP} = \frac{100(-0.0126+0.01475\text{SAR})}{\{1+(-0.0126+0.01475\text{SAR})\}} \qquad \text{(v)}$$

Such a phenomenon often occurs in alkali soils because of abnormally high measured exchangeable Na values. These high values have been attributed to the occurrence of Na compounds (particularly zeolites) that are relatively insoluble in water but are soluble in 1*N* ammonium acetate (Gupta and Abrol, 1990). For that reason, exchangeable Na is sometimes extracted from soils using other extractants such as 1*N* $Mg(NO_3)_2$ adjusted to pH 8.6 (Gupta *et al.*, 1985).

Table 3.3: Classification of soils as saline, non-sodic (A), non-saline, sodic (O), saline-sodic (AO) or non-saline, non-sodic (-) at different depths of soils from four sugarcane fields. Sugarcane growth was identified within each field as being either dead and dying (D), poor (P), satisfactory (S) or good (G). Soil samples were also taken from adjacent undisturbed veld (V).

Field	Cane Growth	0-0.15 m	0.15-0.3 m	0.3-0.6 m	0.6-0.9 m
1	D	AO	AO	O	-
	P	AO	O	-	-
	S	AO	-	-	-
	G	-	-	-	-
	V	O	-	-	-
2	D	AO	AO	AO	AO
	P	-	O	AO	AO
	S	-	-	O	AO
	G	-	-	-	-
	V	-	-	-	-
3	D	O	O	-	-
	P	O	O	-	-
	S	A	O	-	-
	G	-	-	-	-
	V	-	-	-	-
4	D	AO	AO	-	-
	P	AO	O	-	-
	S	O	-	-	-
	G	-	-	-	-
	V	-	-	-	-

The pH values of the study soils were often between 9 and 10, particularly in the profiles of soils where sugarcane grew poorly or had died (Table 3.1). These high pH values were generally associated with high SAR_e, ESP and $Alk_{1:5}$. Gupta and Abrol (1990) defined alkali soils as saline-sodic calcareous soils containing soluble carbonates, an ESP>15% (SAR_e>13), a saturated paste pH>8.2 and variable quantities of soluble salts. It must be noted that the term alkali is used frequently to refer to sodic soils (USSL, 1954a; Barnes, 1964; Shainberg, 1975; Papendick, 1994), however, here it refers to sodic soils containing soluble carbonates. Following irrigation of the study soils (and upward movement of Na) such alkali soil conditions developed. In many saline and/or sodic soils that do not contain carbonates the saturated soil paste pH is observed to be less than 8.2-8.3 (Gupta and Abrol, 1990). It is the presence of exchangeable Na and soluble carbonates that imparts the alkaline nature to alkali soils. pH values may be higher than 10 (Gupta and Abrol, 1990), but are normally between 8 and 9.5 in the top few centimetres of soil (Suarez *et al.*, 1984).

Alkalinity is defined as the neutralizing capacity of an aqueous carbonate system (Stumm and Morgan, 1970). It can be expressed as the total concentration of cations less the total concentration of anions other than carbonates and bicarbonates:

$$\text{Alkalinity} = [Na^+] + [K^+] + 2[Ca^{2+} + Mg^{2+}] - [Cl^-] - 2\,[SO_4^{2-}] \qquad \text{(vi)}$$

or as:

$$\text{Alkalinity} = [HCO_3^-] + 2[CO_3^{2-}] + [OH^-] - [H^+] \qquad \text{(vii)}$$

However, between pH 6 and 10, if CO_2 is present, $[OH^-]$ and $[H^+]$ are negligible and therefore alkalinity becomes the sum of $[HCO_3^-]$ and $2[CO_3^{2-}]$ (see section 3.2) (van Beek and van Breeman, 1973). Residual alkalinity is the alkalinity in excess of the total amount of divalent cations (Mashhady and Rowell, 1978).

When soil solutions high in exchangeable Na are concentrated (for instance when a period of high evaporation without soil water recharge occurs), and subsequently diluted, desorption and hydrolysis of weakly adsorbed Na results in an increase in soil pH and in concentrations of soil solution carbonate and bicarbonate (Shainberg, 1973; Mashhady and Rowell, 1978). Between pH values of 6 and 9.5 HCO_3^- dominates, above this pH, CO_3^{2-} tends to predominate. However, above pH 10 in soil systems that are in equilibrium, monomeric silica ($H_4\,SiO_4$) reacts with CO_3^{2-} producing $H_3SiO_4^-$ and HCO_3^-, preventing a rise in soil pH. Therefore only in systems that are not in equilibrium or do not have adequate levels of silica, does the soil pH rise above 10 (van Beek and van Breeman, 1973). Mashhady and Rowell (1978) therefore found highly significant correlations between soil pH and the logarithm of alkalinity. This was also the case in this study and a highly significant (n = 20, $r^2 = 0.69^{***}$) positive linear relationship was obtained (Figure 3.1a). The pH of alkali soils is correlated to the portion of soil solution Na that is not "electrically balanced" by the "non-alkaline" anions, SO_4^-, Cl^- and NO_3^-, rather than being correlated to the Na concentration (Mashhady and Rowell, 1978). The implications of this are that ESP and alkalinity are not directly related (Mashhady and Rowell, 1978). The pH can therefore be defined in terms of alkalinity and the equilibrium partial pressure of CO_2 (P_{CO2}) (Ponnamperuma, 1972; Mashhady and Rowell, 1978).

$$pH = 7.82 - \log P_{CO2} + \log \text{Alkalinity} - 0.5(I^{1/2}) \qquad \text{(viii)}$$

Where I refers to the ionic strength of the solution (mS m^{-1}). Equation (3) implies that a rise in alkalinity or decline in P_{CO2} results in an increase in soil pH.

In a soil containing residual alkalinity, as evaporation proceeds Ca and Mg are removed from the soil solution by precipitation of calcite ($CaCO_3$), dolomite ($CaMg(CO_3)_2$) and sepiolite ($MgSi_3O_6(OH)_2$) leaving behind monovalent cations. The pH of the system remains relatively constant (between 8.2-8.5) while $CaCO_3$ and sepiolite are precipitating (van Beek and van Breeman, 1973). If after removal of Ca and Mg from the solution, evaporation proceeds, a further increase in pH is possible provided there is still alkalinity left. Hence the residual alkalinity present before evaporation takes place is a measure of potential high alkalinity. Where residual alkalinity is present, evaporation can result in the pH increasing up to values as high as 10 in sodium HCO_3^- or CO_3^{2-} systems due to dissociation of HCO_3^- (Nakayama, 1970; van Beek and van Breeman, 1973). As a result of the key role of residual alkalinity, many workers have reported a direct, positive relationship between ESP and the pH of calcareous alkali soils (Agarwal *et al.*, 1982 cited in Gupta and Abrol, 1990). This relationship was reflected in the results of this study where regression analysis revealed a highly significant (n = 20, $r^2 = 0.85^{***}$) exponential relationship between pH and ESP in the 0-0.9 m of the profile (Figure 3.1b). A similar relationship (n = 20, $r^2 = 0.84^{***}$) was found between pH and SAR (Figure 3.1c).

As expected, CO_3^{2-} was not found in 1:5 soil:water extracts from soils under veld (Appendix 3), and HCO_3^- levels were low. Similarly, many soils under good sugarcane growth also had no or minimal concentrations of CO_3^{2-}, low concentrations of HCO_3^- (Appendix 3) and low $Alk_{1:5}$ values (Table 3.1). Most soils with inadequate sugarcane growth had high levels of CO_3^{2-} and HCO_3^- and $Alk_{1:5}$. The exception to this was the soil from site 1 under dead and dying sugarcane growth which had no CO_3^{2-} and little HCO_3^-. This is the result of the considerably lower pH values encountered in the 0-0.15 m layer under dead and dying sugarcane at site 1 compared to these at sites 2, 3 and 4 (Table 3.1). As a result $Alk_{1:5}$ was relatively low under dead and dying sugarcane at site 1 but was generally relatively high under dead and dying sugarcane at the other three sites (Table 3.1).

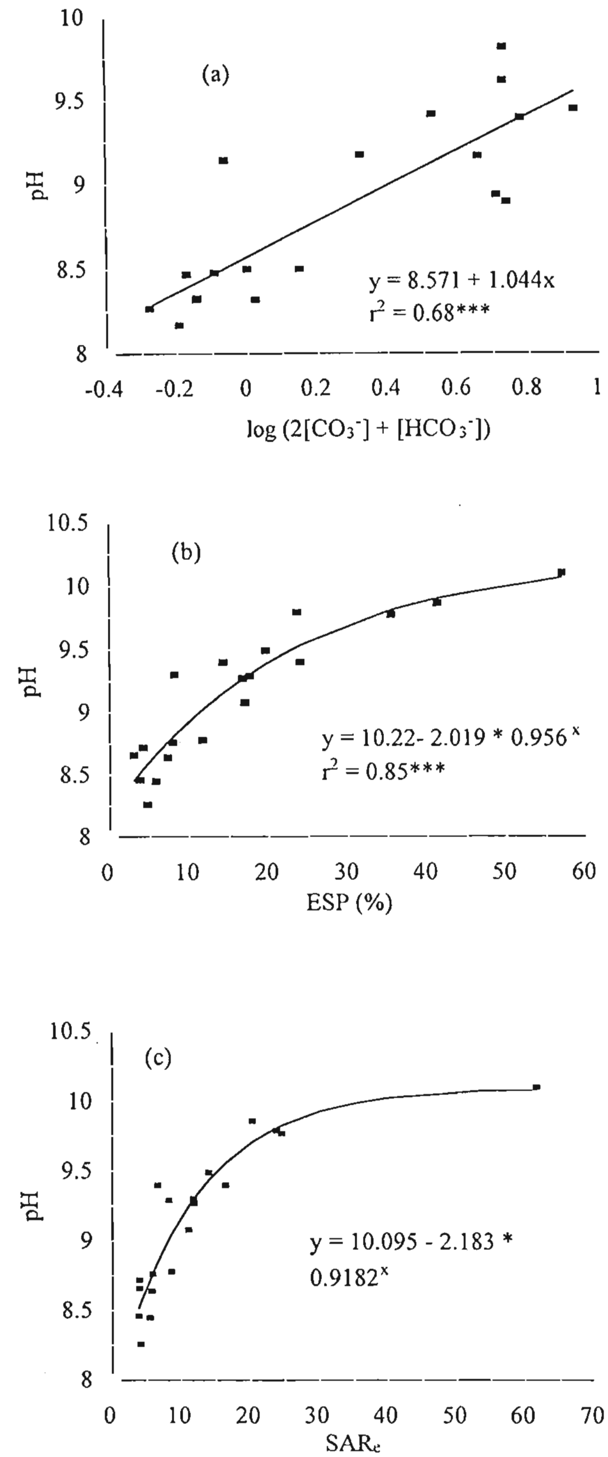


Figure 3.1: Relationship between pH (a) and log alkalinity in the 0-0.15 m of the soil profiles, (b) between pH and exchangeable sodium percentage (ESP) in the 0-0.9 m of the soil profiles and (c) between pH and sodium adsorption ratio (SAR_e) in the 0-0.9 m of the soil profiles. Correlation coefficients (r^2) and significance of correlations (* $0.01 \leq P \leq 0.05$; ** $0.001 \leq P \leq 0.01$; *** $P \leq 0.001$) are indicated on the graphs.

3.3.2 Soil Physical Properties

Poor productivity of sodic soils is often associated with their low infiltration rates and restricted drainage (Shainberg, 1975; Papendick, 1994; Rengasamy, 1998). This is caused by their low macroporosity and macropore instability due to the substantial presence of Na on clay surfaces. The high Na content leads to clay dispersion and this effect is generally magnified by high soil pH (Rengasamy and Olsson, 1991). That is, with increasing pH, the net negative charge on soil surfaces is increased resulting in repulsive forces between particles dominating. Clay dispersion leads to blockage of water-conducting pores, a reduction in hydraulic conductivity and restrictions in water and air movement (Frenkel *et al.*, 1978). As a result sodic soils characteristically have low infiltration rates and water often tends to stagnate at the surface of low-lying areas resulting in temporary waterlogging.

The above effects were evident in the irrigated sugarcane fields of the study. Particularly at the lower ends of the irrigated fields, soil structural breakdown at the soil surface was clearly evident. In addition, following irrigation, water was observed to pond on the surface, sometimes for several days. The very low aggregate stability values measured in both the 0-0.15 m and 0.15-0.3 m layers of all of the study sites demonstrates their tendency to disperse (Table 3.4). That is, the maximum and minimum mean weight diameter values were 0.76 mm and 0.10 mm, but the average values for the 0-0.15 m and 0.15-0.3 m layers were only 0.31 mm and 0.27 mm respectively. In general, mean weight diameter values were least in soils from under dead and dying sugarcane and poor sugarcane (Table 3.4).

Table 3.4: Aggregate stability measures by the methods of Emerson (1967), Loveday (1974) and a modified method by Yoder (1936) of soils from four sugarcane fields. Sugarcane growth was identified within each field as being either dead and dying (D), poor (P), satisfactory (S) or good (G). Soil samples were also taken from adjacent undisturbed veld (V).

Depth layer		0-0.15 m			0.15-0.3 m
Field	**Growth**	**Emerson Class**	**Loveday Score**	**Yoder (MWD) (mm)**	
1	D	3 (3)	5	0.20	0.22
	P	2 (1)	15	0.16	0.27
	S	2 (2)	14	0.22	0.25
	G	2 (2)	12	0.31	0.34
	V	2 (1)	9	0.40	0.36
2	D	3 (3)	5	0.19	0.17
	P	3 (3)	5	0.21	0.17
	S	4	1	0.71	0.62
	G	4	0	0.76	0.70
	V	2 (2)	9	0.45	0.36
3	D	1	16	0.13	0.12
	P	1	16	0.12	0.10
	S	1	16	0.17	0.16
	G	3 (3)	3	0.32	0.27
	V	3 (3)	3	0.37	0.29
4	D	1	16	0.16	0.16
	P	1	16	0.13	0.16
	S	2 (2)	14	0.51	0.21
	G	2 (2)	11	0.40	0.24
	V	3 (3)	5	0.34	0.29

Emerson (1967) recognised that the degree of dispersion of aggregates in the test that he proposed was primarily related to ESP but also to the relative levels of Ca and Mg present (Emerson and Chi, 1977; Emerson, 1983 cited in Murphy, 1995). Murphy (1995) showed that the Emerson index can be used as a screening test for sodicity on the following basis: class 1 and subclass 2(3) are regarded as accurate criteria of sodicity while non-sodic soils fell into classes 5 and 6. The other classes and subclasses were found by Murphy (1995) to be inadequate indicators for appraising sodicity although the probability of sodicity decreased in the order: 2(2)

> 2(1) > 3(4) > 3(3) > 3(2) > 3(1). Emerson classes measured in this study are shown in Table 3.4 and they demonstrate the very unstable nature of the surface 0-0.15 m layer at sites 3 and 4. In particular, values of 1 were recorded at sites 3 and 4 under poor and dead and dying sugarcane and under satisfactory sugarcane growth at site 3.

Emerson's test was modified by Loveday and Pyle (1973 cited by Loveday, 1974). They subdivided the classes while taking the rate and degree of dispersion into consideration which resulted in their test being highly correlated with ESP and they were able to use the test to predict broad classes of hydraulic conductivity in soil (Murphy, 1995). Results of the Loveday test (Table 3.4) again underline the dispersive nature of the soils at sites 3 and 4 under satisfactory, poor and dead and dying sugarcane growth.

Although critical ESP or SAR_e values above which dispersion will occur can be defined for clay-water systems, in soils a multitude of factors may influence the relationship between sodicity and other soil physical properties and thus mask critical ESP values (So and Aylmore, 1995; Sumner, 1995). Important factors include pH, electrolyte concentration, clay mineralogy and soil organic matter content (Sumner, 1995).

Whilst sodicity induces dispersion, salinity reduces this effect since the high electrolyte concentration in solution causes depression of the double layer and flocculation is promoted (Sumner, 1995). In this study, Loveday's score (LS) for dispersiveness of soils was regressed against EC_e and ESP in the 0-0.15 m soil layer, and the relationship was as follows:

$$LS = 7.92 - 0.00628\ EC_e + 0.2501\ ESP \qquad r^2 = 0.28^* \qquad \text{(ix)}$$

This indicates, as expected, that increasing salinity, decreased the Loveday score, while increasing sodicity, increased the score. The interaction of salinity and sodicity on dispersion can be seen when the physical properties of sites 1 and 2 are compared with those of sites 3 and 4. For example, there were no clear differences in ESP and SAR_e values of soils under dead and dying sugarcane growth between sites 1 and 2 and 3 and 4 and yet sites 3 and 4 were much more dispersive. This is presumably as a result of the much higher EC_e values at sites 1 and 2 (Table 3.1) reducing clay dispersion.

The poor physical conditions of the heavy clay soils in the study area are related to poor irrigation management in another way. As a result of the rise in the watertable, the soils remain in a swollen state so that infiltration and hydraulic conductivity are poor as swelling reduces pore sizes (Frenkel *et al.*, 1978). Successful management of the physical conditions of Vertisols usually relies on allowing them to dry out regularly so that they crack (Probert *et al.*, 1987; Hussein, 1998; Puentes *et al.*, 1998). This restores macroporosity and structural form to the profile (Chan and Hodgson, 1984; Probert *et al.*, 1987; Puentes *et al.*, 1998).

The interaction between the poor physical properties caused by the soils being maintained in a moist state and dispersion and aggregate breakdown caused by the sodicity and high pH that has developed is likely to have produced soil conditions that are not conducive to prolific root growth and development.

3.3.3 Relationship between Soil Chemical Properties and Sugarcane Yield

(a) Salinity

Sugarcane is considered to be moderately sensitive to salinity (Bernstein *et al.*, 1966; Maas, 1990). Von der Meden (1966; 1967) found sugarcane in South Africa to be affected at EC_e's more than 200 mS m^{-1} in the field. This level of electrical conductivity was also accepted by Johnston (1978) and Culverwell (2000) in their studies of the effect of salinity on sugarcane growth. However in a glasshouse trial, Maas and Hoffman (1977) found sugarcane growth to be affected by EC_e's as low as 170 mS m^{-1}. At site 1 EC_e in both the 0-0.15 m and 0.15-0.3 m layers under dead and dying sugarcane growth, and at site 2 under dead and dying sugarcane growth to a soil depth of 0.9 m far exceeded 200 mS m^{-1} (Table 3.1). At site 3 the EC_e at the 0-0.15 m and 0.15-0.3 m was 195 mS m^{-1} and 190 mS m^{-1} respectively, while at site 4 it exceeded 200 mS m^{-1} in the 0-0.15 m and 0.15-0.3 m layers under dead and dying sugarcane growth (Table 3.1). It is therefore probable that salinity was a limiting factor to sugarcane production at sites 1 and 2 and to a lesser extent also at site 4. At site 3, EC_e values were slightly lower than the level of salinity considered critical for sugarcane growth in South Africa, and it is probable that sugarcane death was as a result primarily of factors other than EC_e. Above 400 mS m^{-1} sugarcane growth has been found to be severely retarded by several authors (von der Meden, 1967; Clowes, and Breakwell, 1998), although this value severely conflicts with a study by Maas (1990) who found sugarcane yield to be only halved at an EC_e of 980 mS m^{-1}. Based on Zimbabwean information, Clowes and Breakwell (1998) consider that an EC_e greater than 800 mS m^{-1} will result in severe cane yield loss and often cane mortality. Several soils in this study (for instance site 1 under dead and dying cane) far surpassed all these levels of salinity considered severely detrimental to sugarcane growth.

Reasons for the discrepancies between studies in sugarcane tolerance levels to salinity may be as a result of differences in factors such as temperature, humidity, light intensity, moisture regime (as influenced by irrigation frequency), soil fertility and structure (Gupta and Abrol, 1990) as well as crop class (plant or ratoon) and cultivar. For instance, it is well known that the plant always produce higher yields and are less adversely affected by salinity and/or sodicity than the following ratoon crops. This is largely attributable to poor sprouting and reduced shoot numbers in the ratoon crops (Bernstein *et al.*, 1966). Since all the crops in this study were in the second ratoon stage, they would have been relatively sensitive to salinity. Furthermore, sugarcane cultivars can differ substantially in their salinity tolerance (Kumar *et al.*, 1994; Meinzer *et al.*, 1994; Wahid *et al.*, 1997). The cultivar NCo376 used at the study sites is, however, known to be fairly tolerant of salinity when compared to other cultivars (Clowes and Breakwell, 1998).

In Table 3.5, sugarcane yield and the two other growth parameters, average stalk height and average number of nodes per stalk for each sugarcane growth category is displayed. It can be consistently seen from this table that all of these parameters decrease with declining sugarcane growth category. If it is assumed that the four different zones of each field are of equal area and that zone G represents the maximum yield potential of each field, then the percentage yield reductions in fields 1-4 amounted to 46, 55, 56 and 58% respectively. It is therefore clear that yield reductions within fields are substantial and of considerable economic significance.

The correlation coefficients between yield, average stalk height and average number of nodes per stalk of sugarcane plants and EC_e in these soils are presented in Table 3.6. Only the average number of nodes per sugarcane stalk was significantly negatively related to salinity and the regression equation and line of best fit for the negative relationship between EC_e and number of nodes is shown in Figure 3.2.

