

# QUANTIFYING THE EFFECT OF SOIL SALINITY ON THE PHYSIOLOGY OF THREE SOUTH AFRICAN SUGARCANE VARIETIES

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## Abstract

Salinity is of significant economic importance in the sugar industry because it affects the growth rate and sucrose yield of sugarcane. The aims of this study were to assess how various aspects of the physiology of sugarcane are affected by increasing levels of soil salinity during the growing season, and to determine whether or not there are differences in the physiological responses of different varieties to saline conditions.

The trial focused solely on salinity, with the cations  $\text{Ca}^{2+}$  and  $\text{Mg}^{2+}$  (predominantly as chlorides) as the dominant salts, and excluded the effects of  $\text{Na}^+$  and sodicity as a variable, when assessing the effect of high electrical conductivity (EC) (ranging from about 100 to 800 mS/m) on the physiology and yield of varieties N17, N22 and NCo376. Investigations were carried out to assess leaf water potential, stomatal conductance and light-saturated rate of photosynthesis of these varieties under the experimental conditions provided.

It was evident throughout the trial that high levels of salt adversely affected growth for all three varieties; total above-ground biomass decreased significantly with increasing salinity. Although sucrose yields (tons/ha) of all three varieties showed a trend of decline with increasing salinity, only NCo376 showed significant treatment effects. Leaf water potentials at both pre-dawn and midday were found to be lower as EC increased, implying a mild water stress. N17 and NCo376 showed moderate sensitivity to salt because their responses to salinity, although variable depending on the parameter being assessed, were never as severe as the response of N22, which displayed more pronounced reactions at higher levels of salinity.

*Keywords:* sugarcane, salinity, sucrose yield, leaf water potential, photosynthesis, water use

## Introduction

Soil salinity has always been an important factor in the history of mankind and in the agricultural systems on which man has relied, and represents a serious threat to irrigated arable land. It has been estimated that about one-third of the world's irrigated land is affected by a build-up of salts (Rozema, 1994). With the increasing demand to produce crops on salt-affected areas, the relationship between soil salinity and yield needs to be assessed. To increase agricultural production in terms of intensification as well as expansion of the area to be cultivated, it is important to provide irrigation water. This, however, induces problems such as salinisation of soils, the development of a water table, and waterlogging.

Stressful environments are often characterised by the occurrence of more than one stress simultaneously thus overcoming these stresses is similarly complicated. Many environmental factors temporarily or consistently constrain the growth and development of plants. Two of these, water deficit/stress and salt excess/stress, are closely related. Irrigated crops, in particular, are affected by the relationship between these two stresses (reviewed by Shalhevet, 1993).

Salinity affects plants at all growth stages; however, it may be that crop plants can tolerate salinity at one growth stage but show sensitivity at another stage of the life cycle (Maas and Hoffman, 1977; Rozema, 1994). Some of the symptoms of salt stress are those characteristic of water stress. Many crops growing in saline soils do not display symptoms of wilting clearly, resulting in a considerable loss of yield if irrigation is applied only when the plants are obviously wilted. The greater the salinity of a soil, the less water a crop can remove before it begins to suffer a water shortage, so that irrigated soils with an appreciable salt content need more frequent irrigations than non-saline soils. Salt stressed plants are stunted rather than being wilted, which means that the cells must have water potentials to enable them to compete for water from the xylem. One of the ways in which water potential may be lowered is by an increase in solutes (Hale and Orcutt, 1987). General salinity effects on crop growth are thought to be largely osmotic in nature and related to total salt concentration rather than to the individual concentrations of specific salt constituents (Rhoades, 1972).

The most common salinity effect, as salt concentrations increase above a threshold level, is a general stunting of growth; however, not all parts of the plant are affected equally (Maas and Hoffman, 1977), with top growth often being suppressed more than root growth. In a review by these authors, it was agreed that crop yield is usually an agronomically significant criterion for establishing salt tolerance. In general, crops tolerate salinity up to a threshold value, above which yields decrease approximately linearly as salt concentrations increase. Salt damage may not always be apparent in practice and, if there are no patches of low-salt soil in the field to act as controls, yields can be reduced by as much as 20% without salt damage being apparent to the farmer (Russell, 1973). Plants are affected physiologically in many ways by salinity; however, overt injury symptoms seldom occur except under extreme salinisation (Maas and Hoffman, 1977).

It has been confirmed by a number of workers that salinity and/or sodicity have a negative effect on sugarcane yield (Richards, 1954; Bernstein *et al.*, 1966; von der Meden, 1966; Dev and Bajwa, 1972; Nour *et al.*, 1989; Rozema, 1994; Nelson and Ham, 2000; Chowdhury *et al.*, 2001; Rietz and Haynes, 2002). Based on the USDA scale of soil salinity (Richards, 1954), sugarcane would be classified as a sensitive crop. In a review paper, Rozeff (1995) found that the consensus indicated that sugarcane is between moderately sensitive and sensitive to salinity. This author indicated that electrical conductivity (EC) values below 200 mS/m had little or no effect on cane growth and yield. At values of 200 to 400 mS/m, cane yields decreased, with 300 mS/m being the likely break-point to a steeper decline; and at 520 to 700 mS/m yields decreased by 50% or more. At an EC value of 800 mS/m stools of some cultivars may be killed, and at values of 1000 to 1500 mS/m, no stools will survive.

Growth and appearance of sugarcane is affected by excessive quantities of salts (Barnes, 1974). When crops grow to maturity under saline conditions the processing of the juice becomes troublesome, sugar recovery is reduced, and the yield of molasses increased. The colour of leaves is abnormal and may vary from pale green to clear yellow. In extreme cases the leaves may become white, with blackish patches of dead tissue (Barnes, 1974). Sugarcane, exposed to excess salinity will display an irregular, ill-grown habit, with stunted growth, short, thin canes with short internodes (Dev and Bajwa, 1972) and an absence of well

developed stalks having large healthy leaves.

No single value for EC can be universally applicable as the critical point for salinity damage, as the influence of salts on yields will be affected by the nature of the salts, the amount and pattern of rainfall, the irrigation system and the soil type (Maas and Hoffman, 1977; reviewed by Rozeff, 1995). The deleterious effects of salinity become more evident with each cane cycle i.e.: ratoon crops are affected more severely than plant crops, largely because of poor sprouting and reduced shoot numbers (Bernstein *et al.*, 1966).

Studies conducted by Nelson and Ham (1998, 2000) on irrigated sugarcane grown on sites displaying variable salinity and sodicity, showed cane yield being negatively correlated with salinity and sodicity, even at levels normally considered too low to be detrimental, indicating that the combination of salinity and sodicity reduced the availability of water to the crop.

The aim of this study was to quantify and explain the effect of varying levels of salinity on the physiology, growth and sucrose production of selected varieties used in irrigated areas of the South African sugar industry. Since sugarcane, a cross-pollinated crop, exhibits a range of genetic variations there was a need to investigate the response of different varieties to salinity.

### Materials and methods

The pot trial was conducted using the rainshelter facility at the South African Sugar Association Experiment Station (29° 34' N, 30° 08' E, 80 m above sea level). The trial consisted of three varieties with five treatments and five replicates. The varieties chosen were N17, N22 and NCo376, and the treatments consisted of irrigating the trial with solutions that ranged in salinity from *circa* 120 to 840 mS/m. Sixteen trays, each able to hold five 20 dm<sup>3</sup> pots, were arranged in four rows with a row spacing of 1.2 m from the centre of one tray to the centre of the next. Each tray was irrigated with a particular salinity treatment (three trays per treatment), and a randomised block design was used.

