EFFECT OF IRRIGATION-INDUCED SALINITY AND SODICITY ON SUGARCANE YIELD

D N RIETZ and R J HAYNES

Discipline of Soil Science, School of Applied Environmental Sciences, University of Natal,
Pietermaritzburg, Private Bag X01, Scottsville 3209, South Africa
E-mail: haynesd@agron.unp.ac.za

Abstract

The effects of irrigation-induced salinity and sodicity on sugarcane yields, stalk height and number of nodes per stalk were investigated at a sugarcane estate in the Zimbabwean lowveld. 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, 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 died. As expected, pH was positively related to ESP and SAR_e but negatively related to EC_e. Sugarcane yield, stalk height and number of nodes per stalk were not significantly related to EC_e. Nevertheless, yields were negatively correlated with ESP, SAR_e and pH. Foliar analysis of leaf tissue revealed no substantial differences in macro or micronutrient content between good and poorly-growing sugarcane. Nonetheless, the results suggested that sodicity was a more limiting factor for sugarcane growth than salinity.

Keywords: Salinity, Sodicity, Irrigation, Foliar Analysis, Soil chemistry, Sugarcane yields

Introduction

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, Egypt, Iraq, United States, India, Pakistan, Swaziland, South Africa and Zimbabwe (Hussein, 1998; Haynes and Hamilton, 1999). In the more arid, irrigated areas of the world, soil salinity and sodicity are considered to greatly limit sugarcane yield (Rozeff, 1998; Nelson and Ham, 2000). 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 (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 (Workman *et al.*, 1986; 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 a breakdown in soil structure, poor penetration of water, air and roots, low readily-available water holding capacity and difficulties in timely and effective tillage (Gupta and Abrol, 1990; SASEX, 1997; 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 the role of irrigation-induced soil salinity and sodicity.

Methods and Materials

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 altitudes of between 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 and irrigation is essential. 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 is 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 in 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).

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 were 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 contents were analysed by atomic absorption spectrophotometry. The sodium adsorption ratio of the extracts (SAR_e) was calculated as:

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

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 $\mathrm{pH_{(water)}}$ of above 8.0, exchange acidity was not measured. Exchangeable Na percentage (ESP) was calculated as:

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

During routine analysis of saturation paste extracts, the $\mathrm{CO_3^{2-}}$ and $\mathrm{HCO_3^-}$ content was not measured. Since soils generally had pH values ranging from 8 to 10, the $\mathrm{CO_3^{2-}}$ and $\mathrm{HCO_3^-}$ contents were considered important. For that reason, 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 $\mathrm{H_2SO_4}$ to pH values of 8.2, for $\mathrm{CO_3^{2-}}$ determination, and 4.5 for $\mathrm{HCO_3^-}$ determination, (Mashhady and Rowell, 1978). Alkalinity of extracts was then calculated. Between pH 6 and 10 $[\mathrm{OH^-}]$ and $[\mathrm{H^+}]$ are negligible if $\mathrm{CO_2}$ is present (Mashhady and Rowell, 1978) and alkalinity ($\mathrm{Alk_{1:5}}$) was calculated as:

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

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 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 were 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.

Results and Discussion

Soil chemical properties

The alkalinity in the topsoil layer (0-0.15 m) and the $\mathrm{EC_e}$, $\mathrm{SAR_e}$, ESP and $\mathrm{pH_{(water)}}$ of the four soil layers sampled at the five positions at each experimental site are presented in Table 1. The high pH values, between 8 and 9.5 of soils under undisturbed veld were not unexpected as concretions were observed

Table 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. 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	167	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

within the profiles of these calcareous soils. Indeed, very high concentrations of exchangeable Ca and Mg were present in these soil profiles. That is, mean values in the surface 0.9 m layer were 24.7 cmol$_c$kg^{-1} (range 8-35) for exchangeable Ca and 14.3 mmol$_c$kg^{-1} (range 3-21) for exchangeable Mg. This is a reflection of the presence of Ca and Mg carbonates. Some accumulation of soluble salts at the soil surface of the soils under undisturbed veld was evident from the highest EC$_e$ values being recorded in the 0-0.15 m soil layers (Table 1). Surface accumulation of Na was also evident in the undisturbed soil under veld at site 1 (Table 1).