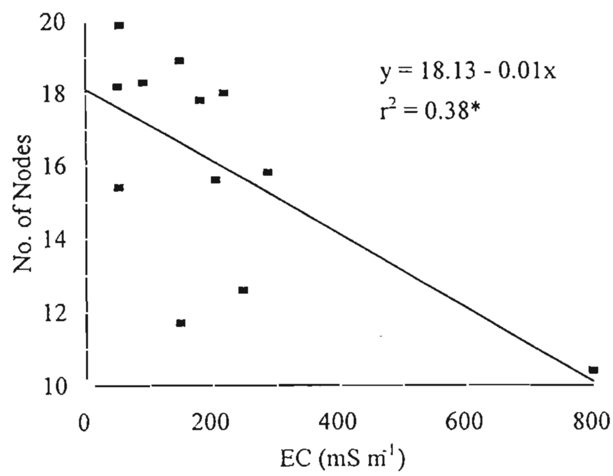


Figure 3.2: Relationship between salinity and average number of nodes per sugarcane stalk. The correlation coefficient (r^2) and significance of correlation (* $0.01 \leq P \leq 0.05$; ** $0.001 \leq P \leq 0.01$; *** $P \leq 0.001$) is indicated on the graph.

Table 3.5: Sugarcane yield (Mg ha^{-1}), average height of stalks (m) and average number of nodes per stalk sugarcane growing on soils under sugarcane classified as either dead and dying (D), poor (P), satisfactory (S) or good (G).

Field	Cane Growth	Sugarcane Yield	Average Height	Average No. of Nodes
1	D	0.0	0.00	0.0
	P	28.3	0.75	15.8
	S	159.2	1.61	18.0
	G	160.6	2.38	18.9
2	D	0.0	0.00	0.0
	P	28.3	0.54	10.4
	S	106.7	1.72	18.3
	G	172.2	1.98	19.9
3	D	0.0	0.00	0.0
	P	4.3	0.38	11.7
	S	81.7	1.12	15.6
	G	111.5	1.39	15.4
4	D	0.0	0.00	0.0
	P	6.2	0.45	12.6
	S	71.7	1.15	17.8
	G	114.7	1.50	18.2

Several workers have suggested that in many saline-sodic soils the effects of sodicity and salinity on plant growth are non-additive and non-interactive and that growth is limited by salinity effects (Lagerwerff and Holland, 1960; Bernstein, 1962 cited in Gupta and Abrol, 1990). They surmised that plant growth is limited by the toxic quantities of neutral salts, no matter how high the SAR in solution is. The main negative effect of salinity is a plant water deficit induced by the more negative water potential of the rooting medium. This results in decreases in water uptake and thus root-pressure-driven xylem transport of water and solutes and a depression in shoot growth (Humbert, 1968a; Flach, 1976; Naidu *et al.*, 1995b; Keren, 2000; Nelson and Ham, 2000).

In the alkali, saline-sodic soils used in this study sugarcane growth was, however, more closely related to sodicity than salinity. Indeed, as already noted, both sugarcane yield and stalk height were not significantly correlated with EC_e levels (Table 3.6). Yields were, however, significantly negatively correlated with ESP, while sugarcane height and number of nodes per stalk were significantly negatively correlated with SAR_e and ESP (Table 3.6). Correlation coefficients were not generally improved by taking account of more than the surface 0.3 m of soil. It was expected that considering soil chemical properties in the soil profile to a depth of 0.6-0.9 m would give better correlations with sugarcane growth because it would account for soil conditions within the crop rooting depth. However, sugarcane roots are generally concentrated in the surface 0.3 m (Swinford and Boevey, 1984) and the high watertable at the study sites may well have meant that the main zone of root activity and nutrient uptake occurred in the surface 0.15-0.3 m.

The poor correlations between sugarcane growth and EC_e observed in this study suggest that salinity *per se* was not the main soil limitation to crop growth. The closer correlations with SAR_e and ESP suggest that sodicity was a more important factor. Multiple linear regressions were not performed on the data as the independent variables (i.e. EC_e, SAR_e, ESP and pH) are related to each other.

Table 3.6: Negative linear correlation coefficients (r^2) and significance of correlations between growth parameters and relevant soil properties calculated to different depths. All values relating to dead and dying cane were excluded from the data set when calculating the regressions.

Property	Sugarcane Yield	Average Stalk Height	Average No. of Nodes
EC_e 0-0.15 m	0.01^{NS}	0.02^{NS}	-
EC_e 0-0.3 m	0.08^{NS}	0.19^{NS}	0.38*
EC_e 0-0.6 m	0.01^{NS}	0.10^{NS}	0.32*
EC_e 0-0.9 m	-	0.06^{NS}	0.25^{NS}
SAR 0-0.15 m	0.02^{NS}	0.06^{NS}	-
SAR 0-0.3 m	0.24^{NS}	0.39*	0.54**
SAR 0-0.6 m	0.04^{NS}	0.15^{NS}	0.37*
SAR 0-0.9 m	-	0.08^{NS}	0.27*
ESP 0-0.15 m	0.38*	0.44**	0.45*
ESP 0-0.3 m	0.38*	0.48**	0.59**
ESP 0-0.6 m	0.22^{NS}	0.34*	0.46**
ESP 0-0.9 m	0.04^{NS}	0.13^{NS}	0.23^{NS}
pH (water) 0-0.15 m	-	-	-
pH (water) 0-0.3 m	0.50**	0.58**	0.56**
pH (water) 0-0.6 m	0.5^{NS}	0.42*	0.37*
pH (water) 0-0.9 m	-	0.10^{NS}	0.08^{NS}

- Percentage variance accounted for too low to be calculated
Significance of regression: ^{NS} Not significant; * $0.01 \leq P \leq 0.05$; ** $0.001 \leq P \leq 0.01$.

(b) Sodicity

An SAR_e of above 10% is considered to be marginal for sugarcane production in South Africa (Johnston, 1975; 1977), and above 20% serious problems are considered likely. The ZSAES classifies soils in the study area with SAR values greater than six per cent as moderately sodic and gypsum application is be recommended (Clowes and Breakwell, 1998).

In the soils of the study under sugarcane, samples with an SAR_e greater than 10% accounted for 63% of the 0-0.15 m and 0.15-0.3 m samples, 38% of the 0.3-0.6 m samples and 31% of the 0.6-0.9 m samples (Table 3.1). In the 0-0.15 m layer, 56% of the samples from under sugarcane had an SAR_e>20%. Thus sodicity is definitely a potential problem on these sites. The significant negative correlation between yield and ESP and the other growth parameters with both SAR_e and ESP confirms this assertion (Table 3.6).

The regression equations and lines of best fit for the relationship between ESP (0-0.3 m) and yield, stalk height and number of nodes per stalk are shown in Figures 3.3a, b and c respectively. The equivalent data for SAR_e and sugarcane stalk height and average number of nodes per stalk is presented in Figures 3.4a and b. The negative linear relationship between sugarcane growth and increasing sodicity (ESP) is similar to that observed by workers in northern Queensland (Spalding, 1983; Nelson and Ham, 1998; 2000). Nelson and Ham (1998) found that with every 1% increase in subsoil (0.25-0.5 m layer) ESP, cane yield dropped by 2.4 Mg ha^{-1}. This was in contrast to Spalding (1983) who found only a 1.5 Mg ha^{-1} drop in cane yield with every 1% increase in subsoil ESP. These conflicting values were attributed to the higher yield potential in the locality where Nelson and Ham (1998) performed their study. In this study, the yield decrease induced by sodicity was similar to that recorded by Nelson and Ham (1998) since for every 1% increase in ESP, sugarcane yield declined by almost 2.1 Mg ha^{-1} (Figure 3.3a).

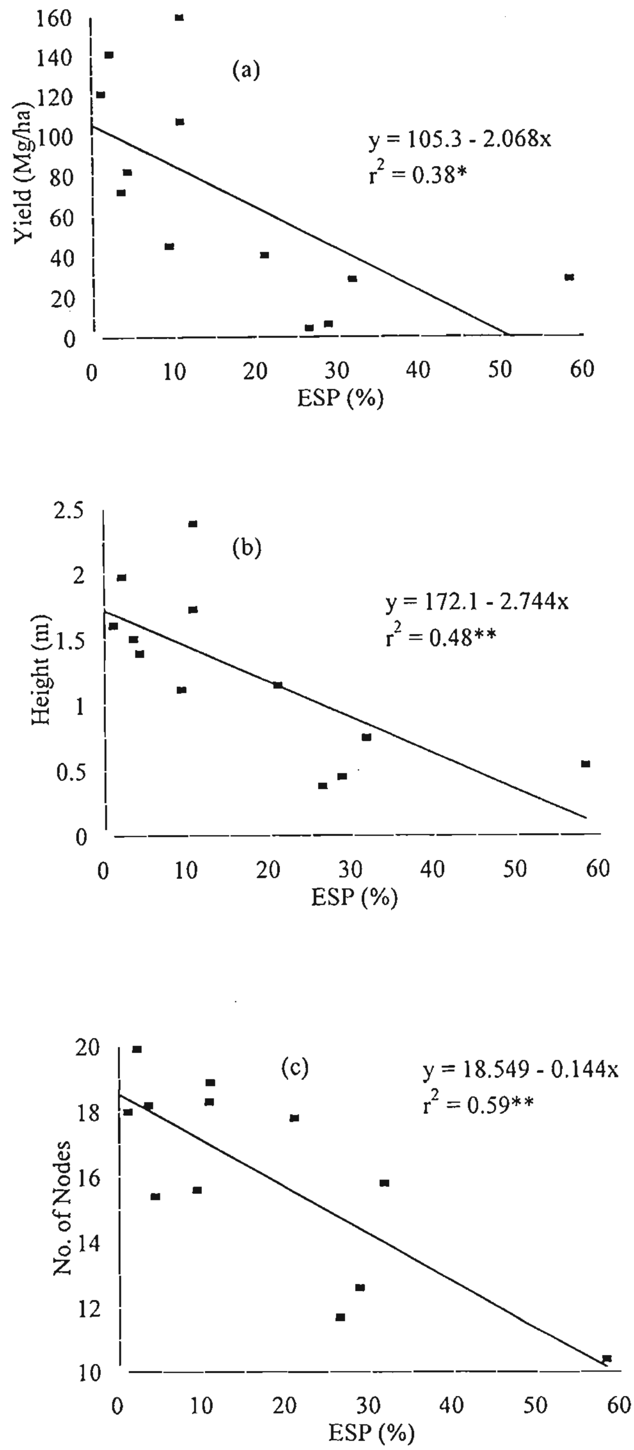


Figure 3.3: Relationship between exchangeable sodium percentage (ESP) in the 0-0.3 m soil layer and (a) sugarcane yield, (b) sugarcane stalk height, and, (c) number of nodes per stalk. Correlation coefficients (r^2) and significance of correlations (* $0.01 \leq P \leq 0.05$; ** $0.001 \leq P \leq 0.01$; *** $P \leq 0.001$) are indicated on the graphs.

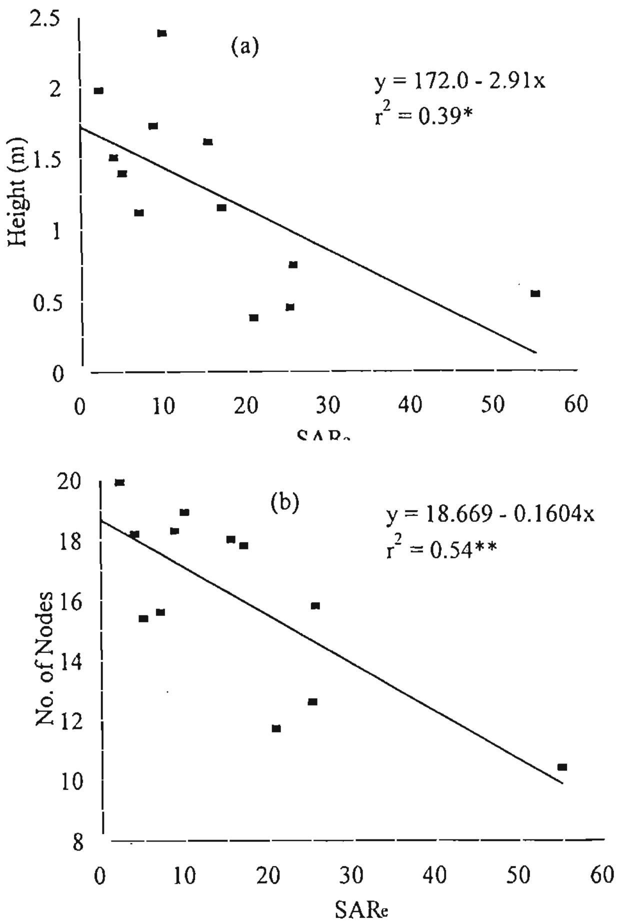


Figure 3.4: Relationship between sodium adsorption ratio (SAR) in the 0-0.3 m soil layer and (a) sugarcane stalk height, and, (b) number of nodes per stalk. Correlation coefficients (r^2) and significance of correlations (* $0.01 \leq P \leq 0.05$; ** $0.001 \leq P \leq 0.01$; *** $P \leq 0.001$) are indicated on the graphs.

Spalding (1983) found the best correlation between yield and ESP was in the 0.25-0.5 m depth layer. Nelson and Ham (1998) on the other hand, found the relationship was more correlated in the 0-0.75 m depth layer than in the 0.25-0.5 m depth layer. In both of the above studies, sodicity and salinity generally increased with increasing depth in the soil profile. In this study, however, sodic soil conditions were often encountered throughout the profile and there was a tendency for Na to be concentrated in the surface 0.3 m. In addition, subsurface soil layers were probably waterlogged. Thus strongest correlations between indices of sodicity and sugarcane growth and yield were found for the 0-0.3 m layer (Table 3.6).

The negative correlations between sugarcane yield, stem height and number of nodes per stalk versus soil pH (Table 3.6) are associated with high ESP or SAR_e values resulting in an increased soil pH. As noted previously, SAR_e and ESP were positively correlated with pH.

There are a number of ways that sodicity could negatively influence sugarcane growth and eventually cause plant death. Firstly, nutrient toxicities and/or imbalances could accrue due primarily to the high Na content in the soil solution. These can occur through:

- ion toxicities associated with excessive uptake of Na and/or Cl (van Wambeke, 1991; Naidu and Rengasamy, 1995). Accumulation of salts in the cytoplasm can result in inhibition of enzyme reactions while their accumulation in the leaf apoplasm can lead to dehydration and death of leaf cells (Naidu and Rengasamy, 1993; Naidu *et al.*, 1995b; Keren, 2000).
- nutrient imbalances induced by a depression in uptake and/or translocation of mineral nutrients. In particular, Na-induced inhibition of other cations such as Ca can occur (van Wambeke, 1991; Naidu and Rengasamy, 1995; Sumner, 1997).

Secondly, the very high pH of the alkali soils under dead and dying sugarcane growth (i.e. 9.0-10.0) will also have had negative effects on plant growth. These effects could have occurred through:

- a high pH and high HCO_3^- content in soil solution causing inhibition of root growth, root respiration, root-pressure-driven solute export to xylem, inhibition of cytokinen export to shoots with subsequently inhibited shoot growth and impaired uptake and translocation of Fe (USSL Staff, 1954b; Brown, 1976; Mortvedt, 1976; Gupta and Abrol, 1990).
- a sharpley decreased solubility of soil Fe, Mn and Zn due to precipitation/adsorption reactions and the risk of deficiencies of these micronutrients, particularly Fe and Zn (van Wambeke, 1991; Naidu and Rengasamy, 1995).

Thirdly, the poor physical properties that result from sodicity can cause limitations to plant growth. Blockage of macropores induced by clay dispersion causes reductions in infiltration capacity and hydraulic conductivity. As noted previously, water tends to pond on the surface of the soil at the lower ends of the fields following irrigation events. This is likely to cause temporary waterlogging problems and the resulting anaerobic conditions are likely to limit crop growth (Gupta and Abrol, 1990).

The sodicity-induced effects on soil physical properties will interact with the already poor physical properties of these heavy clay soils. That is, as noted in section 3.3.2, because of over-irrigation and the resulting high watertable, these vertic soils do not dry out and crack (thus restoring macroporosity) but remain in a swollen state permanently. This already limits air and water movement in the soil profile.

A fourth possibility is that waterlogging (anaerobic conditions) in the subsoil is also limiting crop growth. That is, salinity and sodicity are generally greater at the lower-ends of irrigated fields (where the sugarcane has died) because the watertable is nearest the surface at these ends. In some cases the watertable was observed to be only 0.2-0.3 m from the soil surface. Thus, death of roots due to anaerobic conditions could be occurring to a greater extent at the lower ends of the fields. Unfortunately, due to political unrest prior to the Zimbabwe election it was not possible to investigate this aspect in more detail as it was considered unsafe to do so. Originally, it was planned to measure the redox potential and root activity in the soil profiles under field conditions at the various sites which would have clarified the conclusions of this study.

3.3.4 Foliar Analysis

The macro- and micro-nutrient content of sugarcane leaf samples is presented in Table 3.7. Unfortunately, samples from site 1 were not taken because the field was set on fire during political unrest prior to the Zimbabwean election. The analyses do not show significant treatment effects between good and poor sugarcane. However, on most plots, foliar concentrations of N, P, K and S were low since critical concentrations are about 1.7-1.8%, 0.18-0.19%, 1.05% and 0.12% respectively (see Table 2.2). By contrast, concentrations of leaf Ca and Mg were generally high.

Table 3.7: Results of foliar analyses performed on sugarcane leaves from 22 week old sugarcane from three fields varying in soil pH, salinity and/or sodicity. Sugarcane growth was identified within each field as being either poor (P), satisfactory (S) or good (G).

Field	Growth	(%)						(ppm)			
		N	P	K	S	Ca	Mg	Zn	Mn	Cu	Fe
2	P	[a]1.62	[a]0.17	1.00	[a]0.11	0.29	0.19	15	[b]14	5	158
	S	[a]1.61	[a]0.17	1.01	0.13	0.25	0.17	17	[b]13	5	140
	G	1.73	[a]0.17	[a]0.97	[a]0.11	0.30	0.20	18	[b]14	5	120
3	P	1.74	0.22	[b]0.60	0.14	0.32	0.32	14	40	5	127
	S	[a]1.63	0.20	[b]0.86	[a]0.11	0.25	0.20	19	17	5	84
	G	1.64	0.20	0.98	0.12	0.33	0.13	16	21	5	95
4	P	1.69	0.19	[b]0.68	0.12	0.29	0.25	16	33	5	113
	S	1.67	0.19	[b]0.88	[a]0.11	0.26	0.17	19	33	5	94
	G	[a]1.61	0.19	1.01	0.12	0.34	0.12	15	[a]15	4	112

[a] foliar level considered marginal
[b] foliar level considered deficient

Concentrations of exchangeable Ca, Mg and K were presented for the soil profiles in Table 3.2 and for the various layers in Appendix 2.1 and 2.2. The critical exchangeable Ca, Mg and K concentrations used by SASEX are about 1.0, 0.21 and 0.83 respectively (Meyer *et al.*, 1997). It is also recommended that exchangeable K make up at least 3% of the ECEC. As noted previously, concentrations of exchangeable Ca and Mg were very high so the high concentrations of leaf Ca and Mg were not surprising.

Although concentrations of exchangeable K were low at some sites they were often above 0.83 $cmol_c\ kg^{-1}$in the surface 0.3 m. Nonetheless, concentrations of exchangeable K did generally represent less than 3% of ECEC. This was associated with the high concentrations of exchangeable Ca, Mg and in many cases Na. Competition between cations during active ion uptake across the plasma membrane of root cells occurs (Levitt, 1980 cited by Levy, 2000; Sumner, 1997) and this presumably contributed to the low foliar K levels. Indeed, regression analysis revealed that although foliar K concentrations were not closely related to exchangeable K levels, they were negatively correlated with exchangeable Na ($r^2 = 0.63^{**}$) in the surface 0.3 m of soil (Figure 3.5).

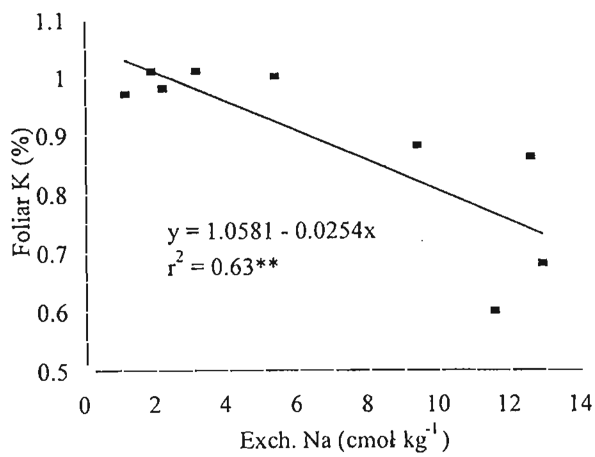


Figure 3.5: Relationship between levels of foliar K in sugarcane leaves with soil exchangeable Na in the 0-0.3 m of the soil profile. The correlation coefficient (r^2) and significance of correlation (* $0.01 \leq P \leq 0.05$; ** $0.001 \leq P \leq 0.01$; *** $P \leq 0.001$) are indicated on the graph.

Phytotoxic concentrations of ions other than Na may also have been interfering with active uptake of nutrients. In particular, the high pH, and resulting high concentrations of HCO_3^-, in solution, may have been damaging (USSL Staff, 1954b; Gupta and Abrol, 1990). Thus low concentrations of leaf N, P, K and S probably reflect interference with root function and ion uptake caused by the alkali, sodic soil conditions. In addition, temporary anaerobic conditions in the topsoil during and after irrigation cycles and anaerobic conditions in the saturated subsoil may also have contributed to the inhibition of nutrient uptake (Humbert, 1968c).