A drip irrigation system was set up using five 200 dm<sup>3</sup> tanks (one for each treatment). Irrigation was scheduled using a programmable timer which controlled a pump and solenoid valves. Treatments were applied in sequence, starting with the solution with the lowest level of salinity and ending with the highest. The pots were flushed periodically with water to prevent salt build-up in the soil.

The pot trial focused solely on salinity, as opposed to sodicity, with the cations Ca<sup>2+</sup> and Mg<sup>2+</sup> as the dominating salts. The effects of Na<sup>+</sup> were excluded when assessing the effect of high ECs on crop physiology and yield. CaCl<sub>2</sub> and MgSO<sub>4</sub> were the salts chosen to obtain the required range of ECs. Hygrotech hydroponic nutrient mixture was used to provide the remaining essential nutrients to the plants, and small amounts of Ca(OH)<sub>2</sub> were used to adjust the pH to approximately 7.2.

**Table 1. Electrical conductivity (EC), pH and sodium adsorption ratio (SAR) of the irrigation solutions.**

EC (aimed) (mS/m)	EC (obtained) (mS/m)	pH (water)	$\psi_{soil}$ (kPa)	K (meq/L)	S (meq/L)	Ca (meq/L)	Mg (meq/L)	Na (meq/L)	HCO <sub>3</sub> (meq/L)	Cl (meq/L)	SAR
100	121	7.19	-97	3.0	2.3	4.9	1.7	0.5	1.1	0.7	0.2
300	340	7.13	-122	3.0	22.4	9.0	15.3	0.7	1.3	9.9	0.2
400	440	7.38	-115	3.1	38.7	11.5	23.0	0.8	1.4	12.7	0.2
500	525	7.06	-146	3.1	52.8	13.0	31.8	0.9	1.4	15.7	0.2
800	844	7.07	-212	3.1	102.8	18.0	52.0	1.2	1.6	27.5	0.2

The cation and anion concentrations of the irrigation solutions are presented in Table 1. The electrical conductivities were achieved using CaCl<sub>2</sub>, MgSO<sub>4</sub>, Ca(OH)<sub>2</sub> and Hygrotech.

Calcium, magnesium, sulphate and chloride values show increases in accordance with the increasing quantities of chemicals used to obtain the range of ECs. The threshold value yield decline for chloride is approximately 10 meq/L, above which plants begin to exhibit toxicity effects. Analyses of the irrigation solutions indicated that the levels of chloride in all the treatments except 120 mS/m were either very close to or well above the threshold value for chloride inducing possible toxicity effects which could worsen with increasing EC. Sodium levels showed a very slight increase with increasing EC; SAR was 0.2 on average, confirming that no sodicity hazard was present; pH remained close to neutral. The water potential of the solutions ( $\psi_{\text{soil}}$ ) indicated that the water stress imposed on the plants was fairly mild in nature.

The initial germination was carried out in a greenhouse at the Experiment Station. Single-eyed setts of N17, N22 and NCo376 (chosen based on their perceived tolerance to salinity) (Anon, 2001a,b) were irrigated with the same range of irrigation solutions used throughout the trial. The pre-germinated plants (2 months of age) were transplanted into 20 dm<sup>3</sup> pots (one plant per pot) filled with coarse sand. A layer of inert hydrated Stokosorb water retention gel was placed in the middle of the pot, to increase the water-holding capacity of the sand. The irrigation schedule was changed with increasing water requirements as the plants got older, and for the second half of the sugarcane cycle, approximately one litre of irrigation solution per pot was delivered every 20 hours.

The cane was harvested at 15 months of age. Measurements taken at harvest included total above-ground biomass of stool<sup>1</sup>, stalk number, weight, diameters (top, middle and bottom of stalk), length, number of internodes, sucrose yield, and fibre and brix percentages.

The middle portion of the third fully expanded leaf from the top (third leaf/blade 3) was used for all measurements of photosynthesis, carried out using a LiCor 6400 portable photosynthesis system. Net photosynthesis and stomatal conductance were among the physiological responses measured. 'Spot measurements' were taken of 40 plants (covering three varieties, five treatments and five replicates) at a fixed light intensity of 1700  $\mu\text{mol}/\text{m}^2/\text{s}$  on six separate occasions. Leaf water potential was measured (using the same 40 plants used for 'spot measurements' of gas exchange), pre-dawn and midday, using the pressure chamber technique described in Saliendra *et al.* (1990).

For reasons that are unclear, a decline in germination was observed in plants irrigated with the 440 mS/m treatment. This was evident from the pre-germination stage and was clearly not an effect of salinity. The data for this EC has been excluded from analyses, although the data points have been shown in all figures. Results were analysed using analysis of variance and linear regressions, performed in Microsoft Excel 2000 (Microsoft Corporation)<sup>2</sup>.

## Results and discussion

### *Growth and yield*

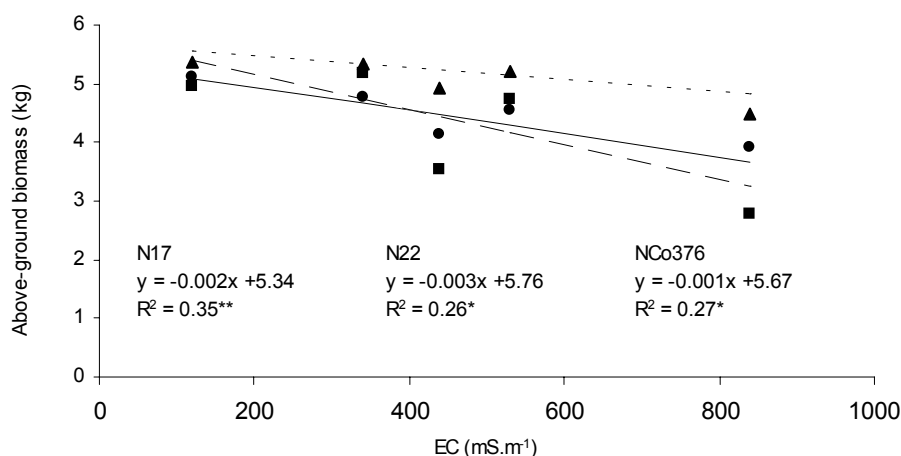
N17, N22 and NCo376 were chosen to represent varieties tolerant, sensitive and of intermediate tolerance to salinity, respectively. It was clearly evident, even in the early stages of growth, that high ECs negatively affected the growth of sugarcane.