At the study sites, irrigation-induced salinity and sodicity had developed. Visual observations were made that the watertable had risen 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 had a high Na content, as confirmed by the SAR$_e$ and ESP values for these soils (Table 1). The relatively high values for EC$_e$, SAR$_e$ and ESP generally encountered in the surface soils of profiles under satisfactory, poor and dead and dying sugarcane growth (Table 1) demonstrated 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 was clearly evident from the high ESP values.

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). In South Africa, the critical SAR value is 6, 10 and 15 for duplex soils, Vertisols and Oxisols respectively (SASEX, 1997).

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. It was also 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.

As expected, CO$_3^{2-}$ was not found in 1:5 soil:water extracts from soils under veld, and HCO$_3^-$ levels were very low (data not presented). Similarly, many soils under good sugarcane growth also had minimal concentrations of or no CO$_3^{2-}$, low concentrations of HCO$_3^-$ and as a result Alk$_{1:5}$ values were low (Table 1). Most soils with inadequate sugarcane growth had high levels of CO$_3^{2-}$ and HCO$_3^-$ and therefore high Alk$_{1:5}$ values. An 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 was a result of the considerably lower pH values encountered in the 0-0.15 m layer under dead and dying sugarcane at site 1 compared with those at sites 2, 3 and 4 (Table 1). Thus Alk$_{1:5}$ was relatively low under dead and dying sugarcane at site 1 but was generally high under dead and dying sugarcane at the other three sites.

Soils such as these, that are generally sodic (ESP > 15%; SAR > 13), have a pH > 8.2, variable amounts of soil salinity and contain soluble carbonates, have been defined by Gupta and Abrol (1990) as alkali. The presence of exchangeable Na and soluble carbonates (originating from the Ca and Mg carbonate deposits in the profile) imparts upon them their alkali nature. The alkalinity of a soil solution is equivalent to the total concentration of cations less the total concentration of anions other than carbonate and bicarbonate present (Mashhady and Rowell, 1978). As evaporation proceeds in an alkali soil, Ca and Mg are removed from solution by precipitation of calcite, dolomite and sepiolite leaving behind residual alkalinity (that in excess of the total concentration of divalent cations). The pH remains relatively constant (8.2-8.5) while Ca and Mg carbonates are precipitating but as evaporation continues the pH may increase up to 10 in sodium HCO_3^-/CO_3^{2-} systems due to dissociation of HCO_3^- (Nakayama, 1970; van Beek and van Breeman, 1973). Thus, pH values of the study soils were often between 9 and 10 particularly in the profiles where sugarcane grew poorly or had died (Table 1). These high pH values were generally associated with high values for SAR_e, ESP and $Alk_{1:5}$ values. Indeed, soil pH was exponentially related to ESP and SAR_e and linearly correlated with the logarithm of alkalinity (Figure 1). Under similar soil conditions, Mashhady and Rowell (1978) observed a similar relationship between pH and the logarithm of alkalinity.

