THE REACTION OF SUGARCANE TO WATER STRESS

by

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INTRODUCTION

Water stress is the single most important factor limiting crop yield and it has probably been investigated more intensively than any other factor that affects crop growth. Of the numerous books and review articles devoted to the subject since 1964 (Kozlowski, 1964; Knight, 1965; Slatyer, 1967; Kramer, 1969; Kozlowski, 1968 ., 1972, 1976; Hsiao, 1973; Begg and Turner, 1976; Turner and Kramer, 1980; Paleg and Aspinal, 1981; Teare and Peet, 1983) few refer to work on sugarcane. This is possibly because sugarcane is grown mainly in the tropics where water stress is not as important as in less humid climates which support the major grain crops and because the major centers of agricultural research are situated largely away from areas where sugarcane is grown.

Sugarcane is grown largely under rainfed conditions in South Africa and water stress occurs frequently in most areas particularly where soils are shallow. New genotypes that survive the five stage selection programme are usually those that endure water stress well. The lack of success with imported genotypes is probably due largely to their inability to cope with these relatively harsh conditions.

During the 1980/81 drought it was apparent that the most successful variety in the industry, NCo376 was the least resistant to prolonged drought although it had the reputation of being a hardy variety. An irrigation experiment during this period confirmed this reaction to water stress in NCo376 (Inman-Bamber, 1982). Three varieties were given 50 mm effective irrigation every 21 days either throughout the crop (W1), during summer only (W2) or during winter only (W3). Some plots were irrigated only when stalks started to die from stress (W4). The sucrose yields were as follows:

	Sucrose yield (t ha^{-1})		
Treatment	NCo376	N52/219	N11
W1	15.7	14.7	13.5
W2	15.3	14.1	12.9
W3	10.8	9.6	10.9
W4	5.1	6.2	9.3

The distinction was made between varieties such as NCo376 that coped with frequent short-lived stress periods that were prevalent in the W3 treatment and those such as N11 that coped relatively well with a period of stress lasting several months as in the W4 treatment.

Apart from the yield differences amongst commercial varieties of sugarcane in South Africa, little is known about the effect of water stress on growth processes or about the kind of adjustments that occur in other crops undergoing water stress (Moss, Woolley and Stone, 1974).

Wadsworth (1932) noted that the young spindle leaves of sugarcane continued to elongate when elongation of the topmost leaf sheath had ceased when soil moisture became limiting. Shaw (1937) compared sugarcane and sunflower in a drying soil and observed that cane did not exhibit external symptoms of wilt for several days after the "wilting point" had been reached thus differing from a range of crops that wilted at roughly the same soil water content (Briggs and Shantz, 1912). Wadsworth (1936) observed a reduction in stalk extension when soil water content was 27.4% and a cessation of extension when water content fell to 23.1% four days later. No wilting occurred during this stage. Since there was apparently no compensatory growth after the stressed plants were irrigated it was assumed that the loss in cane yield due to stress was unrecoverable. When irrigation was delayed for eight days each time soil moisture fell to 27.4% there was a significant reduction in cane yield but no reduction in sucrose yield (Swezey and Wadsworth, 1940). The sensitivity of leaf extension to water stress in sugarcane was demonstrated by Hudson (1968) who recorded leaf height continuously. Leaf growth stopped for most of the day even when transpiration was only 30% below potential. Plant extension rate (PER) fell below maximum when the root medium was drenched with a weak sucrose solution (-0.1 MPa) and PER ceased when a solution with an osmotic potential of -0.7 MPa was used as a drench. Growth rate between 21h00 and 06h00 was constant regardless of the water content of soil in which plants were potted. It was inferred from this that water potential in shoots, roots and soil became equal soon after transpiration ceased and that this property could easily be used to define the lower limit of available water in soils. This hypothesis was not tested in the field. Thompson and de Robillard (1968) measured extension rate of the topmost leaf collar of cane growing in drying soils under field conditions. Growth rate fell below maximum when 75% of the total available water (TAM) of a Clansthal sand had been used and when only 25% of the TAM of a Windermere clay had been used. These thresholds corresponded to soil matric potentials of -0.1 MPa and between -0.03 and -0.1 MPa in the sand and clay respectively using the moisture characteristics published by Johnston (1973).

The role of water in plant and leaf extension has been investigated in many other crops which unlike sugarcane do not necessarily require a large stalk mass to be economically profitable. A rapid increase in leaf area is normally associated with high yields regardless of which part of the plant is of value. The highest seed yields in sunflower subjected to water stress in a rainshelter was obtained from a variety that developed the highest leaf area after stress was relieved (Rawson and Turner, 1982). Leaf angle is likely to be important in sugarcane recovering from stress since the penetration of light into the canopy is increased by a more erect leaf arrangement and this will favour the recovery of small stalks (Rosario and Musgrave, 1974; MacColl, 1976).

It is now generally accepted that a reduction in cell growth is one of the earliest discernible effects of water stress. There are however conflicting reports about the relative sensitivity of the two components of cell growth ,cell division and cell enlargement (Begg, 1980). Green (1968) and Green and Cummins (1974) showed that the growth rate (G) of Nitella cells was found to be a simple function of turgor pressure (P) above a threshold pressure (Pt) and gross extensibility (E) of the cell wall, viz: G=E(P-Pt). Since turgor pressure may be regarded as the difference between total water potential and osmotic potential of the cell (ignoring matric and gravitational components), cell growth rate will be affected by changes in osmotic potential which may be fairly large. Evidence that osmotic potential in higher plants is reduced by water stress has been available for many years (Kreeb, 1963) but the significance of this has been realized only fairly recently (Turner and Begg, 1980). Low osmotic potential was however associated with drought resistance in sugarcane over 50 years ago (Harris and Lee, 1930).

Considerable evidence has accumulated recently showing that osmotic adjustment takes place in leaves, roots and reproductive organs of several plant species resulting in full or partial maintenance of turgor pressure as water stress increases (Turner and Begg, 1980). Water potential may decline as much as 2.3 MPa in wheat leaves without drop in turgor pressure (Munns et al, 1979). Varietal differences in osmotic adjustment have been sought in some crops sometimes without reward (Morgan, 1980). Most cases of osmotic adjustment have been fairly limited and readily reversed when water stress was removed (Turner and Burch, 1983). Nevertheless the importance of this adjustment to drought resistance is not in doubt. Michelena and Boyer, (1982) investigated osmotic adjustment and elongation rate of maize leaves in various water and light regimes. When a normal photoperiod was provided turgor was maintained at about 0.5 MPa as water potential decreased from -0.4 to -1.0 MPa. Turgor potential was reduced to about 0.3 MPa by water stress when leaves were darkened for 24h and to about 0.1 MPa when leaves were darkened for 48 hours. It thus appeared that current photosynthate was necessary for osmotic adjustment and turgor maintenance. The other noteworthy observation made during this experiment was that even when turgor pressure was adequately maintained during the development of water stress leaf elongation rate was reduced. The authors concluded that low leaf water potential may inhibit the growth of leaves for some reason other than the loss of turgor or the lack of substrate for growth.

Although the effect of leaf water potential on plant extension rate is not necessarily direct, a simple association between the two attributes of plant water status may be useful in estimating the reduction in growth rate due to stress either directly from leaf water potential (ψ_l) measurements or indirectly using canopy temperature as a measure of plant water status or ψ_l may be computed from von Honert's flow equations (Slatyer, 1967).

Plant extension rate reflects the rate of cell division and extension near the apical meristem and this rate determines the size of stalk which is one of the components of sucrose yield. The rate of leaf area expansion is also a function of the rates of cell division and extension and this may be of great significance in the recovery of sugarcane from water stress. The effect of water stress on plant extension may be different from its effect on stomatal resistance in sugarcane as in several crops (Hsiao, 1973). It is important to quantify these differences if the effects of stress on sucrose yield are to be understood or modeled.

Naidu and Bhagyalakshimi (1973) studied the relative turgidity and stomatal movement of four varieties of sugarcane during a drought. The relative turgidity of the two drought resistant varieties decreased rapidly to about 60 % of normal turgidity by the end of the drought and nearly 90 % of their stomata were closed after five days of drought. The drought susceptible varieties lost turgidity less rapidly and fewer stomata were closed after five days of drought and these varieties were thought to have been less able to conserve water than the drought resistant varieties. This confirmed the results of earlier experiments by Mallik (1946) reviewed by van Dillewijn (1952) which showed that a hardy and productive variety was able to reduce transpiration rate substantially in a dry atmosphere but this was not true of a less productive genotype. Other experiments reviewed by van Dillewijn (1952) indicated that drought resistant varieties transpired rapidly early in the morning and then almost stopped transpiring at midday whereas drought susceptible varieties continued to transpire throughout the day.

The adaptive significance of stomatal responses to water stress has been comprehensively reviewed by Ludlow (1980). Stomata of many species do not respond to water stress in the leaf until ψ_l falls to a relatively low value (threshold). Ludlow regarded the ψ_l at which leaf conductance, which is the inverse of leaf resistance, approached zero as a more significant adaptive feature than the threshold value. Crops that had their origins in arid climates tended to be those that closed their stomata at lower leaf water potentials than those that originated from wetter climates. Zerophytic crops displayed a greater degree of adjustment to repeated stress than mesophytes and in some grasses stomata closed fully only when ψ_l reached -5 MPa. As with cells extending in the apical region, the response of guard cells, which govern stomatal opening, to bulk leaf water potential depends on the change in osmotic potential within the vacuole. Local adjustments in the stomatal complex of ageing leaves of pearl millet were responsible for the uncoupling of stomatal movement with change in bulk leaf water potential (Henson, Alagarswamy, Mahalakshmi and Bidinger, 1983). Resistances of the younger and more exposed leaves of sugarcane are of greater significance than those of older leaves. Stomata of young leaves of sugarcane have wider apertures than these of older leaves (Kuijper as quoted by van Dillewijn, 1952) and the younger leaves are likely to be more responsive to water stress. The association between ψ_l and stomatal conductance was nevertheless considered to be direct enough to be of use in understanding the reaction of crops to water stress

The use of ψ_l to describe the extent to which plant extension and gas exchange are suppressed by water stress in a crop of sugarcane will allow comparisons with other crops to be made. Varieties of sugarcane may be compared on this basis and the association between ψ_l and growth and the resistance to gas exchange will be useful in the modelling of crop growth. However ψ_l is not likely to be measured by growers and it would be desirable to find a less laborious index of crop water stress that would provide either an estimate of ψ_l or more directly of plant extension rate and stomatal conductance or that would indicate directly the effect of the stress on sucrose yield.

Attention has been drawn to leaf or canopy temperatures as an index of water stress for many years but the interpretation of these temperatures have proved to be elusive (O'Toole and Real, 1986). The advent of the hand-held infra-red thermometer (Fuchs and Tanner, 1966) added considerably to the feasibility of canopy temperature (CT) as an index of crop water stress. Jackson

(1982) has reviewed the many publications on canopy or leaf temperature and plant water stress. Idso (1982) has developed empirical means of using CT to describe the degree of water stress in a number of crops. Several authors have related CT to leaf water potential (Ehrler, Idso, Jackson, and Reginato, 1978; O'Toole and Tomar, 1982; Sharratt, Reicosky, Idso and Baker, 1983). Jackson(1982) and O'Toole and Real (1986) have shown the association between CT and canopy resistance. Sugarcane has not been included in any of the investigations on CT and water stress. A study on water stress in sugarcane would not be complete without measurements on canopy temperature which has reliably indicated stress in other crops and is being used increasingly in research and farm practice (Anon, 1980).

Growth analysis experiments by Gosnell (1968) and Rostron (1972) provided data on the rate at which fresh and dry cane mass may be accumulated per hectare of cane land. There is however little data on the extent to which growth rates are restricted by water stress. It is also not known how rapidly growth rates recover after water stress is relieved or whether water stress has any permanent affect of the growth potential of the crop. This information is required to help growers decide what to do with crops affected by water stress and it is necessary for crop modelling exercises. Water use by irrigated sugarcane has been comprehensively reviewed by Thompson (1976). Water use and cane yield of crops under a wide range of conditions were highly correlated and a water use efficiency (WUE) of 0.097 t ha^{-1} mm^{-1} was obtained by regression. Teare and Peet (1983) reviewed some data on water use efficiency and values ranged from 0.169 t ha^{-1} mm^{-1} (Thompson, Pearson and Cleasby, 1963) to 0.074 t ha^{-1} mm^{-1} (Isobe, 1968). The factors responsible for these variations in WUE are not clear. These WUE values apply to the yield at harvesting and the total amount of water used between planting or ratooning and harvesting. Information on WUE over shorter periods is required for use in a crop model. In addition there appears to be no data available on the effect of water stress on WUE of sugarcane or on the change in WUE when stress is relieved.

Water stress effects cane growth and sucrose accumulation differently as previously suggested. Irrigation farmers are able to increase the sucrose content of fresh cane by withholding water for several weeks prior to harvesting. It is not always clear whether this result is achieved simply by increasing the dry matter content of the cane or by inducing a change in the distribution of assimilate (Bull and Glaziou, 1975). Hartt (1967) imposed water stress on cane stalks either by cutting the stalks at the base, by decreasing the osmotic potential of a nutrient solution or by withholding irrigation from a crop in the field. Water stress depressed the translocation rate of labelled CO_2 more than the rate of photosynthesis. The increase in sucrose content of the stalk due to water stress was thought to arise from a reduction in the hydrolysis of sucrose in transit to the site of storage. Wardlaw (1976) suggested that the reduction in translocation rate observed by Hartt may have resulted from the weakening demand for assimilate in the extensible region of stalk. Clements (1980) provided indirect evidence that water stress caused a net gain in dry mass at the base of cane stalks. Wardlaw (1969) showed that there was a small (12 %) but significant increase in the dry mass of the base of mature leaf sheaths of Lolium temulentum. Sucrose content of whole cane stalks usually decreases after water stress is relieved. There is little relevant information on whether this is due to the hydrolysis of sucrose in the fully extended portion of the stalk or whether the new growth following rain or irrigation decreases the sucrose content by 'dilution'.

The experiments described in the following sections endeavor to address some the deficiencies in our knowledge of the effects of water stress on the growth and sucrose accumulation of different varieties of sugarcane.

SECTION 1. POT EXPERIMENT ON DROUGHT REACTION OF TWO VARIETIES.

Chapter 1. METHODS

Objectives

1. To establish stress thresholds based on total leaf water potential for a) plant extension rate b) start of stomatal closure c) end of stomatal closure d) leaf rolling e) leaf and f) stalk senescence.

2. To investigate the nature of hardening by water stress in regard to adjustments in leaf area and leaf osmotic potential.

3. To determine the effect of water stress on a) water use b) stalk growth rate and c) water use efficiency.

4. To investigate the extent to which varieties may differ in a) thresholds to water stress b) hardening and c) water use efficiency.

Treatments

1. Varieties

At least two varieties differing in reaction to drought were required. N11 proved to be considerably more resistant to drought than other varieties in an irrigation experiment at Pongola in the northern part of the sugar industry (Inman-Bamber, 1982) and was chosen as the representative of drought resistant genotypes. NCo376 which was thought to be intolerant of prolonged drought and was also the most well researched variety, represented the drought susceptible genotypes. N11 which is a cross between CB40/35 and NCo293 has a lower stalk population than NCo376 and its leaves are distinctly broader and less erect than those of NCo376. NCo376 is a cross between Co421 and Co312.

2. Water regime

In order to achieve the above objectives it was necessary to subject plants to two or more cycles of at least one degree of water stress. The most severe stress that could be applied without killing stalks was to allow all but three leaves to die. A more moderate form of stress was to allow plants to wilt until the three oldest green leaves started to change colour just before starting to senesce. These criteria were used to define a 'moderate' (W2) and a 'severe' (W3) form of water stress. The difference between W2 and W3 treatments was not only in the degree of water stress. After the first stress cycle, W2 plants became stressed more rapidly than W3 plants because of the substantial residual effect of the W3 treatment on leaf area. Non-stressed plants (W1) were kept free of water stress.

Water was withheld from W2 and W3 plants on and between the following dates:

Stress period	W2	W3
1	19-28 August	19 Aug.-8 Sept.
2	1- 6 October	1-13 October
3	10-14 November	10-22 November
4	15-21 December	15-31 December

Water was applied to unstressed plants (W1) and to W2 and W3 plants before and after stress periods, in the following manner:

The soil surface of each bin was sealed with paraffin wax shortly before withholding water for the first time. Water was applied through a 50 mm pipe inserted to a depth of 300 mm. The water holding capacity of the soil was determined by allowing covered bins to drain for 24 hours and then weighing them. Water was applied to bins each day until their mass was 90 % of the mass after drainage.

Experimental procedure

Ten drainage holes 8 mm in diameter were made in the base of each of 40 PVC bins which were 620 mm high and 410 mm in diameter. The mass of each bin was made up to 9.5 kg by adding quarry stones and then 7.0 kg builders sand was added to facilitate drainage. The bins were then painted silver to reflect radiation. The A-horizon of a Bonheim series clay (dark blocky non- swelling mollisol) was selected for its high retention of water. The soil was sterilized with methyl bromide and sieved through a 20 mm mesh. Each bin received 70 kg of this soil which contained 183 ml l^{-1} water. The soil was consolidated to a bulk density of 1.0 kg l^{-1} by placing the bins on a vibrating table until the surface had subsided to a predetermined level.

Single budded setts of two varieties NCo376 and N11 were allowed to germinate in vermiculite under a polyethylene sheet and eight germinated setts of each variety were transplanted into each of 20 bins so that when four setts were removed two weeks later the remaining setts were equidistant. Sett roots were easily removed at this stage without disturbing the remaining plants. Tillers were removed whenever they emerged thus allowing only the four primary shoots in each bin to develop.

Table 1. Schedule of operations for establishing, treating and measuring potted sugarcane plants. Numerals demarcate stress cycles 1 to 4.

Date		Operation	Date		Operation
22 MAR		Setts in vermiculite	20 OCT		Pressure/volume anal.
30 MAR		Transplant to bins	24 OCT		Harvested measured in periods 1 and 2
2 APR		1 g N per bin			
13 APR		Thinned to 4 shoots	2 NOV		Pressure/volume anal.
2 JUN		0.5 g N per bin	5 NOV		Total leaf area
6 AUG		Pressure/volume anal.	10 NOV	3	Stopped water to W2,W3
8 AUG		Total leaf area	15 NOV	3	Predawn ψ_l
16 AUG		Sealed soil with wax	15 NOV	3	Resumed water to W2
18 AUG		Started daily readings	19 NOV	3	Pressure/volume anal.
19 AUG	1	Stopped water to W2,W3	23 NOV	3	Resumed water to W2
30 AUG	1	Measure over 24 hours	10 DEC		Harvested measured in period 1 and 2
1 SEP	1	Resumed water to W2			
8 SEP	1	Resumed water to W3	14 DEC		Total leaf area
10 SEP		Total leaf area	15 DEC	4	Stopped water to W2,W3
12 SEP		Pressure/volume anal.	22 DEC	4	Pre-dawn ψ_l
13 SEP		1 g N, 1 g K per bin	22 DEC	4	Resumed water to W2
1 OCT	2	Stopped water to W2,W3	28 DEC	4	Pressure/volume anal.
7 OCT	2	Pre-dawn ψ_l	31 DEC	4	Final harvest
7 OCT	2	Resumed water to W2			
12 OCT	2	Pressure/volume anal.			
14 OCT	2	Resumed water to W3			

The soil contained adequate amounts of P, K, Ca and Mg (80, 393, 1800, and 220 ppm respectively). Nitrogen and potassium were added in the amounts and on the dates given in Table 1. Phosphorous was determined by a modified Troug method (one part soil to 50 parts 0.2 normal sulphuric acid) and the bases (K, Ca, and Mg) were extracted in 1 normal ammonium acetate (one part soil to 10 parts extractant).

The bins were placed outside on trolleys mounted on rails aligned in a north-south direction and were wheeled into polyethylene shelters situated at the southern end of the track (Fig. 1) whenever rain was imminent. Climatic conditions were monitored at a meteorological station situated 500 m from the rails and are shown in Fig. 2. Six bins of each variety were treated in the same way, but only two of these were measured during any one stress period. Previously unmeasured plants replaced those which had been measured during the first two stress cycles and 'fresh' plants in turn replaced these before the final period of stress. Thus measurements were made on eight plants of each variety in each of the water regimes and the means of eight plants are presented in the results.

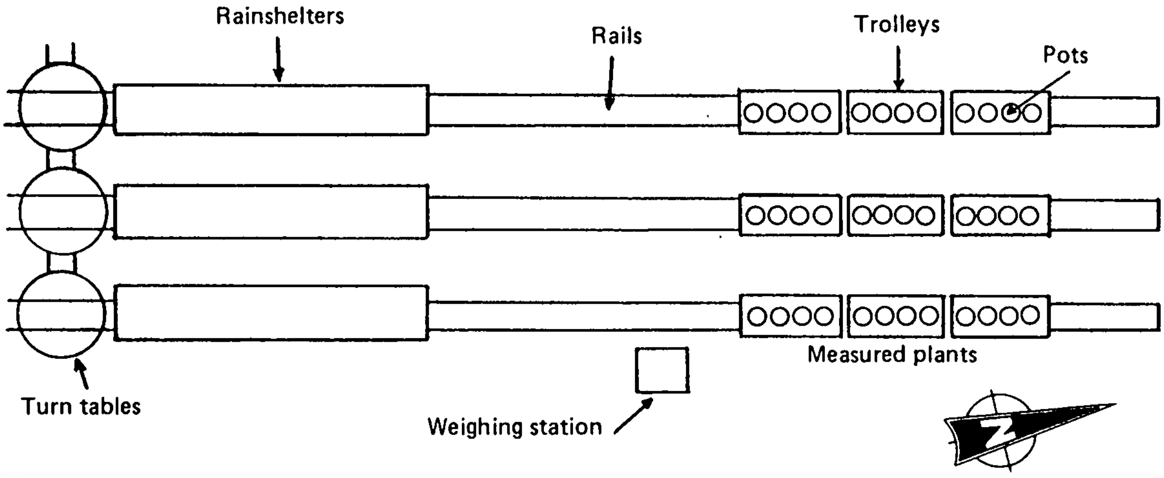

Figure 1. Arrangement of pots, trolleys, rails, rainshelters and weighing station for pot experiment.

Measurements

1. Growth analysis

The mass of stalks prior to each stress period was estimated from the number of internodes that had formed and the mass of each of these internodes at the time of harvesting. Eight stalks per treatment were harvested after each stress period except the first (Table 1). Total leaf area per plant was measured with a Licor 3000 leaf area meter before each stress cycle (Table 1).

The area of expanding leaves (1 to 3) was measured every other day and the area of dead leaf tissue was estimated every day during and after stress periods in order to obtain a daily estimate of total leaf area.

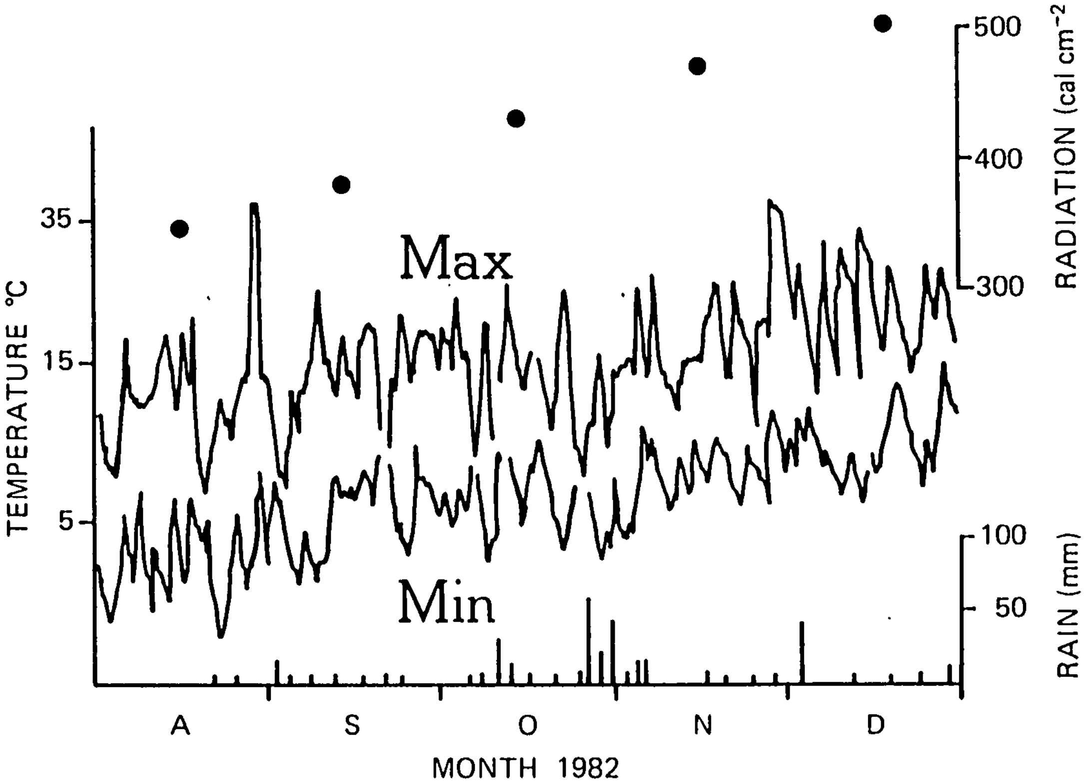

Figure 2. Daily rainfall, maximum and minimum temperature and monthly mean daily radiation at Mount Edgecombe during the experiment.

2. Plant stress

Measurements of the state of stress in plants were made frequently during and after the periods of stress. Plant extension rate was recorded daily by noting the height of two unfolding leaves per plant above a marker fastened to the shoot. A Delta-T MK 3 diffusive resistance meter (Stiles, Monteith and Bull, 1970) was used approximately every day between 11h00 and 12h00 to measure resistance to gaseous diffusion (r_s) of water vapour through the abaxial surface of the three youngest unfurled leaves. Calibration of the porometer is described in appendix 1. The total water potential (ψ_l) of these leaves was measured between 12h00 and 13h00 after completing the r_s readings. Leaf segments about 150 mm long and 8 mm wide were stripped off the blades taking care not to tear across the vascular bundles and were placed immediately into humidified polyethylene sheaths and then into the pressure chamber. Bungs made from a two part rubber compound were slit to hold the leaf segments and seal them in the chamber. The removal of these strips reduced leaf area to small extent (less than 3 %). Rolling of the three youngest leaves was recorded after completing ψ_l readings. Scores of 1 to 5 were used to denote unrolled to fully rolled leaves. A mean score of 4.2 was associated with a 50 % reduction in leaf width.

3. Water use

A bed of rollers was mounted on a hydraulic jack and was raised to lift a pot from the trolley along roller conveyers to the balance (Fig. 3). The roller system was designed to cause minimal disturbance to the rooting mediuim. Pots were weighed daily to the nearest 0.01 kg. The balance was sufficiently sensitive to detect dewfall. Weighing was done between 0800 and 0900 hours when dew was minimal and wind was normally light. Evaporation was prevented by the wax seal and daily changes in pot mass were attributed to transpiration. Drainage did not occur. Daily increments in plant mass were ignored.

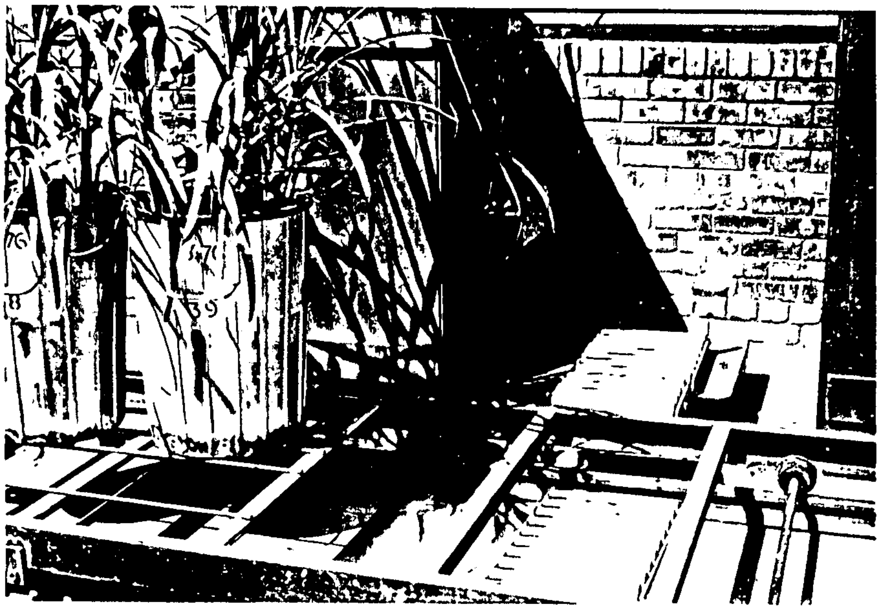

Figure 3. Roller conveyers for transferring pots from trolleys to balance housed in a small shed.

4. Osmotic potential (π)

A lowering of the osmotic potential (π) in response to water stress can arise from the passive concentration of osmotic solutes as water is withdrawn from the vacuole and the cell volume decreases or additionally from the active accumulation of solutes in the cell. Osmotic adjustment refers to active accumulation of solutes in response to water stress and this is reflected by changes in π of leaves which have been allowed to regain full turgor. The total water potential of a fully turgid leaf will be zero.

Strips of leaf lamina 8 to 10 mm wide and 200 to 300 mm long were collected in the field at 0800 hours on the dates given in Table 1 and were placed immediately in contact with water in a container. They were floated on a water surface for at least four hours before the first strips were removed for analysis. A pressure volume technique similar to that of Wenkert (1980) and Richardson and McKell (1980) was followed. Leaf segments were dried with absorbent tissue paper and immediately weighed to the nearest 0.1 mg. Total leaf water potential (ψ_l) was measured immediately after weighing but was always above the upper limit (-0.05 MPa) of the pressure gauge attached to the Scholander pressure chamber. Apart from periodic checks to ensure that leaves were fully rehydrated this step was omitted after the first sampling occasion. One segment from each treatment was weighed and then allowed to dry until ψ_l fell below -1.3 MPa at which point turgor was presumed to be close to zero. This stage was assessed readily after gaining some experience. When sufficiently dry, segments were weighed again and then immediately placed in the pressure chamber. Chamber pressure was increased at approximately 0.05 MPa s^{-1} until xylem water reached the cut surface. The pressure was recorded and was then slowly reduced. The segment was weighed again immediately after being removed from the chamber. The masses before and after measuring water potential were meaned to estimate the mass of the segment at the time ψ_l was recorded. Four to six pairs of mass and ψ_l values were obtained as segments dried. A linear function was fitted by least squares to a plot of inverse ψ_l versus relative water content (RWC) and the inverse of the intercept was taken to be π at full turgor. RWC was as given by Barrs (1968) namely, (current fresh mass - dry mass)/(fresh mass at full turgor-dry mass).

Chapter 2 RESULTS AND DISCUSSION

Plant water relations

1. Diurnal changes in water stress

When measurements were made repeatedly over a 24 hour period, plants had been without water for 13 days and became severely stressed as air temperature rose to a maximum of 36°C. Leaf resistance rose during the evening of the 30th August as stomata closed (Fig. 4). At dawn r_s was low in all treatments and it then increased rapidly in stressed plants reaching a maximum at approximately 1400 hours. There was little change in r_s of unstressed plants during the day. Leaf water potential decreased overnight reaching minimum values just before dawn by which time the water potential in leaves, roots and in soil was likely to be in equilibrium. Soil water potential was thus approaching -1.5 MPa (permanent wilting point) in pots of N11 but was some way from this point in plots of NCo376. ψ_l of stressed plants decreased during the morning of the 31st August and remained low during the afternoon. ψ_l of unstressed plants decreased to about -0.8 MPa at midday. Transpiration rates (E) of stressed plants rose to approximately 10 g shoot^{-1} h^{-1} at 0800 hours and remained at this level until late afternoon. Transpiration rates of W1 plants increased rapidly reaching a maximum of approximately 65 g shoot^{-1} h^{-1} in NCo376 and 78 g shoot^{-1} h^{-1} in N11. W1 plants extended at about 1 mm h^{-1} during the night and at rate of up to 3 mm h^{-1} during the day (Fig. 4, W1). PER appeared to decrease at midday when E and ψ_l were maximum. PER of stressed plants had ceased two days before the overnight measurements were taken.

These results confirmed the need to measure the attributes at the same time each day in order to make valid comparisons. The difference in the response of plant extension and stomatal movement to water stress was evident in that stomata of stressed plants appeared to

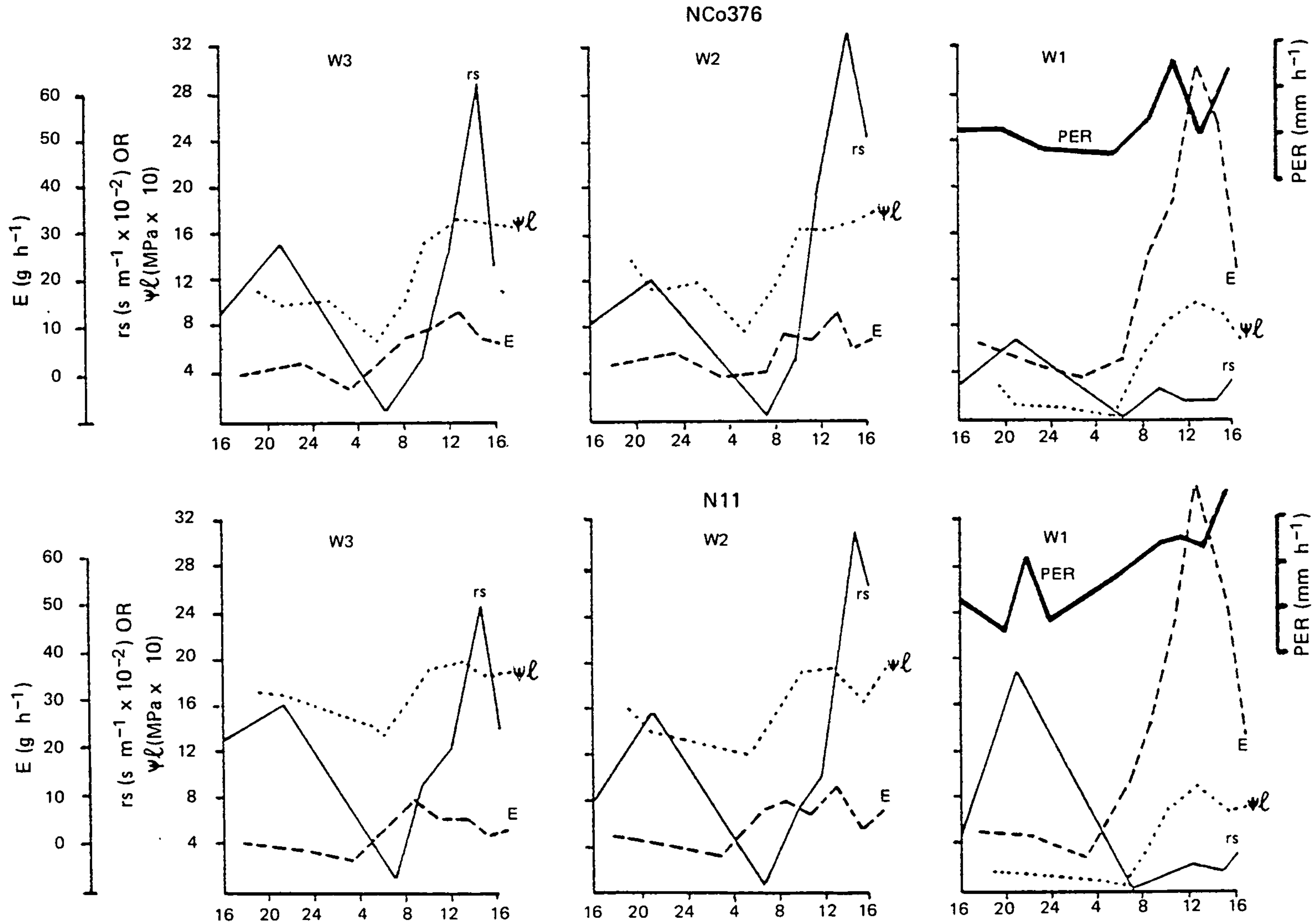

Figure 4. Temporal changes in stomatal resistance (r_s), leaf water potential (ψ_ℓ), transpiration rate per shoot (E) and plant extension rate (PER) in two varieties of sugarcane on the 30/31 August when W2 and W3 pots had not been watered for 13 days.

recover fully overnight and then close completely during the day but there was no recovery of PER until water was once again applied. The relationship between E and r_s appeared to follow van den Honert's flow equations in which water flow through each zone in soil-plant-atmosphere system is proportional to the water potential difference and inversely proportional to the resistance across each zone (Slatyer, 1967). The difference between water potential in the leaf and the partial pressure of water vapour in the atmosphere, increased as r_s increased during the day so maintaining E at a fairly constant, albeit reduced, rate.