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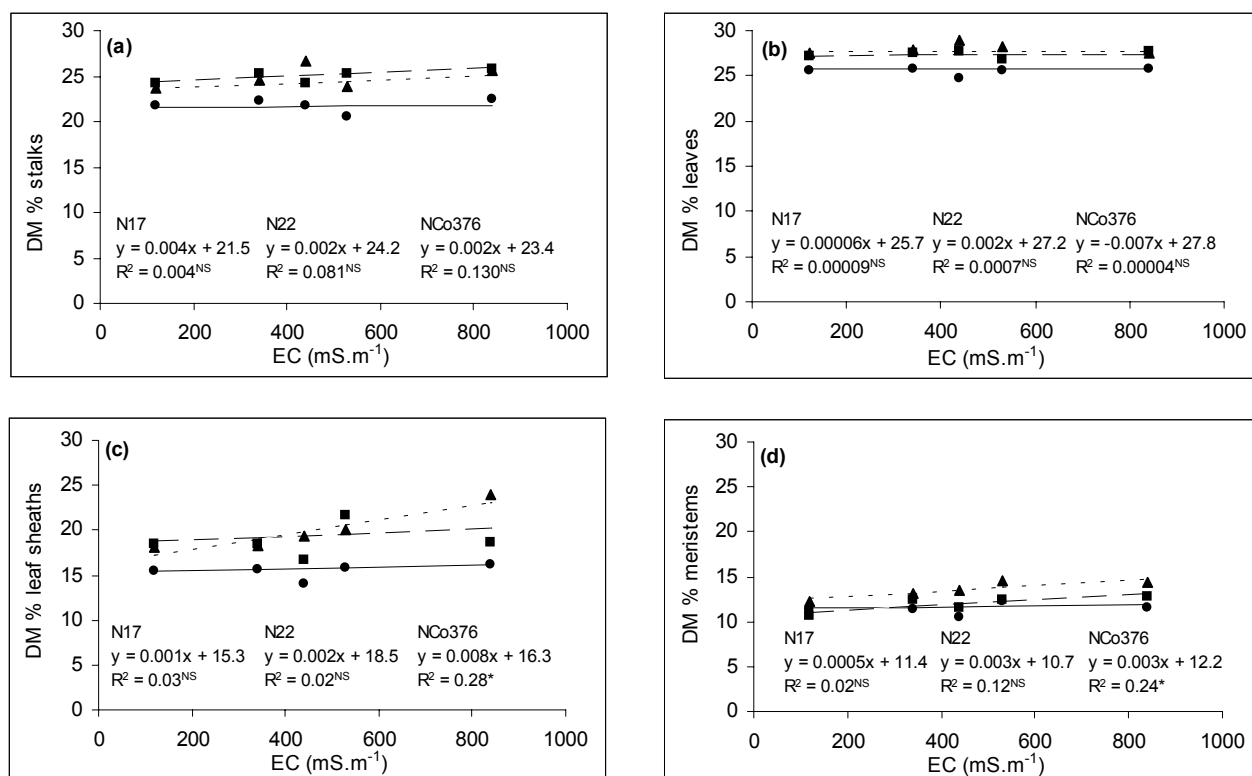
<sup>1</sup> In the context of the pot trial, the term 'stool' is used to refer to all the stalks in one pot.

<sup>2</sup> SPSS vs. 9.01 (SPSS Inc, Chicago, USA) was initially used to verify the results generated by the Microsoft Excel 2000 data analysis package. Outputs from both packages were in agreement.

Total above-ground dry matter at harvest decreased significantly for all three varieties with an increase in salinity (Figure 1). NCo376 had the highest total above-ground biomass across treatments. The decline in total above-ground biomass was most marked at 840 mS/m, with declines of 24, 44 and 17% (compared with the control) experienced by N17, N22 and NCo376 respectively.



**Figure 1. Average above-ground biomass of the stool, coefficients of determination ( $R^2$ ) and significance of correlations ( $^{NS}P>0.05$ ;  $*0.01<P<0.05$ ;  $**0.001<P<0.01$ ). Averages are denoted by ● N17, ■ N22, ▲ NCo376. Regression lines are denoted by N17 \_\_\_\_\_ N22 \_\_\_\_ NCo376 \_\_\_\_\_.**



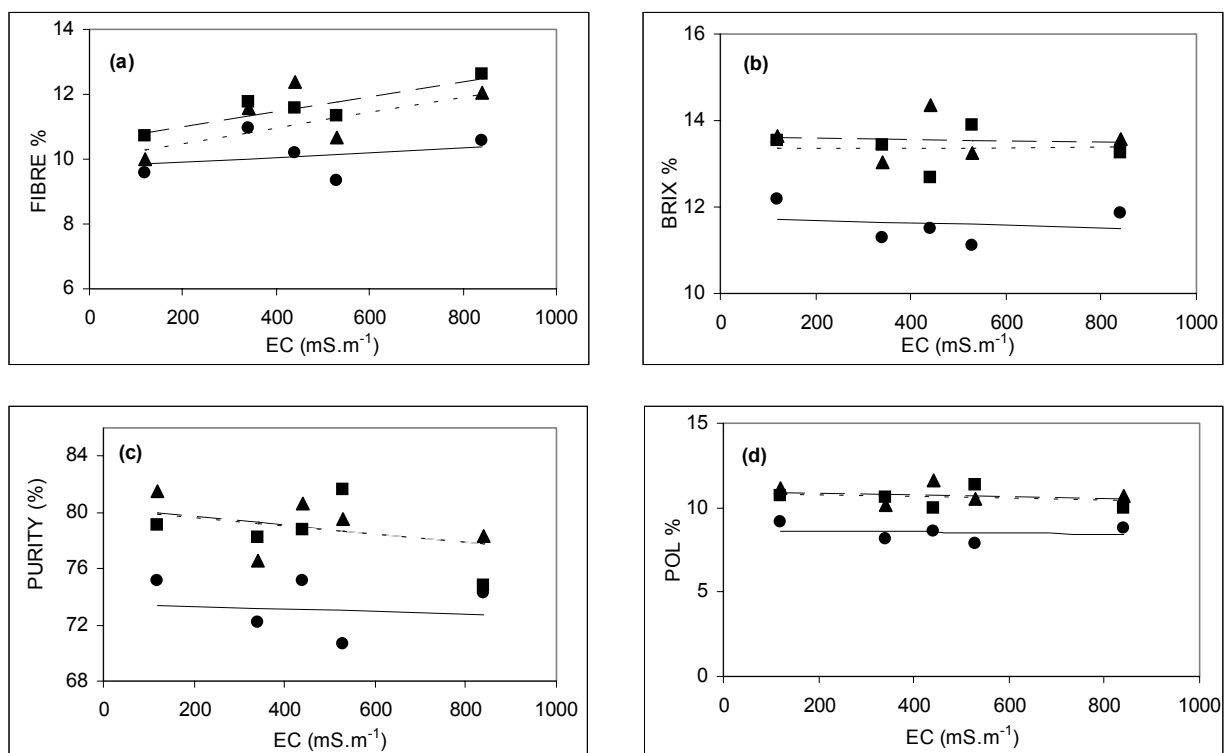
**Figure 2. Average dry matter % of (a) stalks, (b) leaves, (c) leaf sheaths, and (d) meristems. Coefficients of determination ( $R^2$ ) and significance of correlations ( $^{NS}P>0.05$ ,  $*0.01<P<0.05$ ) are shown. Averages are denoted by ● N17, ■ N22, ▲ NCo376. Regression lines are denoted by N17 \_\_\_\_\_ N22 \_\_\_\_ NCo376 \_\_\_\_\_.**

Figures 2 a,b,c,d show the dry matter (DM) percentage of the stalks, leaves, leaf sheaths and meristems respectively. Although trends of increase in DM% with increasing salinity exist for all the above components of the total biomass, in most instances these trends were not statistically significant, with only slight differences observed in DM% when comparing values across treatments.

For all the individual components that made up total above-ground biomass, DM% for N17 was lower than that of the other two varieties; thus no individual component was identified as more 'responsible' for the slight increase in total DM% in N17 in response to changing salinity. A similar situation was observed with N22, where any variations in response to salinity in the above-ground components of this variety were not significant.