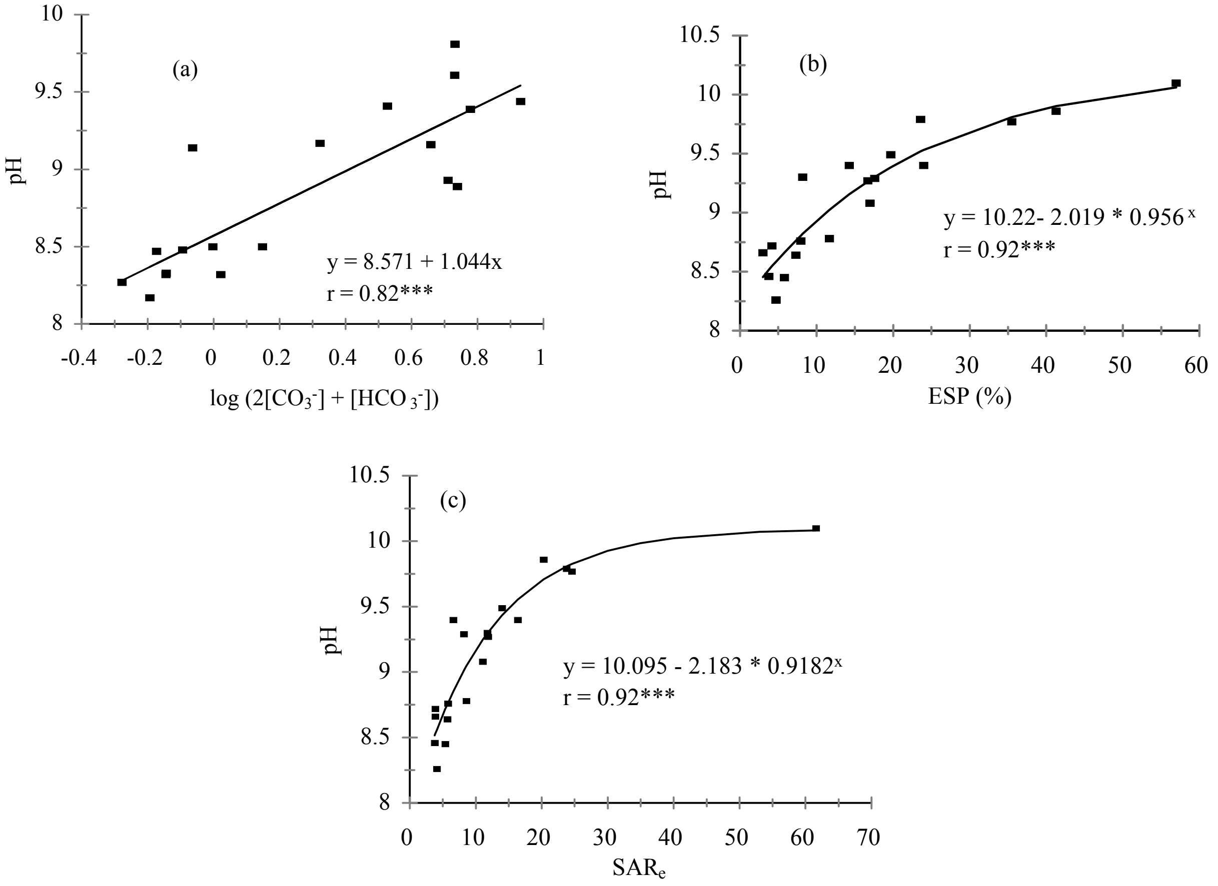

Figure 1. Relationship between pH and (a) log alkalinity in the 0-0.15 m of the soil profiles, (b) exchangeable sodium percentage (ESP) in the 0-0.9 m of the soil profiles and (c) sodium adsorption ratio (SAR_e) in the 0-0.9 m of the soil profiles. Correlation coefficients (r) and significance of correlations (* $0.01 \leq P \leq 0.05$; ** $0.001 \leq P \leq 0.01$; *** $P \leq 0.001$) shown.

Soil properties and plant growth

In Table 2, sugarcane yield and the two other growth parameters, average stalk height and average number of nodes per stalk for each sugarcane growth category are presented. It was evident that all of these parameters decreased with declining sugarcane growth category. If it is assumed that the four different zones of each field were of equal area and that zone G represented 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 were substantial and of considerable economic significance.

Table 2. 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

Sugarcane is considered to be moderately sensitive to salinity (Maas, 1990). von der Meden (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 1). At site 3 the EC_e at soil depths of 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 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 was 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. 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 (Naidu *et al.*, 1995; Keren, 2000; Nelson and Ham, 2000).

The correlation coefficients between yield, average stalk height and average number of nodes per stalk of sugarcane plants and EC_e, SAR_e, ESP and pH in these soils are presented in Table 3. Surprisingly only the average number of nodes per sugarcane stalk was significantly negatively related to salinity.