2. Pre-dawn leaf water potential

The pre-dawn ψ_l values of eight W3 plants of both varieties in all three measurement occasions were compared with the ψ_l values obtained later in the day. The midday ψ_l ranged from -0.9 to -2.3 MPa. Pre-dawn and midday ψ_l were highly correlated (r=0.94) and pre-dawn ψ_l was estimated from the following regression equation.

Pre-dawn ψ_l = (Midday ψ_l x 1.44) - 1.22
SE of one estimate = 0.16 MPa
n = 48

3. Plant extension rate (PER).

PER of stressed plants relative to PER of W1 plants began to decrease six days after water was withheld for the first time and it reached zero after 10 days (Fig. 5). The rate of recovery was as least as rapid as the rate of decline above. PER returned to normal within three or four days after re-watering. In subsequent cycles recovery was usually complete within two days. PER of stressed plants recovering from stress was substantially higher than that of plants which had not been stressed thus compensating to some extent for the reduction in plant extension during stress. Compensatory growth of this nature has been recorded in maize (Acevedo, Hsiao and Henderson, 1971) and rye (Green and Cummins, 1974). Green (1968) working with Nitella cells showed that compensatory growth resulted from an increase in osmotic poential and in gross extensibility of the cell wall.

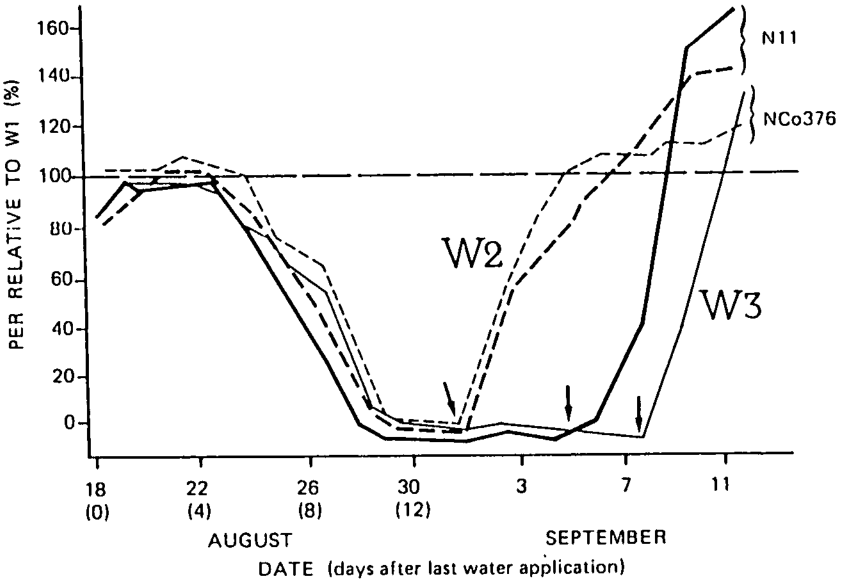

Figure 5. Plant extension rate (PER) of stressed plants (W2 broken line, W3 solid line) as a percentage of PER of unstressed plants (W1) during the first stress period (NCo376 fine, N11 bold). Arrows indicate when watering commenced.

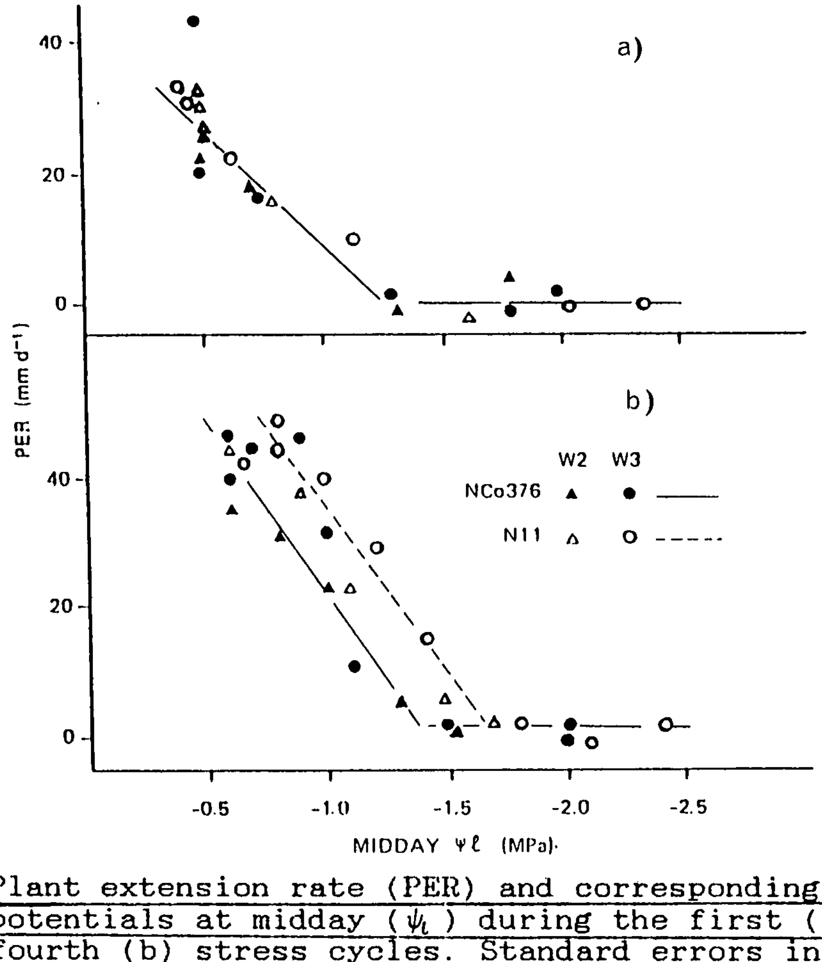

Figure 6. Plant extension rate (PER) and corresponding leaf water potentials at midday (ψ_l) during the first (a) and fourth (b) stress cycles. Standard errors in measurements were smaller than the symbols.

Plants extended about 40 mm per day when midday ψ_l was about -0.5 MPa but extension rates decreased when ψ_l fell below this value (Fig. 6, lines fitted by eye). No extension was observed when ψ_l fell to -1.3 MPa during the first stress cycle. The threshold ψ_l for plant extension was slightly lower in subsequent stress periods (-1.5 MPa) and it tended to be lower for N11 (-1.7 MPa) than for NCo376 (-1.5 MPa) during the fourth period. There was no difference between moderately and severely stressed plants regarding PER and leaf water potential. Growth would have ceased earlier each day as plants dried out (Van Dillewijn, 1952) and would have occurred last just before dawn when ψ_l for the day was minimum. Pre-dawn ψ_l at this stage estimated from the equation above was between -0.7 and -0.9 MPa. Sugarcane appears to be similar to maize (-0.7 MPa), less sensitive than sunflower(-0.4 MPa) and more sensitive than soybean(-1.2 MPa) in this regard (Boyer, 1968 and 1970 ; Acevedo _et al_, 1971).

4. _Stomatal resistance_

Stomatal resistance rose above a minimum value of about 200 s m^{-1} as midday water potential fell below about -0.8 MPa during the first stress period and below about -1.0 MPa during the final stress period (Fig. 7) whereas stomatal resistance in many crops appears not to be affected by internal water deficit until ψ_l falls below approximately -1.2 MPa (Hsiao, 1973; Jarvis, 1980). Resistances in field grown cotton increased only after ψ_l had fallen to -2.0 MPa (McMichael and Hesketh, 1982). Stomatal resistance of W2 plants tended to increase more rapidly once ψ_l had fallen below a threshold value of -1.0 MPa in the fourth period of stress. This was probably due to the more rapid imposition of stress in W2 plants than in W3 plants in which leaf area had been substantially reduced during previous stress periods. The change in leaf resistance with ψ_l depended on the rate at which stress was imposed in _Hydropogon contortus_ (Ludlow, 1981) and in pearl millet (Henson _et al_ , 1983). This was ascribed to a greater degree of osmotic adjustment (_H. contortus_) and a lower rate of abscisic acid accumulation (millet) in the more gradually stressed plants.

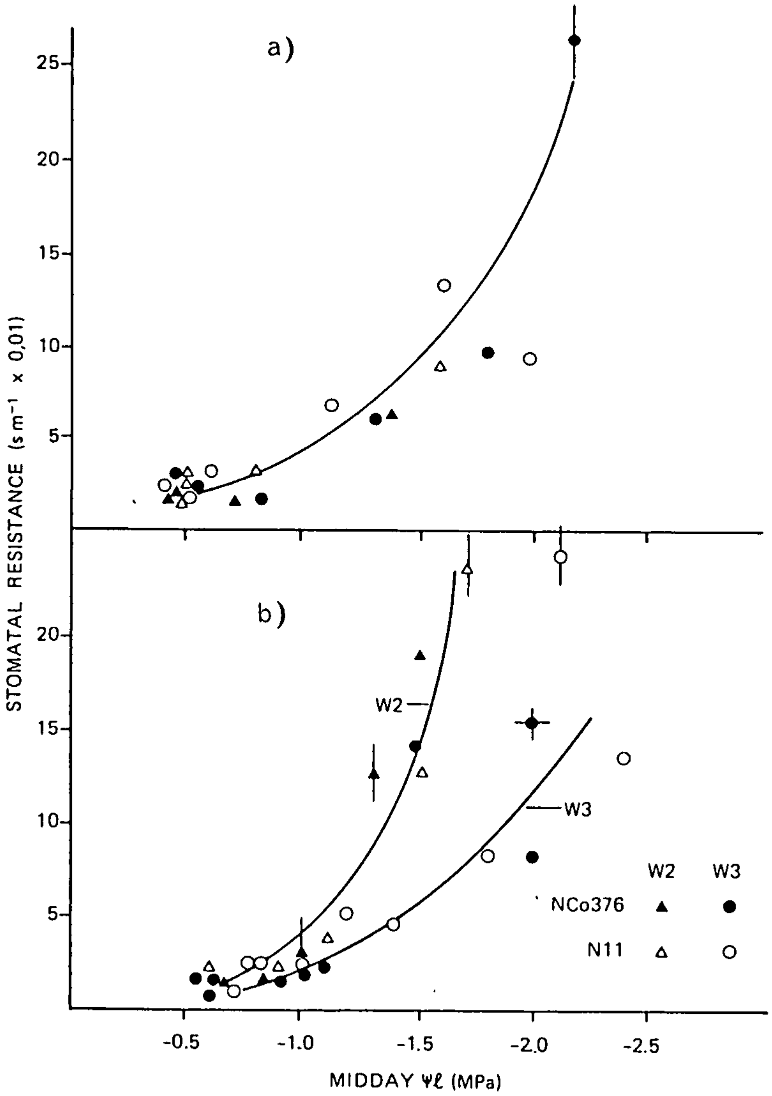

Figure 7. Stomatal resistance and corresponding leaf water potentials at midday (ψ_l) during the first (a) and fourth (b) stress cycles. Bars denote standard errors where these are larger than the symbols.

5. Stomatal conductance

Stomatal conductance (r_s^{-1}) approached a minimum value of 1.0 mm s^{-1} when ψ_l fell to -1.5 MPa during the first stress period. The minimum conductances (0.5 mm s^{-1}) observed during the fourth stress cycle occurred when midday ψ_l was about -1.3 MPa in W2 plants and about -1.7 MPa in W3 plants (Fig. 8). Sugarcane appears to be comparable with maize in this regard as well. Conductances tended to zero when ψ_l was about -1.1 MPa in potted maize plants (Beadle et al, 1973) and about -1.8 MPa in field grown maize (Turner, 1974).

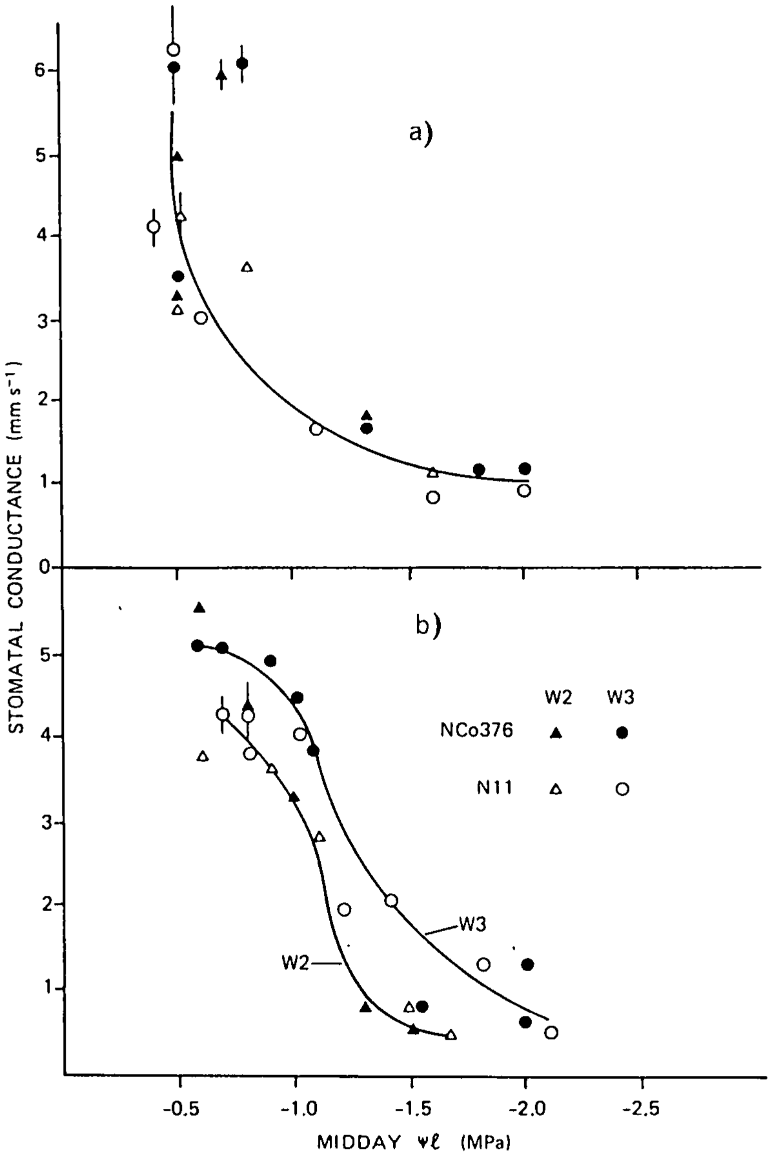

Figure 8. Stomatal conductance and corresponding leaf water potentials at midday (ψ_l) during the first (a) and fourth (b) stress cycles. Bars denote standard errors where these are larger than the symbols.

6. Leaf rolling

Rolling scores of the youngest unfurled leaf of NCo376 and of N11 were similarly related to ψ_l in all stress cycles. When leaf rolling scores of W3 plants in all stress periods were grouped together (Fig. 9) it was evident that rolling was first detected when midday ψ_l fell below about -0.8 MPa and leaves were fully rolled when midday ψ_l reached about -2.0 MPa. The width of leaves at their widest point was determined when rolling was scored during the third stress cycle. The rolling index which is the ratio of the projected leaf width to its maximum width was linearly related to rolling score in the following way :

ROLLING INDEX = 1,1 - 0.14 x ROLLING SCORE
SE of one estimate = 0.13

The rolling index of sorghum leaves declined rapidly only when leaf water potential fell below about -1.2 MPa and changed little when ψ_l fell below -2.0 MPa. (Begg, 1980). Sugarcane leaves behaved more like leaves of rice which started rolling when ψ_l was -0.8 to -1.0 MPa and were fully rolled when ψ_l was -2.0 to -2.5 MPa (O'Toole and Cruz, 1980).

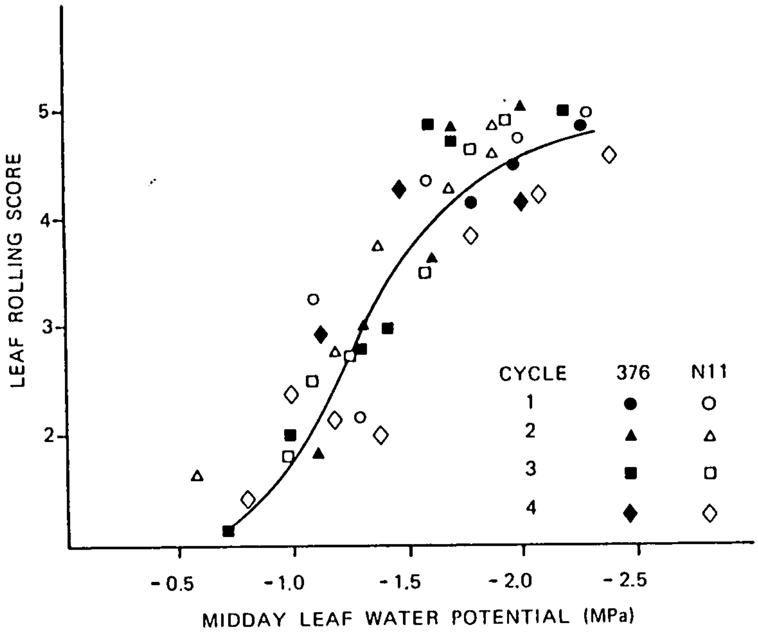

Figure 9. Rolling score (1=none, 5=fully rolled) of the youngest unfurled leaf of W3 plants and corresponding leaf water potentials at midday (ψ_l) during all stress cycles.

7. Leaf area

In the first period of stress the green leaf area of W2 and W3 plants decreased rapidly 11 days after water was withheld (Fig. 10). Green leaf area was reduced first by rolling then by necrosis of the leaf margins and tips and then by the premature senescence of older leaves. The green leaf area of W2 plants had recovered somewhat two days after they were re-watered but recovery in W3 plants was evident after about five days. N11 tended to lose green leaf area more rapidly than did NCo376 in all stress periods. Minimum leaf areas recorded just before re-watering were often lower in N11 than in NCo376 (Table 2). However the rate of recovery in leaf area after stress, was greater for N11 than for NCo376. N11 therefore supported a higher leaf area than did NCo376 prior to each stress period. The leaf area of unstressed N11 plants tended to be greater than that of unstressed plants of NCo376.

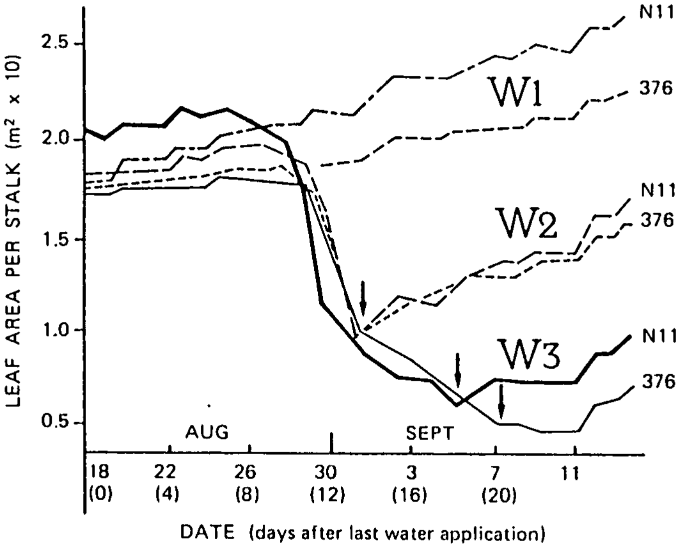

Figure 10. Leaf area per stalk during the first stress cycle. Arrows indicate when watering recommenced.

Table 2. Green leaf area (m^2) of stalks of two sugarcane varieties before (Bef) being subjected to four periods of moderate (W2) or severe (W3) water stress. W1 plants were not stressed. Minimum leaf area (Min) during stress is given for stressed plants.

Stress cycle	NCo376					N11				
	W1	W2		W3		W1	W2		W3	
	Bef	Bef	Min	Bef	Min	Bef	Bef	Min	Bef	Min
1	.17	.17	.09	.17	.04	.18	.18	.10	.19	.06
2	.24	.20	.14	.11	.05	.26	.21	.07	.17	.07
3	.28	.19	.15	.12	.01	.30	.24	.08	.17	.01
4	.24	.15	.15	.09	.07	.24	.23	.16	.14	.05

Green leaf area was reduced when midday ψ_l fell below about -1.0 MPa in NCo376 and below -1.2 MPa in N11 during the first stress period (Fig. 11). The reduced leaf areas recorded during subsequent stress periods were maintained at ψ_l values as low as -1.5 MPa in NCo376 and -1.7 MPa in N11. The apical meristem of sugarcane seldom recovers if less than three leaves are alive when stress is relieved. If the lines fitted by eye to the data in Fig. 12 are extrapolated, it is evident that all leaves but two would have died if ψ_l of these leaves had fallen to about -2.8 MPa. This degree of stress may be regarded as the maximum that could be tolerated by the apical meristem of stalks of NCo376 and N11 growing in these conditions. It should be noted that in sugarcane the life of the plant may be prolonged in the form of axillary buds above or below the ground and the death of the whole plant (stool) would occur only when all such buds are killed by prolonged stress of this nature.

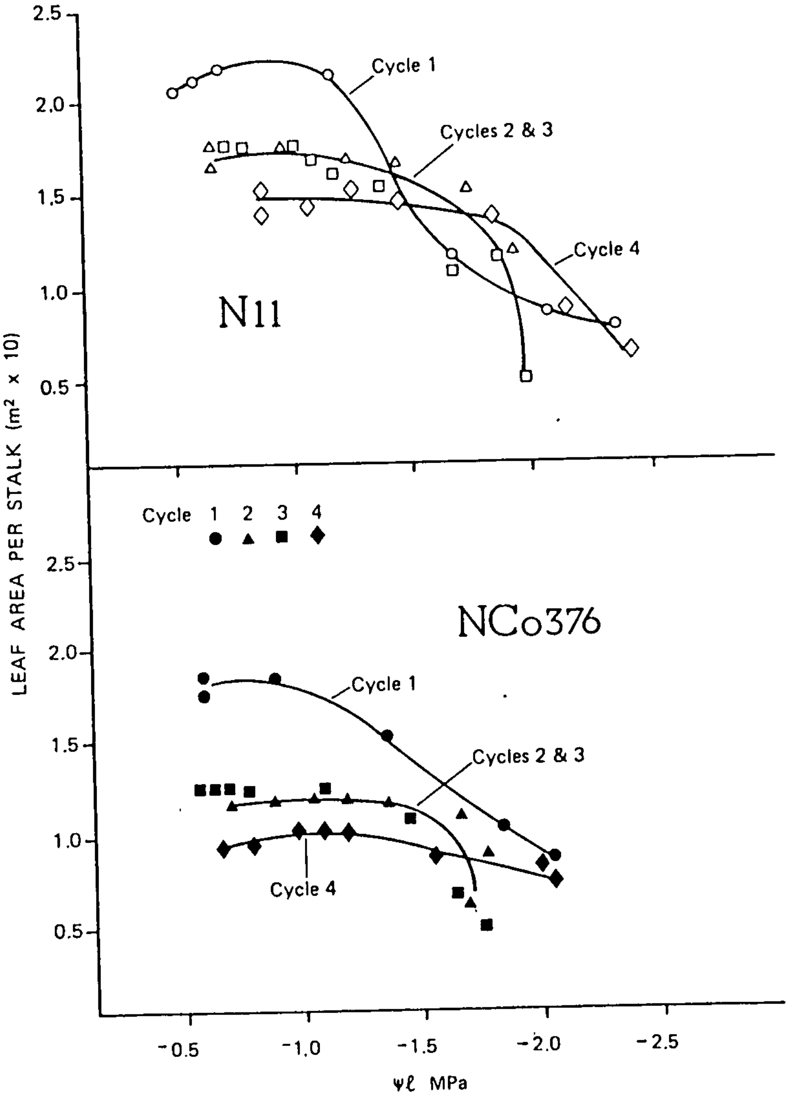

Figure 11. Leaf area per stalk and corresponding midday leaf water potential of W3 plants during four stress cycles.

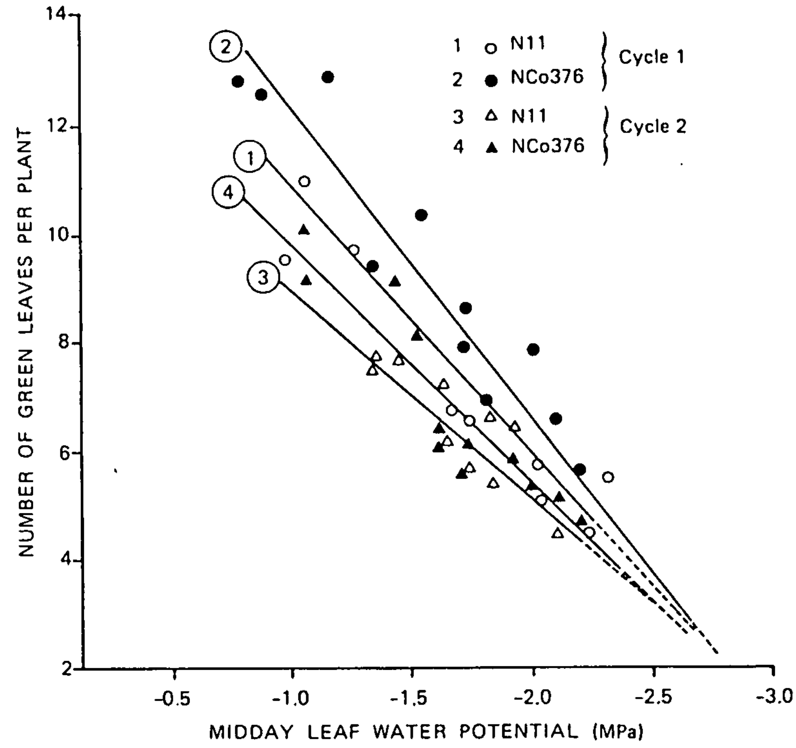

Figure 12. Number of green leaves per stalk and corresponding midday leaf water potential of W3 plants during four stress cycles.

9. Osmotic potential

There was no indication that osmotic potential (π.) differed between the varieties and data for varieties was pooled in Table 3. π decreased steadily during the experiment in stressed and unstressed plants alike. Similarly, a decrease of 0.5 MPa in π. occurred in unstressed soybeans between 45 and 85 days after emergence (Zur et al, 1981). Osmotic potential appeared not to remain low after sugarcane had been relieved of stress but it was apparently reduced in plants under going severe stress for the fourth time possibly resulting in threshold ψ_l values for plant extension, stomatal closure and reduction in leaf area being lower in the last than in the first stress cycle .

Table 3. Osmotic potential (π) at full turgor of unstressed plants (W1), plants enduring (e) moderate stress (W2) or severe stress (W3) or plants recovering (r) from stress during four stress cycles (C). n=number of determinations, SE= standard error of the mean.

Date	C	State of stress	W1			W2			W3		
			π	n	SE	π	n	SE	π	n	SE
6 AUG	1	None	-0.92	16	0.02	-	-	-	-	-	-
12 OCT	2	W2(r),W3(e)	-0.98	4	0.02	-0.88	4	0.02	-1.01	2	-
2 Nov	2	W2 & W3(r)	-1.05	4	0.02	-1.06	3	0.06	-1.00	4	0.08
22 Nov	3	W2(r),W3(e)	-1.18	13	0.04	-1.23	9	0.06	-1.12	11	0.04
28 DEC	4	W3e	-1.27	4	0.08	-	-	-	-1.45	6	0.05

Growth rate and water use

1. Growth rate

The fresh mass of stalks that were measured during the third stress period did not correspond well with that of stalks that were measured during the first two stress periods. The agreement between fresh mass of stalks at the end of the third and start of the fourth stress periods was good (Fig. 13). The relatively short periods of severe water stress reduced fresh stalk mass markedly in all stress cycles. Mild stress affected fresh stalk mass of NCo376 in all stress periods but reduced stalk mass of N11 in the first two periods only. Stalks of NCo376 were generally heavier than those of N11.

2. Water use efficiency (WUE)

The total amount of water used by each of six pots during each stress cycle was related to the increment in stalk mass over the same period (Table 4). The mass of cane produced per unit water transpired (WUE) is analogous to the transpiration efficiency (TE) which refers to total dry matter rather than fresh mass. The variation between pots was sometimes large particularly where stress was severe and water use and stalk growth were comparatively small. The mean WUE of NCo376 was apparently not affected by water stress. WUE of moderately stress N11 was significantly greater than that of unstressed N11 plants. It is possible that growth of W1 plants was restricted by anaerobic conditions that

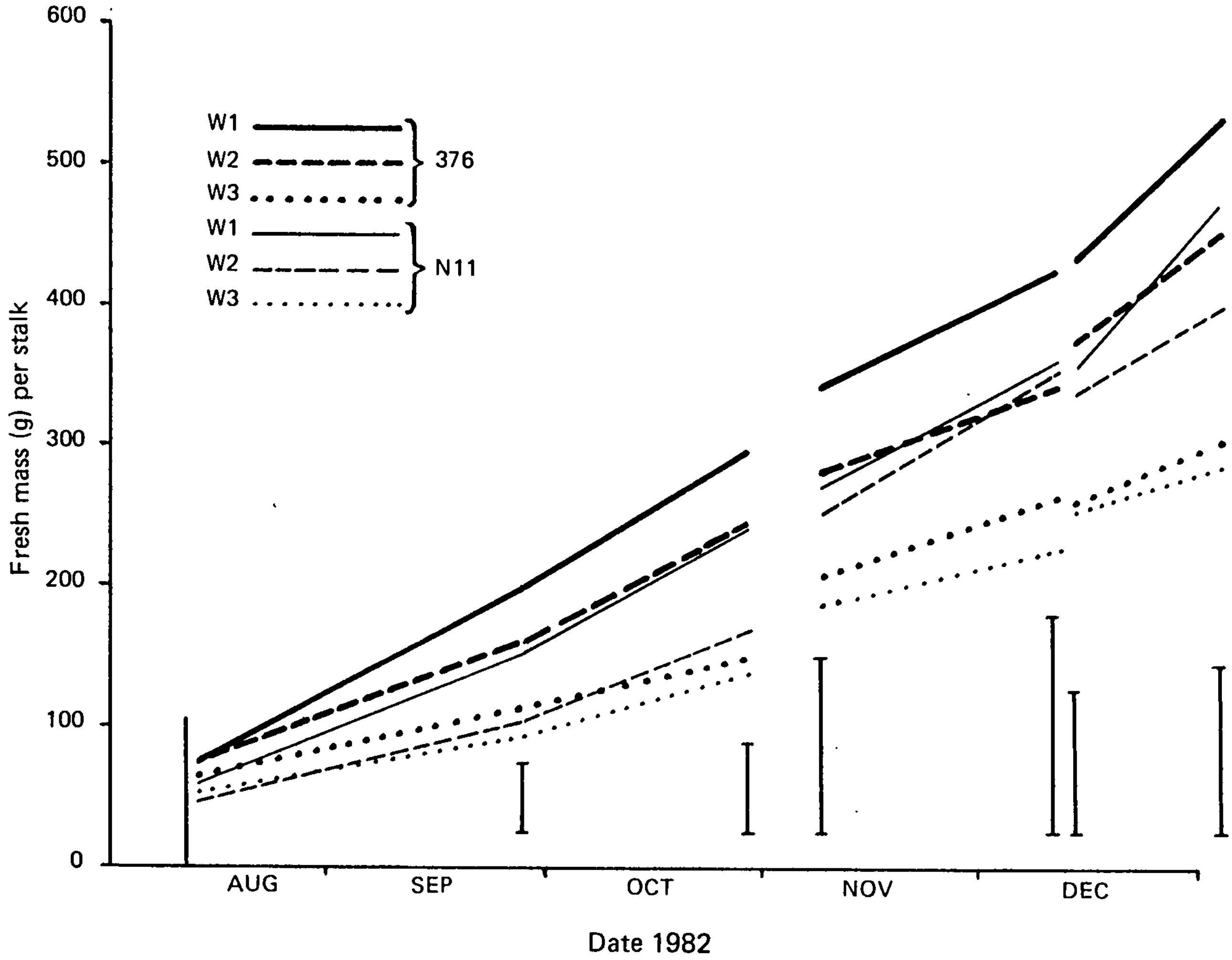

Figure 13. Stalk mass of unstressed (W1), moderately stressed (W2) or severely stressed (W3) sugarcane plants. Bars indicate least significant differences ($p=0.05$)

may have occurred in the confined and sealed rooting medium. Nevertheless, the similarity in WUE between moderately and severely stressed plants indicated that WUE of sugarcane is not markedly affected by large differences in the water regime. This result is in agreement with those of other experiments although the comparison is not strictly valid because fresh mass was measured in this experiment. Rawson (1979) demonstrated a small increase in TE when sunflower was allowed to wilt and Jones and Rawson (1979) found that TE was reduced slightly when sorghum was stressed slowly. A reduction in water supply to wheat reduced transpiration by 70% and increased TE by 20% (Gifford, 1979). The mean WUE data in Table 4 may be compared with the WUE of well irrigated crops of sugarcane (Thompson, 1976) which used 100 mm water for transpiration and evaporation for every 9.7 tons of cane produced per hectare (equivalent to 9.7 g kg^{-1}).

Table 4. Fresh mass (g) of stalk produced per kg water used by sugarcane plants growing in two pots (A and B) and subjected to four cycles of moderate (W2) or severe (W3) water stress or not stressed at all (W1).

	NCo376						N11					
	W1		W2		W3		W1		W2		W3	
	A	B	A	B	A	B	A	B	A	B	A	B
1	8.1	8.8	9.4	9.3	12.2	8.5	6.1	4.3	6.0	8.8	7.6	7.4
2	7.0	8.1	11.6	11.1	10.1	6.9	6.8	4.2	11.8	9.4	6.8	9.4
3	7.6	7.0	6.7	10.9	13.2	9.8	6.9	6.9	11.2	15.2	12.6	11.9
4	10.8	10.3	12.4	10.1	8.7	4.8	11.5	11.0	8.4	10.4	4.8	4.9
Mean	8.4		8.9		8.0		6.5		10.2		8.2	
SE	0.5		1.3		1.7		1.2		1.0		1.0	

Conclusions

In this preliminary investigation using potted sugarcane plants,the following sequence of events was apparent as midday leaf water potential decreased. Plant extension rate was reduced and the youngest unfurled leaves began to roll at -0.8 MPa, stomatal resistance started to rise at -0.8 to -1.0 MPa, green leaf area was reduced at -1.0 to -1.7 MPa, plant extension rate ceased and stomatal conductance reached a minimum at -1.3 to -1.7 MPa), youngest unfurled leaves became fully rolled at -2.0 MPa and the number of living leaves per stalk was reduced to two at -2.8 MPa, at which stage stalk death would eventually occur.

Osmotic potential decreased with age regardless of stress treatment. Osmotic adjustment took place during stress but was readily reversed and plants were not thereby pre-conditioned for subsequent periods of stress.

Plants were pre-conditioned by a delay in the recovery of leaf area after stress resulting in reduced transpiration rates during subsequent stress.

N11 appeared to be better adapted to water stress than NCo376 in that it could adjust its leaf area more rapidly and it tended to elongate at a slightly lower leaf water potential than NCo376.

This concurs with the results of field trials in which N11 produced higher sucrose yields than NCo376 in dry conditions but not under irrigation.

Water stress did not have a measurable affect on the amount of fresh cane mass produced per unit of water transpired.

SECTION 2 FIELD EXPERIMENT USING A MOVABLE RAINSHELTER

Chapter 3 METHODS

OBJECTIVES

1. To measure the effect of water stress on plant extension rate, stomatal resistance, leaf rolling, leaf senescence and osmotic potential in sugarcane in the field.

2. To investigate the degree to which varieties may differ in regard to these effects.

3. To investigate hardening in field grown sugarcane by water stress.

4. To confirm threshold leaf water potentials for plant extension, initial and final stomatal closure, and leaf rolling.

5. To measure the effect of water stress on crop growth rate, water use and water use efficiency.

6. To assess the use of leaf water potential, leaf rolling, canopy temperature and a crop water stress index based on canopy temperature, as indications of the level of stress in a crop of sugarcane.

7. To measure the effect of water stress on dry matter, sucrose and nitrogen accumulation in the stalk.

8. To measure the changes in these components after release from water stress.

Treatments

1. Varieties

At least two varieties varying in reaction to drought were required in order to achieve these objectives. It was also necessary that these varieties be of practical importance. N11 was shown by field experimentation to be considerably more drought resistant than NCo376 (Inman-Bamber, 1982) and was thus suitable for use in the pot experiment. Before the field experiment was established it became evident that N12 was one of the most resistant of varieties to drought and that it was imbued with other characteristics that would ensure substantial commercial use (Inman-Bamber, 1985). NCo376 was required as a standard and as a variety of intermediate drought resistance. N14 proved to be highly susceptible to drought in an irrigation experiment (Inman-Bamber, 1985) and being a highly productive variety under irrigation was likely to become important commercially. The three varieties selected for the field trial were thus:

1,NCo376	(Co421 x Co312)	, released in 1955.
2.N12	(NCo376 x Co331)	, released in 1979.
3.N14	(N7 x "melting pot")	, released in 1980.