NCo376 showed significant increases in the DM% of its leaf sheaths and meristems (Figure 2c,d), with increases in these components of 32 and 17% in DM% respectively, at 840 mS/m compared with the control. This implied a significant reduction in leaf sheath and meristem moisture content as a consequence of the imposition of salt stress. The leaf sheaths and meristems were most responsible for the significant change in total DM% of NCo376 with increasing salinity, since the stalks and leaves (Figure 2a,b) showed little change in response to treatment.

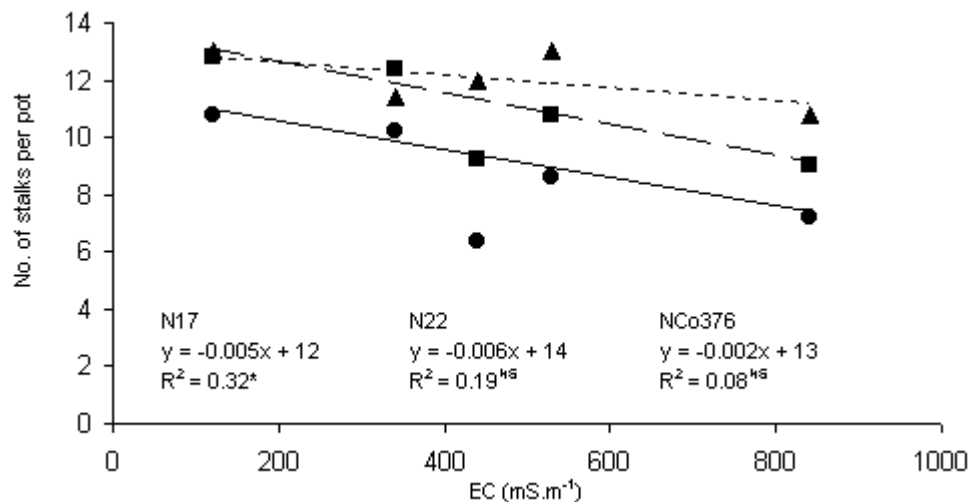
Fibre % increased with increasing salinity for all three varieties; however, the increase was significant only in NCo376 ( $p < 0.05$ ) (Figure 3a). N17 had the lowest fibre % across ECs and showed the least change in fibre % in response to increasing salinity, with the fibre % at 840 mS/m increasing by only 11% compared with that at 120 mS/m. N22 and NCo376 again showed similar trends of increase, since N22 had the highest fibre % of the three varieties but a similar DM% to NCo376. This implied N22 had a lower Brix % and consequently a lower Pol % than NCo376. The fibre % of N22 and NCo376 at 840 mS/m increased by 18 and 21% respectively, compared with the control.



**Figure 3. Averages of stalk components (a) Fibre %, (b) Brix %, (c) Purity and (d) Pol %. Averages are denoted by ● N17, ■ N22, ▲ NCo376. Regression lines are denoted by N17 \_\_\_\_\_ N22 \_\_\_\_ NCo376 \_\_\_\_\_.**

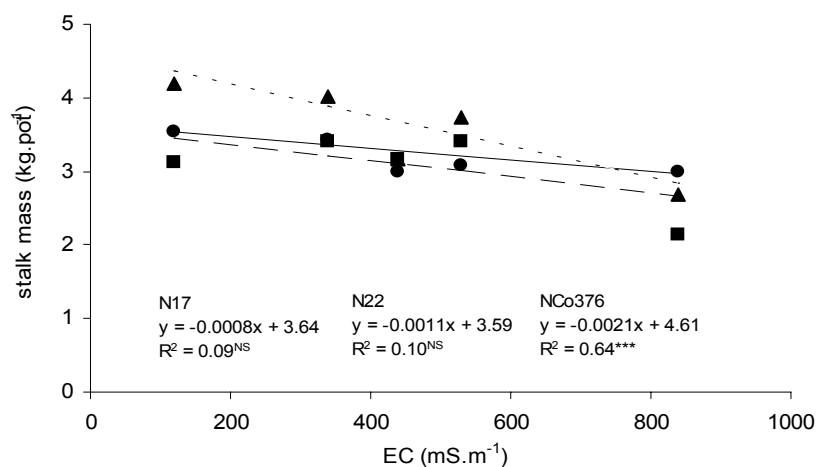
Brix % was not significantly affected by increasing salinity for any of the varieties. N17 and N22 showed a very slight decrease in Brix % and NCo376 showed a slight increase in Brix % with increasing EC (Figure 3b). N17 had the lowest Brix % across treatments, implying that fibre % was the component most responsible for the increase in DM% cane.

Although total stalk population per stool declined with increasing salinity for all three varieties, a significant decline ( $p < 0.05$ ) was observed only in N17, which yielded approximately 33% fewer stalks per stool at 840 mS/m than the control (Figure 4). N17 also had the smallest stalk population of the three varieties across treatments, although this was not an effect of salinity.



**Figure 4. Average stalk population per pot. Coefficients of determination ( $R^2$ ) and significance of correlations ( $^{NS}P > 0.05$ ,  $*0.01 < P < 0.05$ ) are shown. Averages are denoted by ● N17, ■ N22, ▲ NCo376. Regression lines are denoted by N17 \_\_\_\_\_ N22 \_\_\_\_\_ NCo376 \_\_\_\_\_.**

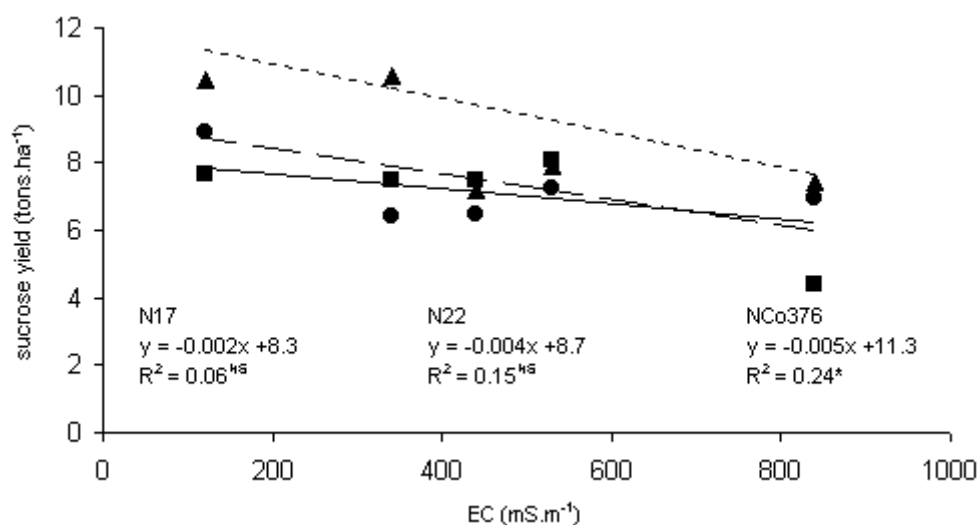
A very significant decline ( $p < 0.001$ ) in stalk fresh mass was observed for NCo376 in response to salinity. Total stalk fresh mass of NCo376 grown at 840 mS/m declined by 36% compared with stalk masses obtained at the lowest salinity treatment (control) (Figure 5).