Critical levels of leaf Zn, Mn, Cu and Fe are about 13, 15, 1 and 50μg g^{-1} (Meyer *et al.*, 1997) so the only measured micro-nutrient deficiency was Mn at site 2. Such results are surprising since the very high soil pH values would be expected to result in deficiencies of these micro-nutrients; particularly Zn and Fe (Marschner, 1995; Gupta and Abrol, 1990; Naidu and Rengasamy, 1995). Generally, even where temporary reducing conditions caused by waterlogging increase the solubility of Zn, Mn, Cu and Fe, the high pH in sodic soils has the dominant effect and their availability is still low (Naidu and Rengasamy, 1995).

The fact that no clear treatment effects within each site were observed in the leaf nutrient content suggests that although poor nutrient status was a limitation to crop growth, it was not the main factor causing the substantial decrease in yields that occurred going from the high to low ends of fields. As discussed previously, important factors may well have included the direct phytotoxic effects of high concentrations of Na^+ and HCO_3^- in soil solution and anaerobic conditions and root death in the subsoil due to the very high watertable.

3.4 Conclusions

Poor irrigation management on a sugarcane estate on heavy clay soils in the Zimbabwean lowveld has resulted in yield declines and even death of sugarcane at the lower ends of furrow irrigated fields. At the lower ends of fields the water table is nearer the soil surface and capillary action has resulted in accumulation of soluble salts at the surface and has induced saline-sodic, sodic and alkali soil conditions in the surface horizons. The reasons for the yield decreases, and deaths, were suspected to be as a result of the interaction of a number of factors. These included the phytotoxic effects of the high concentrations of soil solution Na^+ and also HCO_3^- (which is associated with the high solution pH). A restricted supply of air and water and temporary periods of anaerobicity were also suspected to be limitations. These occurred as a result of the permanently swollen nature of these heavy clay soils coupled with dispersion and aggregate breakdown which was induced by sodic soil conditions. In addition, waterlogging in the subsoil due to a high watertable, and salinity may well be further limitations.

Amelioration of the problems will be a major and expensive undertaking since the watertable will need to be lowered considerably. In order to manage these heavy clay soils effectively they need to be allowed to dry out and crack regularly so that macroporosity is maintained. At present, this does not occur. Ameliorants such as gypsum and/or acidifying agents will also need to be applied in order to counteract the sodicity that has developed. More efficient irrigation management to limit losses of water to ground water will also be extremely important.

CHAPTER 4

EFFECTS OF IRRIGATION INDUCED SOIL SALINITY AND SODICITY ON SOIL MICROBIAL ACTIVITY

4.1 Introduction

The assessment of the effect of any soil disturbance, whether chemical or physical on soil biological properties is critical for the following reasons. First, there has been a large amount of interest in the development of soil health indicators, and soil biological properties are generally considered to be fundamental to this concept (Dick, 1992). Second, soil biological properties are agronomically important, as they affect soil organic matter dynamics, nutrient cycling and soil physical properties (Fraser *et al.*, 1994; Wick *et al.*, 1998; Haynes, 1999).

Little is known about the effects of soil salinity/sodicity on soil biological properties as it has hardly been researched (Oren, 1991, 1999; Szabolcs, 1991), although it's effects on soil chemical and physical properties have been thoroughly investigated (Haynes and Hamilton, 1999), as discussed in sections 2.3.2; 2.3.3 and 2.3.4. Since organic matter (and therefore the size and activity of the microbial biomass) is typically concentrated in the top few centimetres of soil, (Murphy *et al.*, 1998), changes in the chemistry in the surface soil (such as an increase in soil salinity or sodicity) could greatly affect soil microbial activity. Any reduction in microbial activity would be of particular concern, because microbially-mediated processes in soils are central to their ecological function. Important processes include degradation of organic residues, transformations of organic matter, mineralization of nutrients held in organic form (e.g. N, S, P) and formation and stabilization of soil aggregates (Dick, 1992).

As part of the wider study which related induced soil salinity/sodicity to sugarcane yield decline (chapter 3), the effects of increasing salinity on the soil microbial activity were investigated on the same sites in the surface (0-0.15 m) soil layer.

4.2 Materials and Methods

Identical sites and soil samples were used for this part of the study as those discussed in chapter 3. That is, four fields, in which there was an obvious gradient of salinity from the upper to the lower end of the field were selected. These were identified by the following factors: apparently unaffected sugarcane growth at the upper end (where irrigation water is applied), the poor growth and/or death of sugarcane at the lower end, and an obvious accumulation of salts at the soil surface at the lower end of the fields in question.

Four areas of cane were identified down the gradient of each field representing (i) dead and dying cane, (ii) poor cane growth, (iii) satisfactory cane growth and (iv) good cane growth. In each area, a plot 2 rows by 2 metres was marked off, and soil samples (0-0.15 m) were taken at random (both within and between sugarcane rows) in an area 2 metres radius around the marked plots. In all, ten samples were taken, then were bulked per area for each field.

The soil samples were treated and analysed as discussed in section 3.2. In addition, soil organic C was measured by the Walkley and Black method (Walkley, 1947) using ground (<0.5 mm), air-dried soil samples.

Due to logistic and border constraints, it was not possible to transport refrigerated field-moist soil samples from the Zimbabwean lowveld to Pietermaritzburg. Thus, to investigate the effects of salinity on soil microbial activity, it was necessary to use re-wetted samples. Air-dried samples were re-wetted to 70% field capacity and incubated at 20°C for 40 days prior to analysis.

Microbial biomass C was determined by the method of Vance *et al.* (1987) based on the difference between C extracted with 0.5 M K_2SO_4 from chloroform fumigated and un-fumigated soil samples using a K_c factor of 0.38. Basal respiration was determined by placing 30 g of rewetted soil in 50 ml beakers that were put in 1.5 l air-tight jars containing a vial with 20 ml 0.1 M NaOH. The soil was incubated in the jars at 22°C in the dark for 10 days. The CO_2 evolved was determined after 2, 5 and 10 days by titration of the NaOH with 0.2 M HCl (Anderson, 1982). The microbial metabolic quotient (referred to as the metabolic quotient) was calculated as basal respiration (μg CO_2-C hr^{-1}) per mg of microbial biomass carbon. The microbial quotient was calculated by expressing microbial biomass carbon as a fraction of soil organic C. Fluorescein diacetate (FDA) hydrolysis rate was measured by incubation of soil with FDA and a buffer for 1 hour using the method described by Swisher and Carroll (1980), as modified by Schnürer and Rosswall (1982). The concentration of fluorescein produced was measured colorimetrically at 490nm. Arginine ammonification rate was determined by colorimetric measurement of NH_4-N, after soil samples were incubated with an arginine substrate for 3 hours (Alef and Kleiner, 1995). The activity of several soil enzymes was assayed based on the release and quantitative determination of the product in a reaction mixture, the soil samples being incubated with a suitable substrate and appropriate buffer solution. These enzymes are involved in carbon (β-glucosidase; EC# 3.2.1.21), phosphorus (acid and alkaline phosphatase; EC# 3.1.3.1 and 3.1.3.2 respectively) and sulfur (arylsulphatase; EC# 3.1.6.1) mineralization and were performed by the methods described by Tabatabai (1994).

Potential nitrogen mineralization was determined by aerobic incubation. Air-dried soil samples were re-wetted to 70% of field capacity and incubated for at 22°C for 10 days. Exchangeable NH_4^+ and NO_3^- were extracted from soil samples using 2]M KCl (1:50 soil:extraction ratio) at the beginning and end to the incubation and NH_4^+ and NO_3^- were analysed by steam distillation using MgO and Devarda's alloy and titration with 0.005N H_2SO_4 (Bremner, 1965). Mineralized N was calculated as the difference in exchangeable mineral N before and after incubation.

Data relating the various measured biological parameters to measured soil chemical properties were fitted to linear, quadratic, cubic and exponential regression functions using the Genstat (fourth edition) statistical package.

4.3 Results and Discussion

It is evident from chapter 3 that sugarcane yield declined dramatically from the high to low ends of the furrow irrigated fields, and that there was a concomitant increase in both salinity and sodicity. The study soils had accumulated appreciable concentrations of soluble salts and Na was a major contributor (Appendix 1.1). Using criteria outlined in section 3.3.1, one of the 20 soil (0-0.15 m layer) samples would have classified as saline, four as sodic and six as saline-sodic soils (Table 3.3).

Soil organic matter levels increased significantly with increasing sugarcane yield. However, even on good sugarcane growth plots, the data in Appendix 1.1 shows that at all four sites, sugarcane production has resulted in a decrease in soil organic matter content when compared with undisturbed veld. Such a decrease is common under sugarcane production (Haynes and Hamilton, 1999), and can be attributed to both the small amounts of organic matter returned to the soil (the standing crop prior to harvest is burnt to remove trash and the harvested cane is then removed) and to tillage-induced soil organic matter degradation (the soil is intensively cultivated approximately every five years to form furrows prior to re-planting and the interrow space is usually ripped annually). Loss of soil organic matter leads to a decline in soil structural stability and aggregation, a decline in fertility (particularly N supply via mineralization) and a decrease in soil biological activity (Johnston, 1986). Any decrease in aggregation induced by a loss of soil organic matter would potentially result in subsequent irrigation-induced sodicity having an even more negative effect on structural breakdown (see section 3.3.2).

Although the pattern of decline in microbial biomass differed, the negative relationship between EC_e, ESP and SAR_e and the size of the microbial biomass (Table 4.1, Figure 4.1) demonstrates the extremely negative influence that increasing salinity and sodicity had on the soil microbial community. Such results confirm a pattern found in naturally saline soils where the size of the microbial community is usually negatively correlated with total soluble salts (Mallouhi and Jacquin, 1985; Ragab, 1993; García *et al.*, 1994), but positively correlated with organic C contents (Zahran *et al.*, 1992; Ragab, 1993). In this study, microbial biomass carbon was also found to be positively related to soil organic carbon content (r^2=0.6) (Table 4.1; Figure 4.1), as found by many workers (Schnürer *et al.*, 1985; Dick *et al.*, 1988; Haynes and Tregurtha, 1999). In addition, the ratio microbial biomass C:organic C has been used by workers to estimate the proportion of total organic matter present in living form. The ratio generally increases with increasing soil organic matter status and improving soil conditions (Anderson and Domsch, 1989; 1990). In this study, as in other studies (Insam *et al.*, 1991; Anderson and Domsch, 1989), the ratio increased with decreasing soil salinity and sodicity (Figure 4.2) indicating that the size of the microbial community per unit organic carbon increased with improving soil chemical and physical conditions.

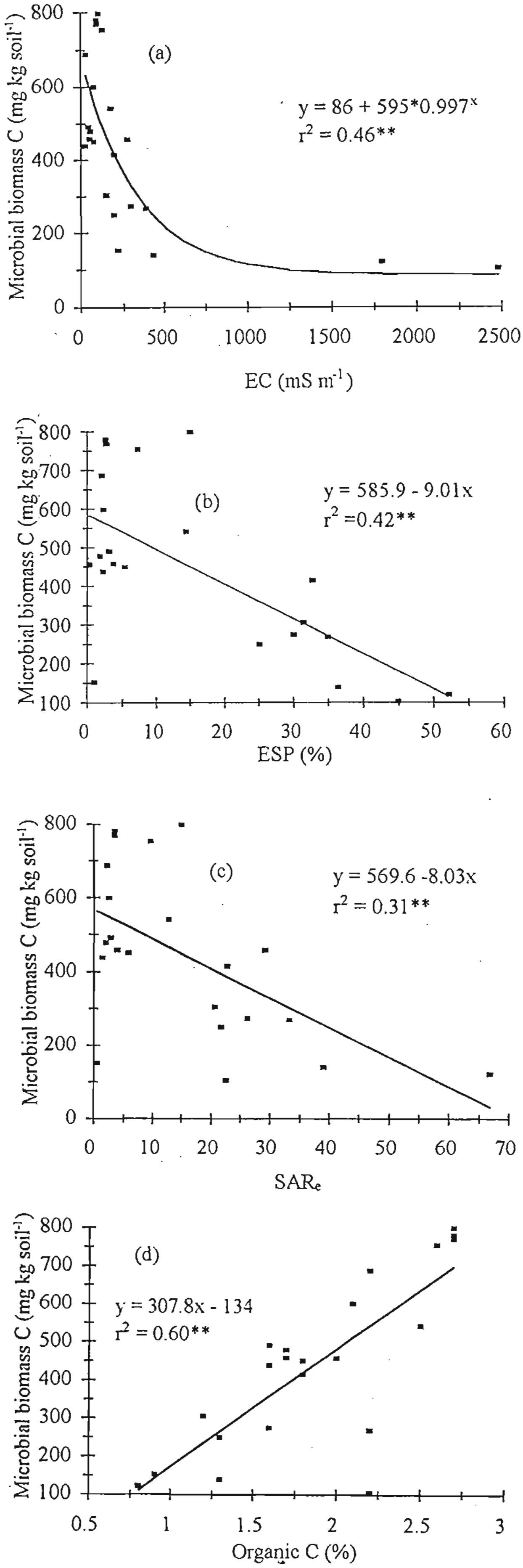


Figure 4.1: Relationship between microbial biomass carbon and (a) salinity (EC_e), (b) exchangeable sodium percentage (ESP), (c) sodium adsorption ratio (SAR_e) and (d) soil organic carbon. Correlation coefficients (r_2) and significance of correlations (* $0.01 \leq P \leq 0.05$; ** $0.001 \leq P \leq 0.01$; ***$P \leq 0.001$) are indicated on the graphs.

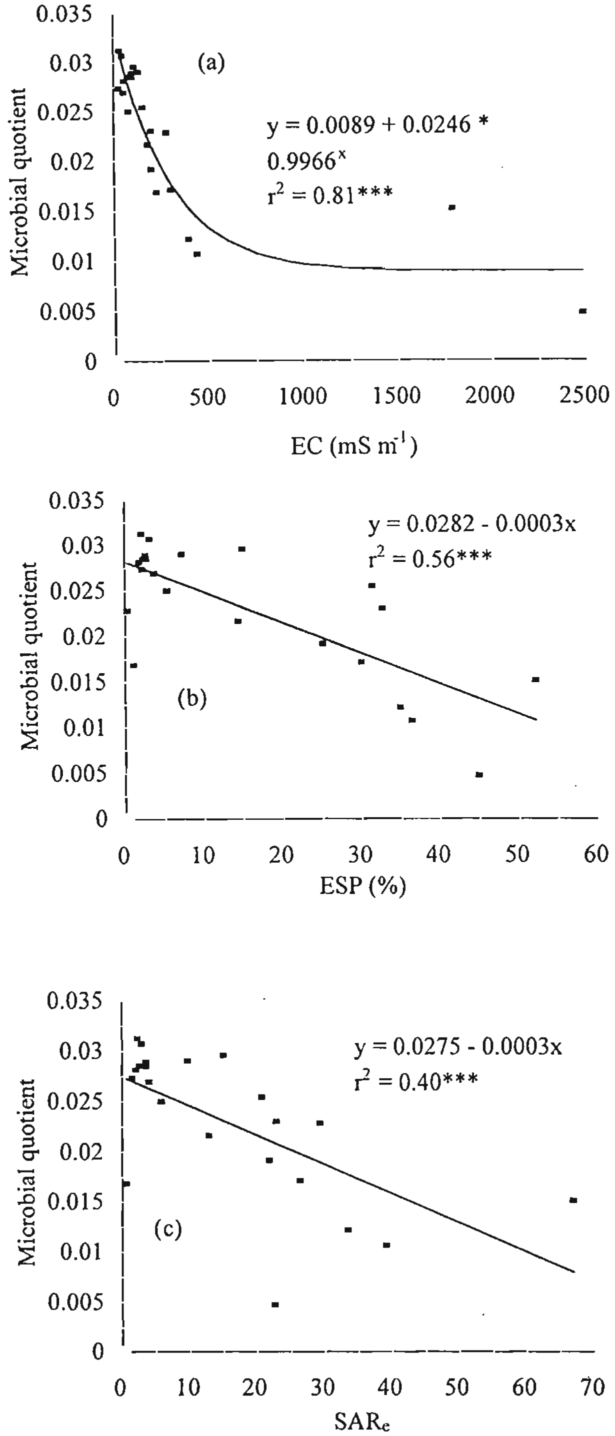


Figure 4.2: Relationship between microbial quotient and (a) salinity (EC_e), (b) exchangeable sodium percentage (ESP) and (c) sodium adsorption ratio (SAR_e). Correlation coefficients (r_2) and significance of correlations (* $0.01 \leq P \leq 0.05$; ** $0.001 \leq P \leq 0.01$; ***$P \leq 0.001$) are indicated on the graphs.

Basal respiration is a measure of the heterotrophic microbial metabolic activity (Haynes, 1999). It was not closely related to either EC_e, ESP or SAR_e (Table 4.1), and significant correlations were not recorded. The lack of any correlation is surprising given that Laura (1974) showed in a laboratory study that total microbial activity (as measured by CO_2 evolution) was generally depressed as soil salinity increased. Similar results to those of Laura (1974) were obtained by Mallouhi and Jacquin (1985) in naturally saline soils. The reason for the lack of correlation was explained once the metabolic quotient (CO_2 respired per unit of microbial biomass C) was calculated. It increased exponentially with increasing EC_e and linearly with increasing ESP and SAR_e (Figure 4.3) demonstrating that the quantity of CO_2 evolved per unit of microbial biomass C increased. Thus, with increasing salinity proportionally greater levels of C are needed to meet the energy demands of the microbial biomass (Lavahun *et al.*, 1996). The metabolic quotient can be used as an index of adverse environmental conditions (including stress and disturbance) for the soil microflora (Wardle and Ghani, 1995). Thus increasing salinity and sodicity resulted in a smaller, more stressed microbial community which was less efficient in utilizing C resources than its less stressed counterparts (Table 4.1, Figure 4.3). Similarly, Sarig and Steinberger (1994) found that respiratory quotients increased in soils with fluctuating salinity, while García *et al.* (1994) recorded, a negative correlation between the respiratory quotient and EC_e in the arid soils of south east Spain. The negative relationship between microbial biomass C and the metabolic quotient, as observed here, is common (García *et al.*, 1994; Sparling, 1997). That is, factors that tend to cause stress to the microbial biomass also tend to reduce it's size. A similar relationship was noted previously in response to increased salinity by Sarig and Steinberger (1994) in soils in the hot, dry Negev Desert of Israel.

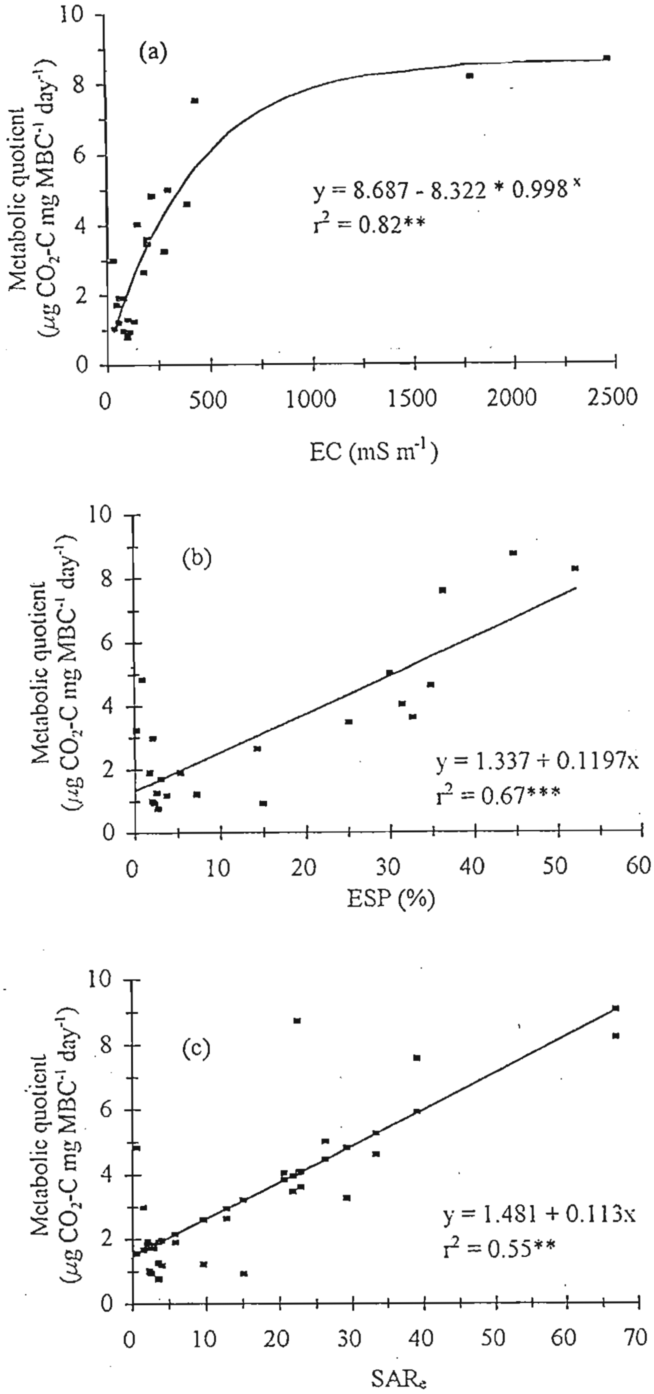


Figure 4.3: Relationship between metabolic quotient and (a) salinity ($EC_{e,}$), (b) exchangeable sodium percentage (ESP) and (c) sodium adsorption ratio (SAR_e). Correlation coefficients (r_2) and significance of correlations (* $0.01 \leq P \leq 0.05$; ** $0.001 \leq P \leq 0.01$; ***$P \leq 0.001$) are indicated on the graphs.