2. Irrigation

It was necessary to compare unstressed plants with those plants that had endured at least two periods of severe water stress. The most severe stress that could be tolerated without loss of mature stalks was identified by the number of green leaves per stalk. Stalks with three green leaves were likely to recover from stress but not those with only two green leaves.

W1. The unstressed control plants were irrigated when 30 to 40 mm of the 230 mm available water was depleted. This occurred at approximately seven day intervals.

W2. In the plant crop, irrigation applied as for W1 was suspended on the 31st January, 1985 when the crop was five months old. These plants did not reach the desired degree of stress before the the scheduled harvest date and a second period of stress could not be imposed. In the ratoon crop amounts of irrigation were limited to 30 mm to prevent roots from gaining access to water that may have been stored deep in the profile as had apparently occurred in the plant crop. Irrigation was suspended on the 30th November 1984 and plants became stressed to the desired extent by the 22nd January when irrigation was again resumed. Irrigation was again suspended on the 28th February and subsequently resumed on the 23rd April 1985.

Experimental site

Table 5. Chemical and physical properties of soil of the experimental site. LS=loamy sand, SCL=sandy clay loam.

Depth	pH	P	K	Ca	Mg	Na	Clay	Silt	Sand	(%)	Text
(cm)		<-----------		ppm		---------->	%	%	Fine	Med.	-ure
5	8.30	80	112	1800	50	20	6	6	22	64	LS
15	8.40	80	105	1800	47	9	8	6	22	64	LS
25	8.40	80	94	1800	47	11	8	7	20	65	LS
35	8.40	80	83	1800	37	13	10	6	22	62	LS
45	8.40	49	70	1337	26	11	10	4	22	64	LS
55	8.40	43	60	941	24	15	8	6	20	66	LS
65	8.35	30	58	687	23	12	8	5	24	63	LS
75	8.20	25	53	525	20	14	10	5	22	63	LS
85	8.00	29	56	511	21	12	12	5	23	60	LS
95	8.00	25	60	535	24	16	15	4	20	61	LS
105	7.95	30	58	586	28	16	16	3	20	61	LS
115	8.00	28	55	668	30	25	18	6	19	57	LS
125	8.00	32	57	704	32	22	16	8	19	57	SCL
135	8.00	38	63	731	33	16	22	7	17	54	SCL
145	7.90	36	69	778	42	16	21	10	16	53	SCL
155	7.90	33	73	828	43	18	22	11	15	52	SCL
170	7.90	46	74	800	48	18	28	9	15	48	SCL
190	7.75	22	83	907	70	25	32	5	14	49	SCL
210	7.65	12	87	956	118	27	30	6	15	49	SCL
230	7.80	7	98	842	167	-	30	5	15	50	SCL
250	7.35	8	102	772	190	-	30	2	16	52	SCL
270	7.20	6	111	602	214	-	30	2	16	52	SCL
290	7.05	6	125	451	182	-	28	4	16	52	SCL

The requirements of the experimental site were that it should be nearly level, be protected from strong southerly winds, be close to supplies of electricity and water and free of lateral surface or sub-surface water flow. A swelling and shrinking soil was to be avoided. A site on a loamy sand (Clansthal series of the Hutton form) at the Central Field Station (CFS) near Umhlanga Rocks met all these requirements. The physical and chemical properties of the soil are shown in Table 5. Clay % represents the fraction less than 0.002 mm, silt % the 0.002 to 0.02 mm fraction and sand the 0.02 to 2.0 mm fraction.

Rainshelter

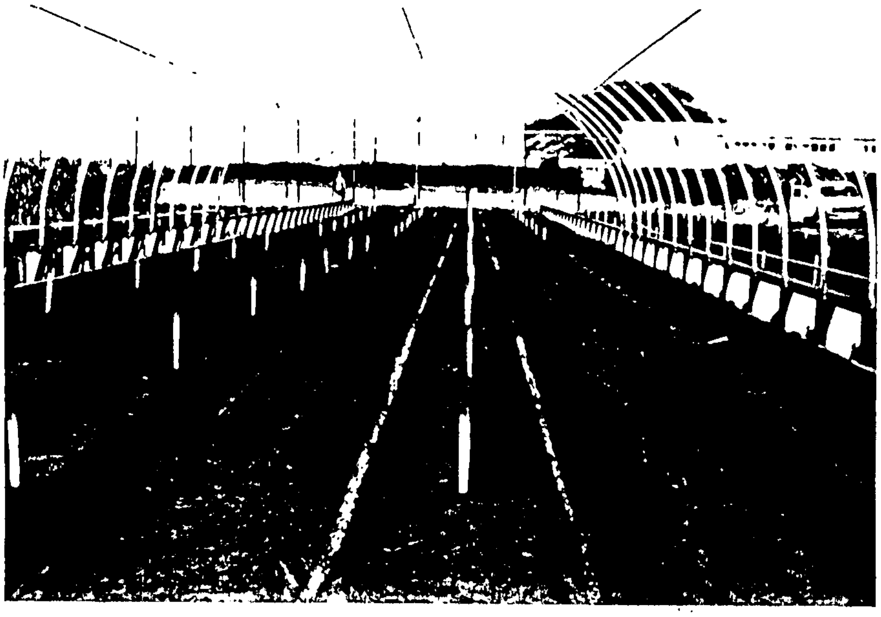

Figure 14. Tubular rainshelter frame mounted on rails before 'Uvidek' sheet was attached. Furrows ready for planting.

The super-structure of the rainshelter was kindly loaned by the Natal Region of the Department Agriculture. It consisted of dome shaped ribs of 50 mm galvanized tubing spaced at 1.5 m apart (Fig. 14). At the base of each rib was a grooved wheel which ran on angle iron welded to the lower flange of channel iron rails mounted 600mm above the ground on concrete pillars spaced 1.6 m apart. The rails were 8.5 m apart. A 12v winch fastened to a concrete block at the east end of the rails drove two chain sprockets at either end of a shaft. Each sprocket engaged a chain which pulled the shelter eastwards along the rails and westwards by means of cable which ran over a lay pulley at the west end of the rail. The successful operation of the shelter was partly due to the location of chain and cable which were directly in line with the wheels. (The shelter had previously been moved by a winch fixed to the apex of the two central ribs, which moved along a stationary chain. The two sides of the shelter were therefore not forced to move simultaneously and the wheels would sometimes jam.)

Rain water falling on a sensor mounted above the shed, housing a 12v battery and switch gear, completed a circuit and so activated the winch. The circuit broke when the sensor dried and started a timing device which activated the winch in reverse when the set time expired. Experience showed that a delay of 30 minutes was sufficient to prevent unnecessary movement of the shelter on days when rain was intermittent. A small 12v globe underneath the sensor prevented dew from activating the winch. Limit switches mounted on the rails stopped the winch when the shelter was in the correct position over the test area or in its standby position. The 12v battery was charged continuously.

A single 30x10 m transparent polyethylene sheet manufactured for resistance to ultraviolet light (Uvidek) was fastened to the tubular frame of the rainshelter. The ends of the rainshelter were closed with a Uvidek sheet which was rolled up as the crop grew taller. The crop and sheet effectively excluded rain. The area covered by the rainshelter was 24x8.5 m. Rain water falling on the shelter was directed away from the trial area by concrete gutters. In the ratoon crop trenches were dug between the second and third crop row away from the gutters. These were lined with polyethylene sheeting which was extended to form an apron 1.5 m wide next to the rails. This was done to keep soil alongside the shelter as dry as possible. The apron had little effect on cane growth. The shelter failed to close once during each crop but less than 5 mm of rain reached the soil on each occasion.

Layout

Fig. 15 shows the layout to scale. Plots were 3.7x4.16 m in size. Sixteen plots (W2) were located within the sheltered area and eight plots (W1) with these dimensions were positioned on each side of the shelter. The plots adjacent to the sheltered area were the W1 plots in the plant crop but in the ratoon crop, W1 was applied to the plots located alongside the shelter in its standby position so that roots of stressed plants inside the shelter would not have access to irrigated soil.

Four blocks of three plots each were demarcated in the sheltered area and in the area outside the shelter. The three varieties were allocated randomly to the three plots within each block. The net area (2.0x2.08 m) on which all growth measurements were taken was demarcated with string.

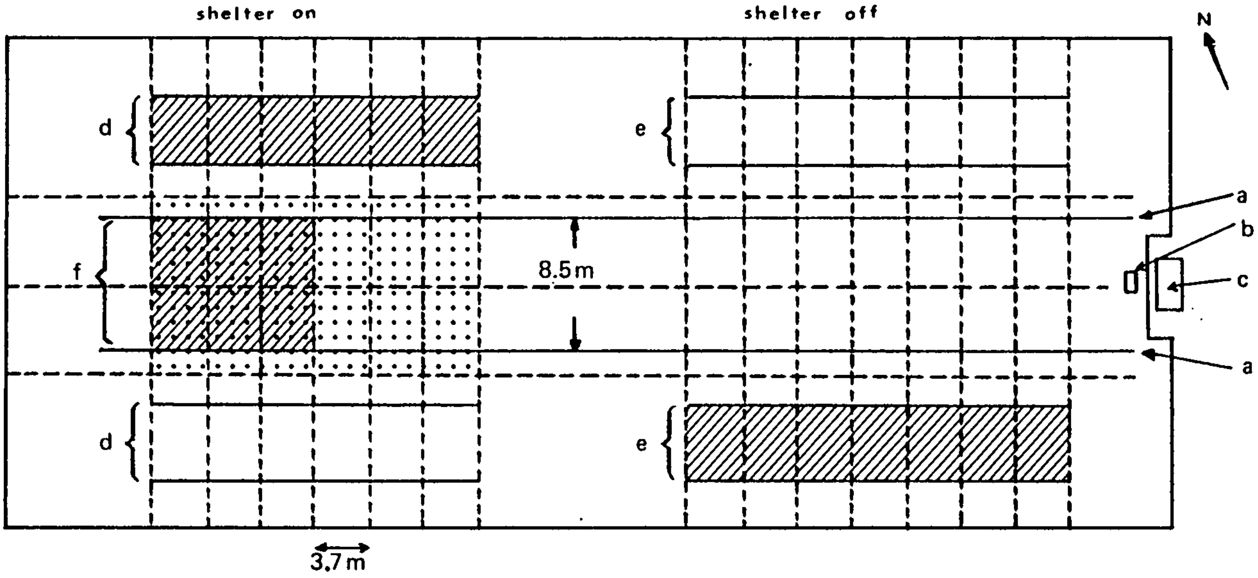

Figure 15. Plan of rainshelter experiment showing positions of a) rails, b) winch, c) shed, housing switch gear, d) W1 plots during plant crop, e) W1 plots during ratoon crop, f) W2 plots, ▨ plots used for destructive samplings, □ plots in which stalks were marked for repetitive growth measurements, ░ sheltered area.

Cultural practices

The plant and ratoon crops were established and harvested in the following sequence.

1983-1984	Plant crop.
18 August	EPTC applied and incorporated, levelled soil surface.
30 August	Applied basal fertilizer and nematicide and planted.
6 September	Levelled soil surface again.
11 November	N and K fertilizer applied.
8 May	Harvested plots under and alongside shelter in 'off' position.
5 July	Harvested remaining area and cut regrowth on area harvested in May. Crop residue removed.
1984-1985	Ratoon crop.
4 September	N, K and Fe Fertilizer and nematicide applied.
13 June	Ratoon crop harvested.

1. Irrigation

Potable water was obtained from a nearby municipal reservoir and fed by gravitation to a trickle irrigation system employing in-line emitters, rated at $4\ l\ h^{-1}$ and spaced 300 mm apart in 10 mm tubing. The tubes were placed 300 mm apart in line with the crop row thus providing nine emitters per square meter thereby ensuring an even distribution of water. The system was operated well below the 100 kPa pressure specified by the manufactures of the emitters but the uniformity in emission rate was satisfactory. The coefficients of variation in the emission rate of three sets of 12 emitters at extreme positions in relation to the water source, were 7.7, 8.6 and 4.4 % respectively.

2. Fertilizers

The equivalent of 400 kg ammoniated superphosphate ha^{-1} containing 3.8 % N and 12.2 % P was placed in furrows before planting. The plant crop was top dressed with 400 kg ammonium sulphate ha^{-1} (21% N) and 300 KCl on the 11th November. The ratoon crop was top-dressed with 147 kg N and 125 kg K per hectare on 4th September 1984. The soil contained adequate phosphorus for cane growth but high soil pH resulted in Fe deficiency in the early stages of the ratoon. This was corrected with an application of a 2 % solution of $FeSO_4$.

3. Nematode control

Aldicarb at 3 kg ha^{-1} was applied to furrows when the crop was planted and again when the ratoon crop was top dressed. Certain nematodes species sometimes damage cane crops in this type of soil.

4. Weed control

The site which had been fallow for several months was sprayed with glyphosate in July 1983 to kill weeds that were present. The equivalent of 4 l EPTC ha^{-1} was applied on the 18th August and incorporated immediately with a rotary power harrow. The ratoon crop was weeded by hand where necessary.

5. Planting

The site was levelled with a tractor and blade. Furrows were drawn by tractor and ridger on the 30th August in a soil which had been moistened with 7 mm of overnight rain. Centers of furrows were spaced 1.04 m apart by guiding the tractor along a carefully placed length of string. Stalks of the varieties NCo376, N12 and N14 was were cut from a seed nursery on the 30th August and were then cut into three budded setts. These were dipped in a suspension of 10 g l^{-1} benomyl and 1 g l^{-1} malathion and placed in pairs in the base of each furrow. The seed was covered by hand and the site was again levelled and consolidated with an iron bar to obtain a surface from which soil depth could be measured accurately and which could not be unduly disturbed.

6. Ratoon management.

When it started to hinder the movement of the shelter in May, the plant crop on the eastern half of the site, under and alongside the shelter in the 'off' position, was harvested. The crop on the western portion was harvested in July and the moderate amount of regrowth that developed on the eastern portion between May and July was cut at the same time to allow both portions to regenerate together. The cutting of the regrowth appeared to encourage tillering. Stalk number and leaf canopy of the crop on the eastern portion increased more rapidly than those of the crop on the western portion which included the new W1 plots for the ratoon crop (Fig. 15). The regrowth and the residue (trash) of the plant crop were removed by hand in July 1984.

Measurements

Measurements made on the plant and ratoon crops were similar but results from the plant crop in which the desired degree of stress was not obtained, were used only to confirm the conclusions reached during the ratoon crop. Descriptions of measurements refer mainly to the ratoon crop.

1. Climate

Data from a meteorological station situated at the Experiment Station of the South African Sugar Association approximately 2 km from the experimental site was available. A few meteorological instruments were erected on a fallow land 50 m away from the site to check the relevance of the Experiment Station data (Fig. 16).

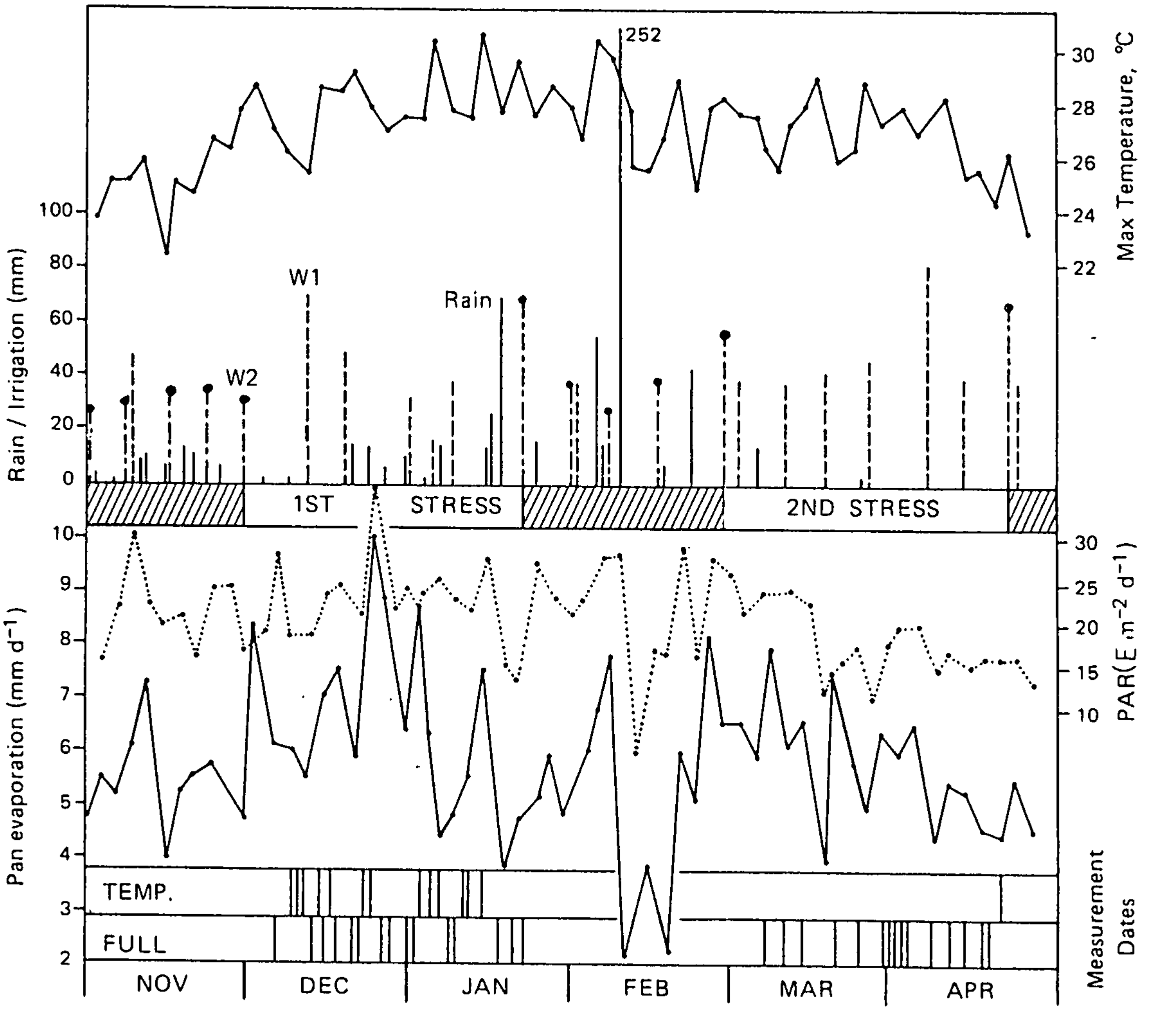

Figure 16. Rainfall, irrigation and three day means of maximum temperature, photosynthetically active radiation (PAR), and pan evaporation at the rainshelter sight. Dates of the first and second stress periods and of plant stress measurements. Canopy temperature was measured more frequently than other stress indicators.

2. Plant water relations

The following measurements were made on W1 and W2 plants of each variety between 1100 and 1500 hours on the days shown in Fig. 16. A rotation amongst like treated plots was followed. These measurements were also repeated several times during the day and night on the 21st/22nd December, 17th/18th January and the 1st/2nd April. One plot of each variety and each treatment was measured on each occasion except in the case of canopy temperature which was obtained from two plots of each variety and treatment.

a) **Osmotic potential**: Osmotic potential (π) at full turgor was obtained on the following dates using the pressure/volume technique described in the pot experiment:

1st November 1984
7th December 1984
21st December 1984
17th January 1985
12th March 1985
3rd April 1985
20th April 1985
13th May 1985

b) **Total leaf water potential** (ψ_l): The ψ_l of 10 leaves per treatment in the plant crop and 6 to 8 leaves in the ratoon crop was determined between 12h00 and 13h00 hours. A portion of the third leaf was covered with wet cloth, cut from the margin to the midrib, stripped from the remainder of the leaf and placed in Scholander pressure chamber. (This method differed from that used in the pot experiment where leaf segments may have dried slightly before being enclosed in watertight sheaths). The pressure from a compressed air cylinder that was required to return water in the xylem to the cut end of the leaf segment which protruded through a hard rubber seal, was recorded as total leaf water potential.

c) **Leaf resistance**: Resistance to gaseous diffusion of the abaxial surface of leaves 2, 3 or 4 was measured between 1100 and 1200 hours with the Delta T Mk3 dynamic porometer that was used in the pot experiment. Ten sunlit leaves were measured in the plant crop and 12 were measured in the ratoon crop. Micro- amperage from a point quantum sensor attached to the porometer hand-piece was recorded.

d) **Plant extension rate** (PER): This was obtained by measuring the height of the spindle leaf above a marker fastened to the non-growing portion of the stalk before and after the other readings were taken, covering a period of approximately four hours. Six stalks per treatment were measured in this way.

e) Canopy temperature (Tc): This was measured with a Teletemp Ag-42 infra-red thermometer (IRT). The instrument was checked periodically against the black body reference plate and was accurate to 0.5 °C. It had a resolution of 0.1°C. The IRT was held about 0.5 m above the canopy at an angle of about 30° above the western horizon in line with the crop rows which ran from east to west. Readings of each of two rows were obtained over periods of up to 60 s depending on how the wind affected the fluctuation in Tc. Air temperature (Ta) was measured in the Stevenson screen nearby. Temperature of the air above the canopy was used as the reference temperature at first but this was about 3 °C higher above dry than above irrigated plots probably because with stress, less radiant energy was used in evapotranspiration and more energy was dissipated as sensible heat. The Tc-Ta values given in the results are means of up to 32 readings per treatment.

3. Soil water content

a) Neutron probe: A "Campbell 503 hydroprobe" was used to measure soil water in the field experiments. This instrument has a 50 millicurie radioactive source (Ammericium 241/beryllium) located in a depth probe 47 mm in diameter. Thermalized neutrons are counted in the depth probe by a boron tri-flouride detector over periods of 15 s to 120 s. Count periods of 120 were used in the calibration and periods of 30 s in the field measurements. A standard count was obtained in a 200 l drum of water each day the meter was used. The coefficients of variation for 120 s counts were less than 1.0 % and for 30 s counts they were less than 1.5 %. All counts obtained in the field either during calibration or measurement were divided by the standard count to obtain a count ratio (CR) from which volumetric water content (WC) was obtained as follows:

For 150 mm depth : WC = (91.5 x CR) - 10.2
For 300 to 1200 mm : WC = (60.0 x CR) - 2.1
For 1350 to 2700 mm : WC = (51.2 x CR) - 1.5

The derivation of the above functions is described in appendix 2. Markers were fastened to the cable which supported the probe in order to position the neutron source at intervals of 150mm to a depth of 1500 mm and at intervals of 200 mm to a depth of 2900 mm.

b) Insertion of access tubes: Aluminium irrigation tubes with internal diameter of 48 mm and 1.0 mm wall were inserted in holes made by a 45 mm auger. The diameter of the hole made by the auger was smaller than that of the tube and a good contact between soil and tube was thus obtained. In W2 plots, two tubes were inserted to a depth of 2.9 m and two to a depth of 1.5 m. The deep tubes were positioned in the net plot area approximately 250 mm away from the centre of the crop row. One shallow tube was located in the crop row and the other mid-way between the two net rows. Access tubes were placed in W1 plots in the same way, but there was only one deep tube per plot and 'shallow' tubes were 2.0 m instead of 1.5 m deep. All tubes protruded 100 mm above the ground and were covered when not in use. Two plots of each water treatment and each variety were provided with access tubes in this way.

c) Determination of field capacity: Field capacity is defined as the water content which remains reasonably constant for a period of about one day after a soil has been saturated to an appreciable depth and then allowed to drain freely (Rose 1966). Field capacity of W1 plots was determined after the ratoon crop was harvested by covering the bare surface with polyethylene sheeting and then applying an excessive amount of water through the trickle irrigation system. An amount of 393 mm was applied on the 28th July, 1985 and the movement of this water in the profile was followed with neutron probe readings on the 30th and 31st July and on the 2nd, 8th and 13th August. The excersize was repeated in September, 1985 when 60 mm water was applied on the 3rd and probe readings were taken on the 4th, 5th, 6th, 9th and 11th September.

4. Growth analysis.

a) Destructive sampling: Crop growth in terms of tons cane per hectare per unit time is used widely in the South African Sugar Industry to compare varieties or crops growing in various conditions. While this is not an absolute measure of the crop's ability to fix solar energy it has practical and economic relevance. The volume of cane stalks can readily be estimated in situ by assuming that they are cylindrical. The density of stalks similar in age and of the same variety may be removed from an area nearby in order to estimate the mass of the growing stalks. This was one of the objectives of the destructive sampling that was carried out on the 31st October, 11th December, 16th January, 7th March, 27 March, 18th April and 8th May.

Two 0.5 m sections of row were removed from a W1 and a W2 plot of each variety on each of these occasions. Plants that may have been favoured by the removal of previous samples were avoided. The top of the stalk was defined as the top most node that could be detected by feeling. With practice it was possible find a node usually within 40 mm from the apical meristem. The stalk was topped and weighed. The fresh and oven-dry mass of green leaf blade, green leaf sheath, top (shoot apex and sheath cone) and trash (dead leaves) was obtained. The diameters of the base, the middle and the top of the stalk were recorded. The lengths of the topped stalk and of the top were measured.

b) Non-desructive sampling: The development of 36 stalks in each of the undisturbed plots were followed from the beginning of November to the end of February. These stalks were selected systematically by taking every fourth stalk along the row within the net plot area. When the base of two or more stalks were at the same position along the row the southern most stalks were counted first (the rows were aligned east to west). Many of these stalks died during this period and additional stalks were included in like manner at the beginning of March to raise the sample size to 20 stalks. Markers made from 40 mm sections of 16 mm irrigation tubing were secured to the fully extended portion of each stalk as soon as stalks were large enough. It was clear from impression of the markers on the sheaths or stalk rind, that they did not move. Once the height above ground of the marker on each stalk was recorded the heights of other points on the stalk were measured from the marker.

New nodes were located in the same way as in excised stalks and their position marked with a blue wax pencil. The number of new nodes and the height of the youngest of these were recorded. These nodes were located again when these stalks were next measured and were marked with a red wax pencil. The height of the most recent red mark was recorded and the difference between blue and red marks showed the amount by which internodes had extended. The blue mark was regarded as the top of the stalk. The diameter of the new portion of stalk (below the blue mark) and that of the fully extended portion of the stalk (below the red mark) were recorded. The total number of green leaves and the number of new leaves on every fifth stalk in the sample was recorded. New leaves were distinguished by a wire ring placed around the youngest leaf that was at least half unfurled. Leaves on all stalks in the sample were counted when leaf numbers were changing rapidly during stress or recovery from stress. When these stalks died they were cut at ground level and taken to the laboratory so that the diameter, length, fresh and dry mass of each internode could be recorded. All marked stalks were processed in this way before the crop was finally harvested in June.

c) <u>Stability of stalk dimensions</u>: In order for the final dimensions of these stalks to be useful it was necessary to establish to what extent they were likely to have changed after internodes were first recorded. The older sheaths of six W1 and six W2 stalks of each variety were removed on the 21st of March to expose the youngest five internodes. The diameters and lengths of these internodes were recorded on this date and again on the 14th April. Some of these stalks in the dry area had died in the intervening period.

d) Leaf area index (LAI): A Licor 3000 area meter was used to measure the green leaf area of stalks sampled destructively. The instrument broke down after the third sampling and the leaf area of 10 stalks per sample was estimated from length and width measurements. Area was equated to width at the widest point x length x 0.7 (Gascho and Shih, 1983). This simple conversion of leaf dimensions to area developed in Florida may not be accurate for the varieties in this experiment. The leaf area per unit ground area (LAI) of W1 and W2 plots was derived from leaf number per stalk, stalk number per unit ground area and area per leaf. Area per leaf changed with crop age and a correction was made for this using quadratic functions fitted by least squares (Table 6). These functions describe the increase in leaf size to a maximum when the plants were about 200 days old and a slight decrease in size thereafter.

Table 6. Coefficients (Coef.) and standard errors (SE) of quadratic regression of area per leaf on days after 1st October.

Variety		Intercept		Linear		Square		r^2	n	F
		Coef.	SE	Coef.	SE	Coef.	SE			
NCo376	W1	-44.1	54.4	3.52	0.66	-0.00913	0.00197	0.36	64	17.6
N12	W1	-70.2	72.7	3.81	0.88	-0.00847	0.00260	0.36	74	20.3
N14	W1	-89.5	51.5	5.74	0.63	-0.01591	0.00190	0.57	68	44.0
NCo376	W2	0.7	55.4	2.53	0.68	-0.00729	0.00203	0.20	58	6.8
N12	W2	-69.1	79.8	3.89	0.93	-0.01034	0.00270	0.23	65	9.3
N14	W2	31.9	84.8	1.67	1.06	-0.00284	0.00314	0.17	56	5.6

Diurnal variations in water stress symptoms

1. Plant extension rate (PER)

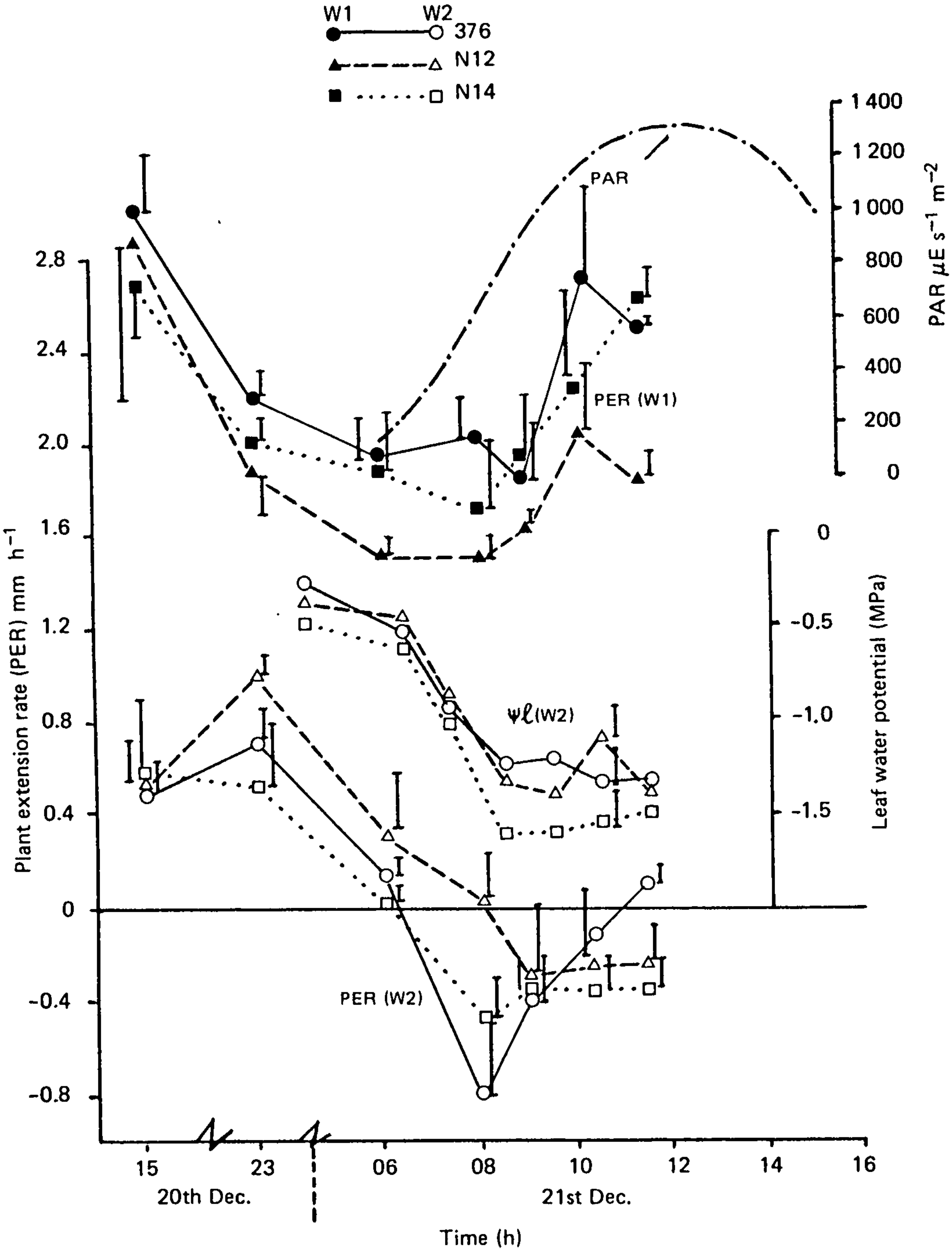

Figure 17. Plant extension rate (PER) measured over various intervals during 20th and 21st December together with leaf water potential (ψ_l) and photosynthetically active radiation (PAR). Standard errors of means for PER and ψ_l indicated by bars where larger than symbols.

Extension rates of stressed (W2) plants were considerably lower than those of unstressed (W1) plants when repeated measurements were made on the 20th and 21st December. PER of W2 plants increased overnight and then decreased to zero or below zero after dawn (Fig. 17). PER of W1 plants decreased overnight and then increased rapidly after 0900 hours. Plant extension before dawn was considerable although the minimum temperature of 21 ^{o}C on the 21st December was only 2 ^{o}C above the threshold temperature for growth (Bacchi and Sousi, 1981).

Extension of N12 plants proceeded less rapidly than did that of NCo376 and N14 plants under irrigated conditions but was more rapid than in these varieties under conditions of stress. It was noteworthy that PER of stressed plants remained comparatively low even when ψ_l was greater than -0.5 MPa before dawn. Shrinkage in the hitherto extending stem and leaf tissue of stressed plants was evident during 21st December. Differences in leaf height from morning to afternoon were usually negative after this date and it is doubtful whether net extension occurred again before irrigation was recommenced on 22nd January. Diurnal shrinkage of extensible plant tissue has not often been reported in the literature. Leading shoots of *Pinus radiata* were reported to have contracted as much as 10 mm d^{-1} (Fielding, 1955). The radial contraction of fully extended stems is well documented and is of practical importance in measuring the water status of plants (Kozlowski, 1972).

PER of stressed plants was also close to zero when measured through the night on the 1st and 2nd April (Fig. 18). It was found that PER increased overnight to nearly 1.0 mm h^{-1} between 0100 and 0700 hours but was zero or negative by 1100 hours. Leaves of N12 ceased extension later in the day than those of NCo376 or N14 as they had done on 21st December during the first stress period. Moderate diurnal variation in PER was evident in irrigated plants as well. Rates were highest in the late afternoon and lowest at midday.

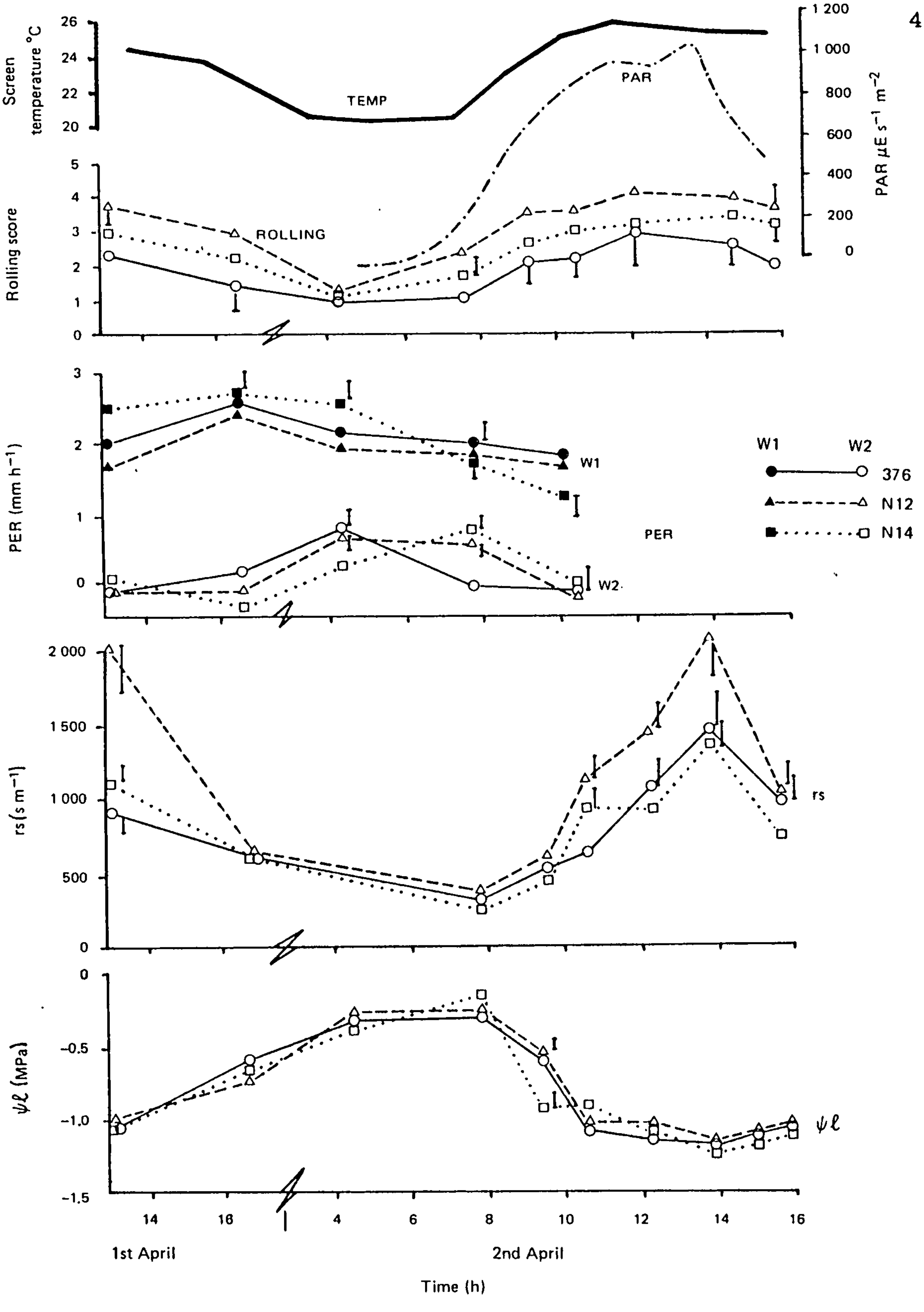

Figure 18. Leaf rolling, diffusive resistance (r_s) and leaf water potential (ψ_ℓ) of W2 plants, plant extension rate (PER) of W1 and W2 plants, and photosynthetically active radiation (PAR) and screen temperature on the 1st and 2nd April during the second stress period when plants had been without water for 31 days. Bars indicate standard errors of means where larger than symbols.