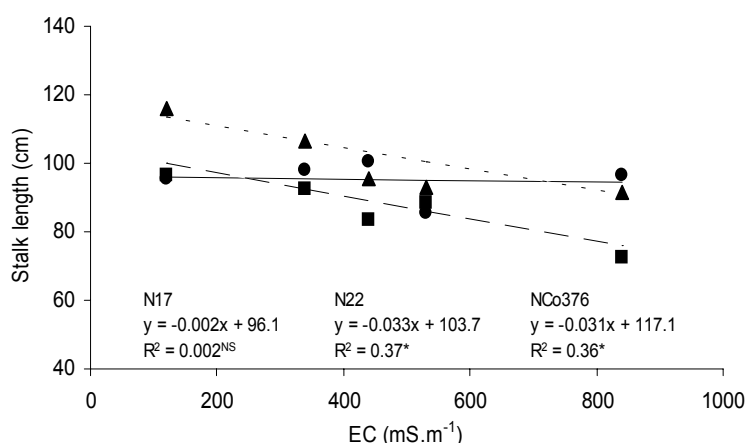
**Figure 5. Mean stalk fresh mass (kg). Coefficients of determination ( $R^2$ ) and significance of correlations ( $^{NS}P > 0.05$ ,  $*0.01 < P < 0.05$ ,  $**0.001 < P < 0.01$ ,  $***P < 0.001$ ) are shown. Averages are denoted by ● N17, ■ N22, ▲ NCo376. Regression lines are denoted by N17 \_\_\_\_\_ N22 \_\_\_\_\_ NCo376 \_\_\_\_\_.**

Sucrose yield (tons/ha) was calculated taking into account stalk mass, population and Pol%.

The data presented in Figure 6 indicates a decline in sucrose yield in response to increasing salinity; however, the decline was significant for NCo376 only ( $p < 0.05$ ). These results are particularly interesting because, although Pol % does not appear to vary much with increasing salinity (Figure 3c), the total sucrose yield (tons/ha) was affected as a direct result of the stalk population and stalk mass both being negatively affected. The sucrose yield of NCo376 was unaffected at 340 mS/m, and showed declines at 530 and 840 mS/m of 24 and 29% respectively, compared with the control. This decline was due to a significant decrease ( $p < 0.001$ ) in stalk fresh weight (Figure 4) of this variety. Although N22 displayed little change in sucrose yield at the lower ECs, at 840 mS/m a considerable decline of 43% compared to the control was observed. The overall decline was not significant, due to little change occurring in sucrose yields in the 120 to 530 mS/m treatments.



**Figure 6. Calculated sucrose yield (tons/ha). Coefficients of determination ( $R^2$ ) and significance of correlations ( $^{NS}P > 0.05$ ;  $*0.01 < P < 0.05$ ) are shown. Averages are denoted by ● N17, ■ N22, ▲ NCo376. Regression lines are denoted by N17 \_\_\_\_\_ N22 \_\_\_\_ NCo376 \_\_\_\_\_.**



**Figure 7. Mean stalk length (cm). Coefficients of determination ( $R^2$ ) and significance of correlations ( $^{NS}P > 0.05$ ,  $*0.01 < P < 0.05$ ) are shown. (Averages are denoted by ● N17, ■ N22, ▲ NCo376. Regression lines are denoted by N17 \_\_\_\_\_ N22 \_\_\_\_ NCo376 \_\_\_\_\_).**

Figure 7 effectively illustrates varietal response to the negative effect of salinity on stalk length, with N17 showing virtually no response to salinity, whereas stalk length in N22 and NCo376 declined significantly ( $p < 0.05$ ) with increasing salinity. N22 and NCo376 show similar patterns of decline; however, NCo376 had longer stalks across treatments.

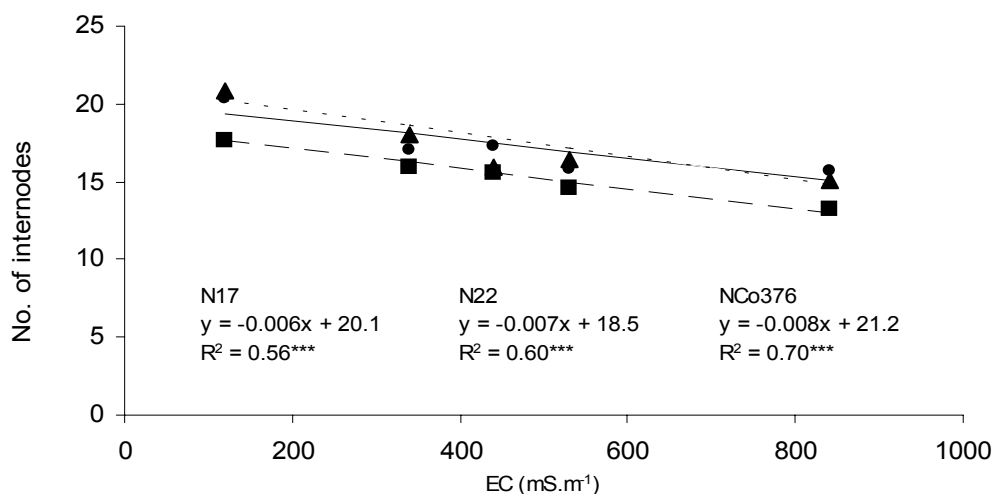
Stalk diameter was measured at the top (close to the natural breaking point), middle and bottom (close to the base) of the stalks.

A pattern of increase in stalk diameter was observed with increasing salinity (Table 2). A trend observed was that diameters were smaller at the top of the stalk and increased closer to the bottom; diameters for the middle and bottom of the stalk did not differ largely.

**Table 2. Changes in mean stalk diameter at different points on the stalk (top, middle and base) in response to changing electrical conductivity.**

EC (mS/m)	Mean diameter (mm)								
	N17			N22			NCo376		
	Top	Middle	Base	Top	Middle	Base	Top	Middle	Base
120	16	19	19	13	17	17	12	16	16
340	14	19	18	14	18	18	14	17	18
440	18	22	22	13	17	18	14	16	18
530	16	21	22	14	18	20	13	18	19
840	17	21	22	12	16	17	13	17	18

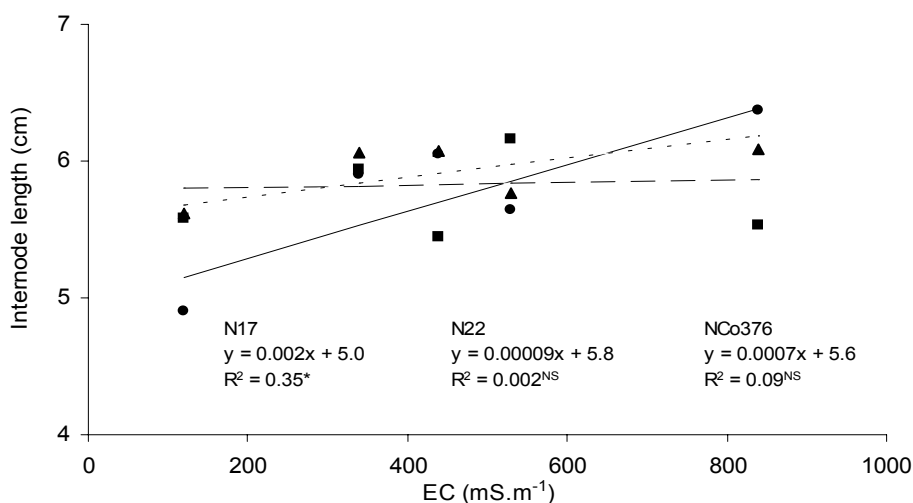
The average number of internodes per stalk showed significant decline ( $p < 0.001$ ) for all varieties in response to varying salinity (Figure 8).