Microbial activity was also estimated by measuring the rate of FDA hydrolysis and arginine ammonification. Arginine ammonification is used as an index of microbial activity since most heterotrophs possess ammonifying capacity, and its rate has been found to be closely correlated with microbial activity in laboratory studies (Alef and Kleiner, 1995). The rate of hydrolysis of FDA by soils is considered as an index of overall microbial activity because its hydrolysis is carried out by active cells using an esterase and fluorescein derivatives are hydrolysed by lipases, esterases and proteases (Schnürer and Rosswall, 1982). Values for both these measurements declined exponentially with increasing EC_e and decreased linearly with increasing ESP (Table 4.1, Figure 4.4) demonstrating that not only the size but also the activity of the microbial community was greatly decreased by increasing salinity.

As with microbial biomass C, both FDA hydrolysis and arginine ammonification rates were positively correlated with organic C content (r^2=0.57*** and 0.56*** respectively) (Table 4.1). Many workers have found that the size and activity of the microbial biomass is positively correlated with soil organic C content (Dick *et al.*, 1988; Haynes, 1999). This is because organic matter is the energy and C source for the bulk of the heterotrophic microbial community.

Table 4.1: Correlation coefficients (r^2) and significance of correlations between measures of the size and activity of the soil microbial community and relevant soil properties (0-0.15 m). Regression equations and lines of best fit are presented in Figures 4.1 to 4.8.

Measurement	EC_e (mS m^{-1})	ESP (%)	SAR_e	$pH_{(water)}$	Organic carbon (%)
Microbial biomass carbon	-0.46***	-0.42***	-0.31**	-	+0.60***
Basal respiration	-	-	-	-	-
Microbial quotient	-0.81***	-0.56***	-0.40***	-	NP
Metabolic quotient	+0.82***	+0.72***	+0.55***	-	-0.26**
FDA hydrolysis rate	-0.28**	-0.27**	-0.26**	-	+0.57***
Arginine ammonification rate	-0.35**	-0.31**	-0.28**	-	+0.56***
Potential Mineralizable N	-0.70***	-0.44**	-0.62**	-	-
Alkaline phosphatase activity	-0.40**	-0.27*	-0.31**	-	+0.15*
Acid phosphatase activity	-	-0.22*	-0.18*	-	+0.38**
Arylsulphatase activity	-0.23*	-	-0.17*	-	+0.2*
Glucosidase activity	-0.31*	-0.33**	-0.29*	-0.29*	+0.44***

Significance of regression: - not significant; * $0.01 \leq P \leq 0.05$; ** $0.001 \leq P \leq 0.01$; ***$P \leq 0.001$.

NP: not performed since independent variable involved in calculation of dependent variable.

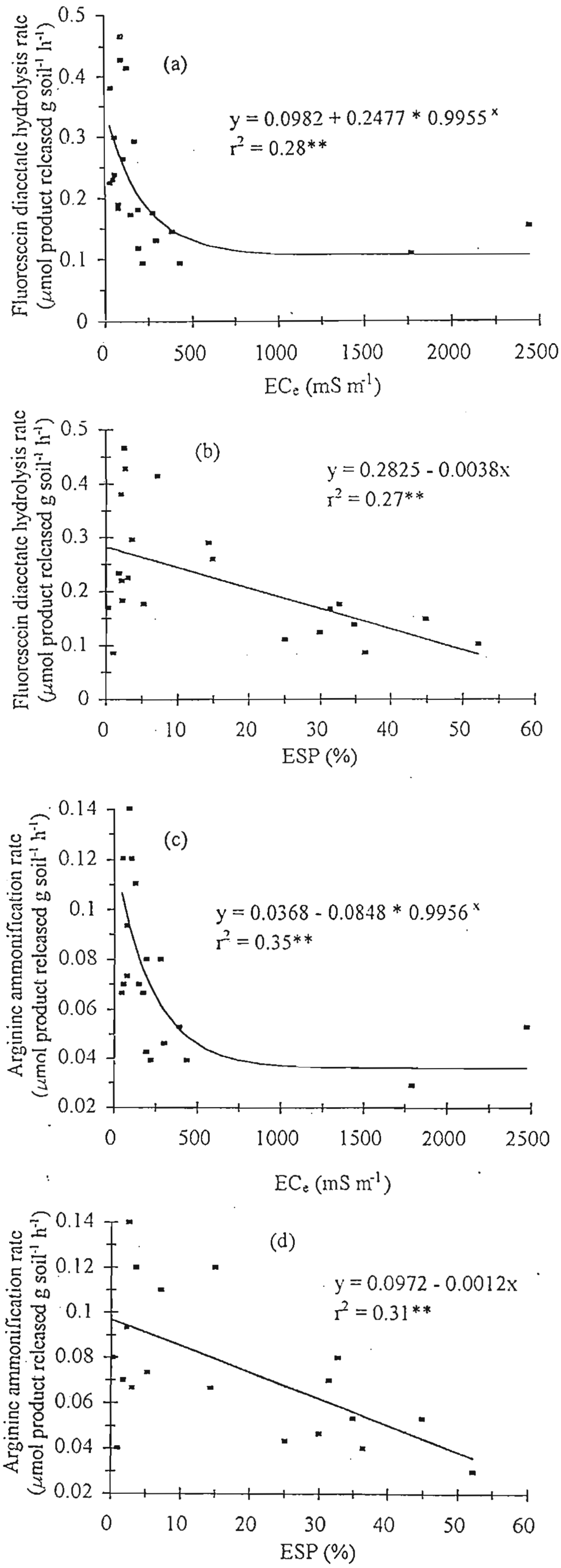


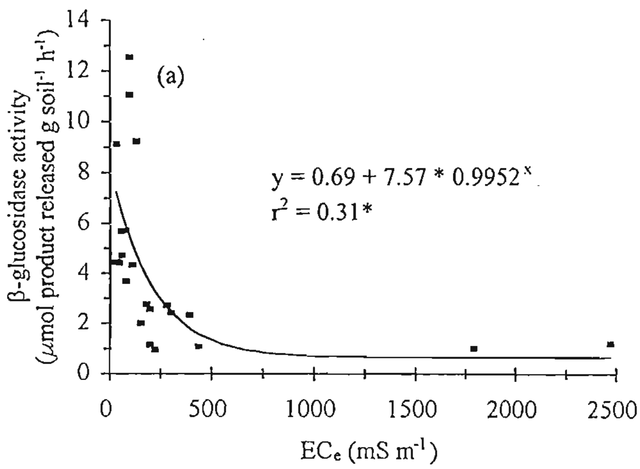
Figure 4.4: Relationship between (a) fluorescein diacetate hydrolysis rate and salinity ($EC_{e,}$), (b) fluorescein diacetate hydrolysis rate and exchangeable sodium percentage (ESP), (c) arginine ammonification rate and salinity ($EC_{e,}$) and (d) arginine ammonification rate and exchangeable sodium percentage (ESP). Correlation coefficients (r_2) and significance of correlations (* $0.01 \leq P \leq 0.05$; ** $0.001 \leq P \leq 0.01$; ***$P \leq 0.001$) are indicated on the graphs.

The reason for the reduced size and activity of the microbial community with increasing salinity is likely to be the osmotic stress which is caused by large concentrations of salts in soil solution (Galinski, 1995; Oren, 1999). Osmoregulation becomes a problem and the hypertonic environment tends to dehydrate the microorganisms. Specific ion toxicities (e.g. those of Na and Cl) may also tend to inhibit microbial growth in saline soils (Zahran, 1997).

Although irrigation-induced salinity decreased the size and activity of the soil microbial community, it is evident (Figures 4.1, 4.2, 4.3 and 4.4) that significant microbial activity persisted under saline soil conditions. Microorganisms that tolerate or require high salt concentrations are termed halotolerant and halophytic respectively. Saline soils generally appear to contain mostly halotolerant microorganisms (Ventosa *et al.*, 1998). Indeed, Zahran (1997) showed that saline soil environments harbour taxonomically diverse microbial groups which exhibit modified physiological and structural characteristics under saline conditions. The majority of halotolerant bacteria can osmoregulate by synthesizing organic osmolytes such as glutamine, proline and glycine but a few of them accumulate inorganic solutes (Zahran, 1997; Ventosa *et al.*, 1998). In a recent study, Pankhurst *et al.* (2001) found that agriculture-induced salinity caused a shift towards a less active, less functionally diverse, bacterial-dominated community.

The activity of exo-cellular enzymes involved in C (β-glucosidase), P (alkaline phosphatase) and S (arylsulphatase) mineralization declined exponentially with increasing salinity, and in general, decreased linearly with increasing sodicity (Table 4.1, Figures 4.5, 4.6 and 4.7). In addition these enzymes were, as expected, positively correlated with soil organic carbon content (Table 4.1). This relationship between soil enzyme activity and soil organic matter content has been found by many workers (Schnürer *et al.*, 1985; Dick *et al.*, 1988; Martens *et al.*, 1992; Haynes, 1999). The enzyme β-glucosidase catalyses hydrolysis of cellulose into glucose whilst phosphatase and arylsulphatase catalyse the hydrolysis of phosphate and sulfate ester bonds with the release of phosphate and sulfate respectively (García *et al.*, 1994; Wick *et al.*, 1998). The practical implication of these results is that mineralization of soil organic C, P and S is likely to be decreased by salinity and sodicity. Acid phosphatase activity was also assayed but its activity was not significantly correlated to EC_e and it was poorly correlated to ESP and SAR_e (Table 4.1). This is possibly related to the high pH of the study soils.

The lowered enzyme activity with increasing salinity will be partially due to a smaller, less active, microbial biomass excreting less enzymes. In addition, high salt concentrations tend to denature proteins through disruption of the tertiary protein structure which is essential for enzymatic activity (Zahran, 1997). In order to counteract such an effect, it is thought that moderately halophytic microorganisms can excrete salt-tolerant enzymes that can carry out their catalytic functions at high salt concentrations (Ventosa *et al.*, 1998).



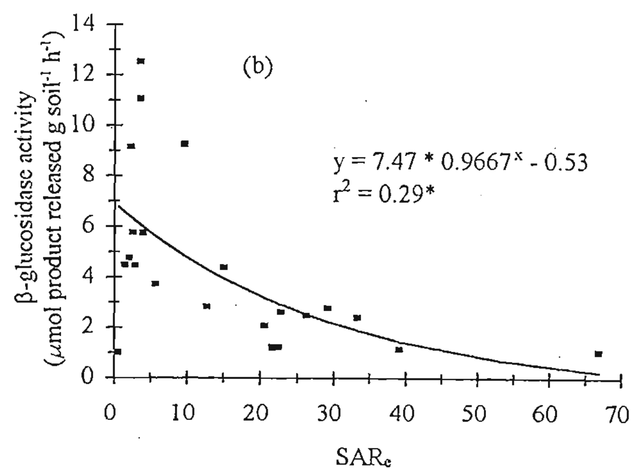


Figure 4.5: Relationship between glucosidase activity and (a) salinity ($EC_{e,}$) and (b) exchangeable sodium percentage (ESP). Correlation coefficients (r_2) and significance of correlations (* $0.01 \leq P \leq 0.05$; ** $0.001 \leq P \leq 0.01$; ***$P \leq 0.001$) are indicated on the graphs.

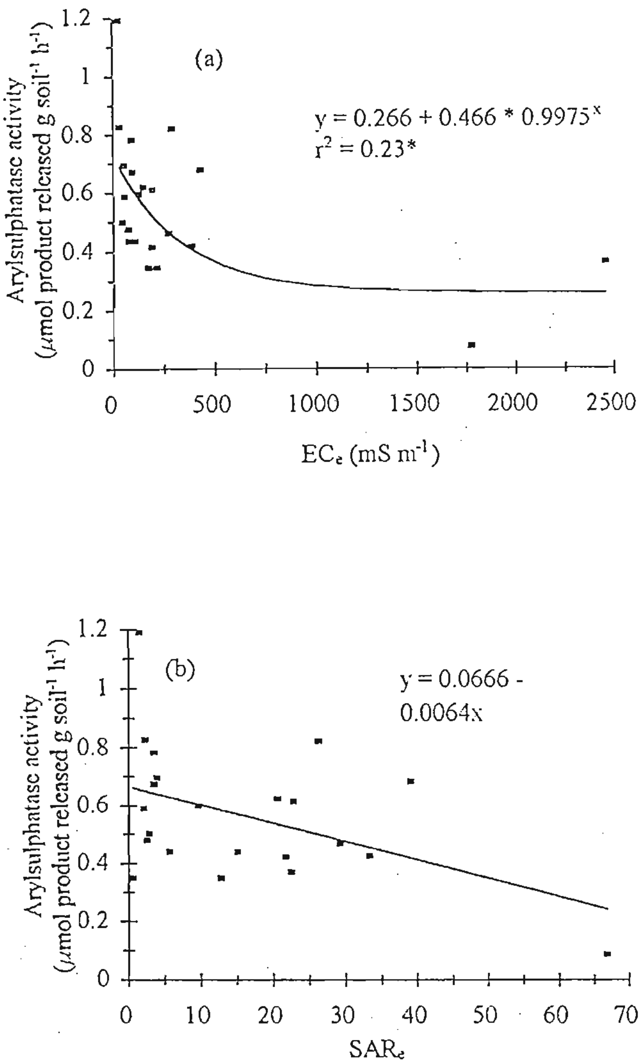
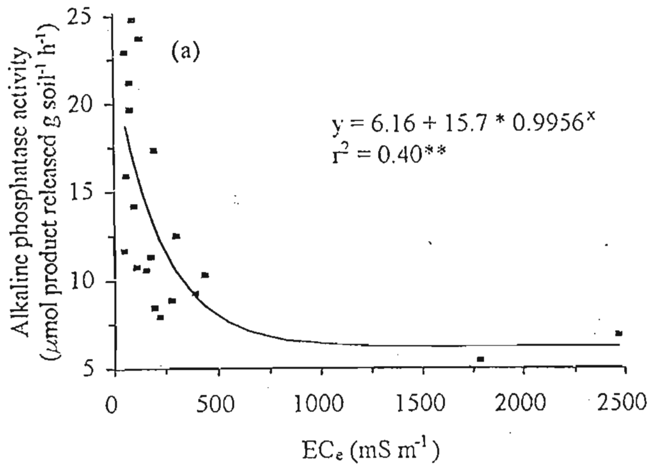


Figure 4.6: Relationship between arylsulfatase activity and (a) salinity ($EC_{e,}$) and (b) exchangeable sodium percentage (ESP). Correlation coefficients (r_2) and significance of correlations (* $0.01 \leq P \leq 0.05$; ** $0.001 \leq P \leq 0.01$; ***$P \leq 0.001$) are indicated on the graphs.



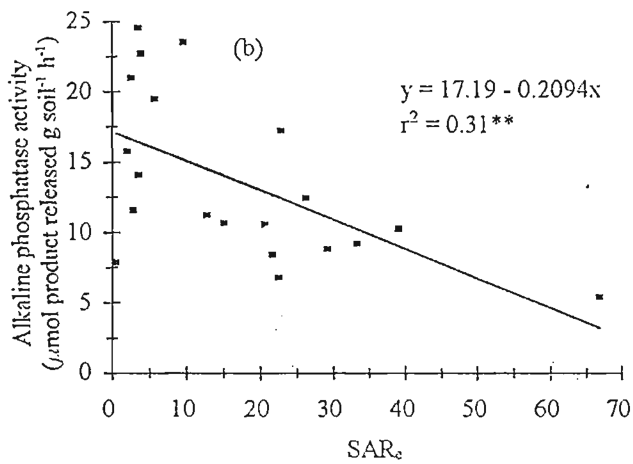


Figure 4.7: Relationship between alkaline phosphatase activity and (a) salinity (EC_e) and (b) exchangeable sodium percentage (ESP). Correlation coefficients (r_2) and significance of correlations (* $0.01 \leq P \leq 0.05$; ** $0.001 \leq P \leq 0.01$; ***$P \leq 0.001$) are indicated on the graphs.

Although soil microbial activity and C mineralization were decreased by increasing salinity there was no evidence of an accumulation of soil organic matter in the salt-affected soils (Appendix 2.1). Indeed, at sites 2, 3 and 4, the lowest organic C content in soils under sugarcane was recorded in the plots with dead and dying sugarcane. It therefore seems likely that the decreased soil organic matter decomposition was balanced by a decreased input of organic material (particularly in the form of turnover of sugarcane roots) due to the poor cane growth induced by salinity and sodicity. Where there is no cane there is no significant input of organic material and therefore organic carbon content declines.

In addition, accumulation of organic matter in sodic soils is inhibited because the high pH and high Na content result in solubilisation of soil organic matter. Indeed, in strongly alkaline conditions, dissolved organic matter gives the soil surface a dark black colour (Gupta and Abrol, 1990). Sodium-organic matter complexes are highly soluble and mobile, particularly at high pH values, and this can lead to leaching of organic matter into lower horizons (Sokoloff, 1938; Naidu and Rengasamy, 1995). However, Ca counteracts this effect by cross-linking with organic molecules and increasing their resistance to chemical and biological degradation (Oades, 1988; cited in Naidu and Rengasamy, 1995; Nelson *et al.*, 1996). In alkaline soils, with a pH > 8, Ca precipitates (see section 3.3), and this could result in even greater solubilisation of organic matter. The result is that under strongly alkaline conditions, soils tend not to retain the products of organic residue decomposition (Naidu and Rengasamy, 1995; Nelson *et al.*, 1996).

Although results presented here showed that increasing salinity and sodicity inhibited microbial activity and N mineralization, results reported in the literature are less clear-cut. For example, decomposition of added plant residues added to soils has been shown to be reduced by increasing salinity, but unaffected or increased by sodicity (Nelson *et al.*, 1996; Pathak and Rao, 1998). By contrast, Nelson *et al.* (1997) found sodicity had a slight negative effect on decomposition of added residues. Sodicity could decrease organic matter decomposition directly by inhibition of microbial growth and activity, and indirectly either by clay dispersion causing poor physical conditions and/or anaerobiosis or protection of particulate organic matter from microbial attack by the formation of coatings of dispersed clay (Nelson *et al.*, 1997). On the other hand, solubilisation of organic matter in sodic soils results in increased substrate availability for the microbial community and this could promote decomposition (Nelson *et al.*, 1996). Thus, the effect of sodicity on organic matter decomposition probably varies depending on the relative importance of the various positive and negative factors involved.

The exponential decline in potentially mineralizable N with increasing EC_e, ESP and SAR_e (Table 4.1, Figure 4.8) is in agreement with the findings of other workers (Bandyopadhyay and Bandyopadhyay, 1983). Indeed, although ammonification (the conversion of soil organic N to NH_4^+) can be stimulated by low salt concentrations, it is characteristically inhibited by higher concentrations (McClung and Frankenberger, 1987; Pathak and Rao, 1998; Zahran, 1997). Although Laura (1977), in a laboratory study found that nitrification (conversion of NH_4^+ to NO_3^-) was more sensitive to salinity than ammonification, the results presented here have provided no evidence of this. Indeed, the initial mean exchangeable NH_4:NO_3 ratio in soils prior to incubation was 2.34 (range 0.03 to 7.28) and after the 10 day incubation it had decreased to 0.29 (range 0.02 to 0.59) and the ratio was unaffected by increasing salinity (data not shown). Since most saline soils have low N contents, the importance of inputs of N increases, and increased N fertilization of crops is necessary to obtain substantial yields (Zahran, 1997).

No significant correlations were obtained between soil pH and organic carbon content, or the various indicators of microbial population size and activity measured in this study (Table 4.1). The only exception was that of glucosidase ($r^2 = 0.29$*), and that alkaline phosphatase, rather than acid phosphatase dominated at the high soil pH values. This is surprising given that soil pH can influence the ionization and solubility of enzymes, substrates and cofactors, so affecting soil enzyme-mediated reactions (Dick *et al.*, 1988). Dick *et al.* (1988) found correlations between soil pH and several enzyme activities. However, soil salinity, sodicity and organic carbon content of the soils appeared to have a greater influence than pH on the soil microbial community. Indeed, in the study soils the pH was strongly related to SAR_e and ESP (see section 3.3.1) so that independent effects of pH *per se.* on microbial and enzyme activity were unlikely.

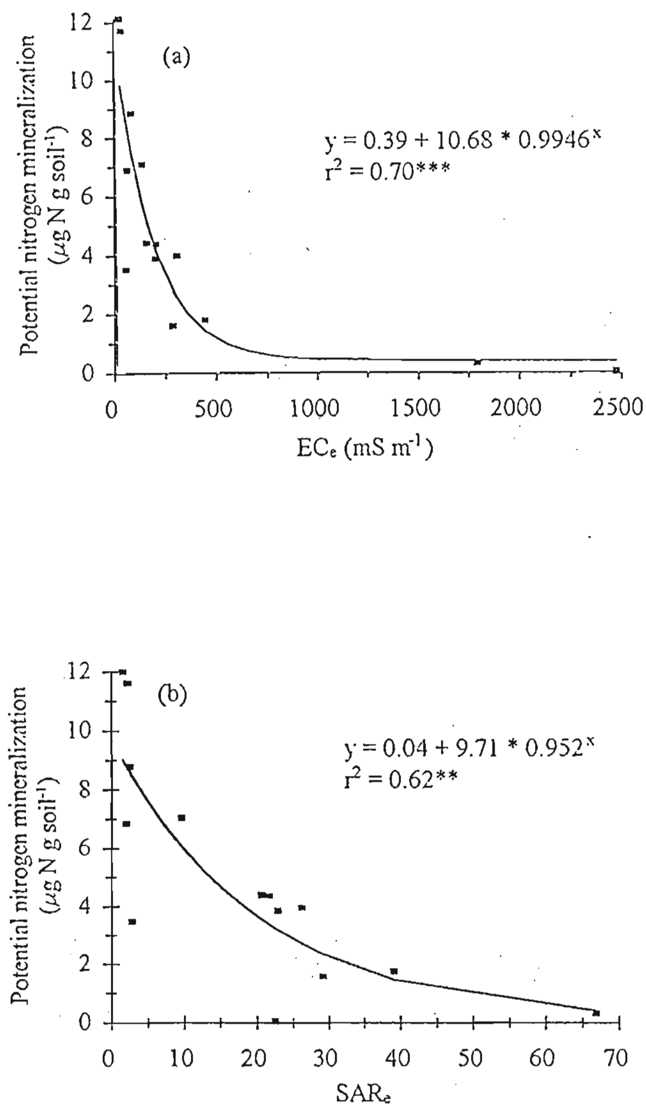


Figure 4.8: Relationship between potential nitrogen mineralization and (a) salinity (EC_e,) and (b) sodium adsorption ratio (SAR_e). Correlation coefficients (r_2) and significance of correlations (* $0.01 \leq P \leq 0.05$; ** $0.001 \leq P \leq 0.01$; ***$P \leq 0.001$) are indicated on the graphs.