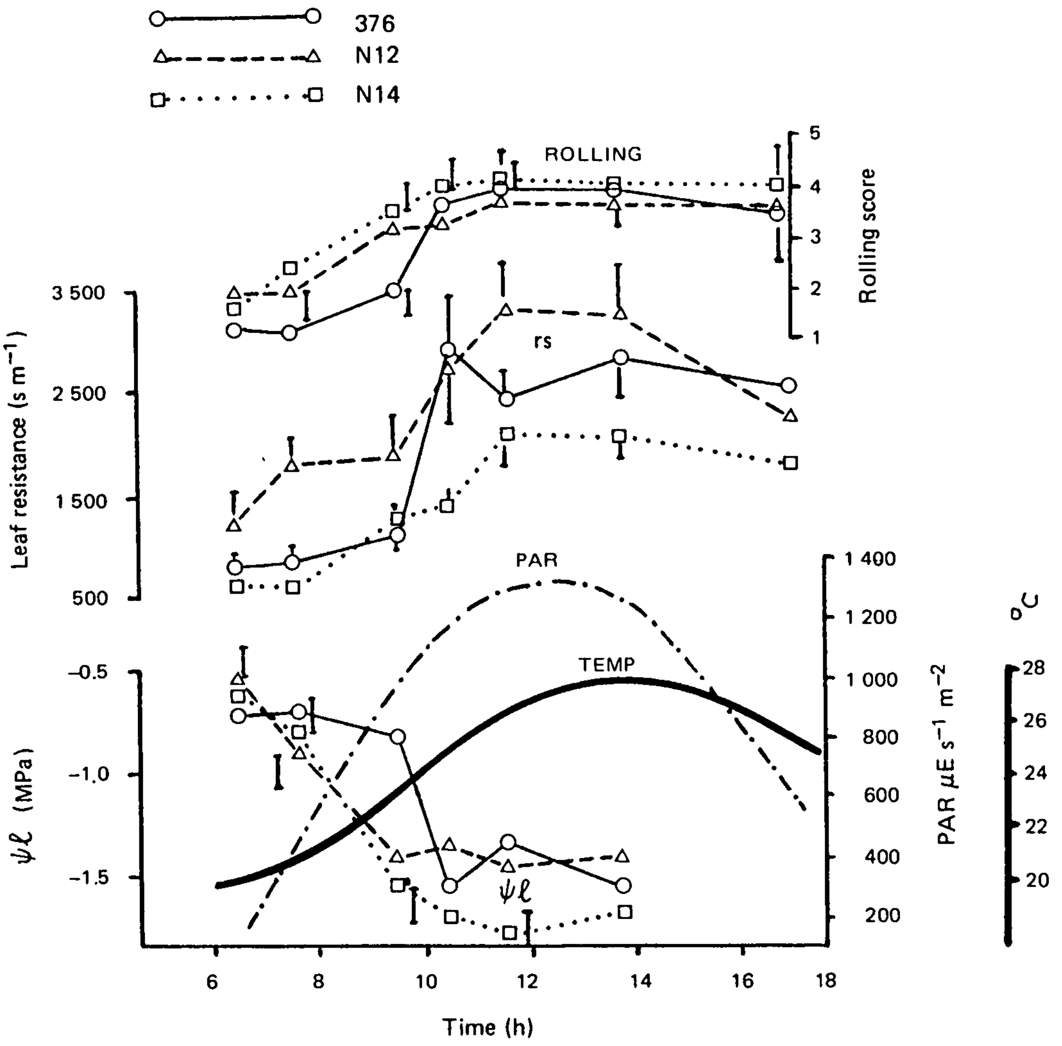

Figure 19. Leaf rolling, diffusive resistance (r_s), leaf water potential (ψ_l), photosynthetically active radiation (PAR) and screen temperature on the 21st January after plants had been without irrigation for 51 days. Standard errors of means indicated by bars where larger than symbols.

2. Leaf water potential (ψ_l)

The pre-dawn ψ_l of stressed plants on the 21st December was -0.27 -0.34 and -0.45 MPa (SE < 0.034 MPa). ψ_l dropped slowly just after sunrise (0700 hours) and then decreased rapidly until 0830 hours changing little thereafter (Fig. 17). ψ_l was 0.2 to 0.5 MPa lower in N14 than in the other varieties from 0800 hours onwards (differences at 0800 and 0930 hours were significant at p=0.05).

At the end of the first stress period (21st January) when pre-dawn ψ_l of each variety was below -0.6 MPa, ψ_l of N14 again reduced to lower values than those of the other varieties after 0930 hours (Fig. 19). At this time leaf water potential of stressed NCo376 remained above that of N12 and N14 until 1030 hours (significant at p=0.01) and then decreased rapidly at the same time as a rapid increase in its leaf resistance (Fig. 19). Changes in ψ_l of the three varieties during 1st and 2nd April (second stress period) were similar apart from a slightly more rapid decline in ψ_l of N14 between 0800 hours and 0945 hours (Fig. 18). ψ_l changed little until PAR rose above $200\ \mu E\ s^{-1}\ m^{2}$ on each day when repeated measurements were made. PAR rose above this value at about 0700 hours on the 21 st December (mid-summer) and reached a peak of approximately $1300\ \mu E\ s^{-1}\ m^{2}$ at midday. On the 2nd April, PAR rose above $200\ \mu E\ s^{-1}\ m^{2}$ at about 0800 hours and reached a maximum of approximately $1000\ \mu E\ s^{-1}\ m^{2}$ at 1400 hours. Radiation at midday was reduced slightly by cloud.

3. Leaf resistance (r_s)

Marked diurnal changes in resistance became evident for the first time on the 21st January (Fig. 19). This was 52 days after irrigation had been suspended for the first time. Stomata were evidently partially closed as early as 0630 hours when ψ_l was above -0.7 MPa, but radiation was very low at this stage and this may have limited stomatal opening. Resistances rose rapidly as ψ_l declined during the morning and they reached maximum values between 1000 and 1400 hours. Leaf resistance of NCo376 tended to be greater than that of N14 and less than that of N12. All differences but one between N12 and N14 were statistically significant (p=0.05).

When diurnal variation in r_s was measured during the second stress cycle plants were not stressed as severely as they had been in the first stress period. Resistances were high for a relatively short period around 1400 hours when ψ_l was low. The highest resistances and the greatest diurnal variation occurred once again in N12 (Fig. 18). Varietal differences were significant (p=0.05) at 1300 hours on both days.

4. Leaf rolling

Leaves 1 and 2 of N12 and N14 were slightly rolled at 0600 hours on the 21st January and they became steadily more rolled as radiation and temperature increased (Fig. 19). Rolling of all varieties reached a maximum for the day at about 1100 hours when ψ_l was low and leaf resistance was greatest. Rolling in NCo376 tended to lag behind the other varieties on the 21st January and 2nd April. On the latter date rolling was most prevalent in N12 (Fig. 18). Rolling, leaf resistance and leaf water potential changed in a similar way during both days when concurrent measurements were made. Rolling could thus provide an indication of the water status and resistance to gaseous diffusion provided varietal differences in rolling habit were taken into account.

Development of water stress symptoms during successive stress periods

1. Plant extension rate (PER)

PER of fully irrigated plants increased during the first two weeks of December when air temperatures were rising and remained between 2.5 and 3.0 mm h^{-1} until measurements were stopped on the 21st December (Fig. 20a). PER of W1 plants during the first stress period was strongly dependant ($r=0.85$, significant at $p=0.0001$) on the difference between screen temperature and the traditional threshold temperature (19 ^{o}C) for sugarcane growth. PER increased by 0.24 ± 0.03 mm h^{-1} for each ^{o}C in temperature. The linear model indicated that PER at 19^{o}C was 0.64 ± 0.26 mm h^{-1} and that growth would have stopped at about 15^{o}C. Bull and Glaziou (1975) recorded leaf expansion rates as high as 20 cm^{2} d^{-1} in sugarcane growing at 16 ^{o}C. Leaves of plants at 21^{o}C expanded 3 to 5 times as fast. PER of irrigated N12 tended to be lower than PER of NCo376 or N14 but differences were not always statistically significant. PER of plants in the sheltered area fell behind that of irrigated plants 12 days after suspending irrigation in this area. PER of the stressed plants fell to zero after another week without rain or irrigation and negative values were often obtained. In conditions of stress PER of N14 tended to be lower than in the other varieties during the decline stage but differences were significant on only three occasions.

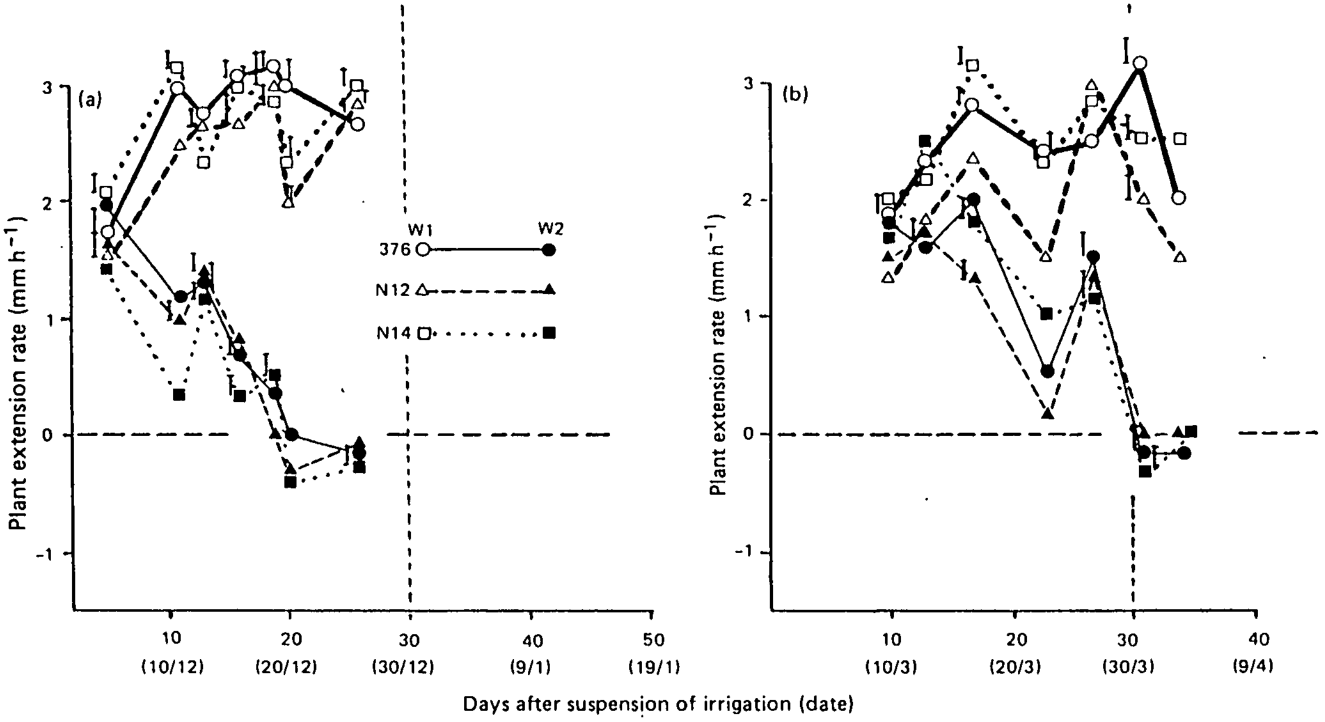

Figure 20. Plant extension rate (PER) of well watered (W1) and stressed (W2) plants during the first stress period in December 1984/January 1985 (a) and during the second stress period during March/April 1985 (b). Bars denote standard errors larger than symbols.

It was apparent from Fig. 20b that during the second period of measurement PER of irrigated NCo376 and N14 ranged between 2.0 and 3.0 mm h^{-1} and apart from one occasion, PER of N12 was about 0.5 mm h^{-1} lower (mostly significant at p=0.05) than that of the other varieties. PER of stressed plants fell behind that of irrigated plants about 20 days after suspending irrigation. This was later than in the first stress period. Leaf extension during the day ceased when plants had been without irrigation for 32 days, about two weeks later than in the first stress period. The rates of evaporation during March were considerably lower than the rates recorded in December (Fig. 16) and this probably resulted in the comparatively long delay in the onset of stress during the second stress period. Varietal differences in stress conditions were significant only on the 21st March when PER of N14, NCo376 and N12 were 1.0, 0.4 and 0.2 mm h^{-1} respectively.

2. Leaf water potential (ψ_l)

Midday leaf water potential of irrigated plants generally remained above -0.3 MPa during both measurement periods (Fig. 21). Although readings were discontinued after a while, it may be assumed with reasonable confidence that these plants were not stressed throughout the duration of the experiment. Leaf water potential of the crop in the sheltered area fell below -0.5 MPa 12 days after irrigation was withheld in December. ψ_l dropped rapidly to -1.3 MPa during the following week and then fell more gradually to -1.5 ± 0.09 MPa in NCo376 and to -1.7 ± 0.03 MPa in N14 (Fig. 21a). ψ_l of N12 appeared to recover temporarily to some extent after the period of rapid desiccation possibly as a result of a rapid increase in its leaf resistance at this stage (Fig. 22a). ψ_l of stressed N12 declined gradually thereafter, but generally tended to be greater than in NCo376 and N14. Midday ψ_l of N14 was significantly lower ($p < 0.05$) than that of NCo376 and N12 from 27th December to 10th January. The slight recovery in ψ_l of N12 and N14 during mid-January corresponded with an apparent, unexplained increase in soil water content.

During the second period of stress (Fig. 21b) leaf water potential of stressed plants dropped below that of irrigated plants about 20 days after the last irrigation and it declined more gradually than in the first period to a minimum of -1.8 MPa 18 days later (Fig. 21b). The more gradual decline in ψ_l was probably due to lower evaporation, radiation and temperature during April than in January (Fig. 16). Varietal differences during the first stress period were undiscernible.

3. Leaf osmotic potential (π)

Differences in π between varieties were not statistically significant and variety data was therefore pooled. Osmotic potential of unstressed plants decreased slightly during the five month period of measurement (Table 7). There was a marked reduction (significant at $p=0.05$) of π in stressed plants after 21 and 48 days of stress in the first stress period. This adjustment in osmotic potential was largely reversed during the period of recovery in February judging by the the small difference after 12 days of stress in the second stress period.

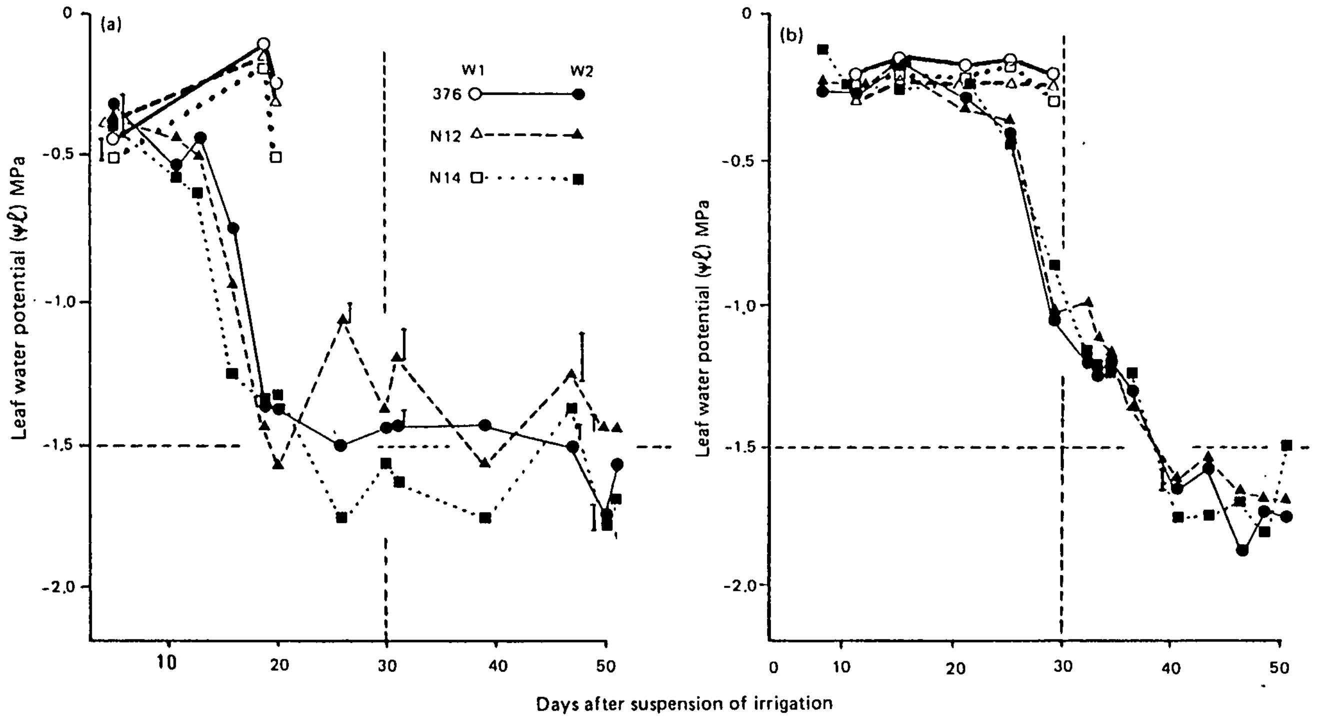

Figure 21. Midday leaf water potential (ψ_l) of well watered (W1) and stressed (W2) plants during the first stress period in December 1984/January 1985 (a) and during the second stress period during March/April 1985 (b). Bars denote standard errors larger than symbols.

Stressed and unstressed plants differed significantly when π was measured on the 35th and 51st day of stress in the second stress period but the differences were not as marked as those observed in the first stress period. The adjustment was no longer evident after irrigation of W2 plants was resumed on the 22nd April.

Table 7. Osmotic potential at full turgor of leaves of unstressed sugarcane plants and plants denied irrigation and rain during two periods of stress.

Date	Days after irrig.	Stress period	Unstressed plants			Stressed plants			W2-W1
			π MPa	SE MPa	n	π MPa	SE MPa	n	π MPa
7 DEC	7	1	1.06	0.019	9	1.08	0.018	9	0.02
21 DEC	21	1	1.08	0.039	9	1.41	0.085	8	0.33
17 JAN	48	1	0.99	0.020	8	1.37	0.045	11	0.38
12 MAR	12	2	1.07	0.020	12	1.16	0.039	14	0.09
4 APR	35	2	1.14	0.025	13	1.25	0.030	16	0.11
20 APR	51	2	1.15	0.050	8	1.28	0.030	21	0.13
13 MAY	4	–	1.14	0.039	10	1.08	0.030	16	-0.06

4. Leaf resistance (r_s)

Diffusive resistance of irrigated plants remained at about 250 s m^{-1} during the first stress period but rose as high as 500 s m^{-1} during the second stress period (Fig. 22). The former value is comparable with minimum resistances of wheat (Bristow, de Jager and van Zyl, 1981). In an experiment by Turner and Begg (1973) the mean resistance of upper and lower maize leaf surfaces was not less than 500 s m^{-1}. Kortschak and Forbes (1969) found that photosynthetic capacity of sugarcane leaves of the same age decreased as the crop aged. This may have resulted from an increase in stomatal resistance similar to that observed in this experiment.

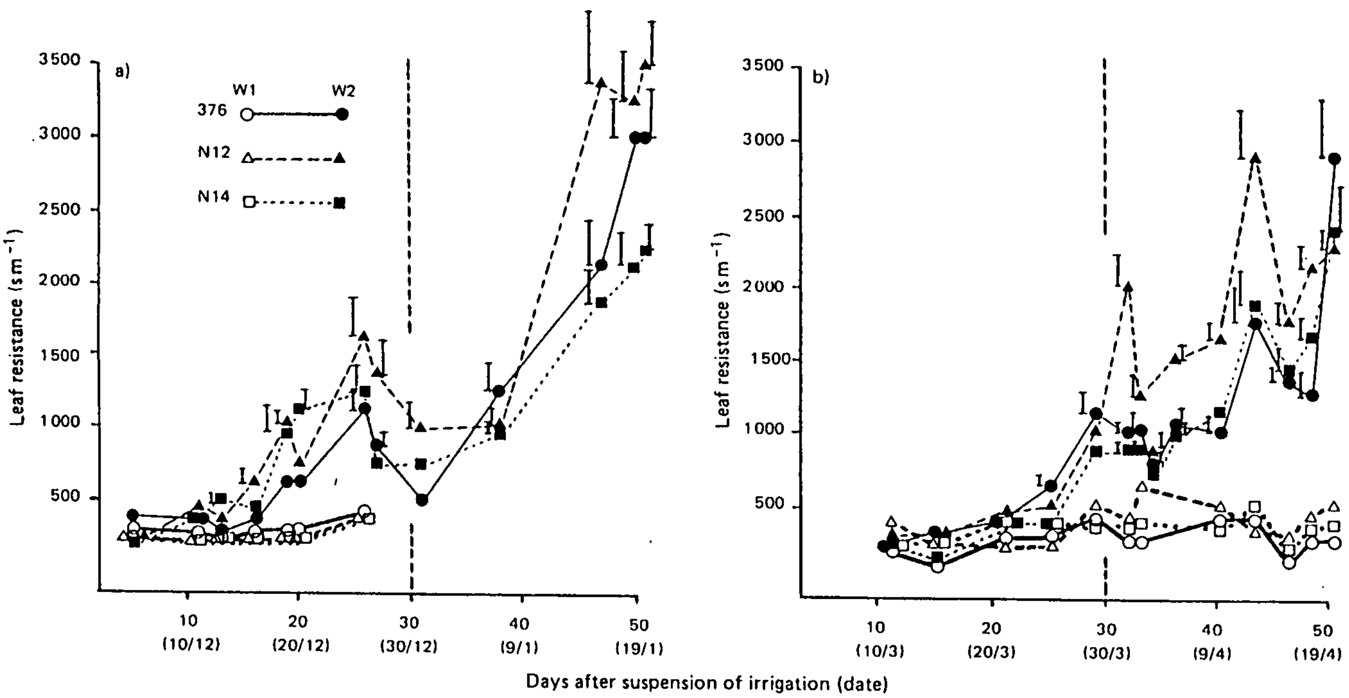

Figure 22. Leaf resistance (r_s) of well watered (W1) and stressed (W2) plants during the first stress period in December 1984/January 1985 (a) and during the second stress period during March/April 1985 (b). Bars denote standard errors larger than symbols.

Resistances of plants stressed for the first time rose above these minimum values when plants had been without irrigation for about 10 days and continued to rise for a further 10 days. After a slight recovery almost coincidental with the temporary increase in ψ_l , leaf resistance rose to the limit of the porometer's range (3500 s m^{-1}) 40 to 50 days after irrigation (Fig. 22a). The increase in resistance was most rapid in N12 and least rapid in N14 but only the largest differences were statistically significant. When irrigation water was withheld from plants for the second time diffusion resistance remained unaffected for about 20 days because of reduced evaporative demand and then rose gradually to maximum values after a further 30 days (Fig. 22b). Resistances of N12 leaves were significantly greater (p=0.05) than those of the other varieties undergoing water stress from the first to the 12th April.

5. Leaf rolling

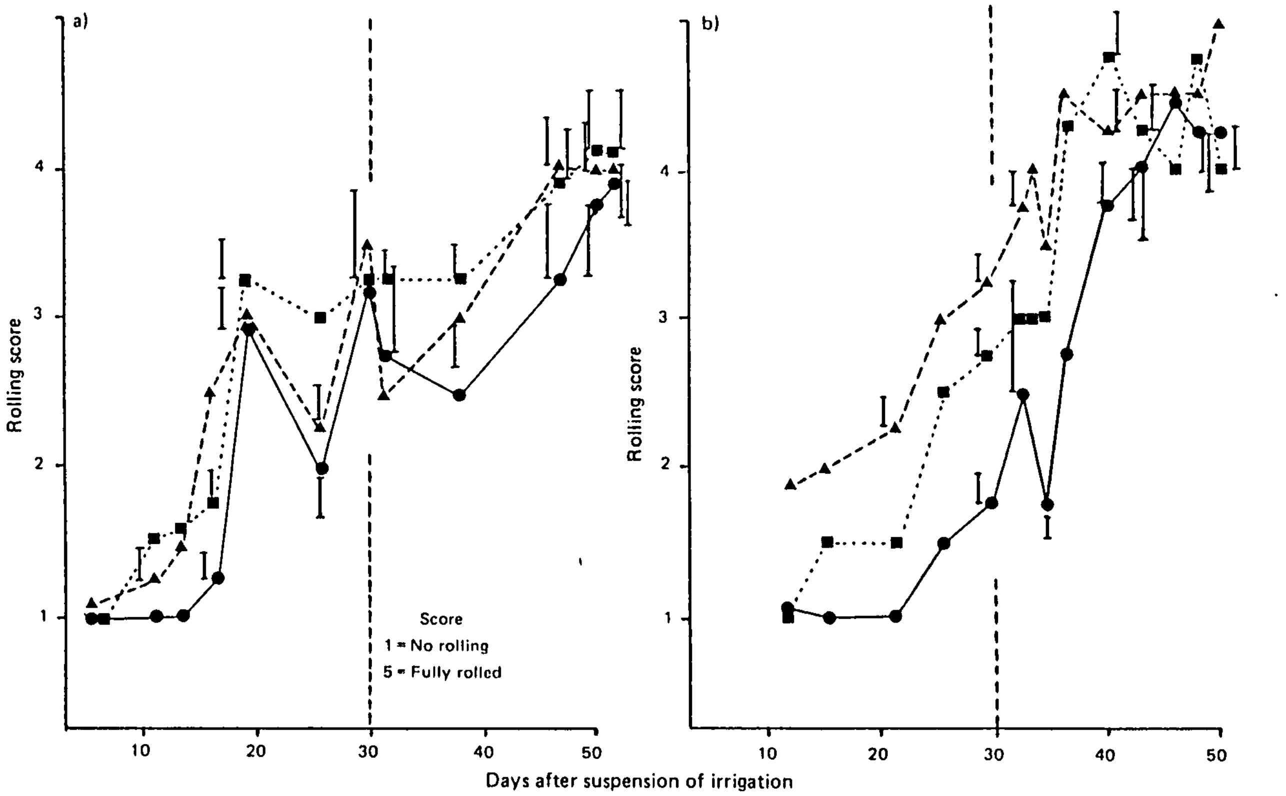

Figure 23. Rolling score of stressed (W2) plants during the first stress period in December 1984/January 1985 (a) and during the second stress period during March/April 1985 (b). Bars denotes standard errors larger than symbols.

Younger leaves always rolled more readily than older leaves. Leaves of NCo376 and N14 below the third position were seldom rolled even when they were dying. Rolling scores of leaves 1 and

2 were averaged to provide the data shown in Fig. 23. The first two leaves of N12 and N14 began to roll at midday about 10 days after suspending irrigation on the 30th November. Midday rolling became more marked with time until stress was relieved on the 22nd January. Rolling in NCo376 generally tended to be less marked than in the other varieties (Fig. 23a) but differences were seldom statistically significant. The slight rolling observed in N12 under full irrigation during the second period of measurement (not shown) appeared to be characteristic of this variety as it aged. Although leaves of N12 and N14 were slightly rolled when irrigation was withheld for the second time, an increase in rolling was observed after approximately 20 days of stress. Rolling was most prevalent in N12 and least in NCo376 during the second stress period . Differences between N12 and NCo376 were significant ($p < 0.05$) until the 10th April when rolling was practically complete in all varieties (Fig. 23b).

Relationships with leaf water potential

1. Plant extension rate (PER)

PER of irrigated and stressed plants was apparently reduced when midday ψ_l fell below -0.2 MPa in the first stress period (Fig. 24). No plant extension occurred when ψ_l fell below -1.0 MPa but by regressing PER on ψ_l above this value it was evident that plant extension stopped when ψ_l reached -0.71 MPa (Table 8). Plant extension in the second stress cycle reduced to zero at even higher ψ_l (-0.44 MPa) than in the first stress period (Fig. 24b). Differences between varieties in the critical ψ_l for plant extension were not evident in the data.

Table 8. Regression coefficient (b), intercept (a) and level of significance (p) and degrees of freedom (DF) for leaf water potential regressed on plant extension rate (PER).

Stress period	r^2	b	SE(b)	a	SE(a)	p%	DF
		(MPa mm^{-1} h)		(MPa)	(MPa)		
1	0.72	0.173	0.025	-0.71	0.050	0.01	18
2	0.40	0.081	0.025	-0.44	0.054	0.45	17

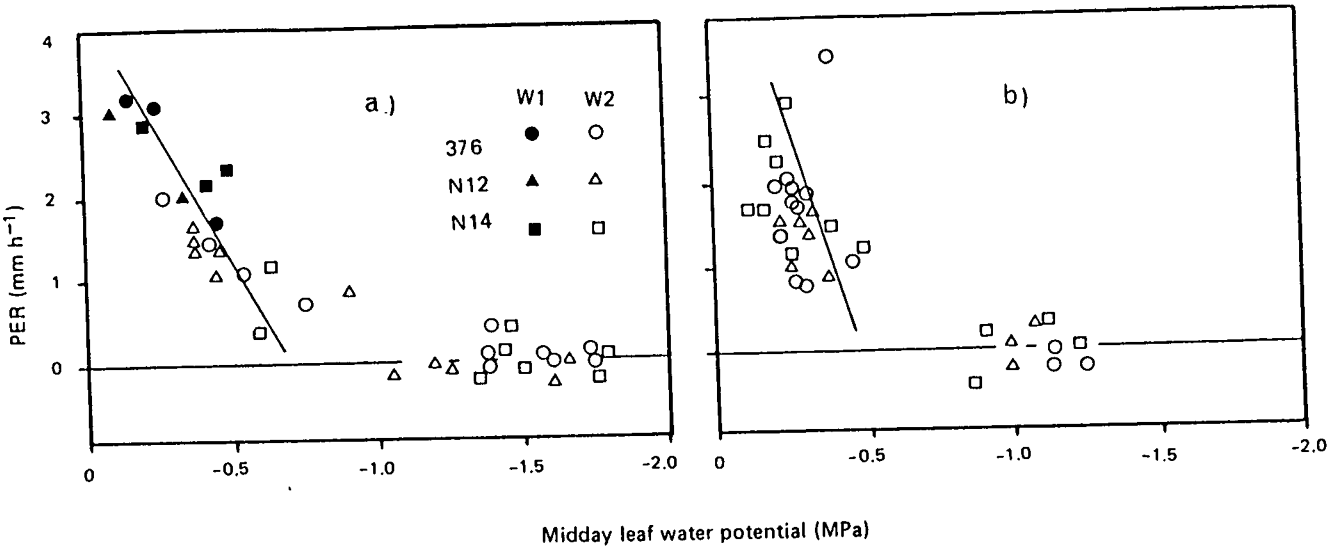

Figure 24. Plant extension rate (PER) measured over a four hour period in the middle of the day and midday leaf water potential (ψ_l) during the first stress period in December 1984/January 1985 (a) and during the second stress period during March/April 1985 (b).

Critical ψ_l values of approximately -0.7 and -0.4 MPa were also evident in the hourly data recorded on the 20th/21st December and 1st/2nd April respectively (Fig. 25) though not as convincingly because PER failed to recover fully when ψ_l rose during the night (Fig. 17). The effect of water stress on PER on these dates was thus not immediately reversible and extension was limited by some factor other than the water potential of the leaf blade. The water potential of the expanded leaf blade was not necessarily the same as that of the meristematic region of the shoot and the association between observed leaf water status and PER may not have been one of cause and effect. Even if total water potential of the meristem and the leaf blade were similar, turgor pressures at the two sites may have been be different. Substantial differences in osmotic potential and hence turgor pressure were found in the apical meristem and the expanded leaf blade of maize plants (Michelena and Boyer, 1982). Nevertheless leaf extension has often been directly associated with leaf water potential. Threshold values for sugarcane previously given as -0.7 to -0.9 MPa (Chapter 2, page 20) were obtained from potted plants by measuring PER over 24 hours and estimating the minimum ψ_l during this period using a previous association between midday and predawn leaf water potential. The critical values (-0.4 to -0.7 MPa) reported here are more precise since they were obtained by recording leaf water potential in the middle of a four hour period over which PER was measured. The values are also more applicable since they were were obtained from a field of sugarcane rather from potted plants.

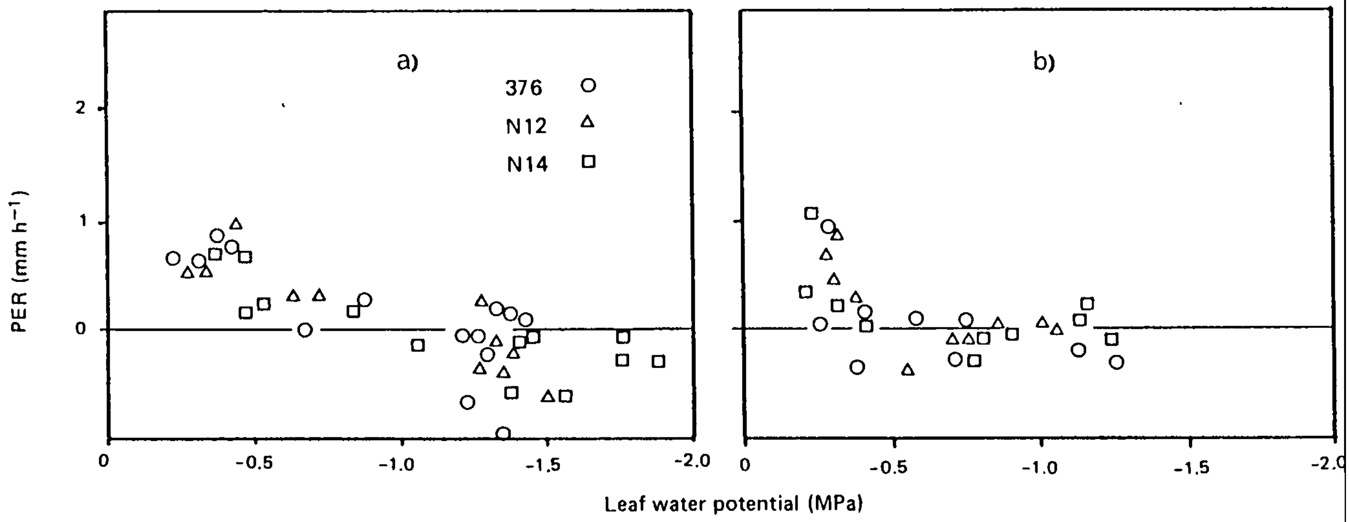

Figure 25. Plant extension rate (PER) measured over successive intervals of 3 to 11 hours and leaf water potential (ψ_l) in the middle of each interval the 21st December 1984 (a) and the 2nd April 1985 (b).

2. Leaf resistance (r_s)

The increase in leaf resistance with water stress may best be described by an exponential function (Bristow et al, 1981) since r_s in most crops tends to increase as leaf water potential falls below some critical value (Kanemasu and Tanner, 1969; Rutherfoord and de Jager, 1975). This critical value may be regarded as the threshold value for stomatal closure. Bristow et al, (1981) defined the critical leaf water potential (ψc) as the ψ_l at which r_s rose to twice the minimum resistance value (r_m) in terms of the follwing equation:

$$r_s = r_m . \ [1+e^{\{-b.(\psi c-\psi_l)\}}]$$

where b is a dimensionless constant governing the rate at which r_s approaches infinity.