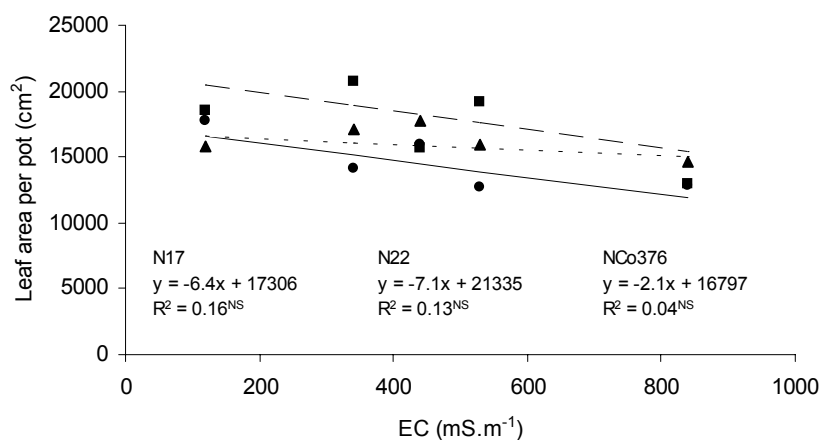
**Figure 8. Mean number of internodes. Coefficients of determination ( $R^2$ ) and significance of correlations (<sup>NS</sup> $P > 0.05$ ,  $*0.01 < P < 0.05$ ,  $**0.001 < P < 0.01$ ,  $***P < 0.0001$ ) are shown. Averages are denoted by ● N17, ■ N22, ▲ NCo376. Regression lines are denoted by N17 \_\_\_\_\_ N22 \_\_\_\_ NCo376 \_\_\_\_\_.**

In all three varieties, there was a decline in number of internodes of approximately 25% at 840 mS/m compared with the control; although little difference in varietal response was seen. N17 showed significant increase in internode length ( $p < 0.05$ ), with 30% longer internodes at 840 mS/m than at 120 mS/m. This was interesting because, although the stalk length for N17 did not show much response to salinity (Figure 9), this variety yielded significantly fewer nodes per stalk (Figure 8), resulting in a smaller number of buds available for future

vegetative growth (i.e. fewer plants produced per stalk when used as seedcane). N22 and NCo376 both showed significant decline in stalk length and mean number of nodes per stalk, so although a slight trend of increase in stalk length did exist, this increase was not significant.



**Figure 9. Calculated mean internode length (cm). Coefficients of determination ( $R^2$ ) and significance of correlations (<sup>NS</sup> $P>0.05$ ,  $*0.01<P<0.05$ ,  $**0.001<P<0.01$ ) are shown. Averages are denoted by ● N17, ■ N22, ▲ NCo376. Regression lines are denoted by N17 \_\_\_\_\_ N22 \_\_\_\_ NCo376 \_\_\_\_\_.**



**Figure 10. Total leaf area per pot. Coefficients of determination ( $R^2$ ) and significance of correlations (<sup>NS</sup> $P>0.05$ ,  $*0.01<P<0.05$ ,  $**0.001<P<0.01$ ) are shown. Averages are denoted by ● N17, ■ N22, ▲ NCo376. Regression lines are denoted by N17 \_\_\_\_\_ N22 \_\_\_\_ NCo376 \_\_\_\_\_.**

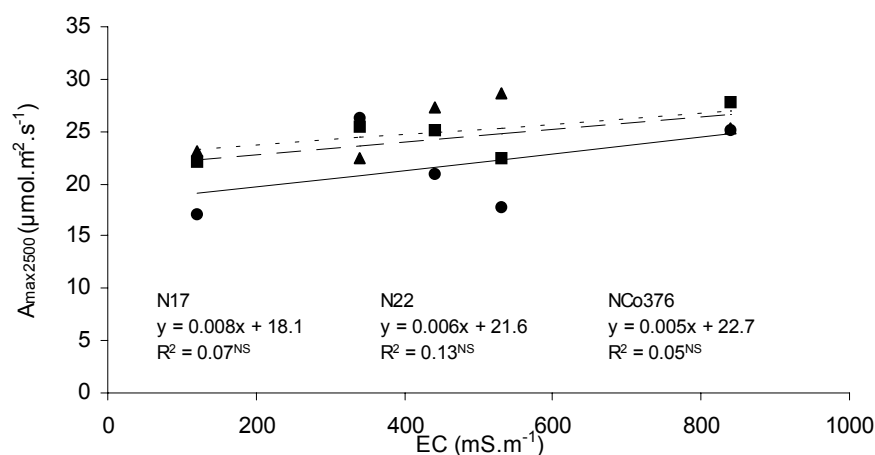
Mean leaf area per stool (calculated by obtaining the sum of leaf areas per stalk) also exhibited a trend of decline with increasing salinity; this decline, however, was not significant (Figure 10). N17 and N22 showed similar slopes of decline, with a reduction in total leaf area per stool of 27 and 30% respectively, at 840 mS/m compared with that at 120 mS/m. NCo376 was not as severely affected by salinity and a decline in total leaf area of only 9% was observed compared with the control.

## Physiology

The importance of solar radiation to agricultural production is perhaps best summarised by Montieith's (1958) statement that agriculture is "an exploitation of solar energy, made possible by an adequate supply of water and nutrients to maintain plant growth" (quoted in Schulze, 1997).

Radiant energy is harvested by the process of photosynthesis, therefore the influence of salinity on net CO<sub>2</sub> assimilation was investigated. The response of assimilation to light intensity was studied when the cane was six months old, and the light saturated rate of assimilation ( $A_{max}$ ) was determined.

The values for  $A_{max}$  at a photosynthetic photon flux density of 2500  $\mu\text{mol}/\text{m}^2/\text{s}$  were compared between treatments and varieties (Figure 11) and no significant differences were found between treatments or varieties, nor with the interactive effects of treatments and varieties. Linear regressions revealed a non-significant trend of increase in  $A_{max2500}$ , with N17 having a lower  $A_{max2500}$  than N22 and NCo376 at both 120 and 840 mS/m. All varieties achieved similar assimilation rates at 340 and 840 mS/m, suggesting that plants grown with these treatments were not impaired in terms of their ability to adequately photosynthesise.



**Figure 11. Maximum assimilation at 2500  $\mu\text{mol}/\text{m}^2/\text{s}$  ( $A_{max2500}$ ) of N17, N22 and NCo376. Coefficients of determination ( $R^2$ ) and significance of correlations ( $^{NS}P>0.05$ ,  $^{*}0.01<P<0.05$ ,  $^{**}0.001<P<0.01$ ) are shown. Averages are denoted by ● N17, ■ N22, ▲ NCo376. Regression lines are denoted by N17 \_\_\_\_\_ N22 \_\_\_\_ NCo376 \_\_\_\_\_.**

Stomatal conductance was also plotted as a function of PAR, and the slopes of linear regressions carried out were compared (data not shown). No clear trends in response to salinity were observed.

Instantaneous measurements of assimilation at 1700  $\mu\text{mol}/\text{m}^2/\text{s}$  ( $A_{1700}$ ) were taken on a number of days. The data exhibited a trend of decline with increasing EC, but this trend was driven mainly by the reduction in  $A_{1700}$  at 840 mS/m (Table 3), and most of the relationships were not significant.