The wide diversity of microorganisms present in soils meant that a significant microbial biomass remained in soils with very high ESP or EC_e values even though the sugarcane had died. Although microorganisms are generally more tolerant to salinity than plants (Sarig and Steinberger, 1994), decreased microbial activity in salt-affected soils, as observed here and by others (such as Mallouhi and Jacquin, 1985; Pankhurst *et al.*, 2001), may have significant implications in the crop-soil system. For example, the microbial community is involved in key soil processes such as formation and stabilization of soil aggregates and decomposition of plant residues as well as mineralization; all these processes will be depressed by increased salinity. It is interesting to note here, that whilst plant growth in the study soils was not significantly related to EC_e it was negatively correlated with ESP. By contrast, measures of the size and activity of the microbial community were equally, or more closely negatively correlated to EC_e than ESP (Table 4.1). Thus, high soluble salt concentrations were apparently more important in inhibiting the growth and activity of soil microorganisms than they were in limiting sugarcane growth. For sugarcane, sodicity seemed to be the more important limiting factor.

In recent times, much research has centred on the use of soil biological properties as indicators of soil health or quality (Pankhurst *et al.*, 1997). The activities of various soil enzymes have been suggested as sensitive, rapid and inexpensive indicators of perturbations to the soil system (Dick, 1992). Our results confirm this. However, of particular interest in this study was the marked increase in metabolic quotient with increased salinity. The metabolic quotient has been shown to be a particularly sensitive indicator of soil pollution (e.g. with heavy metals; Sparling, 1997) and it is evidently also very sensitive to increasing salinity.

4.4 Conclusions

This study showed that irrigation induced salinity and sodicity not only had an extremely adverse effect on plant growth and yield of sugarcane but also had an adverse effect on the size and activity of the soil microbial biomass and on soil microbial processes essential for maintenance of soil quality. An implication of this is that soil fertility will be decreased (particularly due to decreased availability of N, S and possibly P) and organic matter affected, and this will add to salinity and sodicity *per se.* as an additional growth limiting factor for crops in salt-affected soils.

GENERAL CONCLUSIONS

Under undisturbed veld, soils on the sugar estate studied were calcareous and vertic and had high pH values (8 to 9.5) and high exchangeable Ca and Mg contents. There was evidence of some accumulation of soluble salts in the surface 0.15 m. Under furrow-irrigated sugar production, over-irrigation has resulted in a marked rise in the watertable. The watertable is closer to the soil surface at the lower ends of the gently sloping fields, where it can be within 0.2-0.3 m of the surface. The high watertable, particularly at the lower ends of the fields presumably resulted in death of roots due to anaerobic conditions in the subsoil. As a result, the effective crop rooting depth probably decreased progressively from the high to the low ends of the fields.

Due to capillary rise of salts, soluble salts have accumulated near the soil surface particularly at the lower ends of the fields. This has resulted in sodic and saline-sodic conditions developing in the surface soil horizons. Soil pH was often between 9 and 10 particularly in profiles from where sugarcane grew poorly or had died. That sugarcane yields were not significantly related to EC_e but were negatively correlated with ESP suggests sodicity was a more limiting factor for sugarcane growth than salinity. Sodicity did not appear to be limiting plant growth through induction of nutrient imbalances or deficiencies since foliar analysis of sugarcane tissues showed no substantial differences in macro- or micro-nutrient content between good and poorly-growing crops. The sodic, and sometimes saline, conditions may have limited plant growth through ion toxicities (i.e., Na^+ and HCO_3^-) which could inhibit root growth and function and impede physiological processes within plants. In some cases, salinity could also have induced water stress.

Another consequence of the high watertable was that these vertic soils were observed to remain in a permanently swollen state. This limits air and water movement in the soil profile, as such soils need to be allowed to dry out and crack regularly so that macroporosity can be restored. In addition, soils tended to disperse, and dispersion was most apparent where high ESP and SAR_e values occurred in association with elevated pH values and relatively low EC_e values. These measurements confirmed observations at the site of low infiltration rates and restricted drainage particularly on the lower ends of fields where sugarcane had died.

It is concluded that the combination of a high watertable, restricted rooting depth, poor physical conditions and sodic and saline-sodic conditions in the surface soil resulted in a declining sugarcane yield from the high to the low ends of the fields, with crop death occurring at the lower ends.

Most research dealing with the effects of sodicity and salinity on soil fertility have dealt with their negative influence on soil chemical and physical properties. Research reported here showed clearly that irrigation-induced salinity and/or sodicity caused a marked decrease in the size and activity of the soil microbial biomass and in the activity of key enzymes involved in C, N, S and P mineralization. The wide diversity of microorganisms present in soils meant that a significant microbial community remained in soils with a very high ESP and EC_e values even though the sugarcane had died. The microbial metabolic quotient, however, increased suggesting that a smaller, more stressed, less metabolically efficient microbial community had been induced. That measures of the size and activity of the microbial biomass were equally or more closely negatively correlated with EC_e than ESP suggested that high soluble salt concentrations were more important in inhibiting microbial activity than sugarcane growth.

The implication of these findings is that increasing salinity and/or sodicity have an extremely adverse effect on the size and activity of the soil microbial community which is so essential for the maintenance of soil quality. Decreases in the availability of N, S and P through a reduced rate of organic matter decomposition and mineralization are likely. It is interesting to note that, soil organic matter content tended to decrease, rather than increase, with increasing EC_e and ESP. This was attributed to a combination of lower organic matter inputs to the soil because of decreasing crop growth, and the possible solubilization and leaching of organic matter induced by the high soil pH and often high Na content.

In order to ameliorate the problems now evident at the site, the watertable will first need to be lowered substantially. This will require hydrological and engineering expertise and will be expensive to achieve. In association with this, irrigation scheduling and practice will need to be improved so that water-use-efficiency is maximised and future downward movement into the groundwater is minimised. The sodic and saline-sodic conditions will also need to be ameliorated.

The most obvious method is applications of gypsum with subsequent leaching events. Lowering of the watertable is also important so that the soils can be allowed to 'dry off' and crack so that macroporosity can be restored on a regular basis. This will help improve and/or maintain adequate soil physical properties in the crop rooting volume.

In the lowest-lying parts of the fields it may prove unpractical and/or uneconomic to effectively ameliorate the poor soil conditions. In these areas, the use of salt-tolerant sugarcane cultivars or more salt-tolerant crops such as cotton or bermuda grass could be considered. The watertable will, however, still need to be lowered in order to allow for an adequate crop rooting depth.

REFERENCES

Ahmad, N. 1983. Vertisols. p. 91-124. *In* L.P. Wilding, N.E. Smeck and G.F. Hall (eds.) Pedogenesis and Soil Taxonomy. II. The Soil Orders. Elsevier, Amsterdam.

Ahmad, N., C.E. Davis and, R.L. Jones. 1972. Ammonium fixation and its effect on mineralogical properties of West Indian soil clays. Trop. Agric. (Trinidad) 49:347-353.

Ahmad, N., and, R. L. Jones. 1967. Forms of occurence of inorganic phosphorus and its chemical availability in the limestone soils of Barbados. Soil Sci. Soc. Am. Proc. 30:719-722.

Ahmad, N., and, R. L. Jones. 1969a. Genesis, Chemical Properties and Mineralogy of Carribean Grumusols. Soil Sci. 107:166-174.

Ahmad, N., and, R. L. Jones. 1969b. Genesis, Chemical Properties and Mineralogy of Limestone Derived Soils, Barbados, West Indies. Trop. Agric. (Trinidad) 46:1-15.

Alef, K., and, D. Kleiner. 1995. Arginine ammonification. p.238-240. *In* K. Alef and P. Nannipieri (eds). Methods in Applied Soil Microbiology and Biochemistry. Academic Press, London.

Alexander, M. 1961. Mineralization and Immobilization of Nitrogen. p248-271. *In* Introduction to Soil Microbiology. John Wiley & Sons, Inc. New York.

Alymore, L.A.G., and, I.D. Sills. 1982. Characterisation of soil structure and stability using modulus of rupture-ESP relationships. Aust. J. Soil Res. 20:213-224.

Anderson, J.P.E. 1982. Soil Respiration. p. 837-871. In: AL Page (ed). Methods of Soil Analysis, Part 2, 2nd Edition. Soil Sci. Soc. Am. Madison Wisconsin.

Anderson, T.H. and, K.H. Domsch. 1989. Ratios of microbial biomass carbon to total organic carbon in arable soils. Soil Biol. Biochem. 21:471-479.

Anderson, T.H. and, K.H. Domsch. 1990. Application of the eco-physiological quotients (qCO_2 and qD) on microbial biomass from soils of different cropping histories. Soil Biol. Biochem. 22:251-255.

Arora, H.S., and, N.T. Coleman. 1979. The influence of electrolyte concentration on flocculation of clay suspensions. Soil Sci. 127:134-139.

Bakker, A.C., W.W. Emerson, and, J.M. Oades. 1973. The comparative effects of exchangeable calcium, magnesium, and sodium on some physical properties of red-brown earth subsoils. Aust. J. Soil Res. 11:143-150.

Bandyopadhyay, B.K., and, A.K. Bandyopadhyay. 1983. Effect of salinity on mineralization and immobilization of nitrogen in a coastal saline soil of west Bengal. Ind. J. Agric. 27:41-50.

Barnes, A.C. 1964. History and Development as a World Crop. pp1-17. *In* The Sugar Cane. Leonard Hill, London.

Beater, B.A. 1962. The Sampling and Analysis of Field Sites. South African Sugar Association Experimental Station, Mount Edgecombe, Natal, S.A.

Bernstein, L., L.E. Francois, and, R.A. Clark. 1966. Salt tolerance of NCo varieties of sugarcane l-Sprouting growth and yield. Agron. J. 58:489-493.

Birch, C. J., and, J. H. Adriaans. 1984. The effect of applications of nitrogen, phosphorus and gypsum on the yield of wheat (*Triticum aestivum* L.) Grown on Grey Clay Soils of the Moree District, New South Wales. p. 247-252. *In* J.W. McGarity, E.H. Hoult and H.B. So (eds.) The Properties and Utilization of Cracking Clay Soils. University of New England, Australia.

Black, C.A. 1968. Soil-plant relationships. John Wiley and Sons, New York.

Bramley, R.G.V., N. Ellis, R.O. Nable, and, A.L. Garside. 1996. Changes in soil chemical properties under long-term sugar cane monoculture and their possible role in sugar yield decline. Aust. J. Soil Res. 34:967-984.

Braunack, M.V. 1997. The effect of soil physical properties on growth and yield of sugarcane. Sugar Cane2:4-12.

Bremner, J.M. 1965. Inorganic forms of nitrogen. p. 1191-1205. *In* CA Black (ed). Methods of Soil Analysis (Part 2), Chemical and Microbiological Properties. The Am. Soc. of Agron., Inc. Madison, Wisconsin.

Bremner, J.M., and, K. Shaw. 1958. Denitrification in soil. II. Factors affecting denitrification. J. Agric. Sci. 51:40-51.

Brooks, R.H., C.A. Bower, and, R.C. Reeve. 1956. The effects of various exchangeable cations upon the physical conditions of soils. Soil Sci. Soc. Am. Proc. 20:315-327.

Brown, J.C. 1976. Iron deficiency and boron toxicity in alkaline soils. pp.83-94. *In* M.J. Wright (ed.) Plant Adaptation to Mineral Stress in Problem Soils. Cornell Univ., New York.

Bühmann, C., de Villiers, J.M. and M.V. Fey. 1986. The clay mineralogical basis of potassium fixation. p. 63-65. *In* Proc. of the Potassium Symposium. Potassium Symposium Organising Committee, Pretoria.

Burnham, C.P., and, D. Lopez-Hernandez. 1982. Phosphate retention in different soil taxonomic classes. Soil Sci. 134:376-380.

Carter, D.L. 1975. Problems of salinity in Agriculture. p. 25-35. *In* A. Poljakoff-Mayber and J. Gale (eds.) Plants in Saline Environments. Springer-Verlag, Berlin, Germany.

Chan, K.Y., and, A.S. Hodgson. 1984. Moisture regimes of a cracking clay soil under furrow irrigated cotton. p. 176-183. *In* J.W. McGarity, E.H. Hoult and H.B. So (eds.) The Properties and Utilization of Cracking Clay Soils. University of New England, Australia.

Chavan, P.D., and, B.A. Karadge. 1986. Growth, mineral nutrition, organic constituents and rate of photosynthesis in *Sesbania grandiflora* grown under saline conditions. Plant Soil 93:395-404.

Clowes, M. St J., and, W.L. Breakwell. 1998. *In* Zimbabwe Sugarcane Production Manual.

Craswell, E.T. 1979. Isotopic studies of the nitrogen balance in a cracking clay. IV. Fate of three nitrogen fertilizers in fallow soil in the field. Aust. J. Soil. Res. 17:317-323.

Craswell, E.T., and, A.E. Martin. 1975. Isotopic studies of the nitrogen balance in a cracking clay. I. Recovery of added nitrogen from soil and wheat in the glasshouse and gas lysimeter. Aust. J. Soil Res. 13:43-52.

Craswell, E.T., and, W.M. Strong. 1976. Isotopic studies of the nitrogen balance in a cracking clay. III. Nitrogen recovery in plant and soil in relation to the depth of fertilizer addition and rainfall. Aust. J. Soil Res. 14:75-83.

Culverwell, T.L. 2000. Salinity/sodicity from a practical perspective. Proc. AGM of the SA Sug. Ind. Agron. Ass. 61-70.

Culverwell, T.L., and, J.M. Swinford. 1986. Attempts at improving irrigation water quality in northern Zululand. Proc. S. Afr. Sug. Technol. Ass. 60:168-171.

Dalal, R.C. 1977. Soil organic phosphorus. Adv. Agron. 29:83-117.

Dalal, R. C., and, A. L. Clarke. 1984. Kinetics of soil nitrogen in some cracking clays of the Darling and Western Downs, Queensland. p. 221-226. *In* J.W. McGarity, E.H. Hoult and H.B. So (eds.) The Properties and Utilization of Cracking Clay Soils. University of New England, Australia.

Dalal, R.C., and, R.J. Mayer. 1986. Long term trends in fertility of soil under continuous cultivation and cereal cropping in southern Queensland. II. Total organic carbon and its rate of loss from the profile. Aust. J. Soil Res. 24:281-292.

De Geus, J.G. 1973. Fertilizer Guide for the Tropics and Sub-tropics. Centre d'Etude de l'Azote, Zurich, FAO. The state of food and agriculture, FAO - Agriculture Series No. 29, FAO, Rome.

Dick, R.P. 1992. A review: long-term effects of agricultural systems on soil biochemical and microbial parameters. Agric. Ecosys. Environ. 40:25-36.

Dick, R.P., P.E. Rasmussen, and, E.A. Kerie 1988. Influence of long-term residue management on soil enzyme activities in relation to soil chemical properties of a wheat-fallow system. Biol. Fertil. Soils 6:159-164.

Dudal, R., and, H. Eswaran. 1988. Distribution, Properties and Classification of Vertisols. p. 1-22. *In* L.P. Wilding and R. Puentes (eds.) Vertisols: Their Distribution, Properties, Classification and Management. Texas A&M University Printing Centre, Texas.

Ekwue, E.I. 1990. Organic-matter effects on soil strength properties. Soil Till. Res. 16:289-297.

Emerson, W.W. 1967. A classification of soil aggregates based on their coherence in water. Aust. J. Soil Res. 5:47-57.

Emerson, W.W., and, C.L. Chi. 1977. Exchangeable Ca, Mg and Na and the dispersion of illite. II. Dispersion of illites in water. Aust. J. Soil Res. 15:225-265.

Fageria, N.K., V.C. Baligar, and, C.A. Jones. 1991. Sugarcane. pp:332-353. *In* Growth and Mineral Nutrition of Field Crops. Marcel Dekker, Inc., New York.

FAO. 1965. Dark clay soils of tropical and subtropical regions. *In* R. Dudal (ed.) FAO Agricultural Development Paper No. 83. FAO, Rome.

Flach, K.W. 1976. Formation, distribution and consequences of alkaline soils in agricultural development. p. 25-30. *In* M.J. Wright (ed.) Plant Adaptation to Mineral Stress in Problem Soils Cornell Univ., New York.

Fraser, P.M., R.J. Haynes, and P.H. Williams. 1994. Effects of pasture improvement and intensive cultivation on microbial biomass, enzyme activities, and composition and size of earthworm populations. Biol. Fertil. Soils 17:185-190.

Frenkel, H., J.O. Goertzen, and, J.D. Rhoades. 1978. Effects of clay type and content, ESP and electrolyte concentration on clay dispersion and soil hydraulic conductivity. Soil Sci. Soc. Am. J. 42:32-39.

Gale, J. 1975a. Water balance and gas exchange of plants under saline conditions. p. 168-187. *In* A. Poljakoff-Mayber and J. Gale (eds.) Plants in Saline Environments. Springer-Verlag, Berlin, Germany.

Gale, J. 1975b. The combined effect of environmental factors and salinity on plant growth. p. 186-192. *In* A. Poljakoff-Mayber and J. Gale (eds.) Plants in Saline Environments. Springer-Verlag, Berlin, Germany.

Galinski, E.A. 1995. Osmoadaption in bacteria. Adv. Microb. Physiol. 37:273-328.

García, C., T. Hernández, and, F. Costa. 1994. Microbial activity in soils under Mediterranean environmental conditions. Soil Biol. Biochem. 26:1185-1191.

Garside, A.L., R.G.V. Bramely, K.L. Bristow, J.L. Holt, R.C. Magarey, R.O. Nable, C.E. Pankhurst, and, J.O. Skemstad, J.O. 1997. Comparisons between paired old and new land sites for sugarcane growth and yield and soil chemical, physical, and biological properties. Proc. Aust. Soc. Sug. Cane Technol. 19:60-66.

Gianfreda, L., and, J.M. Bollag. 1996. Influence of natural and anthropogenic factors on enzyme activity in the soil. p. 123-193. *In* G. Stotzky and J.M. Bollag (eds.) Soil Biochemistry, Vol. 9. Marcel Dekker, Inc., New York.

Greene, R.S.B., P. Rengasamy, G.W. Ford, C.J. Chartres, and, J.J. Millar. 1998. The effect of Na and Ca on physical properties and micromorphology of two red-brown earths. J. Soil Sci. 39:639-648.

Greene, H., and, O.W. Snow. 1939. Soil improvement in the Sudan Gezira. J. Agric. Sci. 29:1-34.

Gupta, R.K., and, I.P. Abrol. 1990. Salt-affected soils: their reclamation and management for crop production. Adv. Soil Sci. 11:223-288.

Gupta, R.K., D.K. Bhumbla, and I.P. Abrol. 1984a. Ca-Na ion exchange equilibria in an alkali soil: Effect of $CaCO_3$ and organic matter. Soil Sci. 138:109-114.

Gupta, R.K., D.K. Bhumbla, and, I.P. Abrol. 1984b. Effect of sodicity, pH, organic matter and calcium carbonate on the dispersion behaviour of alkali soils. Soil Sci. 137:245-251.

Gupta, R.K., C.P. Singh, and, I.P. Abrol. 1985. Determining cation exchange capacity and exchangeable sodium in alkali soils. Soil Sci 139:326-332.

Ham, G.J., A.Z. Cox, and, G.G. MeMahon. 1997. A review of sodic soils research in the Queensland sugar industry. Proc. Aust. Soc. Sug. Cane Technol. 19:200-207.

Hartemink, A.E. 1998a. Soil chemical and physical properties as indicators of sustainable land management under sugarcane plantation in Papua New Guinea. Geoderma 85:283-306.

Hartemink, A.E. 1998b. Changes in soil fertility and leaf nutrient concentration at a sugar cane plantation in Papua New Guinea. Commun. Soil Sci. Plant Anal. 29:1045-1060.

Hartemink, A.E. 1998c. Acidification and pH buffering capacity of alluvial soils under sugarcane. Exp. Agric. 34:231-243.

Hartemink, A.E., and, L.S. Kuniata. 1996. Some factors influencing yield trends of sugarcane in Papua New Guinea. Outlook Agric. 25:227-234.

Haynes, R.J. 1999. Size and activity of the soil microbial biomass under grass and arable management. Biol. Fertil. Soils 30:210-216.

Haynes, R.J., and, M.H. Beare. 1996. Aggregation and organic matter storage in meso-thermal soils. p. 213-262. *In* M.R. Carter and B.A. Stewart (eds.) Structure and Organic Matter Storage in Agricultural Soils. CRC Lewis, Boca Raton.