The data in Fig. 26 includes data obtained when ψ_l and r_s were measured at frequent intervals during 21st and 22nd December and 1st and 2nd April. The curves in Fig. 26 are based on the parameter estimates (Table 9) of above equation obtained by a least squares procedure.

Table 9. Critical leaf water potential (ψc), constant b and standard error (SE) of an exponential function $r_s = r_m \cdot [1+e^{\{-b.(\psi c - \psi_l)\}}]$ describing leaf resistance (r_s in s m^{-1}) and leaf water potential (ψ_l in MPa). r^2 is the ratio of regression variance to total variance.

Stress period	Vari -ety	r_m (s m^{-1})	ψc (MPa)	b	SE(b)	r^2	DF
1	376	200	-0.72	-2.56	0.33	0.78	18
1	N12	200	-0.72	-3.47	0.49	0.75	18
1	N14	200	-0.82	-2.41	0.27	0.82	18
2	376	200	-0.57	-1.84	0.21	0.77	23
2	N12	200	-0.53	-2.22	0.18	0.85	25
2	N14	200	-0.63	-2.00	0.20	0.80	25

Critical leaf water potential (ψc) of N14 was lower than ψc of the other varieties in both stress periods. The critical ψ_l defined in this way was substantially higher than that obtained for wheat (-2.0 MPa) by Bristow et al, (1981) and is indicative of the generally high sensitivity of sugarcane to water stress. Values of ψc were higher in the second than in the first period of stress and stomata were apparently more sensitive to the onset of the second than that of the first stress.

Stomatal resistance rose more rapidly in N12 than in NCo376 or N14 when ψ_l fell below ψc. Thus the b value of N12 was significantly lower than that of the other varieties in both stress periods. In all varieties the rate (b) at which r_s increased with decreasing $\psi c - \psi_l$, was lower in the second than in the first stress period. Thus the first stress may have rendered stomata more sensitive to mild stress and less sensitive to severe stress.

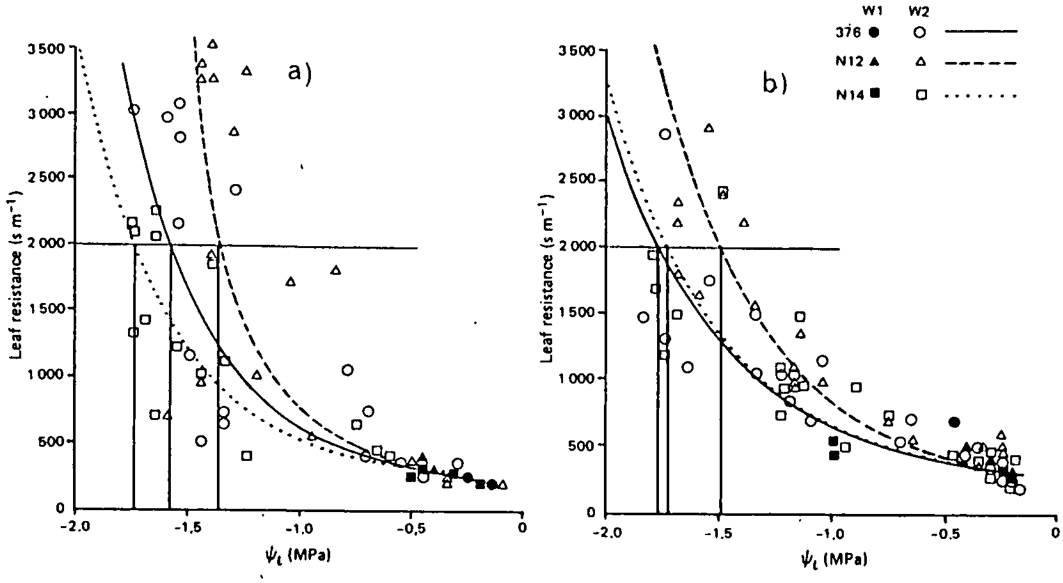

Figure 26. Leaf resistance (r_s) and corresponding instantaneous leaf water potential (ψ_l) measured largely at midday and occasionally in the morning or afternoon during the first stress period in December 1984/January 1985 (a) and during the second stress period during March/April 1985 (b).

During the first stress period it was evident (Fig. 26a) that stomatal closure was nearly complete (r_s > 2000 s m^{-1}), when ψ_l was about -1.4, -1.6 and -1.8 MPa in N12, NCo376 and N14 respectively. During the second stress period (Fig. 26b) stomatal closure appeared to be nearly complete when ψ_l was about -1.5, -1.8 and -1.8 MPa in N12, NCo376 and N14 respectively. The effect of the first imposition of stress on the degree of stress at which stomata finally closed in the second period was therefore minimal.

3. Canopy temperature and crop water stress index

Canopy temperature (Tc) was used to compute a crop water stress index (CWSI) which was first described by Idso et al (1981) and used by several authors including Mottram, De Jager and Duckworth (1983). Jackson (1982) provided a theoretical basis for a crop water stress index (CWSI) in terms of net radiation (Rn), aerodynamic resistance (r_a), canopy (Tc) and air temperature (Ta) and vapour pressure deficit (VPD). CWSI at constant Rn and r_a were represented graphically (Fig. 27). The line X-Y represented the leaf to temperature differential (Tc-Ta) of canopy with minimum resistance (50 s m^{-1}) and the line P-Q represented the Tc-Ta of canopy with infinite resistance. The line X'-Y' (baseline) was obtained empirically from (Tc-Ta) of well watered plants of sugarcane on sunny days (more than five hours of sun) when the wind run was less than 150 Km d^{-1}. The line described below fitted the data reasonably well considering the small range in VPD (kPa) which is a characteristic of the coastal cane belt. Standard errors for the intercept and slope were 0.61 and 0.52 °C respectively.

$$Tc-Ta = 4.14 - 4.00 \times VPD\ ^{o}C \quad (r^2=0.64 \quad p<0.0001)$$

The intercept of 4.14 °C may be regarded as the temperature differential of a non-transpiring sugarcane canopy and was used to locate the line P'-Q' in Fig. 27. This empirical line is reasonably close to the theoretical line P-Q. The difference of 1 to 2 °C between empirical and theoretical baselines may have been due partly to the difference in the height of the sugarcane canopy and the Stevenson screen where air temperature was measured. The other variables in Jackson's model (Rn and r_a) may have differed as well.

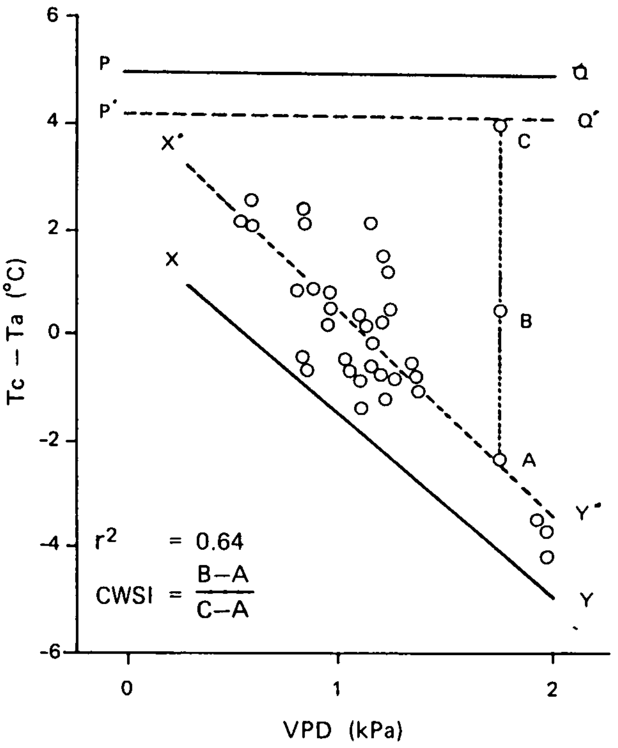

Figure 27. Effect of vapour pressure deficit (VPD) on the difference in temperature between air (Ta) and canopy (Tc) of unstressed (X-Y, X'-Y') and fully stressed (P-Q, P'-Q') crops. Solid lines were drawn from theoretical considerations after Jackson(1928) and broken lines relate to sugarcane. Crop water stress index = (B-A)/(C-A).

CWSI was computed as the deviation (B-A) from the baseline X'-Y'in leaf to air temperature differential divided by the difference in Tc of unstressed and "fully" stressed canopies (C-A). Data obtained on days with less than five hours of sun were excluded.

Leaf water potential and leaf conductance each accounted for more than 60 % of the variation in CWSI (Table 10). The quadratic term for conductance (k) was significant and CWSI decreased more rapidly when k was low than when k was high. Ehrler et al (1978) found that wheat canopy temperature (Tc) was only moderately correlated with ψ_l above -3.0 MPa and Tc was insensitive to changes in ψ_l below -3.0 MPa. The lowest midday leaf water potentials of sugarcane leaves were greater than 2.0 MPa. Jackson (1982) pointed out that large variability in water potential between leaves may make this the less accurate of the two indications of stress at least during the early stages of stress development.

Table 10. Linear (b) and quadratic (c) regression coefficients, intercept (a) and level of significance (p) and degrees of freedom (DF) for crop water stress index (CWSI) regressed separately on plant extension rate (PER), leaf water potential (ψ_l) and leaf conductance (k).

Indepent variable	Variety	r^2	b	SE(b)	c	SE(c)	a	SE(a)	p%	DF
PER mm h^{-1}	376	0.52	-0.19	0.06			0.67	0.11	0.80	11
	N12	0.49	-0.21	0.07			0.71	0.14	1.62	10
	N14	0.72	-0.33	0.07			1.02	0.13	0.05	11
ψ_l MPa	376	0.67	-0.64	0.11			0.00	0.13	0.01	17
	N12	0.71	-0.66	0.10			0.01	0.12	0.01	17
	N14	0.63	-0.62	0.12			-0.01	0.16	0.01	17
k mm s^{-1}	376	0.73	-0.47	0.11	.040	.018	1.30	0.15	0.01	22
	N12	0.64	-0.63	0.18	.084	.035	1.31	0.17	0.01	22
	N14	0.72	-0.74	0.21	.094	.042	1.53	0.20	0.01	22

Some the variation in CWSI not accounted for by variations in leaf conductance may due to variations in the other components of total canopy conductance (Thom, 1975). The correlation between stomatal conductance and canopy conductance depends on air temperature and on eddy velocity and hence crop height and wind speed (Thom, 1975). Wind was the only major climatic factor not explicit in Jackson's model. It was suggested that the effect of wind on CWSI be determined experimentally (Jackson, 1982). O'Toole and Hatfield (1983) found that wind affected Tc-Ta substantially in rice and wind is probably an important factor in the use of a stress index in sugarcane grown on the Natal coast.

The relationship between CWSI and ψ_l was consistent between the varieties and the mean CWSI/ψ_l ratio of -0.64 may of general use in predicting the degree of crop stress from canopy temperaure data. The two critical stages of stress in sugarcane may be regarded as 1) cessation of growth and 2) closure of stomata. The first stage is reached when ψ_l falls to about -0.6 MPa and when CWSI is about 0.4 using the above ratio. The second stage is reached when ψ_l falls to about -1.5 MPa and CWSI rises to about 1.0. Growth rate would probably recover immediately if irrigation was applied at the first critical stage of stress but would recover relatively slowly if irrigation was delayed until the second stage (see PER and ψ_l data in Fig.s 17 and 19) with a possible loss of efficiency in water usage.

Berliner *et al* (1984) criticized the CWSI concept because it excluded wind as a factor affecting canopy temperature. These authors suggested that Tc of a test crop should be compared with Tc of an unstressed crop growing under the same conditions as the test crop in order to cancel the effect of wind. The difference in Tc of stressed and unstressed (Tc-Tci) plots of sugar cane was regressed on ψ_l and leaf conductance (k) and results are presented in Table 11.

The difference in temperature of stressed and unstressed canopies (Tc-Tci) was as dependent on variations in ψ_l and k as was CWSI. Tc-Tci was more dependent on variations in PER than was CWSI. The linear models predicted that Tc of a stressed canopy would be 3 to 4 °C higher than an unstressed canopy when PER tended to zero and 5 to 6 °C higher as k tended to zero. This index of water stress may be more useful and more reliable than CWSI in monitoring irrigation schedules since it is readily obtained in the field and is presumably not as sensitive to wind, net radiation and aerodynamic resistance as is CWSI. Unstressed fields similar in height to the test field would be available on most irrigated farms.

Table 11. Correlation and regression coefficients (r and b), intercept (a) and level of significance (p) and degrees of freedom (DF) for stressed-unstressed canopy temperature regressed on plant extension rate (PER), leaf water potential (ψ_l) and leaf conductance (k).

Indepent variable	Variety	r^2	b	SE(b)	a	SE(a)	p%	DF
PER	376	0.67	-1.81	0.47	3.00	0.54	0.59	8
mm h^{-1}	N12	0.76	-1.89	0.47	2.82	0.54	1.05	6
	N14	0.67	-2.06	0.54	3.71	0.65	0.64	8
ψ_l	376	0.65	-3.39	0.64	-1.04	0.83	0.01	16
MPa	N12	0.69	-3.56	0.61	-1.04	0.76	0.01	16
	N14	0.56	-3.26	0.73	-0.76	0.98	0.05	16
k	376	0.76	-1.46	0.21	6.03	0.53	0.01	16
mm s^{-1}	N12	0.56	-1.27	0.29	5.34	0.66	0.06	16
	N14	0.48	-1.32	0.23	5.77	0.54	0.01	16

Chapter 5 DISCUSSION ON PLANT WATER RELATIONS OF RATOON CROP

The extension of sugar cane leaves occurs largely in the partially undifferentiated tissue 40 to 100 mm above the apical meristem and stalk extension occurs most rapidly about 40 mm below the meristem (van Dillewijn, 1952) .The water potential of the xylem in this region was probably similar to that measured in the expanded leaf blades since pressure gradients in the xylem are generally smaller than 0.05 MPa m^{-1} even when transpiration is rapid (Slatyer, 1967 p214) . Pressure gradients between leaves in the sun and those in the shade may nevertheless be as large as 0.5 MPa in plants with large vascular networks (Kaufmann, 1976).

The osmotic potential of cells in the elongating region may however be considerably lower than that of the expanded blade (Michelena and Boyer, 1982) and turgor pressure of the expanding cells would therefore be greater than that of the expanded blade cells. Cell turgor is thought to be directly involved in the mechanism of cell elongation (Boyer, 1968; Green, 1968; Green and Cummins, 1974) but some experiments have shown that turgor pressure may not always be important (Michelena and Boyer, 1982 ;King and Bush, 1985). The smaller osmotic adjustment in sugarcane leaves during the second stress when compared to the first may have resulted in the relatively high sensitivity of plant extension to leaf water potential during the second stress period. Michelena and Boyer (1982) restricted osmotic adjustment in maize by prolonging darkness and so preventing accumulation of solutes in the meristem. Sucrose accumulation was apparently restricted towards the end of the second stress period (Fig.**46** , chapter 8) and osmotic adjustment may have been limited by a deficiency of assimilate at this stage.

The lack of substantial osmotic adjustment in the second stress period conflicts with earlier evidence from the pot experiment in which osmotic potential (π) decreased with successive stress cycles and allowed plant extension to proceed at relatively low leaf water potentials (Table 3). This decrease in π was also evident in unstressed potted plants and appeared to to be a function of age as well as stress. Osmotic potential of irrigated plants in the field decreased only slightly with age. The threshold ψ_l in the potted plants appeared to be -0.7 to -0.9 MPa which is lower than the threshold values determined more directly for the field grown plants (-0.4 to -0.7 MPa). Comparative values for sunflower ,maize and soybean are -0.4, -0.7,-1.2 MPa respectively (Boyer 1968 and 1970; Acevedo et al, 1971). High resolution measurements on tall fescue leaves indicated that extension rate was highly responsive to factors such as illumination or vapour pressure deficit that were likely to moderate leaf water status (King and Bush, 1985). The apparent reduction in the extension rate of sugarcane plants when ψ_l fell below -0.2 MPa was therefore not surprising. Extension of sugarcane plants growing in soil that was periodically flushed with sucrose solutions of various osmotic strengths ,was apparently reduced when soil water potential (ψ_s) was less than -0.05 MPa and it ceased when ψ_s was -0.7 MPa (Hudson, 1968) . The water potential of leaves was probably similar to that of the soil solution since plants were not transpiring at the time of measurement.

The low extension rates of irrigated N12 were consistent with the tendency for this variety to develop a high population of relatively short stalks. The lack of variation amongst the varieties in sensitivity of plant extension to leaf water status is perhaps surprising, but continued leaf production during high water deficits does not necessarily confer drought resistance on a crop and is viewed by some as a disadvantage (Begg, 1980 p 36).

Plant extension was not rendered less sensitive to leaf water status by a previous occurrence of stress and there was little evidence of hardening due to a prolonged lowering of leaf osmotic potential, as has been suspected in some crops (McCree, 1974; Thomas, et al, 1976). Osmotic hardening has not been readily demonstrated in critical studies (Turner, 1980).

The relatively rapid increase in the diffusive resistance and rolling of leaves of N12 were characteristic of drought avoidance and water deficits understandably developed less rapidly in this variety than in NCo376 during the first stress cycle. Variations in genotypic drought avoidance of this nature have been found in other species. The superior drought resistance of ponderosa pine compared to grand fir, was ascribed to early stomatal closure of pine needles during the onset of stress (Lopushinsky, 1969). Sheriff and Kaye (1977) showed that differences in the response of stomata to stress accounted for the difference in drought resistance of the two legume species, *Macroptilium atropurpureum* and *Desmodium uncinatum*. *M. atropurpureum* displayed the greater tendancy to avoid stress by initiating stomatal closure early during the onset of stress.

An alternative adaptation to stress in higher plants is the reverse of the foregoing in that in some xerophytes, stomata close at very low leaf water potentials and are therefore able to proceed with moderate rates of photosynthesis (Kriedemann and Barrs, 1983). It is suggested that sugarcane, originating from the tropics, would have developed the 'avoidance' type of resistance mechanism since stress is the exeption rather than the norm of the habitat. It is further suggested that by closing its stomata early during the onset of stress, N12 may be more productive than other varieties only in conditions where droughts are frequent and where stalks of other varieties tend to die because of stress.

Although the young leaves of N14 rolled fairly readily, stomatal resistances of this variety were generally lower than those of NCo376 and N12 thus allowing comparatively low leaf water potentials to develop in the first stress period. The lack of difference between N12 and N14 in the rate at which ψ_l decreased during the second stress period may be ascribed to the substantially greater leaf area of N12 at the start of this period (Fig. 34, chapter 7). The leaf water potential at which stomatal closure approached completion, was reduced slightly by previous stress treatments in both the pot and the field experiments but the large adjustments that take place in some grass species after repeated stress (Ludlow, 1980) were absent in sugarcane. Lack of adjustment of this nature is associated with crops that originate from favourable climates (Ludlow, 1980).

In some crops the threshold leaf water potential for stomatal closure decreases markedly as the crop develops. The threshold leaf water potential for stomatal closure in Spring wheat was -1.2 to -1.3 MPa at tillering, -1.6 to -1.8 MPa at heading and -3.1 MPa during grain filling (Frank and Barker, 1976). There was no indication of a marked change in threshold ψ_l for stomatal closure in sugarcane even though the first stress was imposed before stalk elongation had started and the second was imposed during the rapid elongation stage. However, it was impossible to distinguish between the effect of age and that of stress history during the second stress period.

The ψ_l at which stomata finally close in sugarcane is similar to values of ψ_l for high stomatal resistance in maize (Beadle et al, 1973 and Turner, 1974) and lucerne (Brown and Tanner, 1983). The threshold ψ_l for the start of stomatal closure in sugarcane was considerably higher than an equivalent value for wheat (Bristow et al, 1981).

The concept of a daily stress index to estimate yield loss due to water stress using canopy temperature and vapour pressure deficit has now been extended to several crops (Idso et al, 1984) but not as yet to sugarcane. The index provided a reasonable indication of leaf water potential and leaf conductance despite the low vapour pressure deficits and windy conditions of the coastal experiment site. The index may be more precise in inland areas where air humidity is low. The concept of deriving a crop water stress index (CWSI) each day from satellite transmissions in order to predict daily crop water requirement has been given serious consideration (Hatfield et al, 1983; Wigand et al, 1983). It would be desirable to gain more information on how this index relates to cane yield when the concept is developed further. The temperature difference between unstressed and stressed canopies appeared to be a good indication of plant extension rate as well as ψ_l and k, but could only be used in irrigated areas where unstressed reference temperatures would be available. The height of the sugarcane canopy may present practical problems in taking regular temperature readings, but the speed of the technique and its large sample size are distinct advantages in monitoring irrigation situations.

Conclusions

The results confirmed the conclusions of the pot experiment that extension of sugarcane plants is more sensitive to water stress than is stomatal function. Extension was reduced when ψ_l was less than -0.2 MPa and it ceased when ψ_l was -0.4 to -0.7 MPa. Stomatal resistance increased slightly with the onset of stress but remained relatively low until ψ_l fell below -1.2 MPa. The rapid increase in the resistance of N12 leaves and the sluggish response observed in N14 helped to explain why N12 is more, and N14 is less, resistant to drought than NCo376. The extension rate of plants and the start of stomatal closure were not rendered less sensitive to water stress by the occurrence of an earlier stress. There was some indication that both extension rate and start of stomatal closure were more sensitive to stress in the second stress period than in the first.

Differences in temperature between leaf canopy and air were large enough, despite low vapour pressure deficits, to be used in a crop water stress index. An index based upon stressed -unstressed canopy temperature canopy temperature should however prove more useful. This index may be used in variety evaluation trials or in irrigation schemes to monitor crop water status since it may be obtained rapidly.

Chapter 6. RESULTS AND DISCUSSION ON SOIL WATER RELATIONS OF RATOON CROP

Upper and lower limits of available water

1. Pressure plate analysis

The conventional laboratory measure of the upper limit of water availability in the sugar industry is the water content of undisturbed cores equilibrated at -10 kPa air pressure on a porous ceramic plate (Johnston, 1973). Webster and Becket (1972) found that the water potential of British soils at zero deficit was commonly in the range -3 to -7 kPa even in very permeable soils. The upper limit of available water in some Zambian soils was over-estimated by 5 % when the plate pressure was -5 kPa and it was under-estimated by -10 and 35 % when plate pressures were -10 and -33 kPa respectively (McClean and Yager, 1972). Hall, Reeve, Thomasson and Write (1977) suggested that the divergence between water content at -5 kPa and field capacity at 48 hours after saturation would be small in most soils and within the random error inherent in physical measurement of this nature. The highest pressure used in the standard laboratory procedure followed during this experiment, was -7.5 kPa and the water content of cores equilibrated at this pressure was taken as the laboratory estimate of the upper limit (Table 12). The mean upper limit of all depth classes was 18.3 %. This may be compared with a mean value of 20.7 % estimated by the following regression equation developed by Mottram, Hutson and Goodman (1981) for soils in Natal:

$$WC_5 = 21.1 + 0.44C + 0.29Si + 1.06OM - 11.91BD \quad \%$$

in which WC_5=water content at a plate pressure of -5 kPa, C=clay %, Si= silt %, OM= organic matter % and BD= bulk density (kg l^{-1}). Values of C, Si and BD for each depth interval were obtained from tables 5 and 12. The mean OM in the top 0.5 m of soil was 0.88 % and this was applied to all depth intervals. Organic matter may have decreased with depth and reduced the value of WC_5 slightly.

The standard plate pressure of -1500 kPa was used to estimate lower limits of available water. The mean WC of 10.9 % obtained at this pressure (Table 12) may be compared with 11.2 % calculated using an equation similar to that above (Mottram, *et al*) :

$$WC_{1500} = 15.26 + 0.28C + 0.05Si + 2.32OM - 10.6BD \quad \%$$

in which WC_{1500}=water content at a plate pressure of -1500 kPa.

Table 12. Volumetric soil water content (WC), bulk density (BD) and available water capacity (AWC) of small undisturbed cores taken from pits inside (IN) and outside (OUT) the sheltered area and equilibrated at various plate pressures in the laboratory. AWC_l=(WC at -7.5 kPa minus WC at -1500 kPa). Each value is the mean of three determinations. Upper (UL) and lower (LL) limits of available water content (AWC_f=UL-LL) determined in the field.

		Laboratory data							Field data		
	Depth	-7.5 kPa	-10.0 kPa	-33 kPa	-100 kPa	-1500 kPa	BD	AWC_l	UL	LL	AWC_f
	cm	<------------WC %------------>					kg/l	mm/m	%	%	mm/m
IN	11	18.3	16.3	13.4	11.6	9.5	1.64	87	19.2	5.5	137
IN	23	16.3	14.1	13.4	11.4	7.0	1.59	82	16.0	6.6	94
IN	38	14.1	11.9	9.8	7.0	5.4	1.54	82	13.3	6.7	66
IN	53	14.8	12.3	10.0	7.3	5.4	1.54	97			
IN	68	12.5	10.5	8.3	6.2	4.6	1.56	76	13.3	6.4	69
IN	83	15.0	13.3	10.8	8.6	7.7	1.56	71	14.8	7.3	75
IN	98	15.2	13.2	11.4	8.8	7.2	1.57	77	16.4	8.9	75
OUT	98	13.3	11.7	9.5	8.2	6.0	1.56	66			
IN	113	16.3	14.4	12.6	9.0	7.5	1.54	84	18.2	9.4	88
OUT	113	12.3	10.6	8.4	7.1	5.7	1.58	63			
IN	128	18.2	16.5	15.0	10.6	8.8	1.56	93	20.1	8.2	119
OUT	128	14.9	13.1	9.9	8.0	6.6	1.60	83			
IN	143	22.5	20.7	17.7	13.4	11.8	1.62	105	19.2	10.9	83
OUT	143	17.9	16.1	11.6	8.9	7.6	1.64	95			
OUT	158	22.6	21.2	16.7	13.2	10.9	1.55	107	21.3	10.6	107
OUT	173	26.0	24.7	21.8	20.0	16.8	1.52	79	22.0	14.8	72
OUT	188	18.3	17.2	14.1	11.8	10.3	1.51	72	23.6	16.5	71
OUT	203	27.4	26.4	23.8	21.0	18.7	1.56	82	24.8	14.8	100
OUT	218	30.6	29.7	27.9	24.2	22.7	1.53	74			
OUT	233	31.7	30.5	28.2	25.0	23.3	1.53	79	24.6	16.2	84
OUT	248	31.7	30.7	28.3	25.4	23.0	1.53	85	24.0	17.2	68
MEAN		18.3	16.8	14.5	11.9	10.9	1.56	83	19.3	10.6	87

Water contents of cores equilibrated at -7.5 kPa and -1500 kPa varied with bulk density (BD) and clay content (particles < 0.002 mm). Volumetric water content at these limits decreased with soil depth and BD to approximately 0.5 m and then increased considerably with increasing depth and clay content to about 2.5 m (Fig. 28). Available water capacity (AWC_1), defined as the amount of water held between -7.5 and -1500 kPa pressure, decreased with depth to about 1.0 m and then increased to a maximum at about 1.5 m (Table 12). The mean AWC_1 obtained from the pressure plate data was 83 mm m^{-1} and the amount of water available to a depth of 2.7 m was therefore 224 mm. This AWC_1 is lower than the AWC_1 of 106 mm m^{-1} for a Clansthal sand analysed by Johnston (1973). Expected AWC for loamy sands in South Africa and in the USA were given as 100 and 70 mm m-1 respectively by Schulze, Hutson and Cass (1985).

The mean volumetric water content to a depth of 2.1 m in a Clansthal sand, 72 hours after saturation was 14.4% (Thompson *et al*, 1967). The mean water content of undisturbed cores of the same soil equilibrated at -1500 kPa was 4.0 %. The soil investigated by Thompson contained 48 to 53 % fine sand compared to 16 to 22 % fine sand in the Clansthal sand at the rainshelter site and this difference may account for the observed differences in upper and lower limits of available water.

2. Field analysis

The concept of an upper limit of water availability stems from the assumption that water drains rapidly from soil pores greater than 0.03 mm in diameter and then ceases. The soil water potential at this stage is often about -10 kPa. In most soils drainage does not cease at this point but proceeds at a rate that depends on depth of the column of gravitational water (Hamblin, 1985). The common working definition of field capacity, 'the wetness of the initially wetted zone two days after after infiltration', takes no account of factors such as the antecedent wetness of the soil, the depth of wetting and the presence and depth of a ground water table (Hillel, 1980). Nevertheless the concept of field capacity is wide spread and is useful in obtaining comparable values of available water content. Cassel, Ratliff and Ritchie (1983) recorded field capacity when daily changes in water content of a profile after wetting were between 0.1 to 0.2 percentage units. McClean et al, (1972) pointed out that if field capacity is the upper limit of water available for 'consumptive use' then it should be determined within 1 to 4 days after the profile is wetted even if drainage continues therafter. If the upper limit is taken as the point at which drainage practically ceases, then a substantial amount of gravitational water which is available to the crop would be ignored.

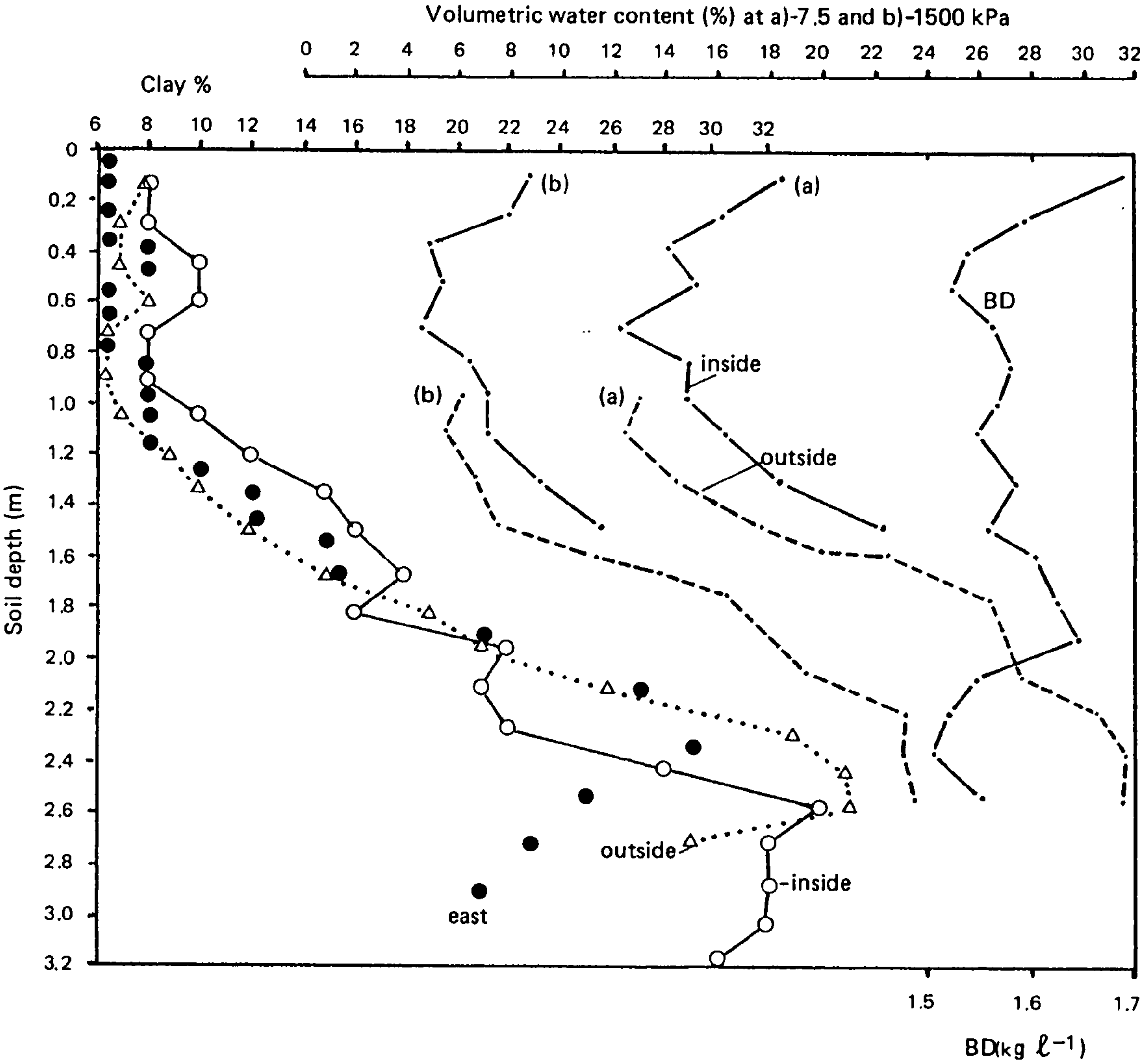

Figure 28. Clay content and volumetric water content of small undisturbed cores removed from different depths of pits inside and outside the sheltered area, mean bulk density of large cores removed from both pits and clay content of cores removed from east end of site.

The 2.7 m profile at the rainshelter site contained 542 ± 4.6 mm water, 48 hours after receiving 390 mm irrigation and this amount of water retained in the soil was regarded as the upper limit of available water or field capacity although the profile continued to drain during the next 34 days (Fig. 29).

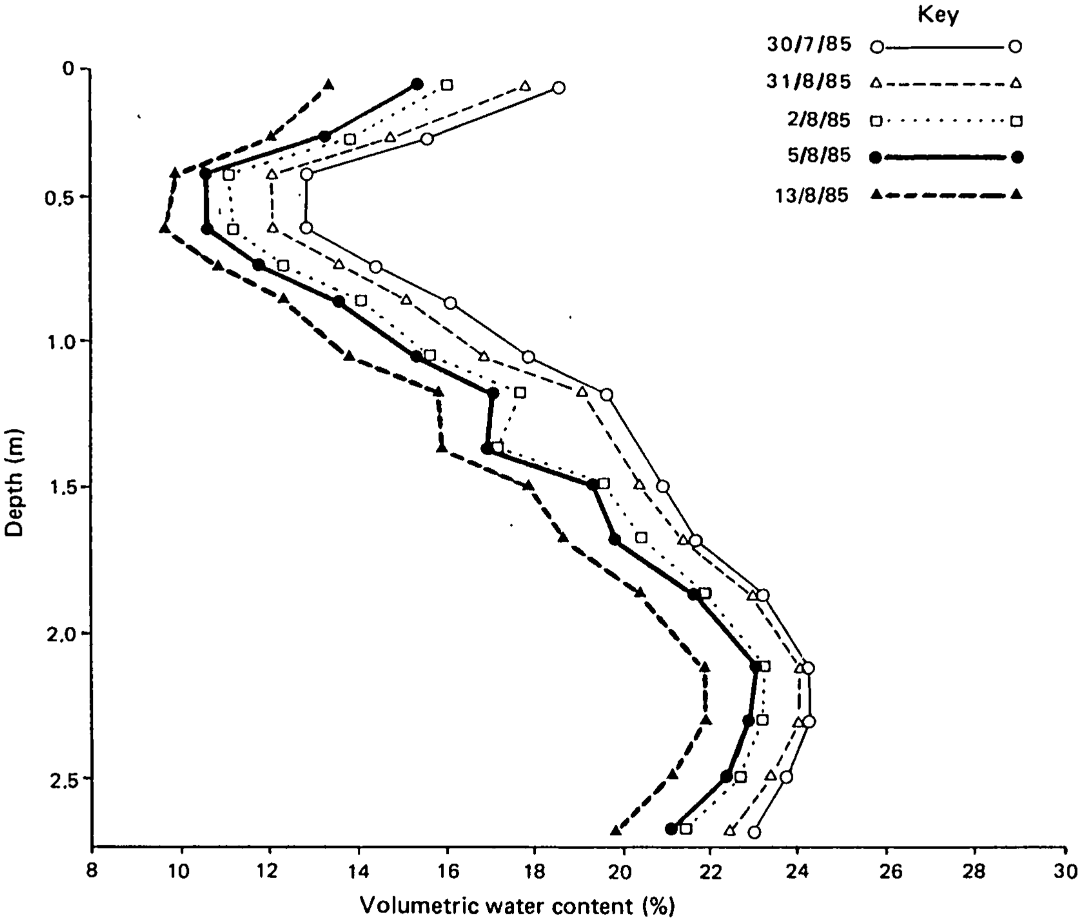

Figure 29. Mean water content of W1 plots at various stages after excess irrigation was applied on the 28th July 1985. Water content (field capacity=FC) of undisturbed cores equilibrated at -10 kPa in the laboratory.