On some occasions, measured assimilation was higher at 340 and 530 mS/m than the control; this supports data from the light response curves that suggested an increase in assimilation with a slight increase in salinity (Figure 11). Photosynthetic rates were affected mainly at 840 mS/m, with results that did not follow a set pattern among the other ECs.

**Table 3. Average assimilation at 1700  $\mu\text{mol}/\text{m}^2/\text{s}$  at different salinities for varieties N17, N22 and NCo376. Coefficients of determination ( $R^2$ ) and significance of correlations ( $^{\text{NS}}P>0.05$ ,  $*0.01<P<0.05$ ,  $**0.001<P<0.01$ ) are shown.**

Variety	EC (mS/m)	12-Feb-03	26-Feb-03	08-Apr-03	23-Apr-03
		Assimilation ( $\mu\text{mol}/\text{m}^2/\text{s}$ )			
N17	120	19.60	12.67	19.90	17.27
	340	14.70	20.40	6.16	14.27
	530	14.47	14.57	12.67	20.03
	840	10.25	13.98	12.93	13.23
$R^2$		0.42*	0.002 <sup>NS</sup>	0.05 <sup>NS</sup>	0.05 <sup>NS</sup>
N22	120	13.48	16.40	14.40	14.47
	340	12.42	18.27	15.87	18.67
	530	16.57	10.20	7.90	18.50
	840	12.07	14.50	10.24	15.03
$R^2$		0.002 <sup>NS</sup>	0.14 <sup>NS</sup>	0.30 <sup>NS</sup>	2e-05 <sup>NS</sup>
NCo376	120	18.30	15.69	12.36	20.70
	340	19.27	19.70	13.06	19.03
	530	20.53	15.84	8.69	21.23
	840	13.10	17.87	8.79	13.83
$R^2$		0.018 <sup>NS</sup>	0.004 <sup>NS</sup>	0.10 <sup>NS</sup>	0.25*

Plant water loss is regulated to a significant degree by stomata. A major factor affecting stomatal conductance ( $g_s$ ) is the leaf water potential ( $\psi_l$ ), which in turn is affected by the interaction of soil water potential ( $\psi_s$ ), evapo-transpirational demand and internal resistances (Davies *et al.*, 1981). The behaviour of stomata is tightly coupled to the processes of carbon assimilation and transpiration, which proceed at rates determined by weather and soil conditions. This coupling appears to be strongly interactive through feedback mechanisms that stabilise the carbon gain : water loss ratio and conserve water.

Stomatal conductance at 1700  $\mu\text{mol}/\text{m}^2/\text{s}$  ( $g_{s1700}$ ) also displayed a weak trend of decline with increasing salinity; almost all regressions carried out on the data were not significant and no obvious patterns of increase or decline were observed (Table 4). Reduced assimilation was not a function of reduced stomatal conductance, since neither showed significant effects of EC; however, since leaf area was reduced (Figure 10) by EC, the photosynthate produced was less at higher ECs, resulting in smaller plants.

In a review by Ishii (1998), it was noted that in only a few instances was a good correlation found between leaf photosynthesis and yield. The reason could be that there are many other factors limiting crop growth, such as sink capacity or leaf area, and photosynthesis per unit leaf area could be masked by these stronger limiting factors.

**Table 4. Average stomatal conductance at 1700  $\mu\text{mol}/\text{m}^2/\text{s}$  at different salinities for varieties N17, N22 and NCo376. Coefficients of determination ( $R^2$ ) and significance of correlations ( $^{\text{NS}}P>0.05$ ,  $*0.01<P<0.05$ ,  $**0.001<P<0.01$ ) are shown.**

Variety	EC (mS/m)	12-Feb-03	26-Feb-03	08-Apr-03	23-Apr-03
		Stomatal conductance ( $\text{mol}/\text{m}^2/\text{s}$ )			
N17	120	0.38	0.20	0.22	0.15
	340	0.19	0.37	0.09	0.14
	530	0.24	0.22	0.14	0.17
	840	0.17	0.26	0.12	0.11
$R^2$		0.32 <sup>NS</sup>	0.002 <sup>NS</sup>	0.28 <sup>NS</sup>	0.09 <sup>NS</sup>
N22	120	0.26	0.30	0.15	0.11
	340	0.16	0.25	0.21	0.15
	530	0.33	0.16	0.07	0.16
	840	0.23	0.20	0.12	0.11
$R^2$		0.002 <sup>NS</sup>	0.34*	0.12 <sup>NS</sup>	0.001 <sup>NS</sup>
NCo376	120	0.31	0.26	0.14	0.18
	340	0.28	0.30	0.19	0.15
	530	0.35	0.22	0.09	0.17
	840	0.19	0.28	0.08	0.11
$R^2$		0.16 <sup>NS</sup>	0.002 <sup>NS</sup>	0.27 <sup>NS</sup>	0.21 <sup>NS</sup>

Water stress can be defined as a reduction in plant  $\psi$  and/or water content to a point at which physiological function and cell metabolism are impaired (Berkowitz, 1998). However, this definition is rather limited in scope because water deficit effects on plant growth and development are dynamic. The severity, duration and timing (with regard to ontological development) of leaf  $\psi$  decline, as well as the stress pre-history and nutritional status of the plant, need to be taken into account before the deleterious effects that the imposed stress has on plant performance can be fully understood. Dehydration is clearly a primary trigger of the growth-damaging processes (Hale and Orcutt, 1987).

Mongelard (1971), quoted in a review by Rozeff (1995), stated that, "Water stress affects practically every aspect of plant growth - modifying the anatomy, morphology, physiology and biochemistry. Growth of a cell is primarily caused by an uptake of water filling the cell vacuole (increase in turgor), accompanied by a synthesis of new cell wall material. Cell enlargement is thus particularly dependent on at least a minimum degree of cell turgor, and stem elongation is quickly checked or stopped by water deficits... (then) loss of turgor, wilting, cessation of cell enlargement, closure of stomata, reduction in photosynthesis, and interference with many basic metabolic processes (occur)."

Leaf water potentials ( $\psi_1$ ), pre-dawn and midday, were measured between February and April 2003. A decline in  $\psi_1$  was expected with increasing salinity, and more marked effects were expected at the highest level of salinity (840 mS/m). It was also thought that the effects of salinity would increase with exposure time (i.e. the older the cane was, the longer it would have been treated with saline solutions, the effect of which would accumulate over time.

Pre-dawn leaf water potentials showed significant decline with increasing salinity on most of the dates measured (Table 5). Average minimum values of leaf water potential for N17 and N22 were -370 and -320 respectively, and these were obtained at 840 mS/m.

Trends of decline in midday leaf water potential with increasing salinity were observed on some occasions and this was consistent between varieties (Table 6). Leaf water potentials

were predictably lower on days of observed high evaporative demand and higher on days of low evaporative demand. Consequently, the trend of decreasing midday leaf water potential with increasing salinity was confounded by evaporative demand and was significant only on the last date of measurement, which was a cool, cloudy and windy day (low evaporative demand).