Haynes, R.J., and, G.S. Francis. 1983. Changes in microbial biomass C, soil carbohydrate composition and aggregate stability induced by growth of selected crop and forage species under field conditions. J. Soil Sci. 44:665-675.

Haynes, R.J., and, C.S. Hamilton. 1999. Effects of sugarcane production on soil quality: a synthesis of world literature. Proc. S. Afr. Sug. Technol. Ass. 73:45-51.

Haynes, R.J., and, R. Tregurtha. 1999. Effects of increasing periods under intensive arable vegetable production on biological, chemical and physical indices of soil quality. Biol. Fertil. Soils 28:259-266.

Hawkins, R.H., and, G.W. Kunze. 1965. Phosphate fractions in some Texas grumsols and their relation to soil weathering and available phosphorus. Soil Sci. Soc. Am. Proc. 29:650-656.

Hetherington, S.J., C.J. Asher, and, F.P.C. Blamey. 1986. Tolerance of sugarcane to Al in soil and solution culture. Proc. Aust. Soc. Sug. Cane Technol. 8:63-68.

Holford, I.C.R. 1981. Changes in nitrogen and organic carbon of wheat-growing soils after various periods of grazed lucerne, extended fallowing and continuous wheat. Aust. J. Soil Res. 19:239-49.

Hubble, G. D. 1984. The cracking clay soils: definition, distribution, nature, genesis and use. p. 3-13. *In* J.W. McGarity, E.H. Hoult and H.B. So (eds.) The Properties and Utilization of Cracking Clay Soils. University of New England, Australia.

Hubble, G.D., and, R.F. Isbell. 1958. The occurence of strongly acid clays beneath alkaline soils in Queensland. Aust. J. Soil Sci. 20:186-187.

Hudson, N.W. 1984. Soil and water management on cracking black clay in India. p. 341-343. *In* J.W. McGarity, E.H. Hoult and H.B. So (eds.) The Properties and Utilization of Cracking Clay Soils. University of New England, Australia.

Humbert, R.P. 1968a. Effects of salinity on plant growth. p. 426-437. *In* The Growing of Sugar Cane. Elsevier Pub., New York.

Humbert, R.P. 1968b. Factors affecting the growth of sugar cane. pp11-54. *In* The Growing of Sugar Cane. Elsevier Pub., New York.

Humbert, R.P. 1968c. Waterlogged soils. pp409-413. *In* The Growing of Sugar Cane. Elsevier Pub., New York.

Humbert, R.P. 1973. Plant analysis as an aid in fertilizing sugar crops: Part II. Sugarcane. *In* L.M. Walsh and J.D. Beaton (eds.) Soil Testing and Plant Analysis. Soil Sci. Soc. Am., Inc., Wisconsin, USA.

Hussein, J. 1998. Management and irrigation of Vertisols derived from basalts in Zimbabwe. *In* M. St. J. Clowes (ed.) Fourth Zimbabwe Sugar Seminar (20 August 1998).

Insam, H., C.C. Mitchell, and J.F. Dormar. 1991. Relationship of soil microbial biomass and activity with fertilization practice and crop yield of three ultisols. Soil Biol. Biochem. 23:459-464.

Jeffery, J.J., and, N.C. Uren. 1983. Copper and zinc species in the soil solution and the effects of soil pH. Aust. J. Soil Res. 21:479-488.

Johnston, A.E. 1986. Soil organic matter effects on soils and crops. Soil Use Manag. 2:97-105.

Johnston, M.A. 1975. The effects of different levels of ESP on soil hydraulic conductivity. Proc. S.A. Sug. Technol. Ass. 49:142-147.

Johnston, M.A. 1977. Reclamation of a saline sodic soil in the Nkwalini Valley. Proc. S. Afr. Sug. Technol. Ass. 51:42-46.

Johnston, M.A. 1978. Soil salinity and sodicity problems in the South African sugar industry. MSc thesis, University of Natal, South Africa.

Johnston, M.A. 1981. Properties of selected soils derived from Middle Ecca and Dwyka sediments with particular reference to their sensitivity to sodium. Soil Sci. Soc. S. Afr. 10th Conference, E. London.

Keating, B.A., K. Verburg, N.I. Huth, and, M.J. Robertson. 1997. Nitrogen management in intensive agriculture: sugarcane in Australia. p. 221-242. *In* Keating, B.A. and Wilson, J.R. (eds.) Intensive sugarcane production. CAB Int., Wallingford, UK.

Keren, R. 2000. Salinity. p. G3-G25. In: ME Sumner (ed.) Handbook of Soil Science. CRC Press, Boca Raton, Florida.

Kingston, G., D.M. Hogarth, and, T.O. Albertson. 1980. Current research with sugarcane in the Ord. Proc. Aust. Soc. Sugarcane Technol., 1980 conference, pp. 43-49.

Kumar, S., K.M. Naidu, and, H.L. Sehtia. 1994. Causes of growth reduction in elongating and expanding leaf tissue os sugarcane under saline conditions. Aust. J. Plant Physiol. 21:79-83.

Kunze, G.W., H. Oakes, and, M. E. Bloodworth. 1963. Grumusols of the Coast Prairie of Texas. Soil Sci. Soc. Am. Proc. 27:412-421.

Lagerwerff, J.V., and, J.P. Holland. 1960. Growth and mineral content of carrots and beans related to varying osmotic and ionic composition effects in saline-sodic sand culture. Agron. J. 52:603-608.

Laura, R.D. 1974. Effects of neutral salts on carbon and nitrogen mineralization of organic matter in soil. Plant Soil 41:113-127.

Laura, R.D. 1977. Salinity and nitrogen mineralization in soil. Soil Biol. Biochem. 9:333-336.

Lavahun, M.F.E., R,G. Joergensen, and, B. Meyer. 1996. Activity and biomass of soil microorganisms at different depths. Biol. Fertil. Soils 23:38-42.

Levy, G.J. 2000. Sodicity. pp.G27-G63. In: ME Sumner (ed.) Handbook of Soil Science. CRC Press, Boca Raton, Florida.

Levy, G.J., I. Shainberg, and, W.P. Miller. 1997. Physical properties of sodic soils. p. 77-94. *In* M.E. Sumner and R. Naidu (eds.) Sodic Soils: Distribution, Processes, Management and Environmental Consequences. Oxford Univ. Press, New York.

Loveday, J. 1974. Aggregate Stability. p.75-77. *In* Methods for Analysis of Irrigated Soils. CAB Int., Wallingford, UK.

Maas, E.V. 1990. Crop salt tolerance. p. 262-304. *In* K.K. Tanji (ed.) Agricultural Salinity Assessment and Management. ASCE, New York, USA

Maas, E.V., and, G.J. Hoffman. 1977. Crop salt tolerance current assessment. J. Irrig. Drain. Div. ASCE 103:115-134.

Maclean, N.R. 1975. Long-term effects of sugar cane production on some physical and chemical properties of soils in the Goondi mill area. Proc. Queensland Soc. Sugarcane Tech. 1975:123-126.

Mallouhi, N., and, F. Jacquin. 1985. Essai de correlation entre proprietes biochimiques d'un sol salsodique et sa biomasse. Soil Biol. Biochem. 17,1:23-26.

Marschner, H. 1995. Adaption of plants to adverse chemical soil conditions. p. 596-680. In Mineral Nutrition of Higher Plants. Academic Press, Cambridge, U.K.

Martens, D.A., J.B. Johanson, and, W.T. Frankenberger. 1992. Production and persistence of soil enzymes with repeated addition of organic residues. Soil Sci. 153:53-61.

Mashhady, A.S., and, D.L. Rowell. 1978. Soil alkalinity. Equilibria and alkalinity development. J. Soil Sci. 29:65-75.

Maud, R.R. 1959. The occurence of two alkali soils in Zululand. Proc. S. Afr. Sug. Technol. Ass. 33:138-144.

McClung, G., and, W.T. Frankenberger, Jr. 1987. Nitrogen mineralization rates in saline vs salt amended soils. Plant Soil 104:13-21.

Meinzer, F.L., Z. Plaut, and, N.Z. Saliendra. 1994. Carbon isotope discrimination, gas exchange and growth of sugarcane cultivars under salinity. Plant Physiol. 104:521-526.

Mermut, A.R., and, G.S. Dasog. 1986. Nature and micromorphology of carbonate glaebules in some Vertisols of India. Soil Sci. Soc Am. J. 50:382-391.

Meyer, J.H., A.B. Tucker, and, R.A. Wood. 1997. The SASEX fertiliser advisory service: over 40 years service to the SA sugar industry. Proc. S. Afr. Sug. Technol. Ass. 71:42-49.

Meyer, J.H., R. van Antwerpen, and, E. Meyer. 1996. A review of soil degradation and management research under intensive sugarcane cropping. Proc. S. Afr. Sug. Technol. Ass. 70:22-28.

Mortvedt, J.J. 1976. Alkaline soils. p. 141-160. *In* M.J. Wright (ed.) Plant Adaptation to Mineral Stress in Problem Soils. Cornell Univ., New York.

Murphy, B. 1995. Relationship between the Emerson aggregate test and ESP in some subsoils from Central West New South Wales. p. 101-105. *In* R. Naidu, M.E. Sumner, and P. Rengasamy (eds.) Australian Sodic Soils: Distribution, Properties and Management. CSIRO Pub., Victoria, Australia.

Murphy, D.V., G.P. Sparling, and, I.R.P. Fillery. 1998. Stratification of microbial biomass C and N and gross N mineralisation with soil depth in two contrasting Western Australian agricultural soils. Aust. J. Soil Res. 36:45-55.

Naidu, R., R.J. Haynes, and, J.S. Gawandar. 1995a. An evaluation of the potassium status of some Fijian soils used for sugarcane production. In: Proceedings of the 21st Congress of the International Society of Sugar Cane Technologists. pp79-89. Bangkok, Thailand.

Naidu, R., and, P. Rengasamy. 1993. Ion interactions and constraints to plant nutrition in Australian sodic soils. Aust. J. Soil Res. 31:801-819.

Naidu, R., and, P. Rengasamy. 1995. Ion interactions and constraints to plant nutrition in Australian sodic soils. p. 127-137. *In* R. Naidu, M.E. Sumner, and P. Rengasamy (eds.) Australian Sodic Soils: Distribution, Properties and Management. CSIRO Pub., Victoria, Australia.

Naidu, R., P. Rengasamy, N.J. de Lacy, and, B.A. Zarcinas. 1995b. Soil solution composition of some sodic soils. p. 155-161. *In* R. Naidu, M.E. Sumner, and P. Rengasamy (eds.) Australian Sodic Soils: Distribution, Properties and Management. CSIRO Pub., Victoria, Australia.

Nakayama, F.S. 1970. Hydrolysis of $CaCO_3$, $NaCO_3$ and $NaHCO_3$ and their combinations in the presence and absence of external CO2 source. Soil Sci. 109:391-398.

Nelson, P., and, G. Ham. 1998. Soil sodicity: its influence on cane yield in the Burdekin. Proc. Aust. Soc. Sug. Cane Technol. 20:248-250.

Nelson, P., and, G. Ham. 2000. Exploring the response of sugar cane to sodic and saline conditions through natural variation in the field. Field Crops Res. 66:245-255.

Nelson, P.N., J.N. Ladd, and, J.M. Oades. 1996. Decomposition of ^{14}C-labelled plant material in a salt-affected soil. Soil Biol. Biochem. 28,4/5:433-441.

Nelson, P.N., A.R. Barzegar, and, J.M. Oades. 1997. Sodicity and clay type: influence on decomposition of added organic matter. Soil Sci. Soc. Am. J. 61:1052-1057.

Nour, A.H., A.F. El-Wakeel, and, A.I. Allam. 1989. Effect of salinity on sugarcane yield. Proc. Int. Soc. Sug. Cane Technol. 20:532-535.

Nyamaphene, K. 1984. Transmission electron microscopy and electron diffraction studies on the clay fractions of three Zimbabwean Vertisols derived from basalt. Zim. J. Agric. Res. 22:111-117.

Nyamudeza, P., J. Hussein, and, B. Matabiri. 1999. Zimbabwe Vertisols: their properties and land use. p139-153. In: K. Syers (ed.) IBSRAM Proceedings (no. 20) from the Workshop on Sustainable Management of Vertisols in Africa (Harare, Zimbabwe). CAB Press, UK.

Oren, A. 1991. Estimation of the contribution of archaebacteria and eubacteria to the bacterial biomass and activity in hyper saline ecosystems: novel approaches. p. 25-31. In: F Rodriquez-Valera (ed.) General and Applied Aspects of Halophilic Microorganisms. Plenum Press, New York.

Oren, A. 1999. Bioenergetic aspects of halophilism. Microbiol. Molecular Biol. Rev. 63:334-348.

Pankhurst, C.E., B.M. Doube, and, V.V.S.R. Gupta (eds.). 1997. Biological Indicators of Soil Health. CAB, Wallingford.

Pankhurst, C.E., S. Yu, B.G. Hawke, and, B.D. Harch. 2001. Capacity of fatty acid profiles and substrate utilization patterns to describe differences in soil microbial communities associated with increased salinity or alkalinity at three locations in South Australia. Biol. Fertil. Soils 33:204-217.

Papendick, R.I. 1994. Maintaining soil physical conditions. p. 215-234. *In* D.J. Greenland and I. Szabolcs (eds.) Soil Resilience and Sustainable Land Use. CAB Int., Wallingford, UK.

Pathak, H., and, D.L.N. Rao. 1998. Carbon and nitrogen mineralization from added organic matter in saline and alkali soils. Soil Biol. Biochem. 30:695-702.

Pearson, R.W. 1952. Potassium supplying power of eight Alabama soils. Soil Sci. 74:301-309.

Peters, 1990. Atlas of the World. p 46. Harper and Row Pub., New York.

Pissarides, A., J.W.B. Stewart, and, D.A. Rennie. 1968. Influence of cation saturation on phosphorus adsorption by selected clay minerals. Can. J. Soil Sci. 48:151-157.

Ponnamperuma, F.N. 1972. The chemistry of submerged soils. Adv. Agron. 24:29-96.

Prasad, R., and J.F. Power. 1997a. Nitrogen. p. 118-170. *In* Soil Fertility Management for Sustainable Agriculture. CRC Press, Boca Raton, Florida, USA.

Prasad, R., and J.F. Power. 1997b. Potassium. p. 211-228. *In* Soil Fertility Management for Sustainable Agriculture. CRC Press, Boca Raton, Florida, USA.

Probert, M. E., I. F. Fergus, B. J. Bridge, D. McGarry, C. H. Thompson and, J. S. Russell. 1987. The Properties and Management of Vertisols. CSIRO. CAB International. Wallingford, England.

Puentes, R., B. L. Harris, and, C. Víctora. 1988. Management of Vertisols of Temperate Regions. p. 29-146. *In* L.P. Wilding and R. Puentes (eds.) Vertisols: Their Distribution, Properties, Classification and Management. Texas A&M University Printing Centre, Texas.

Quinan, D.J., and, A.W. Wood. 1989. The effects of lime applications on acid soils in the Hambledon mill area. Proc. Aust. Soc. Sug. Cane Technol. 11:70-75.

Quirk, J.P., and, R.K. Schofield. 1955. The effect of electrolyte concentration on soil permeability. J. Soil Sci. 6:163-178.

Ragab, M. 1993. Distribution of soil microbial population in salt-affected soils. p. 467-472. *In*: H Lieth, and AA Al-Masoom, (eds.) Towards the Rational Use of High Salinity Tolerant Plants, Vol. 1, Deliberations About High Salinity Plants and Ecosystems. Kluwes Academic Pub., Dordrecht, Netherlands.

Raine, S.R., and, D. Bakker. 1996. Increased furrow irrigation efficiency through better design and management of cane fields. Proc. Aust. Soc. Sug. Cane Technol. 18:119-124.

Ramdial, L. 1974. The mechanism of leaching in Vertisols (Cracking Clays). Proc. Int. Soc. Sug. Cane Technol. 2:649-653.

Rawson, H.M., R.A. Richards, and, R. Munns. 1988. An examination of selection criteria for salt tolerance in wheat barley and triticale genotypes. Aust. J. Agric. Res. 39:759-772.

Rengasamy, P. 1998. Sodic soils. p. 265-277. *In* R. Lal, W.H. Blum, C. Valentine and B.A. Stewart (eds.) Methods for Assessment of Soil Degradation. CRC Press, Boca Raton, New York.

Rengasamy, P., R.S.B. Greene, G.W. Ford, and, A.H. Mehanni. 1984. Identification of dispersive behaviour and the management of red-brown earths. Aust. J. Soil Res. 22:413-431.

Rengasamy, P., and, K.A. Olsson. 1991. Sodicity and soil structure. Aust. J. Soil Res. 29:935-952.

Robertson, M.J., N.G. Inman-Bamber, and, R.C. Muchow. 1997. Opportunities for improving the use of limited water by the sugarcane crop. p. 287-304. *In* Keating, B.A. and Wilson, J.R. (eds.) Intensive sugarcane production. CAB Int., Wallingford, UK.

Rodrigues, G. 1954. Fixed ammonium in tropical soils. J. Soil Sci. 5:264-274.

Rozeff, N. 1998. Irrigation water salinity and macro yields of sugarcane in South Texas. Sugar Cane 2:3-6.

Saffigna, P. G., A. L. Cogle, W. M. Strong, and, S. A. Waring. 1984. The effect of stubble on ^{15}N fertilizer nitrogen balance and immobilization in a Vertisol during the summer fallow. p. 218-220. *In* J.W. McGarity, E.H. Hoult and H.B. So (eds.) The Properties and Utilization of Cracking Clay Soils. University of New England, Australia.

Sarig, S., and, Y. Steinberger. 1994. Microbial biomass response to seasonal fluctuation in soil salinity under the canopy of desert halophytes. Soil. Biol. Biochem. 26,10:1405-1408.

Sawhney, B.L. 1972. Selective sorption and fixation of cations by clay minerals: a review. Clays Clay Min. 20:93-100.

Schachtman, D.P., and, R. Munns. 1992. Sodium accumulation in leaves of *Triticum* species that differ in salt tolerance. Aust. J. Plant Physiol. 19:331-340.

Schjønning, P., B.T. Christensen, and, B. Carstensen. 1994. Physical and chemical properties of a sandy loam receiving animal manure, mineral fertilizer or no fertilizer for 90 years. Eur. J. Soil Sci. 45:257-268.

Schnürer, J., M. Clarholm, and, T. Rosswall. 1985. Microbial biomass and activity in an agricultural soil with different organic matter contents. Soil Biol. Biochem. 17:611-618.

Schnürer, J., and, T. Rosswall. 1982. Fluorescein diacetate hydrolysis as a measure of total microbial activity in soil and litter. Appl. Environ. Microb. 43:1256-1261.

Schroeder, B.L., J.B. Robinson, M. Wallace, and, P. Turner. 1994. Soil acidification: occurence and effects in the South African sugar industry. Proc. S. Afr. Sug. Technol. Ass. 68:70-74.

Sehgal, J.L., A.I. Allam, R.P. Gupta, and, A. Aziz. 1980. The suitability of the soils of the Mesopotamian plain for sugarcane cultivation. Proc. Int. Soc. Sug. Cane Technol. 17:132-151.

Sehgal, J.L., and, G. Stoops. 1972. Pedogenic calcite accumulation in arid and semi-arid regions of the Indo-Gangetic alluvial plain of erstwhile Punjab (India): their morphology and origin. Geoderma 8:59-72.

Shainberg, I. 1973. Rate and mechanism of Na-montmorillonite hydrolysis in suspensions. Soil Sci. Soc. Am. Proc. 37:689-94.

Shainberg, I. 1975. Salinity of soils - effects of salinity on the physics and chemistry of soils. p. 39-55. *In* A. Poljakoff-Mayber and J. Gale (eds.) Plants in Saline Environments. Springer-Verlag, Berlin, Germany.

Shainberg, I., M.E. Sumner, W.P. Miller, M.P.W. Farina, M.A. Pavan, and, M.V. Fey. 1989. Use of gypsum on soils: a review. Adv. Soil Sci. 9:1-111.

Shanmuganathan, R.T., and, J.M. Oades, 1983. Modification of soil physical properties by addition of calcium compounds. Aust. J. Soil Res. 21:285-300.

Sharma, M.L. 1971. Physical and physico-chemical changes in the profile of a sodic soil treated with gypsum. Aust. J. Soil Res. 9:73-82.

Sharpley, A.N., D. Curtin, and, J.K. Syers. 1988. Changes in water-extractability of soil inorganic phosphate induced by sodium saturated benchmark soils. Soil Sci. Soc. Am. J. 52:637-640.

Skjemstad, J.O., R.C. Dalal, and, P.F. Barron. 1986. Spectroscopic investigations of cultivation effects on organic matter of Vertisols. Soil Sci. Soc. Am. J. 50: 354-359.

Skjemstad, J.O., L.J. Janik, and, J.A. Taylor. 1998. Non-living soil organic matter: what do we know about it? Aust. J. Exp. Agric. 38:667-680.

So, H.B., and, L.A.G. Aylmore, 1995. The effects of sodicity on soil physical behaviour. p. 71-80. *In* R. Naidu, M.E. Sumner, and P. Rengasamy (eds.) Australian Sodic Soils: Distribution, Properties and Management. CSIRO Pub., Victoria, Australia.

Soil Classification Working Group. 1991. p. 68-69. Soil Classification, A Taxonomic System For South Africa. The Department of Agricultural Development, Pretoria.

Sokoloff, V.P. 1938. Effect of neutral salts of sodium and calcium on carbon and nitrogen of soils. J. Agric. Res. 57:201-216.