The lower limit is conventionally defined as the WC at which plants fail to recover from wilting when transpiration stops overnight. This degree of stress was not reached in the plant crop even after rain and irrigation had been withheld for five months. However, very little water was removed from the measured profile (2.9 m) between the 29th May and 5th July when the degree of stress was most severe (Fig. 30). During the ratoon crop when rooting depth was restricted by applying limited amounts of irrigation, WC at depths below 1.5 m remained practically constant and equal to WC at the end of the plant crop (Fig. 31). Apart from the top 150 mm soil, water contents at the end of the plant crop and at the end of each stress period in the ratoon crop were similar (Figs. 30 and 31).

The lowest WC of the 2.7 m profile at these times was 312 ± 3 mm and this value was taken as the lower limit of available water. It is doubtful that the crop was capable of removing significant amounts of water at this low concentration even though plants recovered almost completely from wilting overnight. Pre-dawn leaf water potentials were between -0.5 and -0.8 MPa at the end of the first stress period (Fig. 18) and recovery from wilting was therefore to be expected (Fig. 9). The pre-dawn ψ_l may be equated to the bulk soil water potential (ψ_s) of the root zone which probably contained only marginally more water at -0.5 to -0.8 MPa than at -1.5 MPa (Table 12).

The available water content determined in the field (AWC_f) was thus:

$$AWC_f = (542-312) / 2.7 = 85 \text{ mm m}^{-1}.$$

The total amount of available water in the profile may be termed the 'profile available water' or PAW.

Thus $\quad PAW = 542-312 = 240$ mm

The mean AWC_f over all depth classes was 87 mm m^{-1} and the mean AWC_l was 83 mm m^{-1} (Table 12). There was therefore good agreement between the laboratory and the field estimates of available water in the profile. The lack of agreement between AWC_l and AWC_f in all depth classes is perhaps not surprising since AWC_f was obtained from upper and lower limits determined in different parts of the field and AWC_l was determined in yet another location.

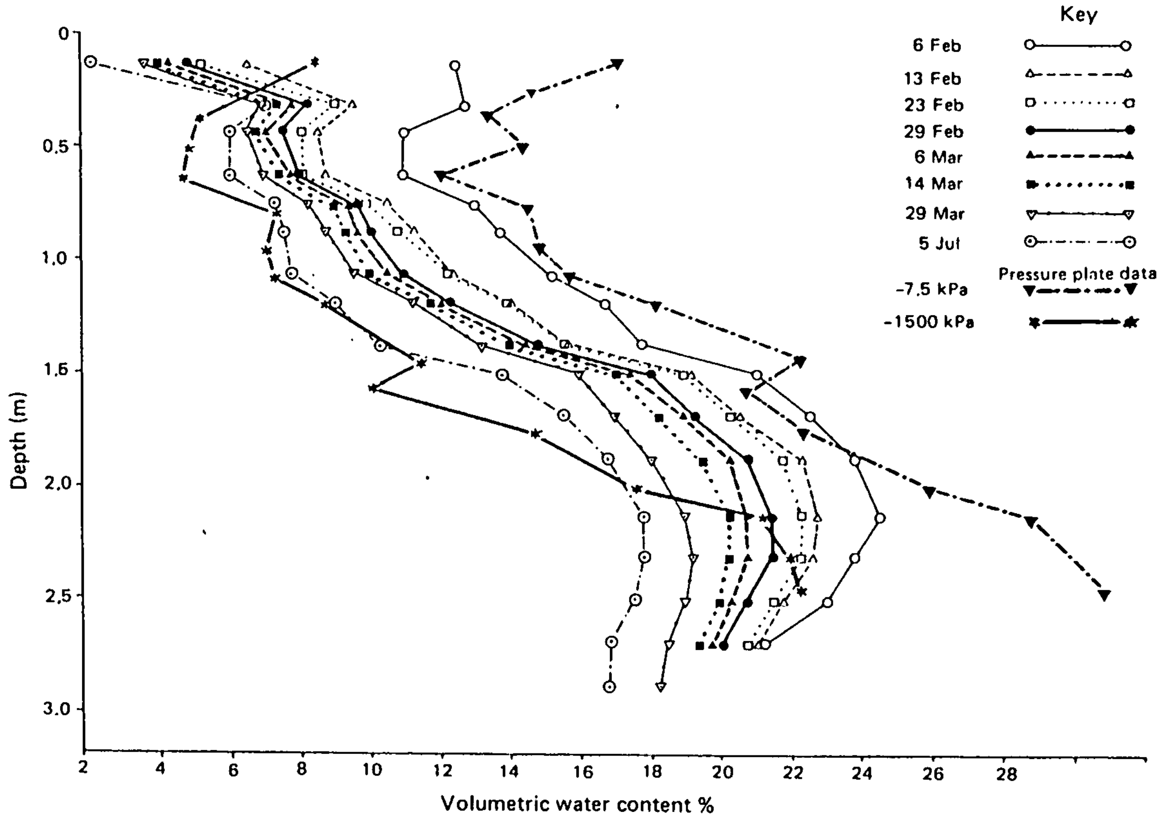

Figure 30. Water content of the profile under the sheltered area after rain and irrigation were excluded during the plant crop. Upper and lower limits of water availability (-7.5 and -1500 kPa) as determined in the laboratory.

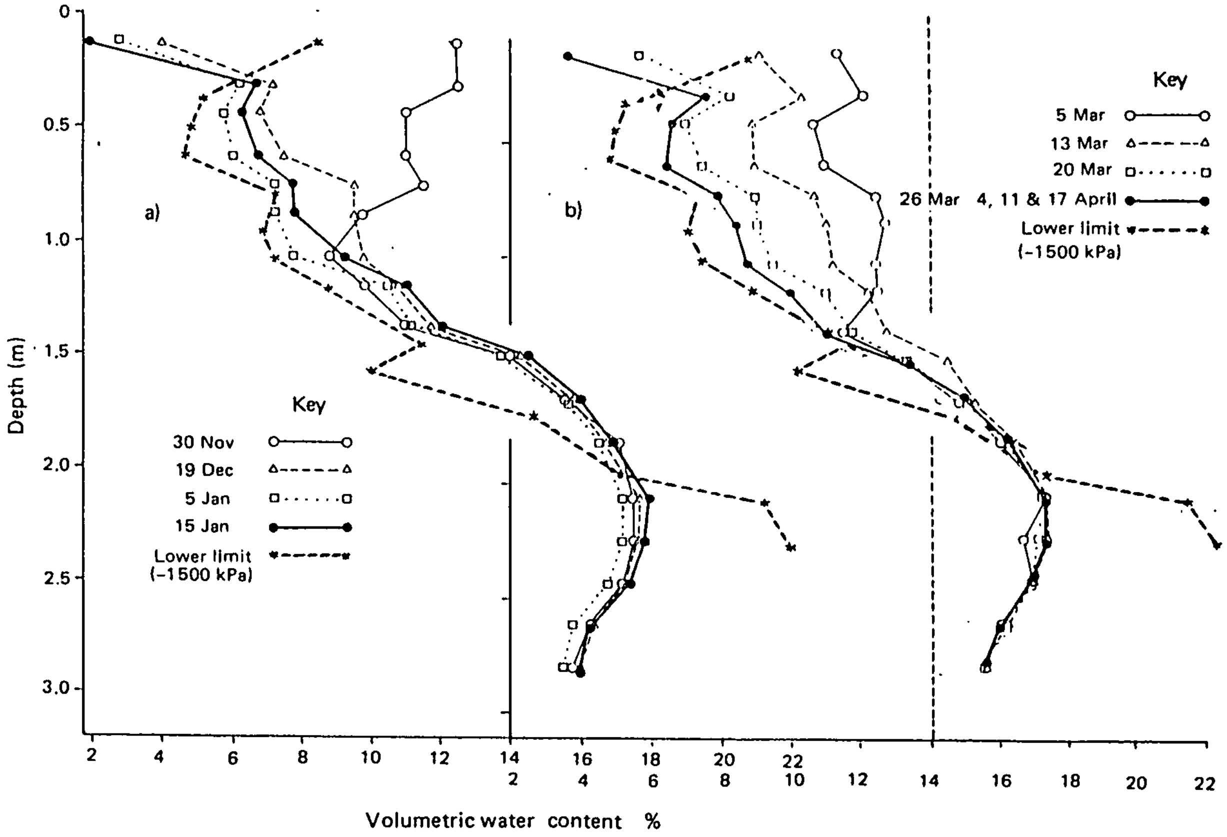

Figure 31. Water content of the profile of W2 plots on the 30th November (a) and the 5th March (b) and at various stages thereafter while irrigation was being withheld during the first stress period. Lower limit of water availability (-1500 kPa) as determined in the laboratory.

The field and laboratory estimates of the upper and lower limits deviated substantially below 2.0 m depth. The field limits followed the trend in clay content and it appears that the limits obtained in the laboratory were wrong.

Depth of water extraction and root density

It is evident from Fig. 30 that the plant crop under the rainshelter removed substantial amounts of water from the greatest depths accessed by the neutron probe during April and June 1984, when water in the surface layers had been exploited. Very little water was removed from the 2.9 m profile between the 20th June and 5th July 1984 and yet the crop was not permanently wilted. It is likely that water was being extracted from below the measured profile at this stage. In the ratoon crop water was not allowed to reach the deeper layers of soil under the rainshelter and WC remained practically constant at depths greater than 1.5 m (Fig. 31). The coefficients of variation (CV) of water contents at these depths (Table 13) were of the same order as the CV's of the standard neutron counts (appendix 2).

Table 13. Coefficients of variation (%) of 20 water content determinations for 16 depth classes of the soil profile under well irrigated plots (W1) and stressed plots (W1) during the ratoon crop.

Depth (m)	CV(%)		Depth (m)	CV(%)	
	W1	W2		W1	W2
0.15	22.1	58.3	1.35	3.2	10.4
0.30	12.5	30.1	1.50	3.4	4.9
0.45	12.9	29.2	1.70	3.1	1.1
0.60	12.9	27.1	1.90	2.7	0.9
0.75	11.2	23.3	2.10	2.4	0.8
0.90	8.9	21.4	2.30	2.6	1.2
1.05	6.5	20.3	2.50	2.8	1.0
1.20	4.6	16.1	2.70	9.4	1.1

The relatively high CV's for WC in the top 1.5 m of soil of W1 plots indicate that most of the water exchange took place in these layers (Table 13). The CV's of the deeper layers were only slightly larger than those of corresponding layers of W2 plots (Table 13) and it is unlikely that the amounts of water extracted at these depths or beyond these depths were large. It should be noted however that the small variation in WC at depth in the W1 profiles could possibly arise from near equal exchanges in drainage water and water removed by roots.

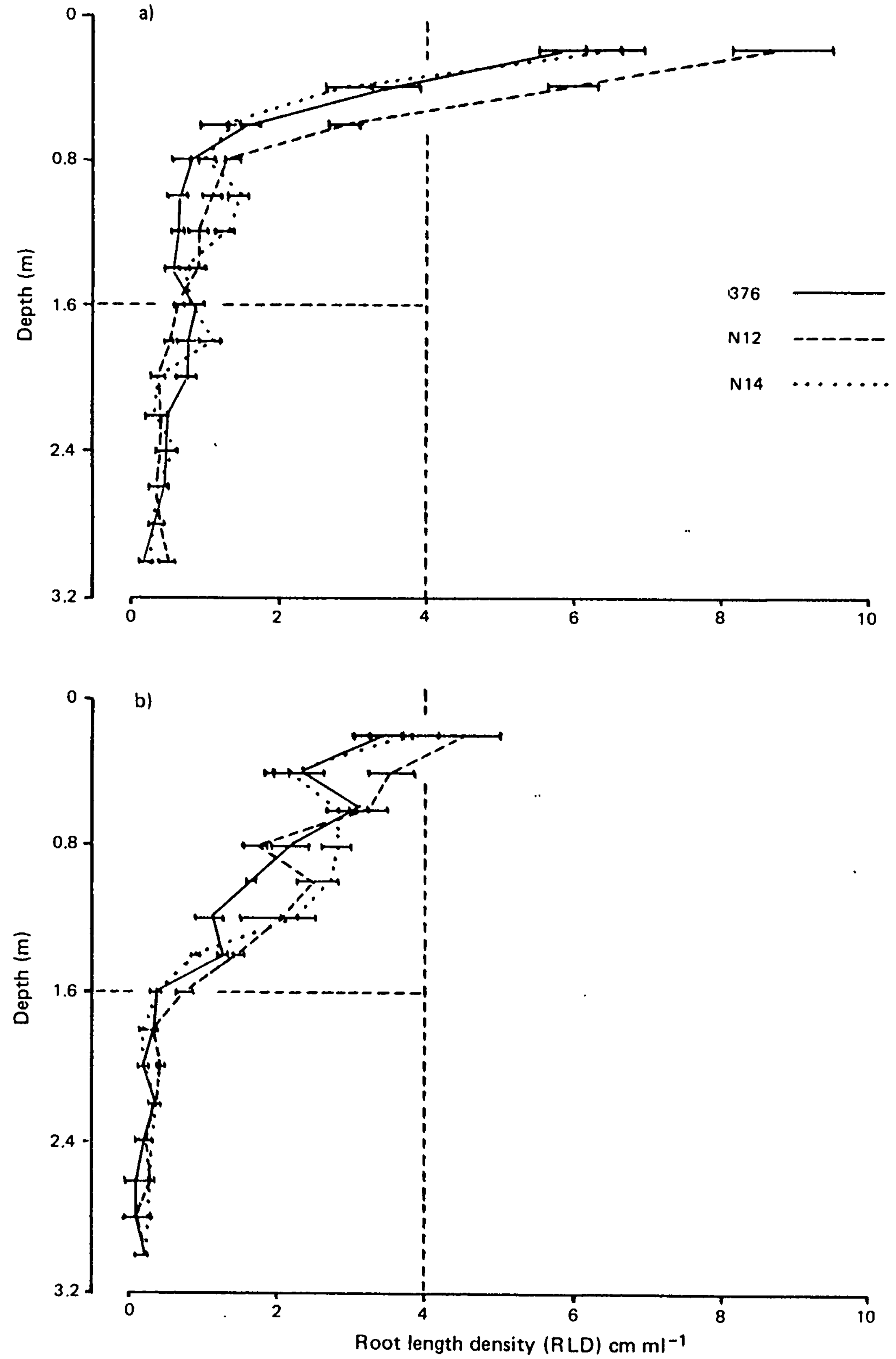

Figure 32. Root length density (RLD) of unstressed plants a) and stressed plants b) shortly after the ratoon crop had been harvested. Values are means of four core samples (two from each replication). Bars denote standard errors.

The pattern of water uptake was similar to the rooting pattern. Root length density (RLD) was greatest at the surface and it decreased rapidly with depth in both irrigated and stressed profiles (Fig. 32). Roots of W1 plants were more prevalent than those of W2 plants at the surface as well as at depth and roots of stressed plants were more prevalent than those of unstressed plants at intermediate depths of 0.8 and 1.2 m. Studies in a root laboratory indicated that varieties of sugarcane may differ substantially in rooting depth particularly under conditions of stress (Rostron, 1974). The soil core technique (Schuurman and Goedewaagen, 1965) used in this experiment may not have been sufficiently precise to show substantial varietal differences under stress. However water was artificially restricted to the top 1.5 m of soil and root growth may have occurred more rapidly in one variety than another if water had penetrated below this depth periodically.

The RLD data obtained for sugarcane in this experiment may be compared with that of maize grown in loamy fine sand in which RLD ranged from 6.2 to 3.7 cm ml^{-1} to a depth of 1.8 m (Taylor and Klepper, 1973). RLD of cotton in the same soil was comparatively low (1.8 to 1.1 cm ml^{-1}). Roots of sugarcane have been shown to be active at a depth of 4.0 m in a sandy soil such as the soil at the rainshelter site (Thompson, 1976).

It was considered that drought resistance in N12 may be due to a greater rooting depth than that of other varieties. N12 evidently had a slightly higher rooting density than the other varieties at a depth of 1.2 to 1.4 m (Fig. 32) which was the limit of water extraction in the ratoon crop. However the amounts of water removed from successive layers relative to the total amount, gave no indication that extraction patterns differed between varieties (Table 14).

Table 14. Amounts of water, relative to the total (WU%), removed by W2 plants from successive depths during the stress periods of the ratoon crop. Values are means of two plots x two stress periods except for 1.05 and 1.20 m depths which were not exploited during the first stress period.

Var-		Soil depth (m)							
iety		0.15	0.30	0.45	0.60	0.75	0.90	1.05	1.20
NCo	%	39.3	27.7	17.2	7.8	4.2	2.7	1.4	0.3
376	SE	3.5	3.5	1.2	3.1	1.8	1.1	.	.
N12	%	30.6	27.6	19.7	11.2	6.2	3.5	1.5	0.1
	SE	2.5	2.8	0.6	1.7	2.1	0.6	.	.
N14	%	34.3	26.5	17.2	9.0	6.0	3.9	3.6	0.7
	SE	3.3	4.1	0.4	3.2	2.2	1.6	.	.

Drainage component of soil water balance

Field capacity was determined after the ratoon crop was harvested. A large polyethylene sheet was placed over W1 plots before applying excessive amount of irrigation on the 28th July and again on the 4th September. Since evaporation from these plots was prevented and no rain fell during the measurement period, changes in water content were equated to the amount of water that drained from the 2.7 m profile. The relationship between drainage rate (D) and profile available water (PAW) in the 2.7 m profile of each W1 plot is shown in Fig. 33. The relationships were adequately described by polynomial functions of the form:

$$D=a+b.PAW+c.PAW^2$$

where a, b and c are constants of regression. The results of the regression analysis are given in Table 15.

Table 15. Coefficients of regression and standard errors (SE) for drainage rate (D in mm d^{-1}) dependant on profile available water (PAW in mm) of the 2.7 m profile. SE of a single estimate (SE est. in mm d^{-1}).

Var-iety	Plot No.	a	SE(a)	b	SE(b)	c	SE(c)	r^2	SE est.
376	27	114.8	29.5	-1.55	0.34	0.005243	0.000954	0.95	1.7
376	29	138.7	32.6	-1.62	0.33	0.004729	0.000829	0.96	1.4
N12	25	177.6	39.8	-2.08	0.41	0.006102	0.001035	0.96	1.9
N12	30	81.7	21.5	-1.09	0.24	0.003659	0.000637	0.97	1.2
N14	26	133.2	25.0	-1.69	0.27	0.005401	0.000742	0.98	1.2
N14	28	135.4	47.4	-1.52	0.46	0.004307	0.001096	0.94	1.7

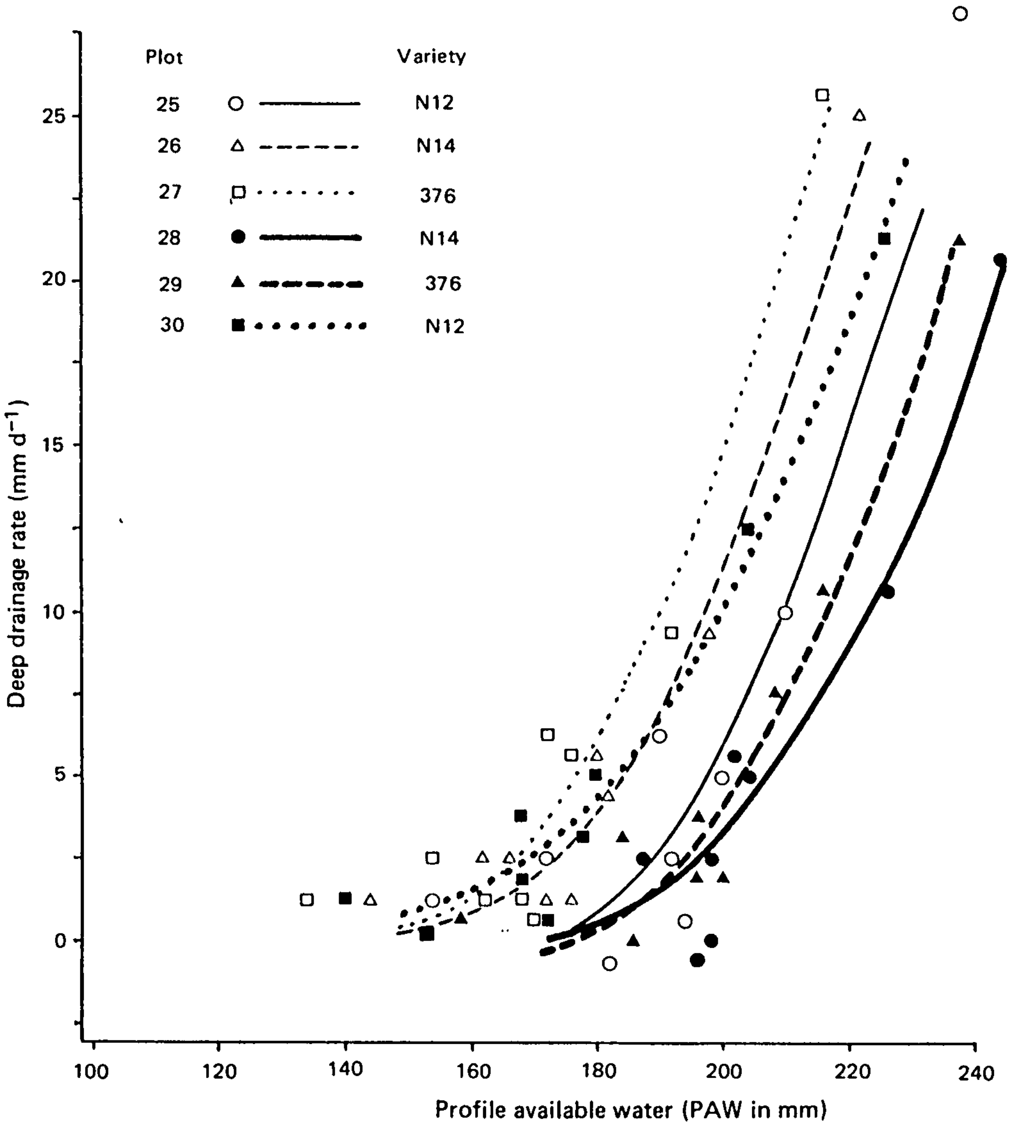

Figure 33. Deep drainage rate in relation to available water in the 27m profile (PAW). Curves fitted by least squares.

The upward and downward components of vertical soil water flux for each layer in the profile may be distinguished if ψ_s , WC and hydraulic conductivity for each layer are known (Scholl, 1976). Since the last of these three factors was unknown it was possible to estimate only the amount of deep drainage that occurred in W1 plots, however this was the only component of drainage that was required in deriving crop water use from neutron probe readings. Deep drainage rate was determined from the regression data in Table 15.

An iterative procedure was used to estimate the daily amounts of drainage and evapotranspiration between dates of neutron probe readings. The steps in the procedure were as follows:

1 Calculate the mean pan ratio (PR) for the interval between two probe readings assuming zero drainage.

$$PR = (PAW_{t+1} - WC_t + \lesssim R_d + \lesssim I_d) / \lesssim Eo_d$$

where ≲EO=daily pan evaporation (mm) accumulated over n days (d) between probe readings at time (t), PAW = profile available water, ≲R , ≲I = rainfall and irrigation (mm), respectively, accumulated over n days. WC = Water content.

2 Calculate a preliminary profile available water PPAW for the next day by adding rainfall and irrigation and subtracting the amount evaporated from the pan times the pan ratio.

$$PPAW_{d+1} = PAW_d + R_{d+1} + I_{d+1} - (Eo_{d+1} \cdot PR)$$

3 Calculate the drainage component (D) using regression data in Table 15. Drainage was assumed to be zero when PAW was lower than the point of inflection of the curve (Fig. 33). Subtract the drainage component from the preliminary PAW.

$$D_{d+1} = a + b.PPAW_{d+1} + c.(PPAW_{d+1})^2$$

$$PAW_{d+1} = PPAW_{d+1} - D_{d+1}$$

4 Do steps 2 and 3 for n days between successive probe readings.

5 If the calculated PAW on day n is not within 2 mm of the PAW measured by the probe then subtract 0.01 from the pan ratio and repeat steps two and three again.

Thus it was assumed that gravitational water was removed first by the crop and then by deep drainage. It also was assumed that no water drained from the profile under the rainshelter during the ratoon crop. This is a reasonable assumption since neutron counts at depths below 2.0 m remained practically constant during both stress periods (Fig. 31). This is not necessarily proof of zero drainage (Greacen, 1981) but the water contents of these layers were well below the lower limit of water availability determined in the laboratory. Also, there was no perceptible change in the water content of each layer under the shelter between 26th March and 17th April when the crop was severely stressed. Any drainage from the profile would have been detected during this period. It was unlikely therefore that soil below the measured profile contained readily available water during the ratoon crop since rainfall was excluded for at least 11 months and amounts of irrigation on the sheltered area were restricted to 70 mm or less.

Evapotranspiration (Et)

The computed mean daily drainage and evapotranspiration components of soil water flux of W1 plots are shown in Table 16. Et of well watered sugarcane apparently differed significantly between the varieties although some caution should be exercised in making this observation since there were only two replications of the varieties. Et from the N12 plots was consistently lower than Et from plots of the other varieties. There was no marked trend in Eo and Et over the six month period but values were lower towards the end of this period as would be expected.

The method of determining drainage was over-simplified and the crop may have used some water stored below the depth of the access tubes. This may have occurred between the 2nd and 15th January and between the 14th and 20th March when Et was considerably lower than Eo. However it was apparent from the small variation in water content of the deepest layers accessed by the neutron probe (Table 13) that water stored at these depths and beyond was probably not used to any great extent.

The experimental site was not ideal for measuring potential evapotranspiration because of the absence of suitable fetch and the proximity of a wind break. The class-A pan was located in a more exposed position than the W1 plots relative to the wind break. Nevertheless Et of W1 plots was a valid measure of evaporative demand on the W2 crop. The mean Et for W1 plots in Table 16 was 5.2 mm d^{-1} which was 0.86 of mean pan evaporation. The Et/Eo ratio was lower than commonly found for sugarcane after canopy closure (Thompson, 1976).

Table 16. Class-A pan evaporation (Eo), evapotranspiration rate (Et) per day meaned over varieties and replications, deviation (Dev.) from mean Et and deep drainage rate per day (D) of plots of three varieties of sugarcane adequately supplied with water (W1) or stressed during December-January and March-April (W2). The second date of two consecutive neutron probe readings is given. Values are mm d^{-1}. Analysis of variance of Et data follows body of table.

		Well watered plots (W1)							Stressed plots (W2)			
		Mean	Dev. from mean			Deep drainage			Mean	Dev. from mean		
Date	Eo	Et	376	N12	N14	376	N12	N14	Et	376	N12	N14
NOV 30	5.6	5.3	0.1	-0.3	0.2	0.1	0.4	0.3	3.8	-0.3	0.7	-0.3
DEC 19	6.7	5.1	0.1	-0.6	0.5	0.0	0.0	0.0	3.4	0.1	0.0	-0.1
JAN 1	6.4	7.0	-0.1	0.0	0.2	0.0	0.2	0.2	1.2	-0.2	0.2	0.0
JAN 15	7.0	3.1	0.5	-0.5	0.1	0.0	0.4	0.3	0.2	0.0	0.0	0.0
JAN 30	4.8	5.7	0.2	-0.6	0.4	3.4	5.0	4.2	2.9	0.2	-0.1	-0.1
FEB 7	7.0	5.7	0.0	-0.5	0.5	0.0	0.2	0.2	5.0	0.3	-0.2	-0.1
FEB 19*	3.5	.	.	.	.	.	.	.	3.0	-0.4	0.6	-0.2
FEB 27	6.7	4.8	0.3	-0.3	0.0	0.0	0.2	0.2	4.4	0.4	-0.2	-0.2
MAR 5	7.1	6.4	-0.4	-0.2	0.6	0.0	0.2	0.2	5.1	1.1	-1.1	0.1
MAR 13	6.6	6.0	0.0	-0.1	0.1	0.4	0.6	0.6	1.7	-0.5	0.0	0.5
MAR 20	6.9	3.9	-0.3	-0.2	0.5	0.6	0.8	0.8	3.7	0.3	0.0	-0.3
MAR 26	6.7	5.6	0.6	-0.5	-0.1	0.1	0.4	0.2	2.0	-0.7	0.1	0.6
APR 4	6.3	4.7	-0.1	-0.2	0.4	0.8	1.2	1.0	2.0	0.0	0.0	0.0
APR 11	5.4	7.1	-0.3	-1.3	1.7	1.1	2.0	1.4	0.3	0.0	0.0	0.0
APR 17	5.5	5.1	0.3	-0.6	0.3	1.1	2.2	1.6	0.2	-0.1	0.3	0.2
APR 23	5.6	4.2	-0.1	0.1	0.1	0.2	0.7	0.4	0.3	0.0	-0.2	0.2
MAY 1	4.8	4.6	0.3	-0.3	0.1	0.4	0.9	0.6	2.5	0.3	0.2	-0.5
MAY 27	3.9	4.2	0.0	-0.3	0.3	0.3	0.4	0.2	2.5	0.2	-0.3	0.1

Analysis of variance:	W1 plots			W2 plots	
Source	DF	Sum of squares	F	Sum of squares	F
Replications	1	0.3648	1.0	0.1664	0.3
Varieties (V)	2	9.4025	13.5	0.1342	0.4
Dates of measurement (M)	16	109.6618	19.7	261.9702	55.5
V*M	32	10.9641	1.0	11.7568	1.2
Error	50	17.3801		14.7508	
Total	101	147.7734		288.7785	
Coefficient of variation =		5.1 %		22.4	
Standard error of single Et value		0.58 mm d-1		0.5	

* A calculation for Et of W1 plots during the 8th to 19th February was precluded by rainfall of over 300 mm.

Evapotranspiration from stressed plots was substantially lower than from unstressed plots even before irrigation was suspended at the end of November. In November leaf area index (LAI) of W2 plots was lower than that of W1 plots (Fig. 3 4, Chapter 7) because tillering in W1 plots had been promoted when shoots that had emerged during the interval between harvesting the W2 and W1 plots, were removed. There were no significant differences in Et between the varieties in W2 plots.

Et of W2 plots remained unchanged for two weeks after irrigation was suspended in November and then it decreased rapidly to zero during January (Table 16). The decline in Et after the 19th December corresponded with a rapid increase in leaf resistance (Fig. 22) and with a decrease in LAI (Fig. 34). Et of W2 plants increased rapidly after irrigation was resumed on the 22nd January and was only 0.4 to 0.7 mm d^{-1} lower than the Et of W1 plants during February. Thereafter Et of W2 plants decreased rapidly to zero probably because of a rapid increase in leaf resistance at this stage (Fig. 22). Et of W2 plants increased rapidly once irrigation was resumed in April it did not reach the Et values observed in W1 plants before the crop was harvested.

Conclusions

1. The lower limit of soil water availability determined in the laboratory corresponded reasonably well with the minimum soil water content that could be tolerated by sugarcane without death of mature stalks.

2. Available water stored at a depth of more than 2.5 m in a sandy clay loam was readily removed by a crop undergoing water stress.

3. Evapotranspiration increased rapidly to rates near potential when sugarcane was relieved of stress.

4. Evapotranspiration after full canopy was apparently lower in N12 than in NCo376 and N14.

5. There was no appreciable difference between the varieties regarding changes in Et during or after water stress.

Chapter 7 RESULTS AND DISCUSSION ON GROWTH ANALYSIS AND WATER USE EFFICIENCY OF RATOON CROP

Leaf area index

Leaf area index (LAI) of W1 plots was greater than that of W2 plots in November prior to the imposition of the first stress period (Fig. 34). This arose because the plant crop in the unsheltered area (W1) was harvested a few weeks before the W2 plots and shoots that developed in the intervening period were removed. This stimulated tillering in W1 plots and consequently increased LAI.

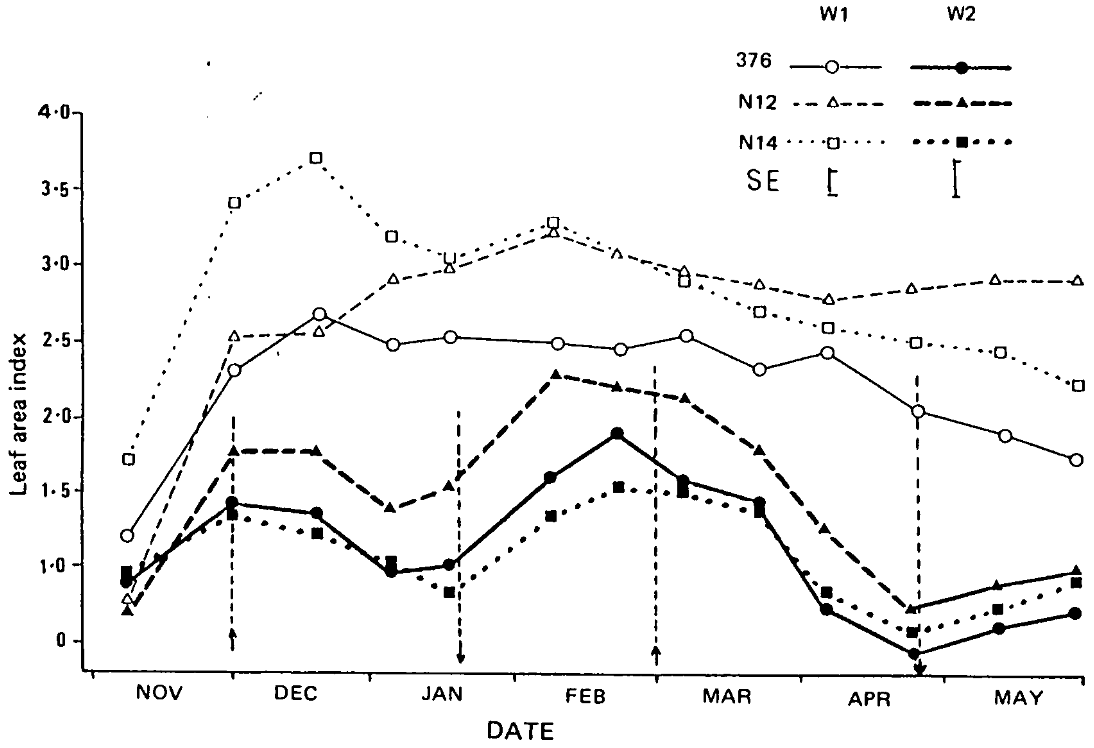

Figure 34. Leaf area index (LAI) of well watered plants (W1) and plants subjected to periods of stress in December 1984 / January 1985 and in March/April 1985 (W2). Arrows show when irrigation was suspended (↑) and resumed (↓). Root error mean square (SE of single value) shown by bars.

LAI of the unstressed N14 increased rapidly reaching a peak of about 3.5 in December before declining somewhat. N12 developed a LAI of 3.0 which was similar to that of N14 for a while before the LAI of N14 decreased to about 2.3 just before harvesting. The

LAI of unstressed NCo376 rose only to 2.5 and declined slightly prior to harvesting. LAI of NCo376 in irrigated conditions rose to 3.0 in a growth analysis experiment by Gosnell (1968) and then decreased as cane matured. N12 may differ from N14 and NCo376 in maintaining a high LAI for a longer period. Bull and Glaziou (1975) report leaf area indices approaching 8.0 when cane was about 10 months old. The relatively low LAI values of sugarcane in South Africa are probably due to the narrow leafed varieties that are selected for persistance under relatively marginal growing conditions.

Water stress appeared to alter the leaf area indices of the three varieties differently. N12 maintained a greater LAI than that of the other varieties during and after the two periods of stress. LAI of all varieties recovered rapidly soon after the first stress treatment was terminated and it decreased again soon after stress was imposed for the second time.

Interception of light

The photosynthetically active radiation (PAR) intercepted by foliage at midday was considered to be the amount that was neither reflected nor transmitted. The proportion of PAR intercepted by the unstressed crop, although measured on one occasion only (not shown), was likely to have remained above 0.9 after the 2nd January when measurements on PAR interception of stressed crops were started (Table 17). At this stage stressed plots of N14 were intercepting considerably more PAR than N12 or NCo376 although LAI of N12 was greater. N12 has erect leaves while those of N14 tend to droop and intercept more light. PAR interception of W2 plants increased to about 0.9 after irrigation was resumed in January. The varieties differed little in this regard until PAR interception started to decrease in April. The decrease in interception was more marked in NCo376 than in the other varieties. Plots of NCo376 intercepted less than 0.6 of incident PAR when plants were severely stressed on the 22nd April whereas plots N12 and N14 intercepted 0.64 or more of incident PAR.

Table 17. Proportion of photosynthetically active radiation (PAR) intercepted by foliage of W2 plants largely during the second stress period. Irrigation was resumed on the 22nd January, suspended on the 28th February and resumed again on the 22nd April.