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 (Table 3) 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. Linear correlation coefficients (r) between growth parameters and relevant soil properties calculated to different depths.

Property	Sugarcane yield	Average stalk height	Average No. of nodes
EC_e 0-0.15 m	-0.01^{NS}	-0.14^{NS}	-
EC_e 0-0.3 m	-0.28^{NS}	-0.44^{NS}	-0.62*
EC_e 0-0.6 m	-0.01^{NS}	-0.10^{NS}	-0.57*
EC_e 0-0.9 m	-	-0.24^{NS}	-0.50^{NS}
SAR 0-0.15 m	-0.14^{NS}	-0.24^{NS}	-
SAR 0-0.3 m	-0.49^{NS}	-0.62*	-0.73**
SAR 0-0.6 m	-0.02^{NS}	-0.39^{NS}	-0.61*
SAR 0-0.9 m	-	-0.28^{NS}	-0.52*
ESP 0-0.15 m	-0.62*	-0.66**	-0.67*
ESP 0-0.3 m	-0.62*	-0.69**	-0.77**
ESP 0-0.6 m	-0.47^{NS}	-0.58*	-0.68**
ESP 0-0.9 m	-0.02^{NS}	-0.36^{NS}	-0.48^{NS}
pH (water) 0-0.15 m	-	-	-
pH (water) 0-0.3 m	-0.71**	-0.76**	-0.75**
pH (water) 0-0.6 m	-0.38^{NS}	-0.65*	-0.61*
pH (water) 0-0.9 m	-	-0.10^{NS}	-0.28^{NS}

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

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

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 Figure 2. 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 declined by 2.4 Mg ha^{-1}. This was in contrast to Spalding (1983) who found only a 1.5 Mg ha^{-1} decline 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 2a).