Spalding, R.D. 1983. Cane yield investigations on a sodic soil. BSES Report, Project 103.10.34.

Sparks, D.L. 1987. Potassium dynamics in soils. Adv. Soil Sci. 6:1-63.

Sparling, G.P. 1997. Soil microbial biomass, activity and nutrient cycling as indicators of soil health. pp. 97-119. *In* C.E. Pankhurst, B.M. Doube and V.V.S.R. Gupta (eds.) Biological Indicators of Soil Health. CAB, Wallingford.

Stephens, C.G., and, C.M. Donald. 1958. Australian soils and their responses to fertilizers. Adv. Agron. 10:168-257.

Stumm, W., and, J.J. Morgan. 1970. *In* Aquatic Chemistry. Wiley-Interscience, New York.

Suarez, D.L., J.L. Rhoades, R. Lavado, and, C.M. Grieve. 1984. Effect of pH on saturated hydraulic conductivity and soil dispersion. Soil Sci. Soc. Am. J. 48:50-55.

Sumner, M.E. 1993. Sodic soils: new perspectives. Aust. J. Soil Res. 31:683-750.

Sumner, M.E. 1995. Sodic soils: new perspectives. p. 1-34. *In* R. Naidu, M.E. Sumner, and P. Rengasamy (eds.) Australian Sodic Soils: Distribution, Properties and Management. CSIRO Pub., Victoria, Australia.

Sumner, M.E. 1997. Opportunities for amelioration of soil physical and chemical constraints under intensive cropping. p. 305-326. *In* Keating, B.A. and Wilson, J.R. (eds.) Intensive sugarcane production. CAB Int., Wallingford, UK.

Sumner, M.E., and, R. Naidu (eds), 1997. *In* Sodic Soils: Distribution, Processes, Management and Environmental Consequences. Oxford Univ. Press, New York.

Swinford, J.M., and, T.M.C. Boevey. 1984. The effects of soil compaction due to in-field transport on ratoon cane yields and soil physical characteristics. Proc. S. Afr. Sug. Technol. Ass. 58:198-203.

Swisher, R., and, G.C. Carroll. 1980. Fluorescein diacetate hydrolysis as an estimator of microbial biomass on coniferous needle surfaces. Microb. Ecol. 6:217-226.

Szabolcs, I. 1991. Soil salinity and biodiversity. p. 105-115. *In* D.L. Hawksworth (ed.) The Biodiversity of Microorganisms and Invertebrates: Its Role in Sustainable Agriculture. CAB, Wallingford.

Tabatabai, M.A. 1994. Soil enzymes. p. 801-809, 814-818, 823-826. *In* R.W. Weaver, S. Angle, P. Bottomley, D. Bezdicek, S. Smith, A. Tabatabai, A. Wollum (eds.) Methods of Soil Analysis Part 2 - Microbiological and Biochemical Properties. Soil Sci. Soc. Am., Inc, Madison, Wisconsin.

Tisdall, J.M., and, J.M. Oades. 1982. Organic matter and water-stable aggregates in soil. J. Soil Sci. 33:141-163.

Tiwari, T.N., R.P. Srivastava, and, G.P. Singh. 1997. Salinity tolerance in sugarcane cultivars. Sugar Cane 1:7-11.

Torres, J.S., and, F. Villegas. 1993. Differentiation of soil compaction and cane stool damage. Sugar Cane 1:7-11.

Trouse, A.C., Jr. and, R.P. Humbert. 1961. Some effects of soil compaction on the development of sugarcane roots. Soil Sci. 91:208-217.

USSL Staff. 1954a. Origin and nature of saline and alkali soils. p. 1-6. *In* L.A. Richards (ed.) Diagnosis and Improvement of Saline and Alkali Soils. US Dept. of Agriculture, Washington D.C., USA.

USSL Staff. 1954b. Plant response and crop selection for saline and alkali soils. p. 55-68. *In* L.A. Richards (ed.) Diagnosis and Improvement of Saline and Alkali Soils. US Dept. of Agriculture, Washington D.C., USA.

USSL Staff. 1954c. Determination of carbonate and bicarbonate. p. 363-364. *In* L.A. Richards (ed.) Diagnosis and Improvement of Saline and Alkali Soils. US Dept. of Agriculture, Washington D.C., USA.

Vallis, I., W.J. Parton, B.A. Keating, and, A.W. Wood. 1996. Simulation of the effects of trash and N fertilizer management on soil organic matter levels and yields of sugarcane. Soil Till. Res. 38:115-132.

van Antwerpen, R., and J.H. Meyer. 1996. Soil degradation under sugarcane cultivation in northern KwaZulu-Natal. Proc. S. Afr. Sug. Technol. Ass. 70:29-33.

van Beek, C.G.E.M., and, N. van Breeman. 1973. The alkalinity of alkali soils. J. Soil Sci. 24:129-136.

van Wambeke, A. 1991. Vertisols. In: Soils of the Tropics. pp189-206. McGraw-Hill Inc., New York.

Vance, E.D., P.C. Brookes, and, P.S. Jenkinson. 1987. An extraction method for measuring microbial biomass C. Soil Biol. Biochem. 19:703-707.

Vaughan, D., and, B.G. Ord. 1984. Soil organic matter- a perspective on its nature, extraction, turnover and role in soil fertility. p.1-35. *In* D. Vaughan, and, R.E. Malcolm (eds.) Soil Organic Matter and Biological Activity, Martinus Nijhoff/Dr W. Junk Pub., Dordrecht.

Ventosa, A., J.J. Nieto, and, A. Oren. 1998. Biology of moderately halophilic aerobic bacteria. Microbiol. Molecular Biol. Rev. 62:504-544.

von der Meden, E. 1966. Note on salinity limits for sugarcane in Natal. Proc. S. Afr. Sug. Technol. Ass. 40:273-275.

von der Meden, E. 1967. Problems of saline soils and their management. S. Afr. Sug. J.51:750-751.

Wahid, A., A. Rao, and, E. Rasul. 1997. Identification of salt tolerance traits in sugarcane lines. Field Crops Res. 54:9-17.

Walkley, A. 1947. Organic carbon by the Walkley-Black oxidation procedure. Soil Sci 63:251-264.

Wardle, D.A., and A. Ghani. 1995. A critique of the microbial metabolic quotient (qCO_2) as an bio-indicator of disturbance and ecosystem development. Soil Biol. Biochem. 27:1601-1610.

Waring, S.A., and P. G. Saffigna. 1984. Biological processes affecting nutrient element availability and distribution in Australian Cracking Clays. p. 187-204. *In* J.W. McGarity, E.H. Hoult and H.B. So (eds.) The Properties and Utilization of Cracking Clay Soils. University of New England, Australia.

Warkentin, B.P. 1982. Clay soil structure related to soil management. Trop. Agric. (Trinidad) 59:82-91

Webber, M.D., and, G.E.G. Mattingly. 1970. Inorganic soil phosphorus. II. Change in monocalcium phosphate and lime potentials on mixing and liming soils. J. Soil Sci. 21:121-126.

Wick, B., R.F. Kühne, and, P.L.G. Vlek. 1998. Soil microbiological parameters as indicators of soil quality under improved fallow management systems in south-western Nigeria.

Wilding, L. P., and, R. Puentes. 1988. Preface. p. ix-x. *In* L.P. Wilding and R. Puentes (eds.) Vertisols: Their Distribution, Properties, Classification and Management. Texas A&M University Printing Centre, Texas.

Willett, I.R., and, M.L. Higgins. 1978. Phosphate sorption by reduced and reoxidised rice soils. Aust. J. Soil Res. 16:319-326.

Wood, A.W. 1985. Soil degradation and management under intensive sugarcane cultivation in North Queensland. Soil Use Manag. 1:120-123.

Wood, A.W. 1991. Management of crop residues following green harvesting of sugarcane in North Queensland. Soil Till. Res. 20:69-85.

Wood, A.W., R.G.V. Bramley, J.H. Meyer, and, A.K.L. Johnson. 1997. Opportunities for improving nutrient management in the Australian sugar industry. p. 243-266. *In* Keating, B.A. and Wilson, J.R. (eds.) Intensive sugarcane production. CAB Int., Wallingford, UK.

Wood, R.A., J.H. Meyer, and, M. Govender. 1985. A rapid system of cane leaf analysis using X-ray spectrometry and infra-red reflectance. Proc. S. Afr. Sug. Technol. Ass. 59:195-201.

Workman, M., P.M. Scott, and, D.J. Nixon. 1986. A review of the management and amelioration of saline/sodic soils at Mhlume (Swaziland) Sugar Company. Proc. S. Sfr. Sug. Technol. Ass. 60:162-167.

Yadav, R.L., and S.R. Prasad. 1992. Conserving the organic matter contents of the soil to sustain sugarcane yield. Exp. Agric. 28:57-62.

Yerima, B. P. K., L. R. Hossner, L. P. Wilding, and, F. G. Calhoun, 1988. Forms of Phosphorus and Phosphate Sorption in Northern Cameroon Vertisols and Associated Alfisols. p. 147-164. *In* L.P. Wilding and R. Puentes (eds.) Vertisols: Their Distribution, Properties, Classification and Management. Texas A&M University Printing Centre, Texas.

Yoder, R.E. 1936. A direct method of aggregate analysis and a study of the physical nature of erosion losses. Agron. J. 28:337-351.

Young, A. 1976. Tropical Soils and Soil Survey. Cambridge University Press, London.

Zahran, H.H. 1997. Diversity, adaptation and activity of the bacterial flora in saline environments. Biol. Fertil. Soils 25:211-223.

Zahran, H.H., A.M. Moharram, and, H.A. Mohammad. 1992. Some ecological and physiological studies on bacteria isolated from salt-affected soils of Egypt. J. Basic Microbiol. 32:405-413.

Zein El Abedine, A., G. H. Robinson, and, J. Tyego. 1969. A Study of Certain Physical Properties of a Vertisol in the Gezira Area, Republic of Sudan. Soil Sci. 108:359-366.

Appendix 1.1

$pH_{(water)}$, exchangeable cations ($cmol_c\ kg^{-1}$), soluble cations ($cmol_c\ kg^{-1}$), electrical conductivity (EC_e), exchangeable sodium percentage (ESP), sodium adsorption ratio (SAR_e), exchangeable cation exchange capacity (ECEC) ($cmol_c\ kg^{-1}$), organic carbon percentage (%) and clay percentage (%) of the 0-0.15m depth layer of soils from four sugarcane fields. Sugarcane growth was identified within each field as being either dead and dying (D), poor (P), satisfactory (S) or good (G). Soil samples were also taken from adjacent undisturbed veld (V).

			Soluble cations			Exchangeable cations				ESP	SAR_e	EC_e		Organic	Clay
Field	Growth	pH	Ca	Mg	Na	K	Ca	Mg	Na	(%)	(%)	($mS\ m^{-1}$)	ECEC	carbon	percentage
1	D	8.17	1.19	1.87	9.11	0.71	14.36	10.79	21.06	44.9	22.6	2480	46.9	2.15	26
	P	9.16	0.08	0.16	4.02	0.79	16.07	15.96	17.59	34.9	33.4	390	50.4	2.17	25
	S	8.89	0.05	0.05	1.78	1.53	23.70	13.03	0.12	0.3	29.3	278	38.3	2.04	25
	G	9.17	0.08	0.26	1.88	0.39	16.02	16.85	5.60	14.4	12.8	177	38.8	2.50	25
	V	9.14	0.07	0.04	1.06	0.58	32.33	9.91	7.55	15.0	15.1	108	50.3	2.73	25
2	D	9.61	0.21	0.09	7.83	1.10	15.34	3.69	22.00	52.2	66.9	1795	42.1	0.85	25
	P	8.50	0.10	0.08	0.50	1.04	33.70	10.36	2.50	5.3	5.8	78	47.6	1.76	26
	S	8.48	0.09	0.06	0.32	0.60	35.96	11.70	1.83	3.7	4.0	54	50.0	1.74	25
	G	8.47	0.19	0.12	0.29	1.21	44.31	9.58	1.31	2.3	2.6	77	56.4	2.07	26
	V	8.50	0.18	0.13	1.57	1.53	28.12	14.34	3.39	7.2	9.7	129	47.3	2.64	26
3	D	9.44	0.13	0.07	3.03	1.53	25.02	15.56	14.14	25.1	21.8	195	56.2	0.92	35
	P	9.39	0.03	0.04	1.04	1.02	17.92	9.42	12.96	31.4	20.7	151	41.3	1.28	32
	S	7.57	0.71	0.51	0.15	1.84	30.64	11.09	0.46	1.0	0.6	220	44.0	1.23	31
	G	8.32	0.12	0.05	0.27	0.75	38.08	6.61	1.45	3.1	2.9	45	46.8	1.60	32
	V	8.33	0.18	0.13	0.49	1.49	37.32	12.82	1.44	2.7	3.7	89	54.0	2.64	32
4	D	8.93	0.08	0.06	2.80	1.56	22.27	11.21	20.03	36.4	39.1	435	55.0	1.25	30
	P	9.81	0.09	0.17	3.35	0.92	14.56	15.87	13.43	30.0	26.3	298	44.7	1.61	35
	S	9.41	0.05	0.03	1.27	1.56	18.55	9.26	14.26	32.7	22.9	195	43.6	1.82	35
	G	8.32	0.17	0.13	0.28	0.44	41.23	13.52	1.02	1.8	2.1	56	56.2	1.68	29
	V	8.27	0.18	0.13	0.43	1.51	38.32	13.03	1.42	2.6	3.6	95	54.2	2.66	33

Appendix 1.2

$pH_{(water)}$, exchangeable cations ($cmol_c\ kg^{-1}$), soluble cations ($cmol_c\ kg^{-1}$), electrical conductivity (EC_e), exchangeable sodium percentage (ESP), sodium adsorption ratio (SAR_e) and exchangeable cation exchange capacity (ECEC) ($cmol_c\ kg^{-1}$) of the 0.15-0.3m depth layer of soils from four sugarcane fields. Sugarcane growth was identified within each field as being either dead and dying (D), poor (P), satisfactory (S) or good (G). Soil samples were also taken from adjacent undisturbed veld (V).

			Soluble cations			Exchangeable cations				ESP	SAR	EC	
Field	Growth	pH	Ca	Mg	Na	K	Ca	Mg	Na	(%)	(%)	($mS\ m^{-1}$)	ECEC
1	D	10.16	0.05	0.06	3.07	0.77	12.85	9.32	21.28	48.1	45.7	483	44.2
	P	9.38	0.09	0.16	2.37	0.49	9.16	16.86	10.59	28.5	17.8	181	37.1
	S	7.96	0.22	0.22	0.22	1.82	30.73	12.94	0.86	1.8	1.7	160	46.3
	G	8.06	0.10	0.11	0.70	0.38	21.15	14.45	2.87	7.4	7.1	121	38.8
	V	8.55	0.09	0.16	0.59	1.33	18.91	16.53	3.24	8.1	5.9	105	40.0
2	D	10.30	0.06	0.03	5.54	1.53	12.04	2.44	28.59	64.1	104.0	1518	44.6
	P	8.74	0.09	0.07	1.42	0.88	25.01	15.97	8.23	16.4	13.6	128	50.0
	S	8.71	0.04	0.04	0.41	0.26	26.86	13.61	4.46	9.9	7.2	83	45.1
	G	7.92	0.07	0.06	0.14	1.16	30.08	14.99	0.97	2.0	1.9	33	47.1
	V	9.08	0.06	0.11	0.49	0.32	21.39	17.90	4.81	10.8	7.0	91	44.4
3	D	8.96	0.10	0.08	1.14	0.56	25.20	15.55	8.86	17.7	13.3	190	50.1
	P	9.15	0.05	0.05	1.17	0.95	22.25	12.29	8.96	20.2	18.5	167	44.4
	S	8.96	0.07	0.04	1.78	1.48	27.38	15.67	12.22	21.5	20.7	146	56.7
	G	8.76	0.07	0.04	0.52	0.40	37.73	11.80	2.94	5.6	7.1	59	52.8
	V	8.42	0.05	0.03	0.19	0.56	24.92	6.00	1.83	5.5	3.7	36	32.2
4	D	8.89	0.06	0.07	1.65	1.51	27.24	14.49	13.65	24.0	23.4	260	56.8
	P	9.19	0.06	0.04	1.64	1.02	21.29	10.57	12.40	27.4	24.0	196	45.2
	S	8.27	0.12	0.09	1.12	1.15	31.03	11.59	4.49	9.3	11.1	167	48.2
	G	8.79	0.07	0.04	0.40	0.55	39.68	10.57	2.75	5.1	5.8	46	53.5
	V	8.37	0.06	0.03	0.19	0.58	25.09	6.88	1.33	3.9	3.5	43	33.8

Appendix 1.3

pH$_{(water)}$, exchangeable cations (cmol$_c$ kg^{-1}), soluble cations (cmol$_c$ kg^{-1}), electrical conductivity (EC$_e$), exchangeable sodium percentage (ESP), sodium adsorption ratio (SAR$_e$) and exchangeable cation exchange capacity (ECEC) (cmol$_c$ kg^{-1}) of the 0.3-0.6m depth layer of soils from four sugarcane fields. Sugarcane growth was identified within each field as being either dead and dying (D), poor (P), satisfactory (S) or good (G). Soil samples were also taken from adjacent undisturbed veld (V).

			Soluble cations			Exchangeable cations				ESP	SAR	EC	
Field	Growth	pH	Ca	Mg	Na	K	Ca	Mg	Na	(%)	(%)	(mS m^{-1})	ECEC
1	D	10.30	0.09	0.09	2.30	0.40	5.28	15.86	16.61	43.5	15.8	166	38.1
	P	9.51	0.11	0.06	1.13	0.37	7.22	23.46	12.00	27.9	8.9	86	43.0
	S	9.64	0.05	0.03	0.55	0.22	24.95	16.50	6.36	13.2	8.9	77	48.0
	G	8.23	0.10	0.07	0.31	0.22	37.10	17.04	1.82	3.2	3.3	49	56.1
	V	7.79	0.05	0.03	0.02	0.16	27.85	12.63	0.28	0.7	0.4	18	40.9
2	D	10.40	0.06	0.01	6.59	0.94	14.44	2.46	26.80	60.0	90.0	765	44.6
	P	10.10	0.07	0.03	2.75	0.44	21.53	6.55	19.51	40.6	32.1	327	48.0
	S	10.20	0.08	0.05	1.51	0.83	15.82	16.89	15.36	31.4	14.2	147	48.8
	G	10.00	0.04	0.02	0.50	0.16	23.61	18.24	7.46	15.1	9.1	65	49.4
	V	8.80	0.10	0.08	0.07	0.36	45.10	12.91	0.35	0.6	0.7	26	58.7
3	D	9.85	0.08	0.06	1.03	1.41	27.32	20.01	14.19	22.5	8.4	62	62.9
	P	9.25	0.09	0.04	1.11	0.78	29.16	20.35	9.11	15.3	9.1	44	59.3
	S	9.52	0.15	0.07	1.49	1.51	31.00	17.04	14.16	22.2	10.3	117	63.7
	G	8.48	0.09	0.03	0.23	0.48	28.46	6.38	1.33	3.6	3.2	41	36.6
	V	8.40	0.27	0.27	1.13	1.25	32.94	15.95	3.39	6.3	5.2	158	54.3
4	D	9.32	0.11	0.05	1.37	1.48	25.89	19.85	12.63	21.1	10.1	83	59.8
	P	9.52	0.09	0.03	0.85	1.02	29.01	16.09	9.02	16.4	8.4	66	55.1
	S	8.91	0.10	0.04	0.51	0.94	31.20	18.22	5.23	9.4	5.3	65	55.5
	G	8.66	0.08	0.04	0.30	0.34	24.07	5.55	1.00	3.2	4.2	59	30.9
	V	8.30	0.28	0.29	1.03	1.26	34.07	17.14	3.04	5.5	5.0	162	55.5

Appendix 1.4

$pH_{(water)}$, exchangeable cations ($cmol_c\ kg^{-1}$), soluble cations ($cmol_c\ kg^{-1}$), electrical conductivity (EC_e), exchangeable sodium percentage (ESP), sodium adsorption ratio (SAR_e) and exchangeable cation exchange capacity (ECEC) ($cmol_c\ kg^{-1}$) of the 0.6-0.9m depth layer of soils from four sugarcane fields. Sugarcane growth was identified within each field as being either dead and dying (D), poor (P), satisfactory (S) or good (G). Soil samples were also taken from adjacent undisturbed veld (V).