Treat -ment	Plot	Date in 1985										
		January 2	January 21	March 21	April 4	April 5	April 9	April 12	April 17	April 19	April 22	May 21
376W2	A	.48	.51	.89	.82	.78	.66	.62	.66	.61	.56	.78
	B	.53	.50	.84	.73	.73	.64	-	.61	.57	.59	.80
N12W2	A	.60	.52	.92	.87	.83	.80	.77	.76	.72	.70	.85
	B	.59	.48	.83	.77	.74	.70	.71	.71	.67	.65	.84
N14W2	A	.76	.64	.89	.84	.80	.73	.71	.70	.67	.64	.77
	B	.77	.64	.92	.84	.82	.83	.81	.79	.77	.79	.88

Estimation of stalk mass

There were two methods of estimating stalk mass non-destructively during the growth of the crop. The one was to use the relationship between volume and mass of stalks removed at approximately three week intervals and the other was to use the final dimensions of the stalks that were marked for recurrent measurement and were destroyed only when the crop was harvested.

1. Method 1. Mass/volume of stalks destroyed at intervals

Stalk volume provided a good estimate of fresh mass in each of the seven destructive samplings. Although regression coefficients differed significantly amongst some treatments and amongst some sampling occasions there were no trends in the data and it appeared reasonable to use one regression equation to estimate fresh mass from stalk dimensions. When all mass and corresponding volume data were pooled (Fig. 35) fresh mass (FM) was related to stalk volume (SV) in the following way :

$$FM = [(1.05 \times SV) - 0.68] \quad ; r=0.993 ; DF=228$$

The 95% confidence limits for the slope, b, were 1.034 to 1.067 g ml^{-1} and for the intercept in the equation they were -9.44 to 8.09 g. In order to use this equation to estimate the mass of stalks *in situ*, the stalks were regarded as cylinders even though they tended to taper towards the top. The mean diameter of all internodes _in situ_ was used to calculate stalk volume.

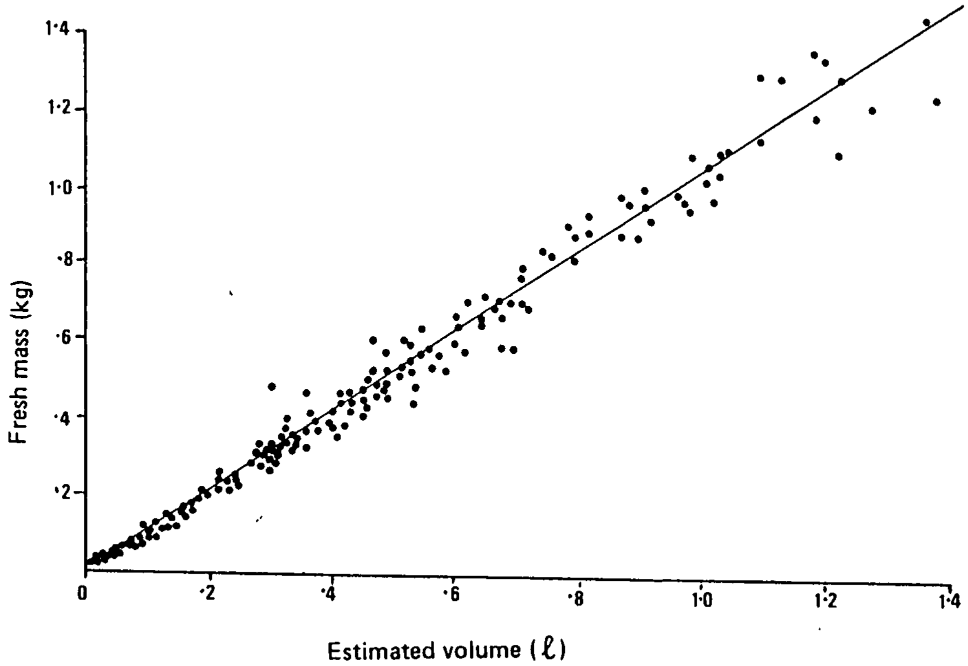

Figure 35. Stalk volume estimated from length and diameter of stalks and fresh stalk mass of three varieties in two water regimes on six sampling occasions.

2. _Method 2_.

a) _Final dimensions of marked stalks_: The diameter and length of each internode of marked stalks in the undisturbed plots were measured more accurately in the laboratory than in the field. When other stalks in the field were measured on the 21st March and again on the 14th June it was evident that the diameter of the youngest internode that could be detected on the intact stalk increased significantly by a small amount (0.5 mm) over the three month period. The length of the youngest internode and the length and diameter of older internodes remained practically constant over this period (Table 18).

Table 18. Average change in diameter and length of the top five internodes of ten W1 stalks and twelve W2 from 21st March to 16th June. Varieties were pooled.

	Diameter (mm)					Length (mm)				
Internode	1	2	3	4	5	1	2	3	4	5
Wet plots										
Mean change	0.48	0.18	-0.02	-0.03	0.01	0.2	-0.6	-0.8	-0.7	0.7
SE of mean	0.12	0.12	0.08	0.12	0.11	0.5	0.4	0.7	0.6	0.7
Dry plots										
Mean change	0.44	0.19	0.12	0.13	0.17	-0.6	-1.3	0.4	-1.1	0.1
SE of mean	0.24	0.02	0.16	0.25	0.16	0.4	0.8	0.6	1.1	1.2

b) *Estimation of stalk mass using stalk density*: The apparent density of measured stalks in the undisturbed plots changed slightly with distance from the top (Fig. 36) particularly in W1 plots. The apparent density of NCo376 was generally higher than that of N12 or N14 probably because the internodes tended to narrow in the middle where the diameter was measured. It was assumed when estimating the mass of growing stalks that density gradients from top to bottom were constant for variety and stress treatment. This was not an unreasonable assumption since gradients of dry matter content and of concentrations of soluble solids tend to be similar at the top of both young and old stalks (Fig. 41 , chapter 8).

The volume of the fully extended portion of intact stalks was calculated from internode lengths and diameters measured in the laboratory at the end of the experiment and from the height of the extending internode measured in the field on each sampling occasion. The mass of each internode was estimated from its apparent density and volume and stalk mass was the sum of the the mass of all internodes produced at the time.

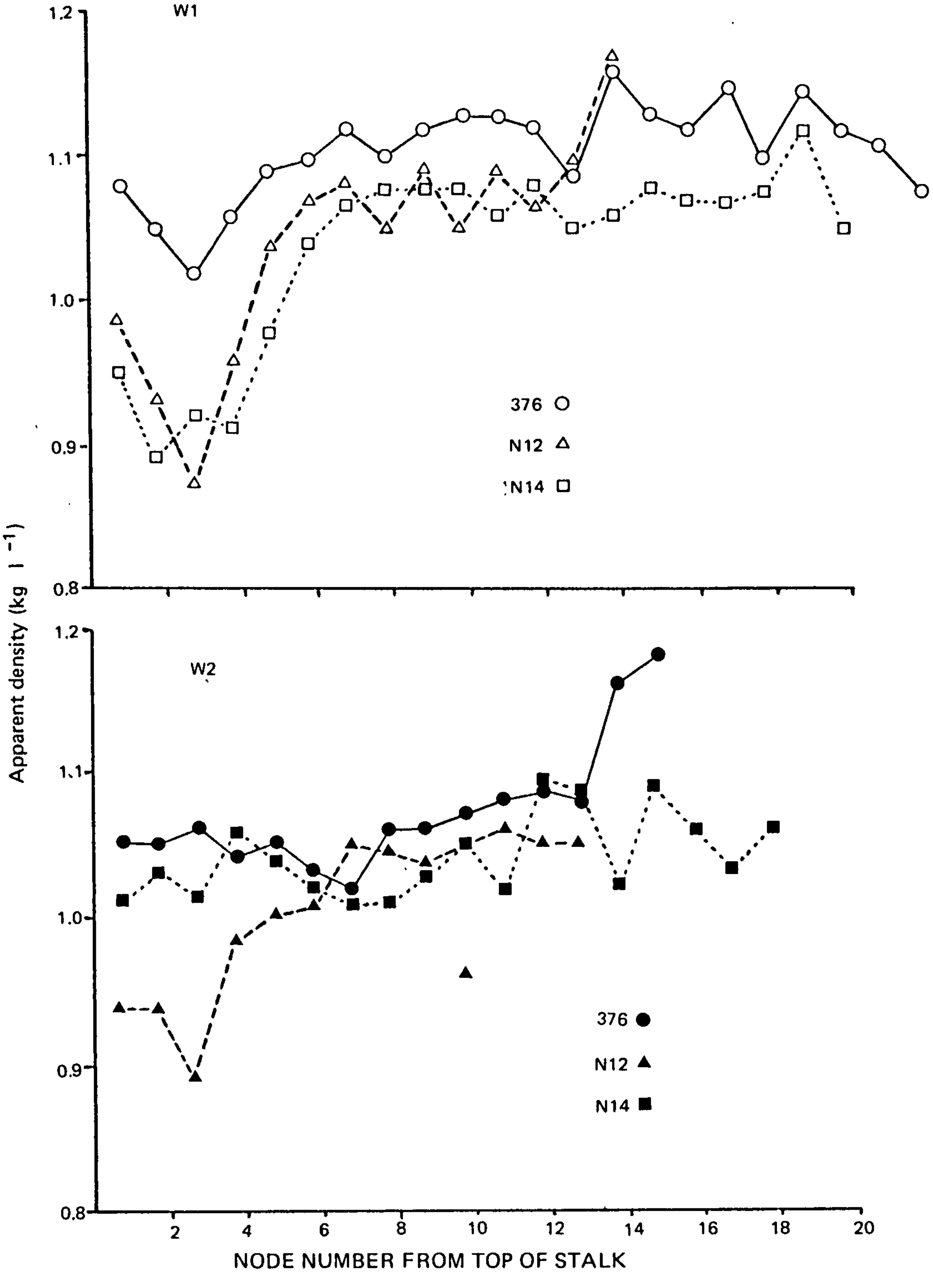

Figure 36. Apparent density (estimated volume/mass) of internodes ordered from top to bottom, in three varieties grown with adequate water (W1) or with two periods of water stress (W2). Data obtained from repeatedly measured stalks at harvesting.

Estimation of the area represented by the stalks marked for non-destructive measurements

The 36 stalks in each plot that were marked for recurrent measurement for the duration of the first stress period, represented various proportions of the total plot area depending on the total number of stalks in the plot. The 36 stalks were marked at a time when the stalk population was decreasing rapidly as a result of the usual over- production of tillers (Bull and Glaziou, 1975). The number of marked stalks decreased at approximately the same rate as total stalk number with the result that the ratio of marked to total stalks (sampling intensity) of any one plot remained fairly constant within each stress period (Tables 19 and 20). This gave the assurance that the marked stalks represented the total reasonably well. The number of marked stalks was increased to 20 at the start of the second stress period to partly replace stalks that had died. The estimates of growth between the 21st February and the 8th March were rejected because of the possible bias resulting from the addition of new stalks to the sample.

Table 19. Stalk number (SN) and the proportion of the total stalks per plot (sampling intensity or SI) in non-destructive growth samples of W1 plots. CV = coefficient of variation in SI.

Sampling date	NCo376				N12				N14			
	Plot 27		Plot 29		Plot 25		Plot 30		Plot 26		Plot 28	
	SN	SI	SN	SI	SN	SI	SN	SI	SN	SI	SN	SI
8 Nov.	36	0.15	36	0.16	36	0.15	36	0.17	36	0.14	36	0.15
30 Nov.	36	0.15	36	0.16	36	0.13	36	0.12	36	0.15	36	0.15
19 Dec.	33	0.15	35	0.18	36	0.14	34	0.15	34	0.16	32	0.15
4 Jan.	31	0.15	31	0.17	35	0.14	34	0.15	31	0.17	25	0.15
15 Jan.	22	0.15	23	0.16	33	0.16	32	0.16	22	0.20	15	0.15
7 Feb.	15	0.13	17	0.15	25	0.14	26	0.18	15	0.15	13	0.14
21 Feb.	12	0.13	17	0.18	21	0.16	22	0.17	13	0.18	13	0.17
Mean		0.14		0.17		0.15		0.16		0.16		0.15
CV %		6.0		6.8		7.7		12.5		12.6		5.9
8 Mar.	20	0.23	20	0.22	20	0.18	20	0.16	20	0.28	20	0.27
20 Mar.	18	0.24	20	0.24	20	0.20	17	0.18	18	0.31	21	0.38
4 Apr.	18	0.24	20	0.22	18	0.19	17	0.18	17	0.30	19	0.30
23 Apr.	14	0.20	19	0.20	17	0.20	17	0.18	17	0.30	18	0.31
10 May	14	0.21	17	0.21	16	0.18	17	0.18	16	0.30	18	0.30
Mean		0.22		0.22		0.19		0.18		0.30		0.31
CV %		8.1		6.8		5.5		5.1		3.6		13.1

It was decided to regard the marked stalks as representative of an area of crop that was constant for each stress period. The mean sampling intensity (SI) for each plot and each stress period (Tables 19 and 20) was used to calculate this area. Thus the area represented by the marked stalks was 0.832 m^2 (4.16 m^2 x 0.2) if the mean SI was 0.2. The total fresh mass of stalks in the sample was divided by this area to obtain fresh stalk mass per hectare (cane yield).

The use of mean sampling intensity rather than the single values to compute plot yield would tend to reduce the yield estimate when a disproportionate number of small stalks in the sample died and it would increase the yield estimate when an unrepresentative number of small stalks remained in the sample. However, small stalks did not always die before larger stalks because of the variable penetration of light into the canopy and the bias in some of sample data may not have been reduced by this method and it could have been increased in some cases. The wide scatter of data in Fig. 37a was attributed to such bias.

Table 20. Number of stalks (SN) and the proportion of the total stalks per plot (sampling intensity or SI) in non-destructive growth samples of W2 plots. CV = coefficient of variation of SI.

Sampling date	NCo376				N12				N14			
	Plot 8		Plot 15		Plot 7		Plot 14		Plot 9		Plot 13	
	SN	SI	SN	SI	SN	SI	SN	SI	SN	SI	SN	SI
8 Nov.	36	0.26	36	0.25	36	0.19	36	0.20	36	0.21	36	0.27
30 Nov.	36	0.26	36	0.26	36	0.19	36	0.20	36	0.22	36	0.29
19 Dec.	36	0.27	36	0.25	36	0.22	36	0.20	29	0.21	34	0.29
4 Jan.	33	0.27	31	0.28	35	0.22	35	0.19	25	0.22	31	0.31
15 Jan.	30	0.27	29	0.24	27	0.18	34	0.19	20	0.18	28	0.34
7 Feb.	27	0.27	27	0.25	22	0.16	33	0.20	19	0.17	25	0.30
21 Feb.	24	0.29	24	0.23	19	0.17	27	0.21	16	0.16	24	0.32
Mean		0.27		0.25		0.19		0.20		0.20		0.30
CV %		3.7		6.2		12.1		3.5		12.8		7.5
8 Mar.	20	0.29	20	0.23	20	0.28	20	0.20	20	0.25	20	0.31
20 Mar.	18	0.27	18	0.28	19	0.28	19	0.21	18	0.28	18	0.34
4 Apr.	17	0.26	18	0.30	16	0.25	16	0.18	14	0.25	17	0.35
23 Apr.	16	0.29	17	0.31	16	0.26	14	0.17	14	0.26	17	0.36
10 May	16	0.28	17	0.30	15	0.27	14	0.18	14	0.27	17	0.34
27 May	16	0.28	15	0.28	15	0.26	14	0.18	14	0.26	16	0.32
Mean		0.28		0.28		0.27		0.19		0.26		0.34
CV %		4.2		10.1		4.5		8.0		4.5		5.5

Stalk growth rate

The rate of change in fresh stalk mass measured in the living stalks differed little between the two methods of measurement but the second method using final internode dimensions and apparent densities was preferred since it took changes in diameter and density with stalk height into account. Few shoots had produced discernible nodes when non-destructive measurements were first made in November 1984 and the observed stalk growth rate was therefore close to zero. Stalk growth rate increased steadily during December and January and remained high during February and March before decreasing again during April as air temperatures decreased (Fig. 37). The variations in estimates of growth rate were probably due to sampling errors arising from unrepresentative changes in the number marked stalks. The curves fitted by least squares provided a reasonable estimate of the real changes that occurred in unstressed plants. The following equations describe stalk growth rate (SGR in g^{-1}) of unstressed plants in relation the number of days after 30th October (d).

376: $SGR= -2.37+0.150d-0.000686d^2$ ± 1.5 ($r^2=0.66$)
N12: $SGR= -0.95+0.036d+0.000548d^2 -3.58d^3x10^{-6}$ ± 1.0 ($r^2=0.81$)
N14: $SGR= -2.86+0.217d-0.001038d^2$ ± 2.6 ($r^2=0.62$)

Stalks of N14 grew more rapidly than those of NCo376 or N12 throughout the summer months and stalks of N12 were less vigorous than those of NCo376 while the crop was less than nine months old. These varietal differences were also observed (Inman-Bamber, 1985) when measuring stalk height in routine field trials. Stalk growth in stressed plants was lower than potential soon after irrigation was suspended in November and little growth occurred until irrigation was resumed in January after which stalk growth rate increased rapidly (Fig. 37). Stalks of NCo376 were soon gaining fresh mass as rapidly as unstressed stalks of this variety but N12 and particularly N14 failed to reach potential growth rates when irrigation was resumed. The drought resistance of N12 appears not to be due to a particularly rapid recovery in growth rate after water stress is relieved. The mechanism appears rather to one of drought avoidance in that early stomatal closure would tend prolong stalk life during drought.

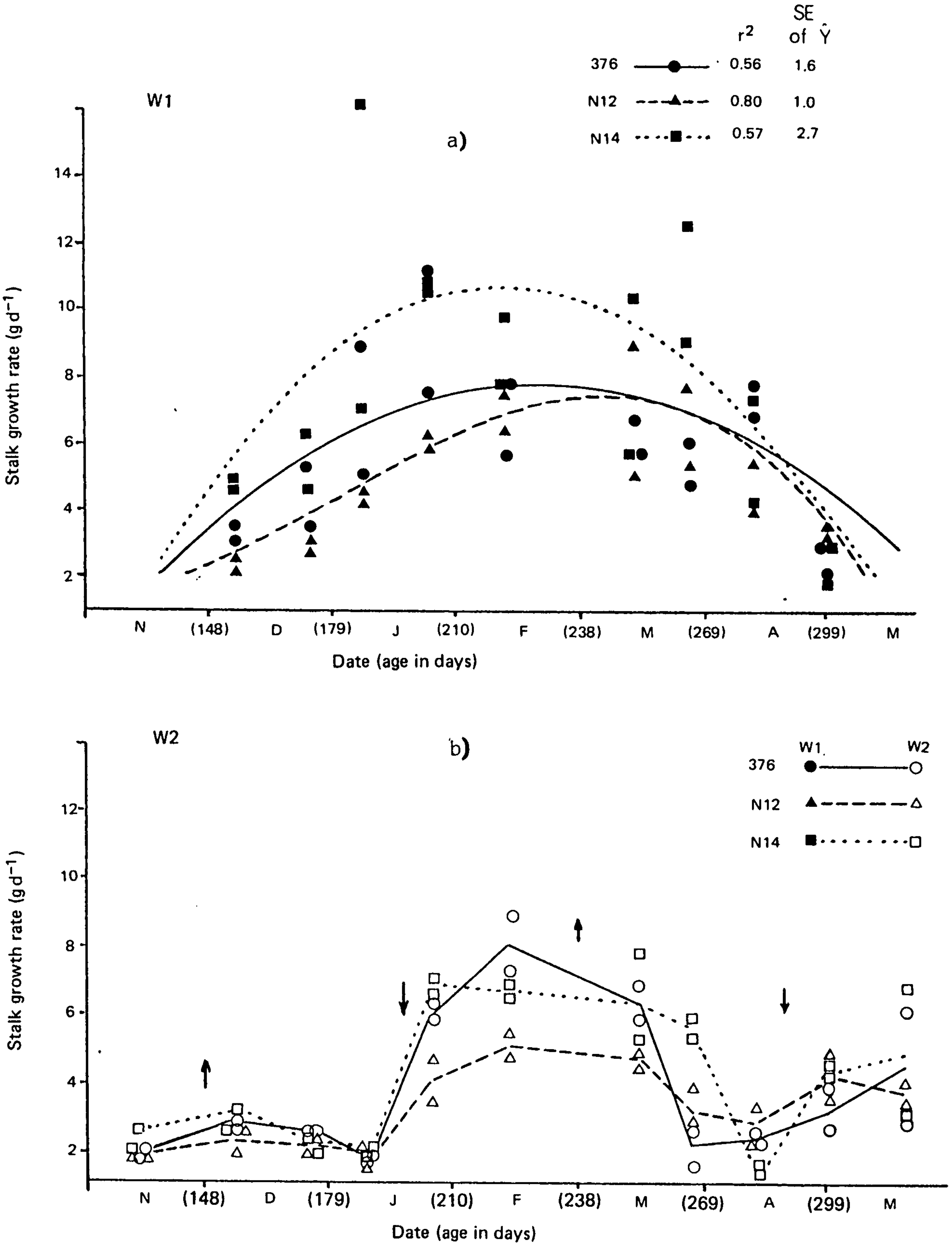

Figure 37. Gain in fresh stalk mass per day of three sugarcane varieties given adequate water (W1) or deprived of water in December 1984/January 1985 and March/April 1985 (W2). Arrows show when irrigation was suspended (↑) and resumed (↓).

Stalk population

Populations were initially higher in W1 than W2 plots because tillering was stimulated when W1 plots were cut back to allow all plots to ratoon simultaneously. Population decreased steadily after November until the crop was about 250 days old (Fig. 38a).

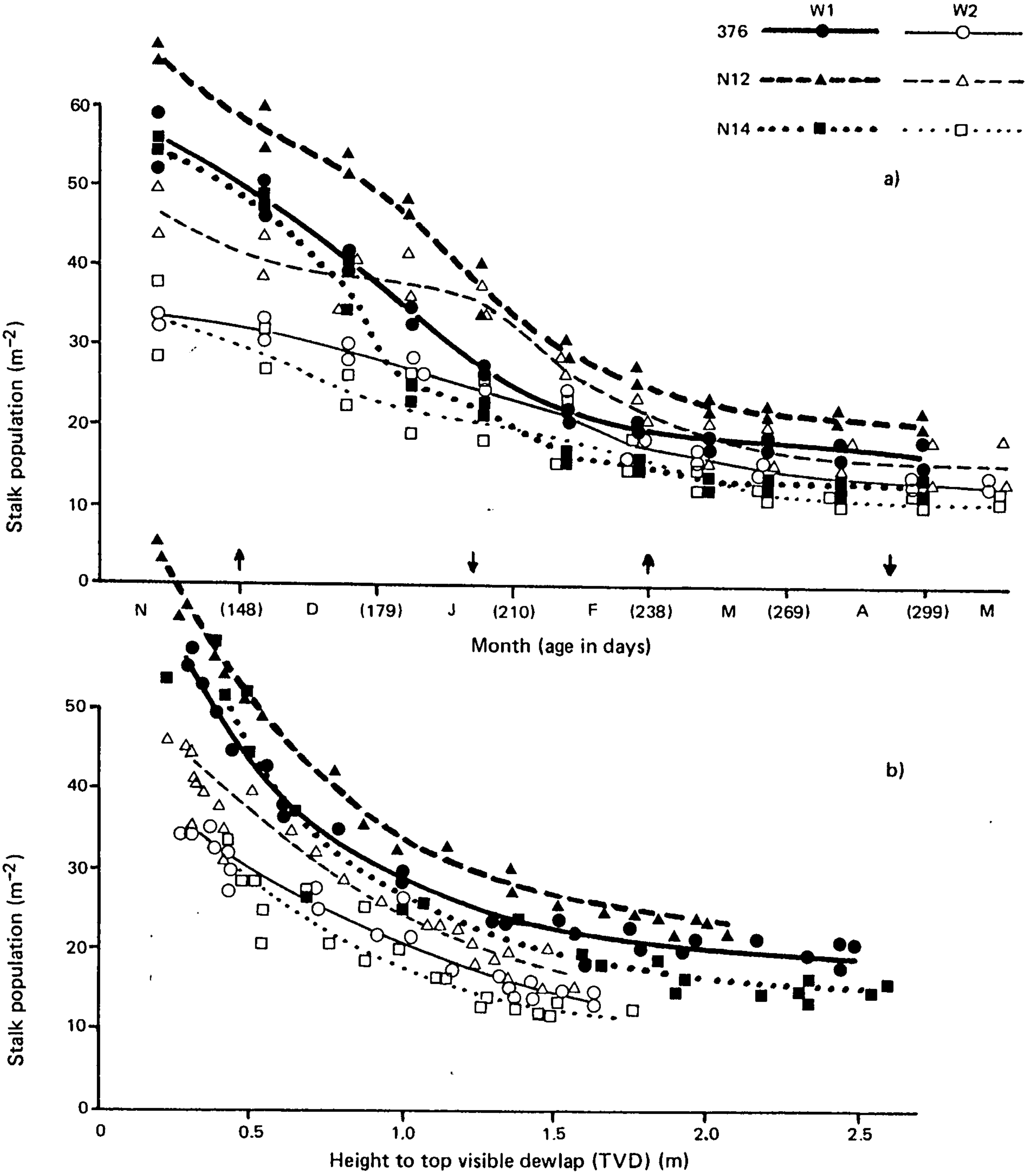

Figure 38. Stalk population in relation to crop age (a) or crop height (b) of well watered plants (W1) and plants subjected to periods of stress in December 1984/January 1985 and in March/April 1985 (W2). Arrows show when irrigation was suspended (↑) and resumed (↓).

The differences between the varieties were similar to those commonly observed in field trials (Inman-Bamber, 1985). Stalk mortality appeared to be no greater in W2 plots than in W1 plots but this observation is not strictly valid since the unstressed crops were taller and would have reduced tiller numbers earlier than stressed crops. Populations in stressed plots were substantially lower than in unstressed plots when compared at the same crop (TVD) height (Fig. 38b). However rapid stalk mortality due to water stress was undesirable in this experiment and stress was relieved before large stalks died. Differences in drought resistance amongst commercial sugarcane varieties can probably be ascribed to differing stalk mortality rates (Inman-Bamber, 1985). Adjustments in leaf area and resistance to gaseous exchange possibly determine the number of stalks that survive a drought.

Cane growth rate

Estimates of cane growth rate in South Africa have hitherto been obtained by conventional, serial growth analysis techniques (Gosnell, 1967; Rostron 1974). These authors harvested plots of homogenous crops at weekly, monthly or two monthly intervals and regarded the differences in yield between sequential harvests as a measure of growth. The limited area of the rainshelter precluded this type of investigation and it is doubtful whether this technique would have provided the precision required by this experiment. The scatter in the cane growth data shown in Fig. 39a was due partly to the death of stalks that were marked for recurrent measurement. As with stalk growth rate, polynomial curves were fitted by least squares to smooth these data since changes in the cane growth rate of unstressed plants should not be abrupt. Cane growth rate (CGR) was related to the number of days (d) after the 30th October in the following way:

376: $CGR=-0.660 + 0.0607d - 6.06d^2x10^{-2} + 1.64d^3x10^{-6}$

N12: $CGR= 0.048 - 0.0087d + 8.48d^2x10^{-4} - 8.52d^3x10^{-6} + 2.28d^4x10^{-8}$

N14: $CGR=-0.559 + 0.0909d - 1.50d^2x10^{-3} + 9.83d^3x10^{-6} -2.35d^4x10^{-8}$

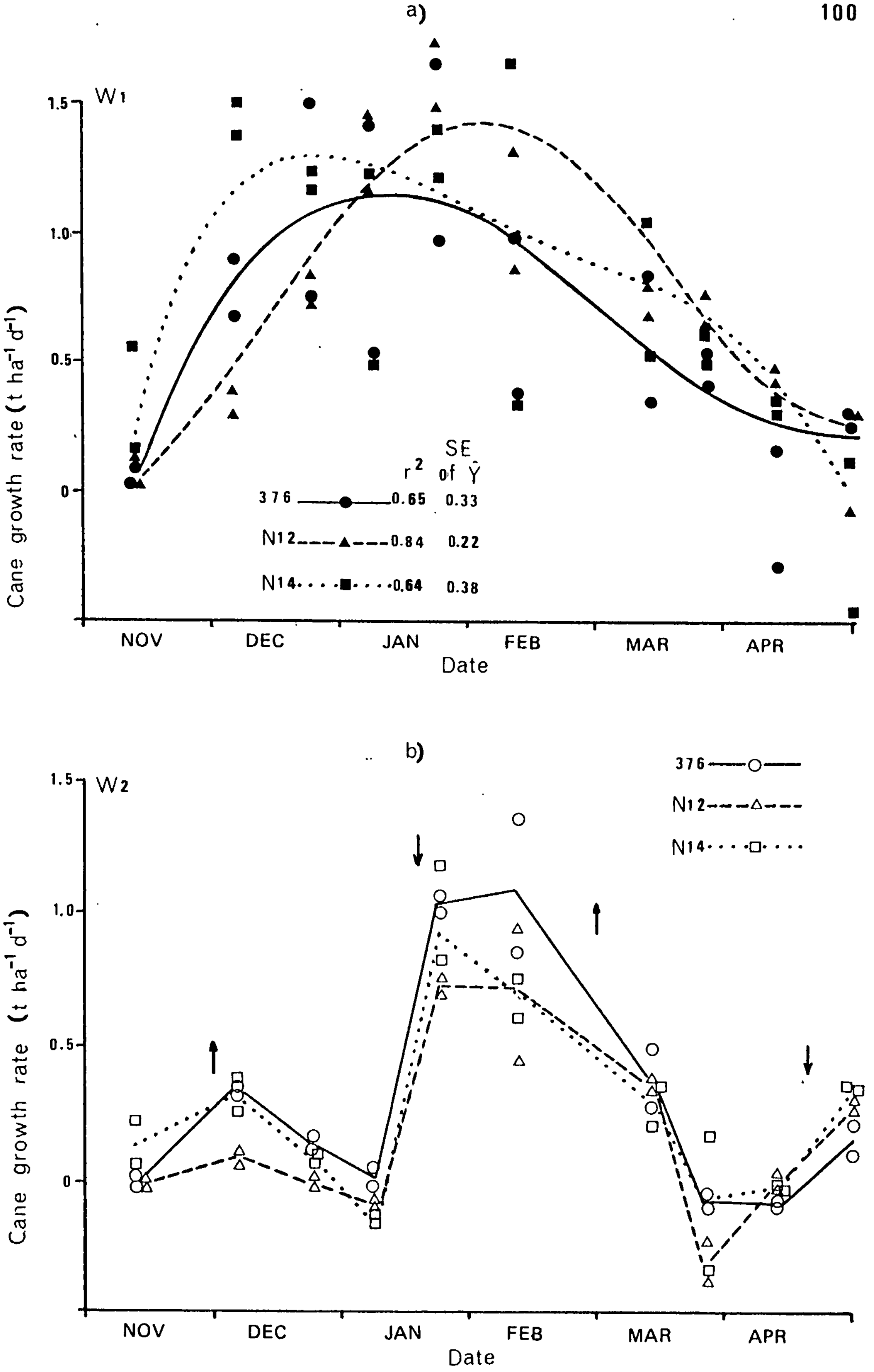

Figure 39. Gain in fresh stalk mass per hectare (cane growth rate) of well watered plants (W1) and plants subjected to periods of stress in December 1984/January 1985 and in March/April 1985 (W2). Arrows show when irrigation was suspended (↑) and resumed (↓).

The r^2 values for the above equations were 0.65, 0.84 and 0.64 respectively. The growth rates of unstressed crops ranged between 1.0 and 1.5 t ha^{-1} d^{-1} during January and February and were only slightly greater than those obtained in the plant crop during these months (Inman-Bamber and de Jager, 1984). These rates are high when compared to average growth rates between planting or ratooning and harvesting. In a favourable environment cane yields of up to 250 t ha^{-1} have been obtained in 12 months (Anon., 1967) and in South Africa yields approaching 200 t ha^{-1} in 12 months have been obtained. The use of an average growth rate may be misleading because over short periods the crop appears to be capable of growth rates two or three times the average growth rate. An irrigated crop at Pongola produced as much as 16 t dry cane mass per hectare between harvest dates eight weeks apart (Rostron 1974). This was equivalent to a growth rate of about 1.2 t fresh cane mass per hectare per day. The irrigated crop analyzed by Gosnell (1967) accumulated fresh cane mass at about 0.8 t ha^{-1} d^{-1} during the period of most rapid growth. It is possible that growth rates were greater than 0.8 t ha^{-1} d^{-1} during short periods in the hottest months because differences in the yields of plots harvested at weekly intervals were as high as 12 t ha^{-1}. However these large yield differences could not be ascribed entirely to an increase in yield over the seven day period because of the variabilty of the data.

The marked decline in growth rate of the unstressed crop during autumn was probably due to decreases in radiation and temperature (Fig. 16) as well as the decreased vigour associated with crop age. Crop age was shown to be a the most important factor affecting growth rate in earlier analyses carried out by Gosnell and Rostron. In this experiment the growth rate of unstressed cane was greatest in N14 and least in N12 during November and December but N12 grew most rapidly later in the season (Fig. 39a). The high stalk population of N12 was thus adequate compensation for a low rate of growth of individual stalks (Fig. 37a).

Cane growth of W2 crops fell behind potential (W1 plots) soon after water was withheld in December and again in March but it increased rapidly when water was re-applied in January and in April (Fig. 39b). During February growth rates of previously stressed NCo376 and N14 were close to those of unstressed crops of these varieties. N12 which was accumulating cane mass rapidly under full irrigation at this stage failed to recover fully from water stress. It is not permissible in this experiment to conclude that the growth rate of N12 cannot recover fully after stress is relieved. Stressed and unstressed plants differed widely in mass and in leaf area. The previously stressed N12 crop might have reached the same high growth rates as the unstressed crop had its leaf canopy been allowed to recover fully. It may be inferred from these data that water stress has little permanent effect on cane growth rate, provided stalks are not killed by stress.