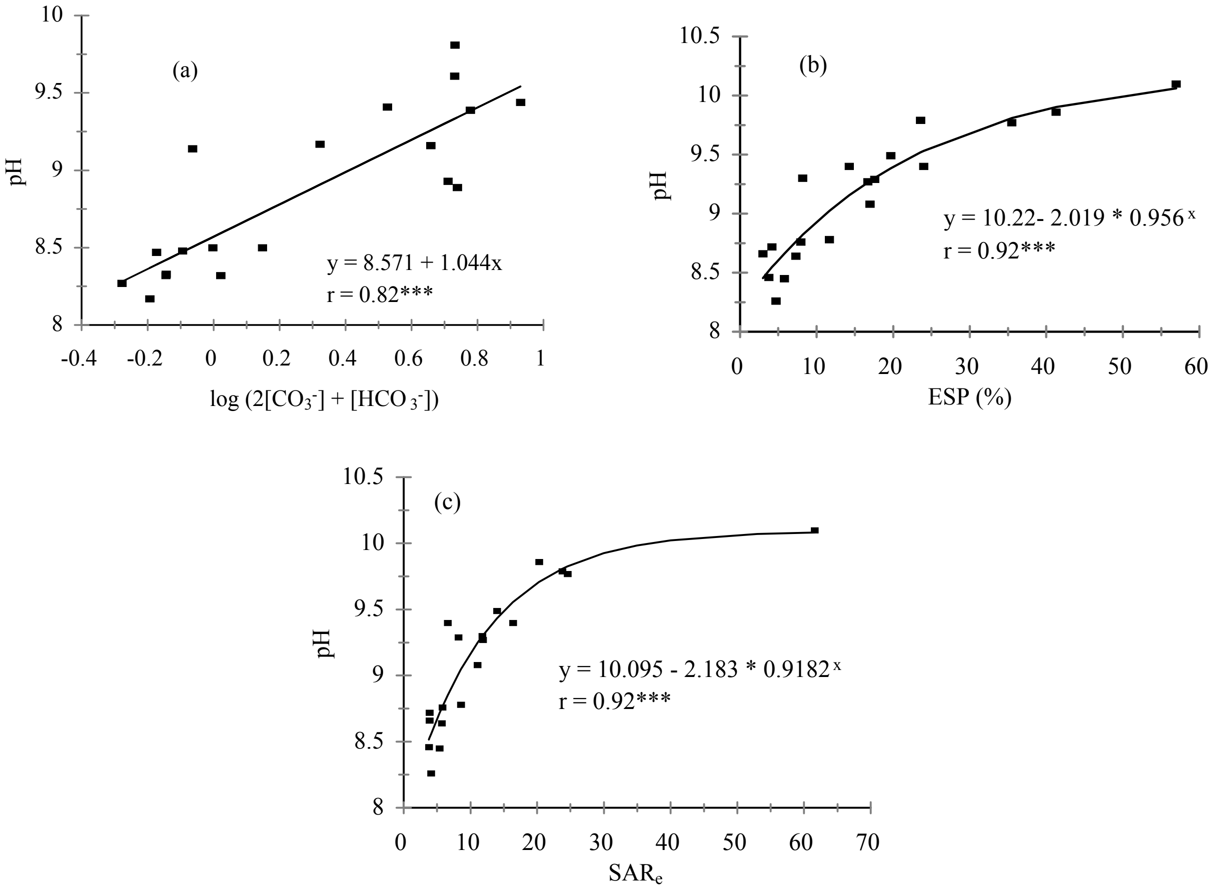

Figure 2. Relationship between exchangeable sodium percentage (ESP) in the 0-0.3 m soil layer and (a) sugarcane yield, (b) sugarcane stalk height, and, (c) number of nodes per stalk. Correlation coefficients (r) and significance of correlations (* $0.01 \leq P \leq 0.05$; ** $0.001 \leq P \leq 0.01$;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

The negative correlations between sugarcane yield, stem height and number of nodes per stalk versus soil pH (Table 3) 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.

The mechanisms by which sodicity inhibited sugarcane growth are likely to have been complex. Ion toxicities (particularly those of Na and Cl) and imbalances (e.g. Na-induced inhibition of Ca uptake and translocation) are likely to be important (Swinford *et al*, 1985; van Wambeke, 1991; Keren, 2000). The high pH in association with large concentrations of HCO_3^- in soil solution can inhibit root growth and function and may also induce deficiencies of Fe, Mn, Zn and Cu (Naidu and Rengasamy, 1995; Sumner, 1997). In addition, poor physical conditions induced by Na induced clay dispersion can lead to water ponding on the soil surface and the anaerobic soil conditions that result can inhibit crop growth (Gupta and Abrol, 1990). The poor physical conditions can also inhibit root growth directly.

Another possibility is that waterlogging (anaerobic conditions) in the subsoil maybe limiting crop growth. That is, salinity and sodicity were generally greater at the lower-ends of irrigated fields (where the sugarcane had died) because the watertable was 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 the political situation in Zimbabwe it was not possible to investigate this aspect in more detail. 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.

Foliar analysis

The macro- and micro-nutrient content of sugarcane leaf samples is presented in Table 4. Unfortunately, samples from site 1 were not taken because the field was burnt due to political unrest prior in Zimbabwe. The analyses showed no 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 normally about 1.7-1.8%, 0.18-0.19%, 1.05% and 0.12% respectively. By contrast, concentrations of leaf Ca and Mg were generally high, which is not surprising bearing in mind the high concentrations of exchangeable Ca and Mg found in the soils.

Table 4. Nutrient content of 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

Phytotoxic concentrations of ions other than Na may also have interfered 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, 1968).

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 (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 exerts 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 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.

Conclusions

Poor irrigation management on a sugarcane estate on heavy clay soils in the Zimbabwean lowveld resulted in yield decline and even death of sugarcane at the lower ends of furrow irrigated fields. At the lower ends of fields the water table was nearer the soil surface and capillary action resulted in accumulation of soluble salts at the surface and induced saline-sodic, sodic and alkali soil conditions in the surface horizons. The reasons for the yield decreases, and deaths, were suspected to be due to 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 the 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 could 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.

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