**Table 5. Average pre-dawn leaf water potential at different salinities for varieties N17, N22 and NCo376. Coefficients of determination ( $R^2$ ) and significance of correlations ( $^{NS}P>0.05$ ,  $*0.01<P<0.05$ ,  $**0.001<P<0.01$ ,  $***P<0.001$ ) are shown.**

Variety	EC (mS/m)	26-Feb-03	26-Mar-03	08-Apr-03
		Pre-dawn leaf water potential (kPa)		
N17	120	-167	-142	-125
	340	-200	-125	-117
	530	-267	-225	-167
	840	-317	-367	-167
$R^2$		0.89***	0.80***	0.08 <sup>NS</sup>
N22	120	-242	-150	-117
	340	-208	-142	-125
	530	-267	-217	-258
	840	-225	-317	-242
$R^2$		0.0002 <sup>NS</sup>	0.69***	0.44*
NCo376	120	-200	-183	-117
	340	-258	-100	-83
	530	-333	-242	-308
	840	-325	-350	-317
$R^2$		0.50*	0.56**	0.44*

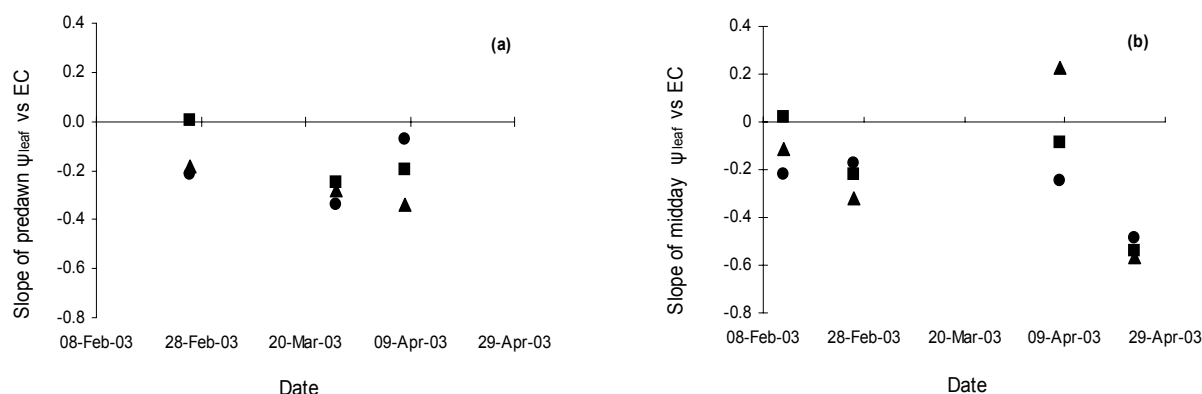
**Table 6. Average midday leaf water potential at different salinities for varieties N17, N22 and NCo376. Coefficients of determination ( $R^2$ ) and significance of correlations ( $^{NS}P>0.05$ ,  $*0.01<P<0.05$ ,  $**0.001<P<0.01$ ) are shown.**

Variety	EC (mS/m)	12-Feb-03	26-Feb-03	08-Apr-03	23-Apr-03
		Midday leaf water potential (kPa)			
N17	120	-1267	-1233	-917	-775
	340	-1225	-917	-1292	-867
	530	-1450	-1267	-1167	-967
	840	-1383	-1258	-1158	-1117
$R^2$		0.24 <sup>NS</sup>	0.06 <sup>NS</sup>	0.07 <sup>NS</sup>	0.54**
N22	120	-1350	-1108	-917	-700
	340	-1175	-858	-1233	-800
	530	-1300	-1233	-733	-1083
	840	-1292	-1167	-1108	-1050
$R^2$		0.002 <sup>NS</sup>	0.07 <sup>NS</sup>	0.01 <sup>NS</sup>	0.62**
NCo376	120	-1300	-1083	-1150	-700
	340	-1193	-975	-1208	-792
	530	-1433	-1267	-917	-1058
	840	-1325	-1250	-1042	-1075
$R^2$		0.07 <sup>NS</sup>	0.19 <sup>NS</sup>	0.05 <sup>NS</sup>	0.66**

On days of high evaporative demand (12 and 26 February 2003), leaf water potential did not go lower than a threshold value of approximately -1450 kPa; this implied some sort of stomatal control, where stomatal conductances are lower under conditions of high salinity and high evaporative demand to reduce transpiration-induced water stress. This contention is supported by stomatal conductance data (Table 4), where trends of decline in stomatal conductance with increasing salinity were observed; however, these trends were not significant. Further repeat measurements are required to assess this suggestion, since trends in this data set are not clear enough.

Unless complete osmotic adjustment has occurred, low leaf water potentials suggest the existence of low turgor potential in the cells of the leaves, which results in reduced cell expansion. This implies that leaves with low  $\psi_l$  will be smaller and may result in smaller plants. This suggestion is supported by the reduction in leaf area (Figure 10), and total above-ground biomass produced (Figure 1) as the salinity increased.

Figure 12 a and b were constructed to test the assumption that the effects of salinity on leaf water potential would increase with exposure time. It was thought that, as exposure time increased, the slopes relating leaf water potential to EC would get steeper, thus indicating possible accumulated damage.



**Figure 12. Comparison of slopes of predawn (a) and midday (b) leaf water potential over time. Varieties are denoted by ● N17, ■ N22, ▲ NCo376.**

However, no clear trends were observed with time (Figure 12). It was concluded that changing evaporative demand confounded the effects of salinity on midday leaf water potential because of the existence of a threshold value of midday leaf water potential on days of high evaporative demand, resulting in unclear treatment effects.

### Concluding comments

A general trend of decline in overall growth was observed with increasing salinity, with the occasional exception of cane grown at 340 mS/m sometimes displaying 'superior' growth compared with the control. This could possibly be due to solutions of 340 mS/m having a higher amount of calcium and magnesium than the 120 mS/m solution which contained only Hygrotech. Although growth did decline at 530 mS/m, 840 mS/m produced more pronounced negative effects.

In terms of overall growth and yield, at high salinity, the response to salinity of N17 was often similar to that of NCo376. Total above-ground biomass was significantly affected by increasing salinity; however, in parameters such as stalk length, leaf area and sucrose yield,

N17 often showed little response to salinity. Stalk population declined with increasing EC but stalk diameter and internode length increased substantially, and sucrose yield at 840 mS/m of N17 was similar to that of NCo376.

NCo376 had the highest total above-ground biomass and sucrose yield overall, this could be explained by a higher number of leaves and total leaf area per pot. However, at 840 mS/m, NCo376 showed marked decline in stalk fresh weight, and had the highest increase in sheath DM% at 840 mS/m. This suggested that the leaf sheaths of this variety did not respond well to water stress. However, since the sucrose yield was high even at high salinity, this could suggest that NCo376 allocated more resources to its stalks in times of stress. N22 showed the most sensitivity to salinity at 840 mS/m; this variety had shorter stalks, reduced leaf area and lower sucrose yield as result of high salinity.

Photosynthetic rate did not exhibit a direct, straightforward relationship to increasing salinity; however, a slight but non-significant increase in maximum photosynthetic rate was observed with increasing salinity. Leaf water potential declined with EC and there was evidence of some degree of stomatal control on days of high evaporative demand (i.e. combined effect of salt and water stress). This could have been the effect of mild water stress rather than a direct salinity effect.

The deleterious effects of salinity become more evident with each cane cycle. The expected loss in yield due to salinity and sodicity for the ratoon crop is estimated to be approximately two to four times higher than the plant crop. Further work could include comparing measurements between plant and ratoon cane, as well as varying the salts used to obtain the range of salinities while still excluding the variable of sodicity. There remains a need for a more complete data set from a range of situations to clarify differences between varieties, and a range of salinities. A more profitable approach to the problem addressed with this trial could be to select directly for sugar yield.

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