			Soluble cations			Exchangeable cations				ESP	SAR	EC	
Field	Growth	pH	Ca	Mg	Na	K	Ca	Mg	Na	(%)	(%)	($mS\ m^{-1}$)	ECEC
1	D	10.10	0.06	0.03	0.85	0.23	5.16	18.64	12.32	33.9	10.9	78	36.3
	P	9.76	0.08	0.05	0.84	0.32	6.64	24.62	7.73	19.7	7.9	71	39.3
	S	9.83	0.02	0.02	0.50	0.15	12.03	19.88	3.72	10.4	10.9	62	35.7
	G	8.51	0.10	0.06	0.28	0.32	36.40	18.03	1.85	3.3	2.8	35	56.6
	V	8.15	0.02	0.02	0.04	0.09	22.63	14.45	0.76	2.0	1.3	30	37.9
2	D	10.50	0.08	0.02	3.83	0.50	16.07	4.17	23.21	52.8	40.0	318	43.9
	P	10.60	0.06	0.03	2.64	0.71	14.84	4.49	24.40	54.9	32.8	302	44.4
	S	10.00	0.09	0.04	2.15	0.74	17.56	13.86	15.55	32.6	20.2	201	47.7
	G	10.00	0.07	0.03	0.67	0.16	8.08	20.20	9.81	25.6	8.4	65	38.2
	V	8.57	0.10	0.06	0.25	0.32	35.70	17.54	1.69	3.1	2.7	40	55.2
3	D	9.74	0.11	0.05	1.33	1.34	26.64	19.85	12.67	20.9	9.1	64	60.5
	P	9.27	0.10	0.03	0.70	0.77	35.05	20.20	7.69	12.1	6.3	49	63.7
	S	8.53	0.15	0.14	0.35	0.57	33.40	15.98	1.14	2.2	2.4	39	51.0
	G	8.35	0.13	0.07	0.34	0.51	27.62	8.56	1.36	3.6	3.2	52	38.0
	V	9.50	0.06	0.04	0.98	0.80	18.94	20.94	6.31	13.4	8.5	74	46.8
4	D	9.96	0.16	0.09	1.58	1.19	22.94	21.29	11.90	20.8	7.9	64	57.3
	P	9.45	0.11	0.04	1.11	0.78	31.79	16.57	7.98	14.0	8.4	59	57.1
	S	8.59	0.09	0.05	0.35	0.83	29.11	19.19	2.43	4.7	3.6	36	51.5
	G	8.75	0.12	0.05	0.31	0.27	29.18	4.80	0.79	2.3	3.5	50	35.0
	V	9.30	0.08	0.06	0.94	0.90	18.97	21.16	6.23	13.2	8.4	79	47.2

Appendix 2.1

Depth weighted mean $pH_{(water)}$, exchangeable cations ($cmol_c\ kg^{-1}$), soluble cations ($cmol_c\ kg^{-1}$), electrical conductivity (EC_e), exchangeable sodium percentage (ESP), sodium adsorption ratio (SAR_e) and exchangeable cation exchange capacity (ECEC) ($cmol_c\ kg^{-1}$) of the 0-0.3m depth layer of soils from four sugarcane fields. Sugarcane growth was identified within each field as being either dead and dying (D), poor (P), satisfactory (S) or good (G). Soil samples were also taken from adjacent undisturbed veld (V).

			Soluble cations			Exchangeable cations				ESP	SAR	EC	
Field	**Growth**	pH	Ca	Mg	Na	K	Ca	Mg	Na	(%)	(%)	(mS m^{-1})	ECEC
1	**D**	9.16	0.62	0.96	6.09	0.74	13.60	10.06	21.17	46.5	34.2	1481.5	45.6
	P	9.27	0.09	0.16	3.20	0.64	12.61	16.41	14.09	31.7	25.6	285.5	43.8
	S	8.43	0.13	0.13	1.00	1.68	27.22	12.99	0.49	1.1	15.5	219.0	42.3
	G	8.62	0.09	0.19	1.29	0.38	18.59	15.65	4.24	10.9	10.0	149.0	38.8
	V	8.85	0.08	0.10	0.83	0.96	25.62	13.22	5.39	11.5	10.5	106.5	45.2
2	**D**	9.96	0.13	0.06	6.69	1.32	13.69	3.07	25.29	58.2	85.4	1656.5	43.4
	P	8.62	0.10	0.07	0.96	0.96	29.35	13.17	5.36	10.8	9.7	103.0	48.8
	S	8.60	0.07	0.05	0.37	0.43	31.41	12.65	3.14	6.8	5.6	68.5	47.6
	G	8.20	0.13	0.09	0.22	1.18	37.20	12.28	1.14	2.2	2.2	55.0	51.8
	V	8.79	0.12	0.12	1.03	0.92	24.76	16.12	4.10	9.0	8.4	110.0	45.8
3	**D**	8.26	0.41	0.30	0.65	1.20	27.92	13.32	4.66	9.3	7.0	205.0	47.0
	P	9.30	0.09	0.06	2.10	1.24	23.64	13.92	11.55	22.7	20.2	181.0	50.3
	S	9.18	0.05	0.04	1.41	1.25	22.65	12.55	12.59	26.4	20.7	148.5	49.0
	G	8.54	0.09	0.05	0.40	0.57	37.91	9.20	2.19	4.3	5.0	52.0	49.8
	V	8.38	0.11	0.08	0.34	1.02	31.12	9.41	1.64	4.1	3.7	62.5	43.1
4	**D**	8.91	0.07	0.06	2.23	1.54	24.76	12.85	16.84	30.2	31.2	347.5	55.9
	P	9.50	0.07	0.10	2.50	0.97	17.93	13.22	12.91	28.7	25.2	247.0	45.0
	S	8.84	0.08	0.06	1.19	1.36	24.79	10.42	9.38	21.0	17.0	98.3	45.9
	G	8.56	0.12	0.08	0.34	0.50	40.45	12.05	1.88	3.5	4.0	51.0	54.8
	V	8.32	0.12	0.08	0.31	1.04	31.71	9.95	1.37	3.3	3.6	69.0	44.0

Appendix 2.2

Depth weighted mean $pH_{(water)}$, exchangeable cations ($cmol_c\ kg^{-1}$), soluble cations ($cmol_c\ kg^{-1}$), electrical conductivity (EC_e), exchangeable sodium percentage (ESP), sodium adsorption ratio (SAR_e) and exchangeable cation exchange capacity (ECEC) ($cmol_c\ kg^{-1}$) of the 0-0.6m depth layer of soils from four sugarcane fields. Sugarcane growth was identified within each field as being either dead and dying (D), poor (P), satisfactory (S) or good (G). Soil samples were also taken from adjacent undisturbed veld (V).

			Soluble cations			Exchangeable cations				ESP	SAR	EC	
Field	Growth	pH	Ca	Mg	Na	K	Ca	Mg	Na	(%)	(%)	(mS m^{-1})	ECEC
1	D	9.73	0.36	0.53	4.19	0.57	9.44	12.96	18.89	45.0	25.0	823.8	41.8
	P	9.39	0.10	0.11	2.16	0.50	9.92	19.94	13.04	29.8	17.2	185.8	43.4
	S	9.03	0.09	0.08	0.77	0.95	26.08	14.75	3.43	7.2	12.2	148.0	45.2
	G	8.42	0.10	0.13	0.80	0.30	27.84	16.34	3.03	7.1	6.6	99.0	47.4
	V	8.32	0.07	0.07	0.42	0.56	26.73	12.92	2.84	6.1	5.4	62.2	43.0
2	D	10.18	0.10	0.04	6.64	1.13	14.07	2.76	26.05	59.1	87.7	1210.8	44.0
	P	9.36	0.09	0.05	1.86	0.70	25.44	9.86	12.44	25.7	20.9	215.0	48.4
	S	9.40	0.07	0.05	0.94	0.63	23.61	14.77	9.25	19.1	9.9	107.8	48.2
	G	9.10	0.08	0.06	0.36	0.67	30.40	15.26	4.30	8.6	5.7	60.0	50.6
	V	8.80	0.11	0.10	0.55	0.64	34.93	14.52	2.23	4.8	4.5	68.0	52.3
3	D	9.06	0.24	0.18	0.84	1.31	27.62	16.66	9.42	15.9	7.7	133.5	55.0
	P	9.27	0.09	0.05	1.61	1.01	26.40	17.13	10.33	19.0	14.6	112.5	54.8
	S	9.35	0.10	0.06	1.45	1.38	26.83	14.79	13.37	24.3	15.5	132.8	56.4
	G	8.51	0.09	0.04	0.31	0.53	33.19	7.79	1.76	4.0	4.1	46.5	43.2
	V	8.39	0.19	0.17	0.73	1.14	32.03	12.68	2.51	5.2	4.4	110.2	48.7
4	D	9.12	0.09	0.06	1.80	1.51	25.32	16.35	14.73	25.6	20.7	215.2	57.8
	P	9.51	0.08	0.07	1.68	1.00	23.47	14.65	10.96	22.5	16.8	156.5	50.0
	S	8.88	0.09	0.05	0.85	1.15	27.99	14.32	7.30	15.2	11.2	81.7	50.7
	G	8.61	0.10	0.06	0.32	0.42	32.26	8.80	1.44	3.3	4.1	55.0	42.9
	V	8.31	0.20	0.19	0.67	1.15	32.89	13.54	2.21	4.4	4.3	115.5	49.8

Appendix 2.3

Depth weighted mean $pH_{(water)}$, exchangeable cations ($cmol_c\ kg^{-1}$), soluble cations ($cmol_c\ kg^{-1}$), electrical conductivity (EC_e), exchangeable sodium percentage (ESP), sodium adsorption ratio (SAR_e) and exchangeable cation exchange capacity (ECEC) ($cmol_c\ kg^{-1}$) of the 0-0.9m depth layer of soils from four sugarcane fields. Sugarcane growth was identified within each field as being either dead and dying (D), poor (P), satisfactory (S) or good (G). Soil samples were also taken from adjacent undisturbed veld (V).

			Soluble cations			Exchangeable cations				ESP	SAR	EC	
Field	Growth	pH	Ca	Mg	Na	K	Ca	Mg	Na	(%)	(%)	($mS\ m^{-1}$)	ECEC
1	D	9.85	0.26	0.36	3.08	0.46	8.01	14.85	16.70	41.3	20.3	575.2	40.0
	P	9.51	0.09	0.09	1.72	0.44	8.82	21.50	11.27	26.4	14.1	147.5	42.0
	S	9.30	0.07	0.06	0.68	0.68	21.40	16.46	3.52	8.2	11.8	119.3	42.0
	G	8.45	0.10	0.11	0.62	0.31	30.70	16.90	2.64	5.8	5.4	77.7	50.5
	V	8.26	0.05	0.05	0.30	0.40	25.36	13.43	2.14	4.7	4.1	51.5	41.3
2	D	10.28	0.09	0.03	5.70	0.92	14.74	3.23	25.10	57.0	71.8	913.2	43.9
	P	9.77	0.08	0.04	2.12	0.70	21.91	8.07	16.43	35.5	24.9	244.0	47.1
	S	9.60	0.08	0.05	1.34	0.67	21.60	14.47	11.35	23.6	13.3	138.8	48.0
	G	9.40	0.08	0.05	0.46	0.50	22.96	16.91	6.14	14.3	6.6	61.7	46.5
	V	8.72	0.11	0.09	0.45	0.54	35.18	15.52	2.05	4.2	3.9	58.7	53.2
3	D	9.29	0.20	0.14	1.00	1.32	27.29	17.72	10.50	17.6	8.2	110.3	56.8
	P	9.27	0.09	0.05	1.30	0.93	29.28	18.15	9.45	16.7	11.8	91.3	57.8
	S	9.08	0.12	0.08	1.08	1.11	29.02	15.19	9.30	17.0	11.1	101.5	54.6
	G	8.46	0.10	0.05	0.32	0.52	31.33	8.04	1.63	3.8	3.8	48.3	41.5
	V	8.76	0.15	0.13	0.82	1.03	27.67	15.44	3.78	8.0	5.8	98.2	48.1
4	D	9.40	0.11	0.07	1.73	1.40	24.53	18.00	13.79	24.0	16.4	164.8	57.7
	P	9.49	0.09	0.06	1.49	0.92	26.24	15.29	9.97	19.7	14.0	124.0	52.4
	S	8.78	0.09	0.05	0.69	1.04	28.37	15.94	5.68	11.7	8.6	66.4	51.0
	G	8.65	0.11	0.06	0.32	0.37	31.23	7.47	1.22	3.0	3.9	53.3	40.2
	V	8.64	0.16	0.14	0.76	1.07	28.25	16.08	3.55	7.3	5.7	103.3	48.9

Appendix 3

Carbonate and bicarbonate levels of 1:5 soil:water slurries ($cmol_c$ kg^{-1}) of the 0-0.15m depth layer of soils from four sugarcane fields. Sugarcane growth was identified within each field as being either dead and dying (D), poor (P), satisfactory (S) or good (G). Soil samples were also taken from adjacent undisturbed veld (V).

Field	Growth	Carbonate	Bicarbonate
1	D	0.00	0.64
	P	1.57	2.98
	S	2.34	3.14
	G	0.40	1.71
	V	0.00	0.86
2	D	2.33	3.04
	P	0.26	1.15
	S	0.00	0.80
	G	0.00	0.67
	V	0.00	0.99
3	D	3.66	4.87
	P	2.30	3.71
	S	0.80	2.63
	G	0.00	0.72
	V	0.00	0.72
4	D	1.38	3.75
	P	1.58	3.82
	S	0.56	2.80
	G	0.00	1.05
	V	0.00	0.53

Appendix 4.1

Ammonium acetate extractable cations (NH_4OAc in $cmol_c\ kg^{-1}$), soluble cations ($mmol_c\ L^{-1}$) and saturation percentage (%) of the 0-0.15m depth layer of soils from four sugarcane fields. Sugarcane growth was identified within each field as being either dead and dying (D), poor (P), satisfactory (S) or good (G). Soil samples were also taken from adjacent undisturbed veld (V).

		NH_4OAc Extractactable Cations				Soluble Cations			Saturation
Field	Growth	K	Ca	Mg	Na	Ca	Mg	Na	Percentage
1	D	0.71	15.55	12.66	30.17	11.3	17.7	86.4	105.4
	P	0.79	16.15	16.12	21.61	0.7	1.3	33.4	120.4
	S	1.53	23.75	13.08	1.90	0.7	0.6	23.7	75.1
	G	0.39	16.10	17.11	7.48	0.6	2.1	14.9	125.9
	V	0.58	32.40	9.95	8.61	0.7	0.4	11.2	94.6
2	D	1.10	15.55	3.78	29.83	2.3	1.0	86.0	91.1
	P	1.04	33.80	10.44	3.00	1.3	1.0	6.3	79.1
	S	0.60	36.05	11.76	2.15	1.0	0.7	3.7	86.2
	G	1.21	44.50	9.70	1.60	2.3	1.5	3.6	80.6
	V	1.53	28.30	14.47	4.96	1.1	0.8	9.5	164.9
3	D	1.84	31.35	11.60	0.61	8.8	6.3	1.9	81.0
	P	1.53	25.15	15.63	17.17	0.7	0.4	16.2	187.0
	S	1.02	17.95	9.46	14.00	0.4	0.5	13.9	75.0
	G	0.75	38.20	6.66	1.72	1.1	0.5	2.6	105.4
	V	1.49	37.50	12.95	1.93	1.9	1.4	5.3	92.6
4	D	1.56	22.35	11.27	22.83	1.0	0.8	37.1	75.6
	P	0.92	14.65	16.04	16.78	0.7	1.3	26.3	127.4
	S	1.56	18.60	9.29	15.53	0.6	0.4	16.2	78.3
	G	0.44	41.40	13.65	1.30	1.6	1.2	2.6	107.1
	V	1.51	38.50	13.16	1.85	2.0	1.5	4.8	89.5

Appendix 4.2

Ammonium acetate extractable cations (NH_4OAc in $cmol_c\ kg^{-1}$), soluble cations ($mmol_c\ L^{-1}$) and saturation percentage (%) of the 0.15-0.3m depth layer of soils from four sugarcane fields. Sugarcane growth was identified within each field as being either dead and dying (D), poor (P), satisfactory (S) or good (G). Soil samples were also taken from adjacent undisturbed veld (V).

		NH_4OAc Extractactable Cations				Soluble Cations			Saturation
Field	Growth	K	Ca	Mg	Na	Ca	Mg	Na	Percentage
1	D	0.77	12.90	9.38	24.35	0.7	0.8	39.6	77.5
	P	0.49	9.25	17.02	12.96	0.6	1.1	16.5	143.8
	S	1.82	30.95	13.16	1.08	2.7	2.7	2.8	80.0
	G	0.38	21.25	14.56	3.57	1.1	1.2	7.7	90.8
	V	1.33	19.00	16.69	3.83	1.2	2.0	7.5	78.9
2	D	1.53	12.10	2.47	34.13	0.9	0.4	83.9	66.0
	P	0.88	25.10	16.04	9.65	0.7	0.5	10.6	134.4
	S	0.26	26.90	13.65	4.87	0.6	0.6	5.6	73.6
	G	1.16	30.15	15.05	1.11	0.9	0.8	1.8	80.2
	V	0.32	21.45	18.01	5.30	1.0	1.9	8.5	57.4
3	D	0.56	25.30	15.63	10.00	1.2	1.0	14.0	81.6
	P	0.95	22.30	12.34	10.13	0.6	0.6	14.4	81.0
	S	1.48	27.45	15.71	14.00	0.5	0.3	13.1	136.0
	G	0.40	37.80	11.84	3.46	0.8	0.5	5.8	89.1
	V	0.56	24.97	6.03	2.02	0.8	0.4	2.9	65.2
4	D	1.51	27.30	14.56	15.30	0.8	0.9	21.6	76.5
	P	1.02	21.35	10.61	14.04	0.6	0.4	17.0	96.5
	S	1.15	31.15	11.68	5.61	1.3	1.0	12.0	93.1
	G	0.55	39.75	10.61	3.15	0.8	0.4	4.5	89.8
	V	0.58	25.15	6.91	1.52	0.9	0.5	3.0	63.5

Appendix 4.3

Ammonium acetate extractable cations (NH_4OAc in $cmol_c\ kg^{-1}$), soluble cations ($mmol_c\ L^{-1}$) and saturation percentage (%) of the 0.3-0.6m depth layer of soils from four sugarcane fields. Sugarcane growth was identified within each field as being either dead and dying (D), poor (P), satisfactory (S) or good (G). Soil samples were also taken from adjacent undisturbed veld (V).

		NH_4OAc Extractactable Cations				Soluble Cations			Saturation
Field	Growth	K	Ca	Mg	Na	Ca	Mg	Na	Percentage
1	D	0.40	5.37	15.95	18.91	0.4	0.4	10.0	230.2
	P	0.37	7.33	23.52	13.13	0.6	0.3	6.0	188.7
	S	0.22	25.00	16.53	6.91	0.6	0.3	6.0	91.3
	G	0.22	37.20	17.11	2.13	1.1	0.8	3.3	93.1
	V	0.16	27.90	12.66	0.30	0.9	0.6	0.4	55.9
2	D	0.94	14.50	2.47	33.39	0.4	0.1	45.0	146.5
	P	0.44	21.60	6.58	22.26	0.5	0.2	19.0	144.7
	S	0.83	15.90	16.94	16.87	0.5	0.3	9.0	168.3
	G	0.16	23.65	18.26	7.96	0.4	0.2	5.0	100.0
	V	0.36	45.20	12.99	0.42	1.2	0.9	0.8	84.4
3	D	1.41	27.40	20.07	15.22	0.4	0.3	5.0	206.9
	P	0.78	29.25	20.39	10.22	0.4	0.2	5.0	222.6
	S	1.51	31.15	17.11	15.65	0.8	0.4	8.0	186.0
	G	0.48	28.55	6.41	1.56	1.0	0.4	2.7	86.1
	V	1.25	33.21	16.22	4.52	1.8	1.8	7.6	148.2
4	D	1.48	26.00	19.90	14.00	0.5	0.2	6.0	228.3
	P	1.02	29.10	16.12	9.87	0.5	0.2	5.0	170.9
	S	0.94	31.30	18.26	5.74	0.8	0.3	4.0	127.4
	G	0.34	24.15	5.59	1.30	1.0	0.5	3.7	81.6
	V	1.26	34.35	17.43	4.07	1.9	2.0	7.0	146.5

Appendix 4.4

Ammonium acetate extractable cations (NH_4OAc in $cmol_c\ kg^{-1}$), soluble cations ($mmol_c\ L^{-1}$) and saturation percentage (%) of the 0.6-0.9m depth layer of soils from four sugarcane fields. Sugarcane growth was identified within each field as being either dead and dying (D), poor (P), satisfactory (S) or good (G). Soil samples were also taken from adjacent undisturbed veld (V).

		NH_4OAc Extractactable Cations				Soluble Cations			Saturation
Field	Growth	K	Ca	Mg	Na	Ca	Mg	Na	Percentage
1	D	0.23	5.22	18.67	13.17	0.4	0.2	6.0	142.0
	P	0.32	6.72	24.67	8.57	0.5	0.3	5.0	168.3
	S	0.15	12.05	19.90	4.22	0.3	0.3	6.0	82.8
	G	0.32	36.50	18.09	2.13	0.8	0.5	2.3	119.6
	V	0.09	22.65	14.47	0.80	0.8	0.7	1.2	31.0
2	D	0.50	16.15	4.19	27.04	0.4	0.1	20.0	191.6
	P	0.71	14.90	4.52	27.04	0.4	0.2	18.0	146.5
	S	0.74	17.65	13.90	17.70	0.5	0.2	12.0	179.4
	G	0.16	8.15	20.23	10.48	0.5	0.2	5.0	133.6
	V	0.32	35.80	17.60	1.94	1.0	0.6	2.5	99.5
3	D	1.34	26.75	19.90	14.00	0.4	0.2	5.0	265.8
	P	0.77	35.15	20.23	8.39	0.6	0.2	4.0	174.2
	S	0.57	33.55	16.12	1.49	1.1	1.0	2.5	138.6
	G	0.51	27.75	8.63	1.70	1.2	0.7	3.2	106.6
	V	0.80	19.00	20.98	7.29	0.3	0.2	5.2	189.1
4	D	1.19	23.10	21.38	13.48	0.5	0.3	5.0	315.6
	P	0.78	31.90	16.61	9.09	0.5	0.2	5.0	222.6
	S	0.83	29.20	19.24	2.78	0.7	0.4	2.7	131.2
	G	0.27	29.30	4.85	1.10	1.3	0.5	3.4	91.3
	V	0.90	19.05	21.22	7.17	0.4	0.3	5.0	188.7