Water use efficiency (WUE)

The amount of water required by sugarcane in South Africa to produce one ton of cane was obtained by Thompson (1977) using lysimeters. The relationship between cane yield and the amount of water evaporated from the soil surface plus the amount transpired by the crop from planting or ratooning to harvesting (mean WUE) was adequately described by the following regression equation :

$$\text{Cane yield} = 0.097 \times \text{Water use (mm)} - 2.4 \pm 15.1 \text{ t ha}^{-1}$$

Since no harvestible cane is produced for several months after planting or ratooning, WUE is obviously greater than 0.097 t ha^{-1} mm^{-1} during the period when harvestible cane <u>is</u> being produced. In this experiment growth rate and water use were measured by the neutron probe (chapter 6) after closure of the canopy and little water would have been lost by evaporation. Water use efficiency in terms of the mass of cane produced per unit water transpired would be greater than the average WUE of 0.097 t ha^{-1} which accounts for water lost by evaporation as well as water transpired. Stalk height measurements indicated that WUE may be greater in summer than in winter but there was no seasonal trend in the amount of water used to produce a unit of dry mass above ground at Pongola (Anon. 1970). Sucrose yield was not reduced

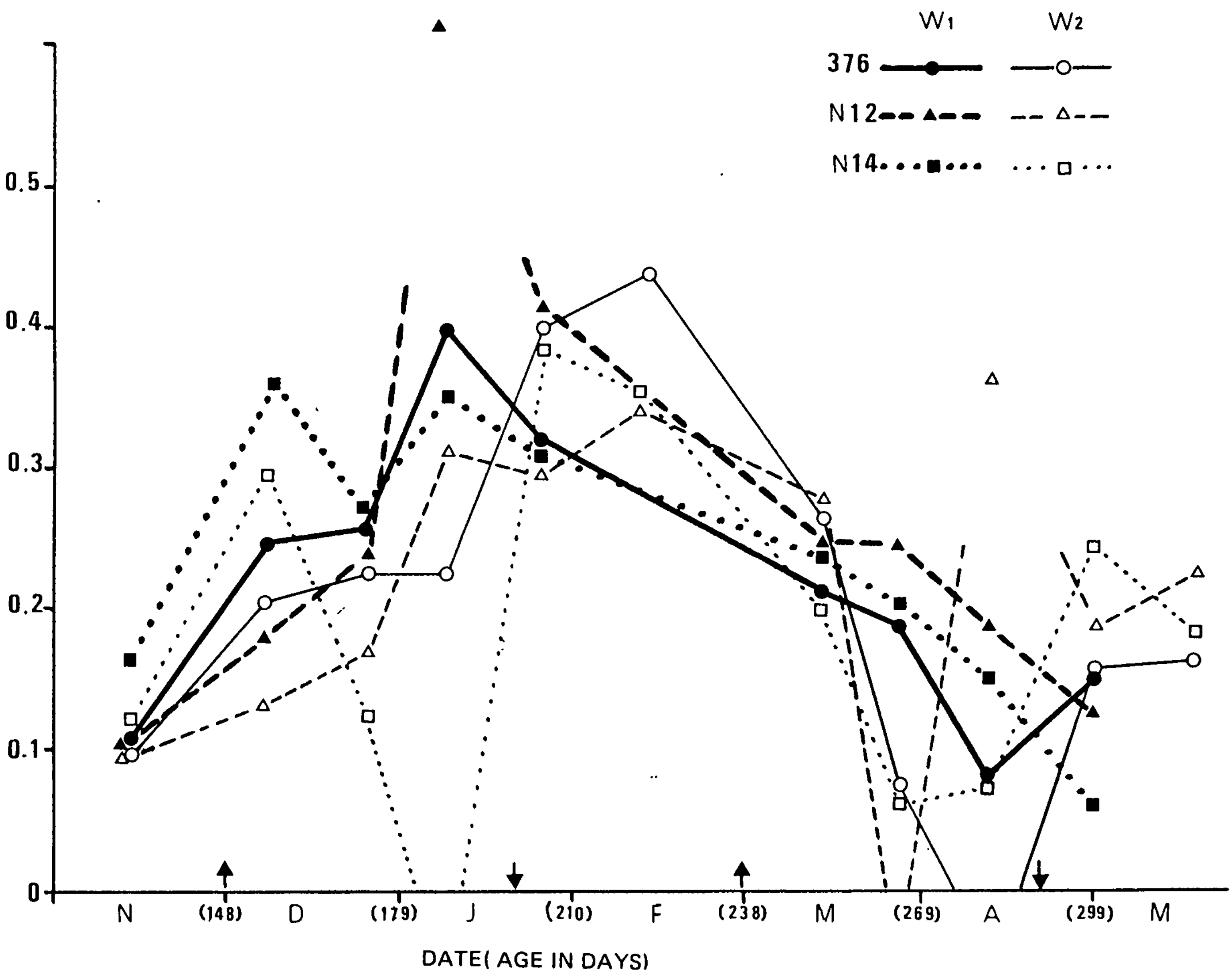

Figure 40. Mass of fresh cane stalk produced per hectare per millimeter of water used (water use efficiency or WUE) by well watered plants (W1) and plants subjected to periods of stress in December 1984/January 1985 and in March/April 1985 (W2). Arrows show when irrigation was suspended (↑) and resumed (↓).

when irrigation was withheld for 13 weeks after harvesting the previous crop in September in the lowveld of Zimbabwe (Ellis, Wilson and Spies, 1985). The amount of water saved may not have been great since the crop water requirement during tillering is relatively low. However water use efficiency may be increased by withholding water during tillering. Such a practice should reduce the amount of water lost both by evaporation because of infrequent wetting of the surface and by transpiration since unnecessary tillering would be reduced (Gosnell, 1967). Mean WUE may also be increased by withholding water during winter if the mass of cane produced per unit water used is lower at this time than in summer as was apparent in the rainshelter data (Fig. 40). WUE in this case was obtained by dividing the mean water use per day (Table 16) by the mean cane growth rate of two plots of each variety in each water treatment (Fig. 39). The low rates of water use and of growth in W2 plots resulted in the low precision in WUE values when water stress was severe in January and April. WUE of W1 crops reached a maximum of 030 to 0.40 t ha^{-1} mm^{-1} during January and it decreased steadily to near zero in May. Thus WUE over short periods in summer appeared to exceed the mean WUE of 0.097 t ha^{-1} mm^{-1} found by Thompson (1976) by a factor of three or four. Water use may have been under-estimated to some extent by not measuring water extraction below 2.7 m. However, measured Et was not markedly different to pan evaporation (Et/Eo=0.86) which is normally similar to crop water use (Et/Eo=1.0, Thompson 1976).

In each variety WUE was reduced when water stress was imposed in December and March but was equal or better than that of the unstressed crop of that variety when irrigation was resumed. When spurious values obtained during severe stress were omitted the mean WUE over the total period of measurement from November to May were:

	NCo376	N12	N14	
Well irrigated	0.129	0.126	0.148	t ha^{-1} mm^{-1}
Stressed	0.128	0.114	0.115	

These values are greater than the mean WUE given by Thompson (1976) because they were obtained after canopy closure although water stress resulted in some exposure of the soil to direct radiation when older leaves died. A significant amount of water is evaporated from the soil between germination and canopy closure (Thompson, 1977). This period may last several months and the WUE measured from germination to harvesting will depend to some extent on the frequency of irrigation or rainfall prior to canopy closure. The greater mean water use efficiency of N14 over NCo376 under adequate irrigation may be explained by its tendency to initiate stalk growth earlier than NCo376.

An important conclusion of this section is that water stress may reduce water use efficiency temporarily but WUE tends to return to normal when stress is relieved provided the stalk population has not been substantially reduced.

Chapter 8 RESULTS AND DISCUSSION ON CHEMICAL CONSTITUENTS OF CANE STALKS OF PLANT AND RATOON CROPS

The discussion on growth has been based mainly on the fresh mass of stalks. This was relevant because growth rate and water use efficiency of sugarcane in South Africa are perceived largely in terms of fresh cane mass. A study of the nature of sucrose storage and removal during and after water stress is necessary in order to explain the effect of stress on sucrose yield which is that component of crop production on which growers' profits depend at present. Other factors affecting sugar manufacture such as fibre and non-sucrose soluble solids contents may be included in the payment formula in the future.

The determination of sucrose yield may be described as follows:

Sucrose yield (t ha^{-1}) = cane yield
x percentage of fresh mass which is dry matter (DMP) x 0.01
x proportion of soluble solids (brix) in dry matter
x juice purity (%) x 0.01

Dry matter content

The decrease in dry matter content (DMP) from the base to the top of the stalk was marked in young plants and more gradual in older plants (Fig. 41a). Dry matter content increased steadily with age except after W2 plants were relieved of stress at the end of April. Dry matter content of W2 internodes barely changed from the 19th April to 9th May. This was probably due to an increase in water content of the stalk following the resumption of irrigation to W2 plants on the 22nd April. However, DMP of W2 internodes was substantially higher than that of W1 internodes on the 28th March and the 19th April when W2 plants were undergoing stress despite their more recent development. The rapid increase in DMP of W2 internodes during stress was not noticably reversed when irrigation was resumed and it can therefore be inferred that the change in DMP was not only a passive loss of water from the stalk. Dry matter of W2 internodes increased during May but not to the same extent as in W1 internodes. Changes in DMP of the basal sections were less marked than changes observed in the distal sections.

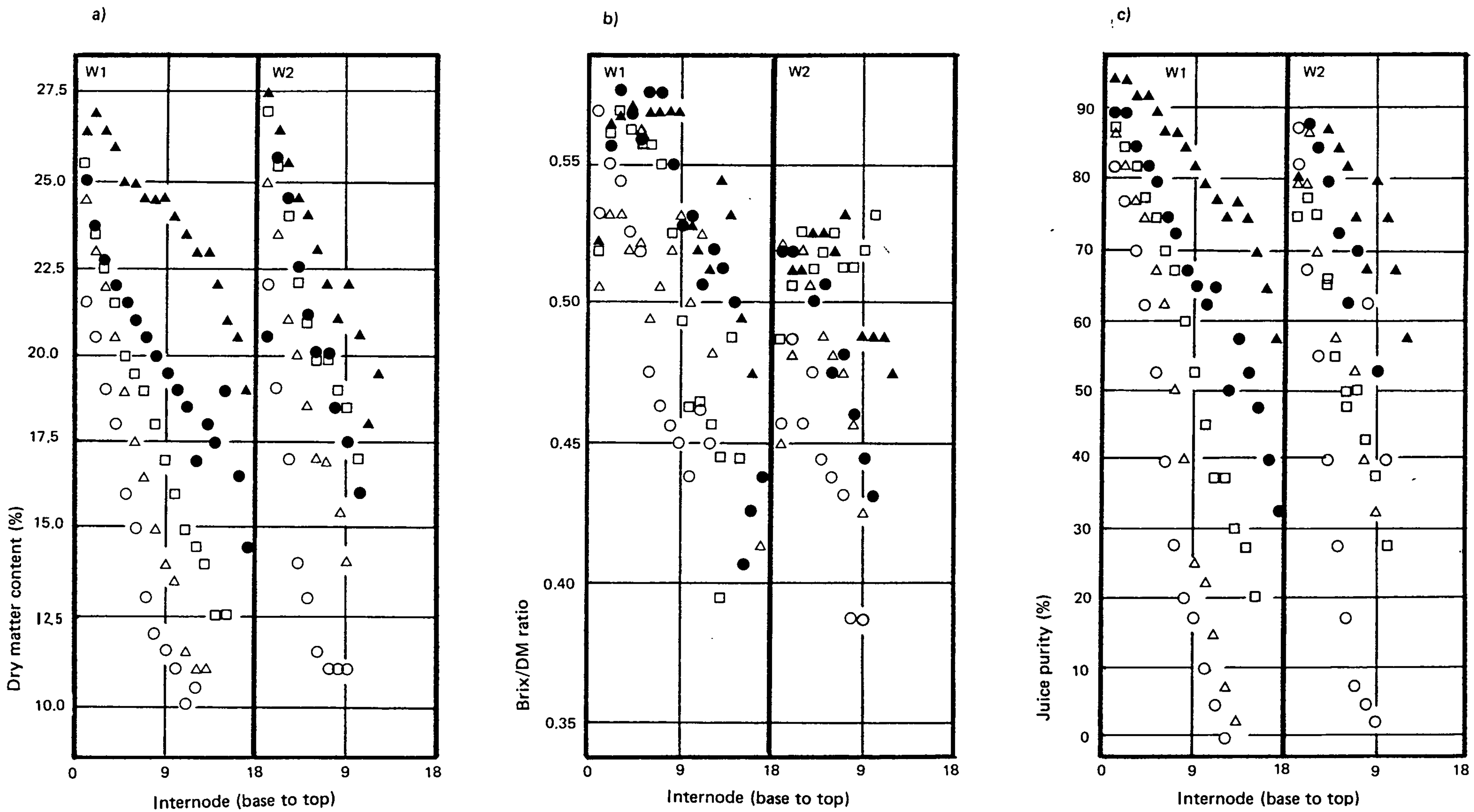

Figure 41. Dry matter content (a), Soluble solid (brix) content (b) and Sucrose % of soluble solids (c) of internodes 1 (base) to 17 (top) sampled on March 6 (○), March 23 (△), April 19 (□), May 9 (●) and May 30 (▲) of unstressed (W1) sugarcane and sugarcane deprived of water from 1st March to 23rd April (W2). Co-ordinates are means of varieties.

Brix fraction of the dry matter

Brix is a measure of the soluble solid content of cane juice obtained from the refractive index of the juice. When expressed as a proportion of the dry matter content of stalks brix provides an indication of the extent to which the plant allocated photosynthate between labile reserves and structural material (fibre). Although the variation in the data was large it was evident that brix to DM ratio tended to decrease towards the top of the stalk and increase with age (Fig. 41b). Brix to DM ratio was generally lower in W2 than in W1 internodes.

Juice purity

Purity (sucrose % in brix) in basal internodes was high even when plants were eight months old (Fig. 41c). This part of the cane stalk could be termed ‘mature’ since a large amount of the sucrose it contained could be recovered in the factory. Purity of the distal internodes of unstressed plants increased steadily during March to May. The purity of stressed plants increased rapidly during March but was unchanged when stress became more severe in April.

Nitrogen percentage of dry matter

The N content of dry matter of unstressed cane generally increased markedly towards the top of the stalk and decreased rapidly with cane age as expected (van Dillewijn, 1957). The youngest internodes of stressed stalks contained the most N per unit dry matter but N content was relatively high in basal sections of stressed stalks after stress was relieved in April (Fig. 42a). Water stress tended to counter the natural tendency for a reduction in N content with age. Thus N content of stalk samples were higher when plants had been without water for 39 days (19th April) than when water had been withheld for 28 days (28th March). The N content of all internodes of W2 stalks decreased when irrigation was resumed but not to the low levels found in unstressed stalks. This observation and that of the relatively high N content of W2 stalks at the start of the second stress cycle indicate that N may not have been readily mobilized to support new growth and/or that the plants took up further amounts of N when irrigation was resumed. The soil organic matter content was low and the increased mineralization of N after irrigation was probably not great.

There is circumstantial evidence that eldana borer favours high N content in the stalk and is known to be encouraged by water stress (Anon. 1983). The borer is also most prevalent in the base of the stalk where N content of dry matter is usually low. However if N content of the fresh matter that is consumed by the

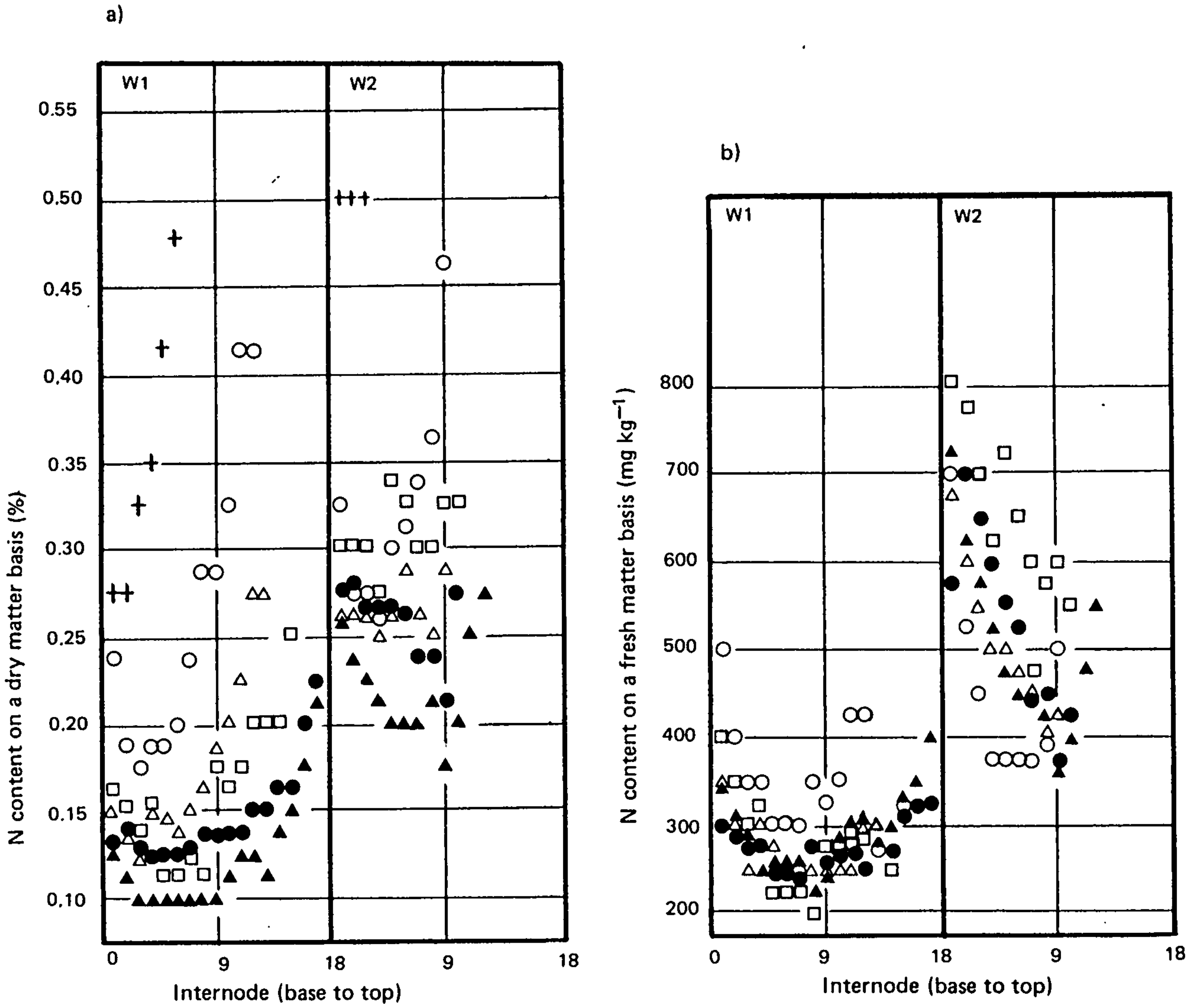

Figure 42. Nitrogen content of dry matter (a) and Nitrogen content of fresh matter (b) of internodes 1 (base) to 17 (top) sampled on February 16 (+), March 6 (○), March 23 (△), April 19 (□), May 9 (●) and May 30 (▲) of unstressed (W1) sugarcane and sugarcane deprived of water from 1st March to 23rd April (W2). Co-ordinates are means over all the varieties.

borer is critical for its success then the base of the stalk would be a better habitat than the top since the N content of fresh matter increased markedly towards the base of the stalk in stressed stalks (Fig. 42b). This was not true of unstressed stalks.

Sugars analysed by gas chromatography (GC)

The GC data confirmed the accuracy of the sucrose values obtained using the saccharimeter (Fig. 43) even at very low concentrations. The glucose fraction of the soluble solids (brix) was greater than that of the fructose fraction initially and both sugars became less prominent as the cane aged (Fig.s 44a and 44b). The reducing sugars increased markedly towards the top of the stalk where juice purity was low and they decreased steadily with age except when water stress became severe during April and concomitantly juice purity stopped rising.

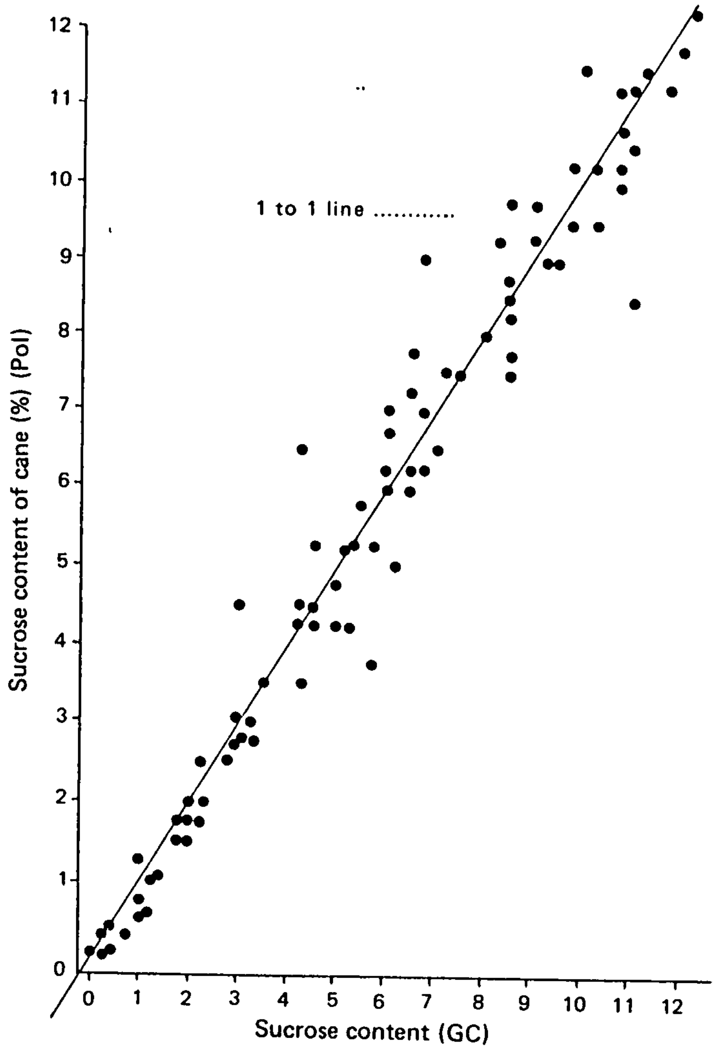

Figure 43. Sucrose content % of fresh cane mass determined by light polarization in a saccharimeter (pol) or by gas chromatography (GC). Co-ordinates are means over all the varieties.

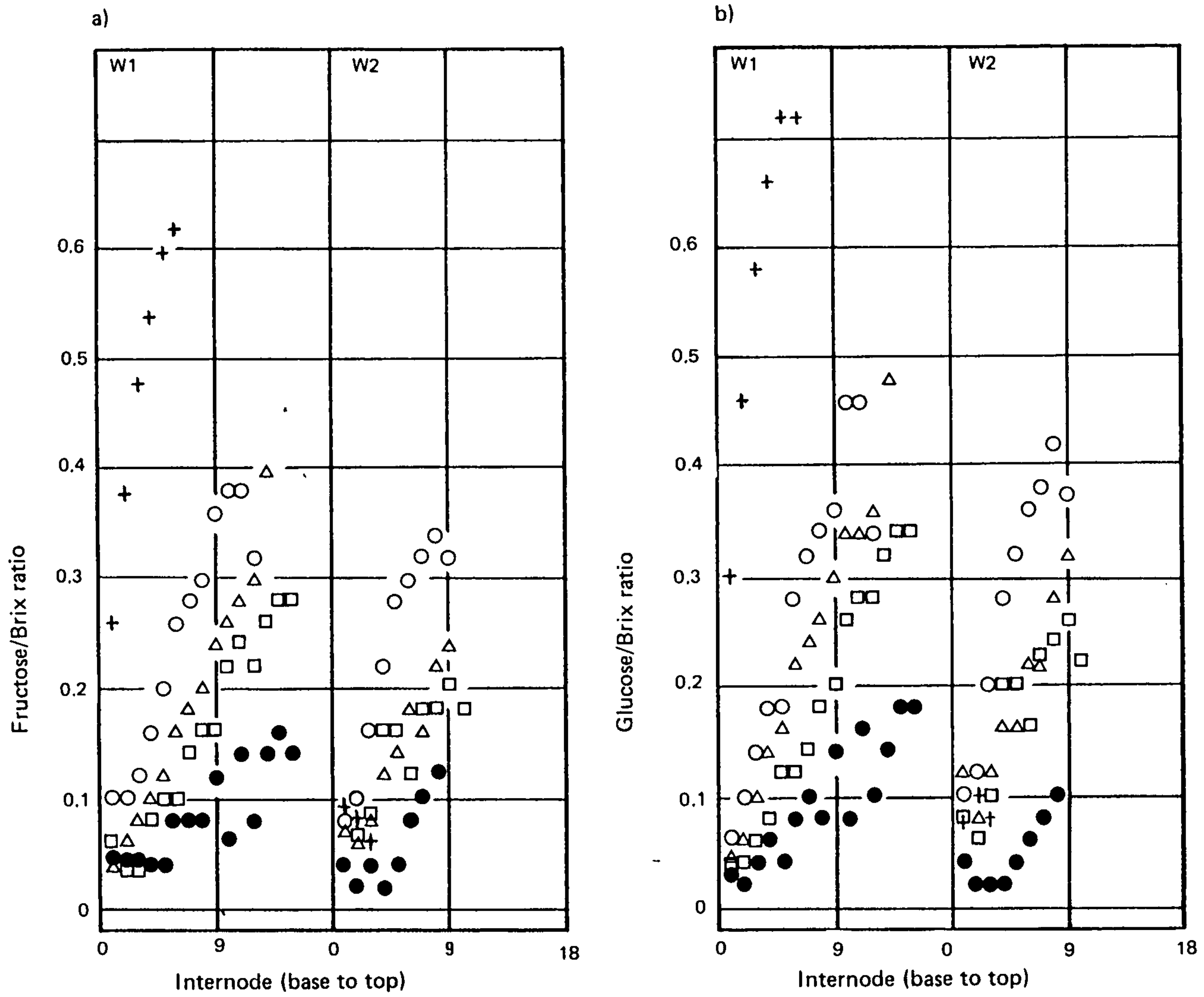

Figure 44. Fructose content (a) and Glucose content (b) of soluble solids (Brix) of internodes 1 (base) to 17 (top) sampled on February 16 (+), March 6 (O), March 23 (Δ), April 19 (□), May 9 (●) of unstressed (W1) sugarcane and sugarcane deprived of water from 1st March to 23rd April (W2). Co-ordinates are means over all the varieties.

Dry matter content of internodes in relation to radiation

Dry matter content (DMP) in each internode depended largely on internode age or on the amount of photosynthetically active radiation (PAR) intercepted by the crop after the internode had stopped elongating. The date of this occurrence was obtained for each internode group from records of node appearance in stalks that were measured repeatedly. The amount of PAR intercepted was calculated as the difference between PAR incident above the canopy and the sum of PAR transmitted and PAR reflected by the canopy (Table 17). The total PAR intercepted was probably underestimated because measurements of the fraction of PAR reflected and transmitted were made between 1200 and 1500 hours when transmission was greatest (Ross 1975). Daily PAR above the crop was obtained from daily integrations of readings at 60 s intervals of a quantum sensor mounted 3 m above the ground. Three day means of daily total PAR are shown in Fig. 16. The means fluctuated above and below about 20 Einsteins per square meter per day (E m^{-2}). The first internodes completed extension during the first half of December and were thus nearly six months old when harvested on the 30th May. The maximum amount of PAR intercepted over that period was thus about 3500 E m^{-2} (Fig. 45).

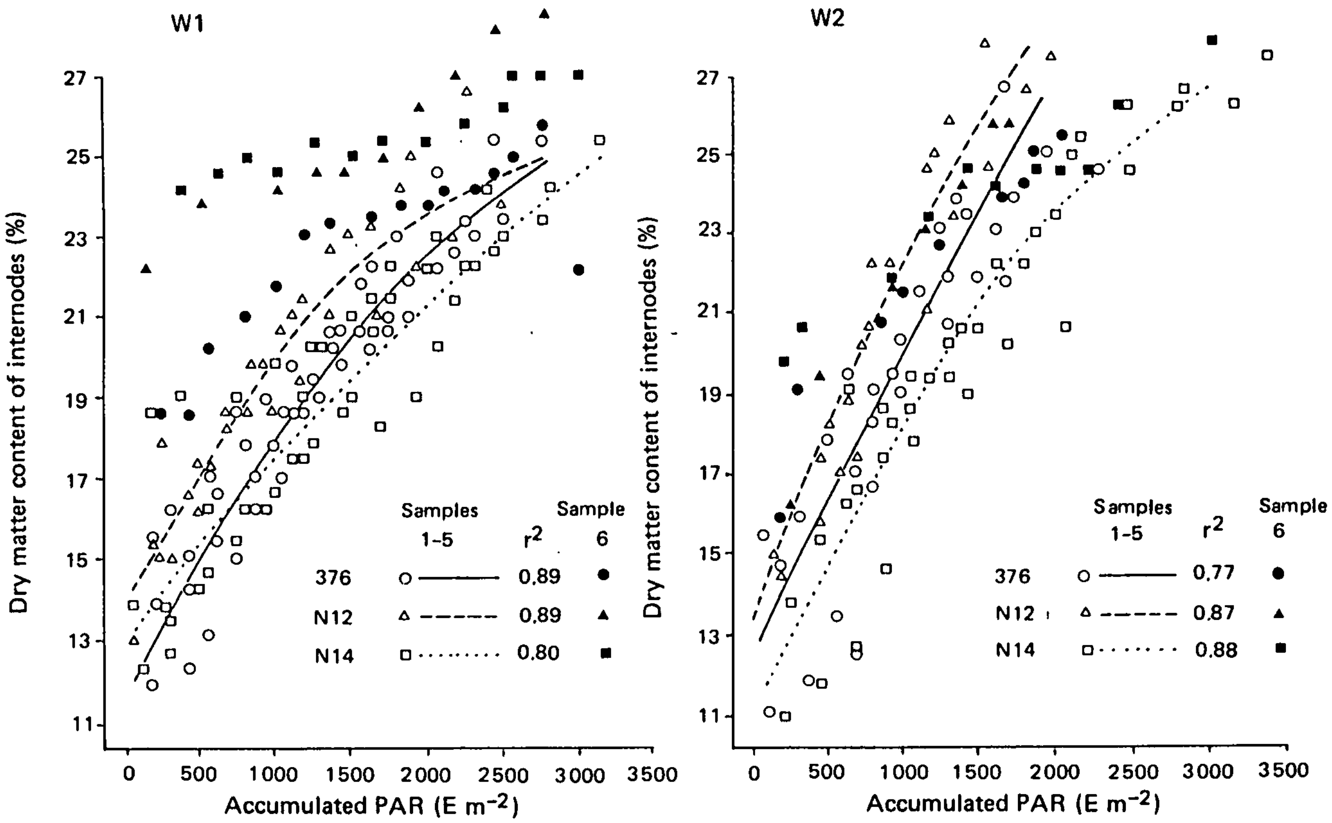

Figure 45. Dry matter content of internodes of unstressed (W1) and stressed (W2) plants in relation to total amount of photosynthetically active radiation (PAR) intercepted by foliage after an internode had developed. Curves fitted by least squares to data from first five samplings (open symbols). Closed symbols show data from 6th sampling.

DMP of W1 internodes sampled on the 30th May was considerably greater than that of W1 internodes of a similar age that were sampled earlier (Fig. 45a). This was probably due to a marked reduction in stalk growth rate of W1 plants towards the end of

May when temperatures were falling and the crop was ageing. When data collected on the 30th May was ommitted, the total amount of PAR intercepted by the canopy after the formation of internodes (ΣPAR_i) accounted for more than 80% of the variation in their DMP (Fig. 45a). The difference in DMP between W2 internodes sampled on the 30th May and those of comparable age sampled earlier was not as great as in the case of W1 plants (Fig. 45b) but data from the final sampling was excluded from the analysis from which the curves in Fig. 45b were produced. Dry matter content from the the first five samplings tended to be greater in N12 than in the other varieties at any particular value of ΣPAR_i (Fig. 45).

Since the deviation from the trend evident in DMP data of the first five samplings appeared to be due to a reduction in stalk growth rate (SGR) in May, SGR was included as a variable in multiple regression analyses in order to determine the indepenant effect of SGR on DMP (Table 21). In all treatments except stressed N12, dry matter % varied significantly with stalk growth rate after variation due to accumulated PAR_i had been removed. The DM % of the fully extended portion of the stalk appeared to be increased by about 0.6 % for every gram decrease in the daily increment of fresh stalk mass.

Table 21. Partial regression coefficients of internode DMP upon accumulated, intercepted PAR_i (ΣPAR_i) in E m^{-2} , $:PAR_i$ squared and stalk growth rate (g d^{-1}). Adjusted R squared for ΣPAR_i variables and for all variables are given separately. (ns=not significant at p=0.05).

1	2	3	4	5	6	7	8	9	10
Variety	Water treat	Intercept	ΣPAR_i $x10^{-3}$	ΣPAR_i^2 $x10^{-6}$	SGR	r^2 $:PAR_i$	r^2 All	F All	DF
376	W1	14.2	8.59	-1.67	-0.67	0.77	0.90	180	63
N12	W1	16.7	5.49	-0.58ns	-0.40	0.70	0.74	39	41
N14	W1	16.8	5.09	-0.63ns	-0.60	0.56	0.73	54	59
376	W2	15.0	6.25	-0.11ns	-0.87	0.78	0.88	92	38
N12	W2	14.2	9.03	-1.02ns	-0.34ns	0.90	0.90	92	30
N14	W2	17.1	5.33	-0.41ns	-1.25	0.74	0.81	67	46
All treat.		15.5	6.96	-1.06	-0.64	0.65	0.77	312	282

It is commonly accepted that factors such as low temperature, nutrient deficiency and water stress that restrict internode elongation tend to favour sucrose storage (Bull and Glaziou, 1975) and hence dry matter accumulation. Hatch and Glaziou (1963) described a series of experiments in which the rate of internode elongation was negatively correlated with acid invertase activity. Acid invertase was regarded as the main factor responsible for the partitioning of photosythate between growth and storage. Bull and Glaziou (1975) cautioned against mistaking a net increase in sucrose accumulation with loss of water when water stress is responible for increased sucrose content. Clements (1980) analysed the oldest nine internodes of stalks removed from a ripening cane crop at monthly intervals over a period of eight months. There was no measurable change in the fresh mass of this portion of the stalk, but DMP and sucrose content increased steadily. The lack of change in fresh mass was given as evidence that the increase in DMP was due a net gain in dry matter rather than to a loss in water from the stalk.

A similar analyses was performed on data obtained from ratoon crop of the rainshelter experiment. At least nine internodes had developed on most stalks of all varieties in both water regimes when stress was imposed for the second time. Fresh mass of the oldest two internodes was inconsistent because of variations in their length. Fresh mass varied little between W1 internodes 3 and 9 and between samplings 2 to 5. There appeared to be slight increase in the mean mass of these internodes during May (Fig. 46).

Fresh mass was more variable in W2 internodes 3 to 9 but the data was considered to be a reasonable reflection of mass changes in the fully extended portion of the stalk. The mean fresh mass of W2 internodes decreased during the second stress period and it increased again to pre-stress values after irrigation recommenced. The rapid increase in DMP of W2 internodes (Fig. 47) appeared therefore to be partly due to the loss of water from the stalk. When fresh mass was multiplied by DMP and sucrose % to obtain the mass of dry matter and sucrose in internodes (Fig. 46), it was evident that dry mass and sucrose mass of W1 internodes 3 to 9 increased steadily during March to April. As was the case in the Clements (1980) data, dry matter and sucrose appeared to 'replace' water without increasing fresh mass of the stalk at least during March and April.

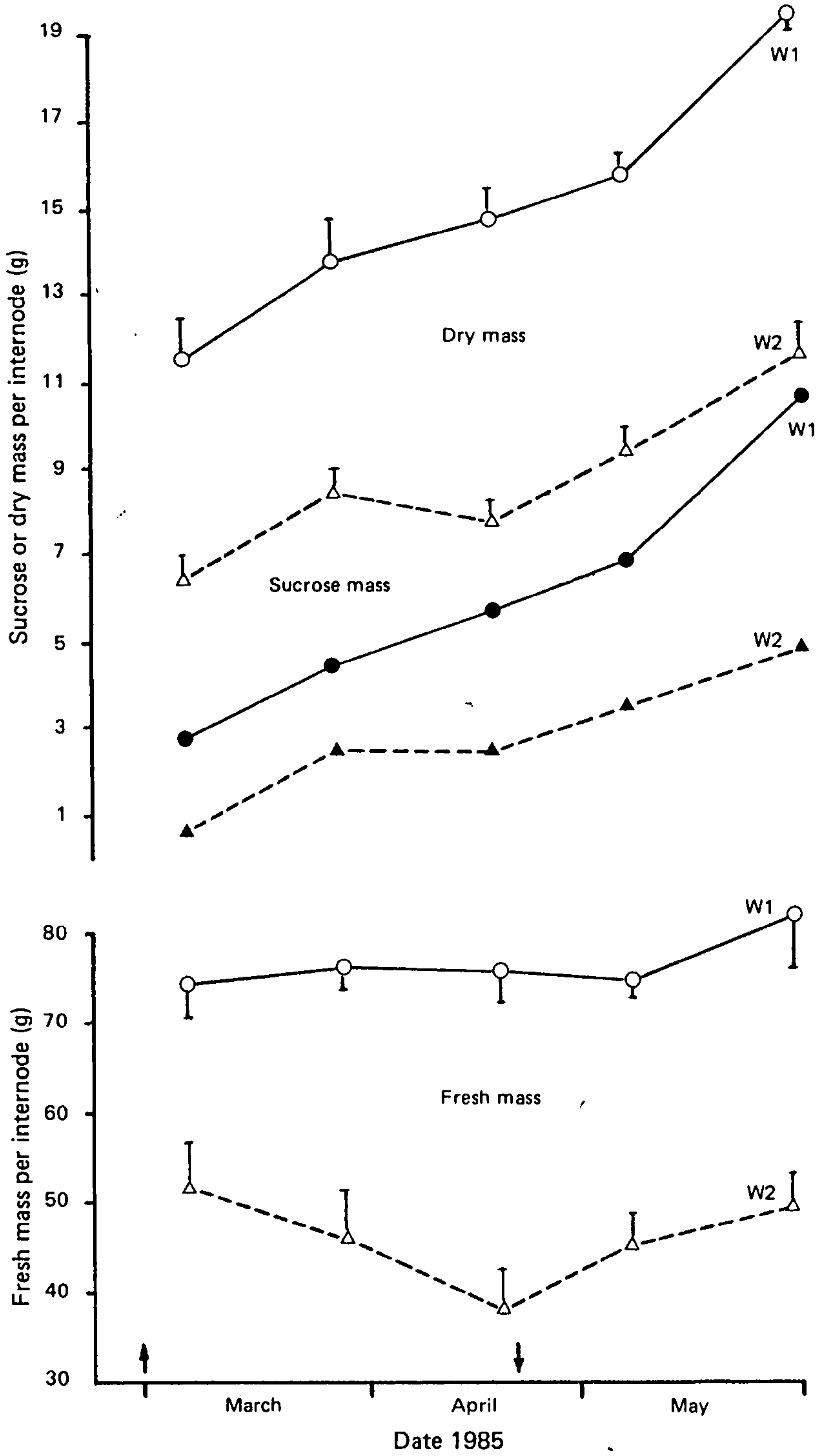

Figure 46. Mean mass of sucrose, dry matter and fresh matter of internodes 3 to 9 (from base) of well watered plants (W1) and plants subjected to stress in March/April 1985 (W2) during the ratoon crop. Arrows show when irrigation was suspended (↑) and resumed (↓). Bars denote standard errors.

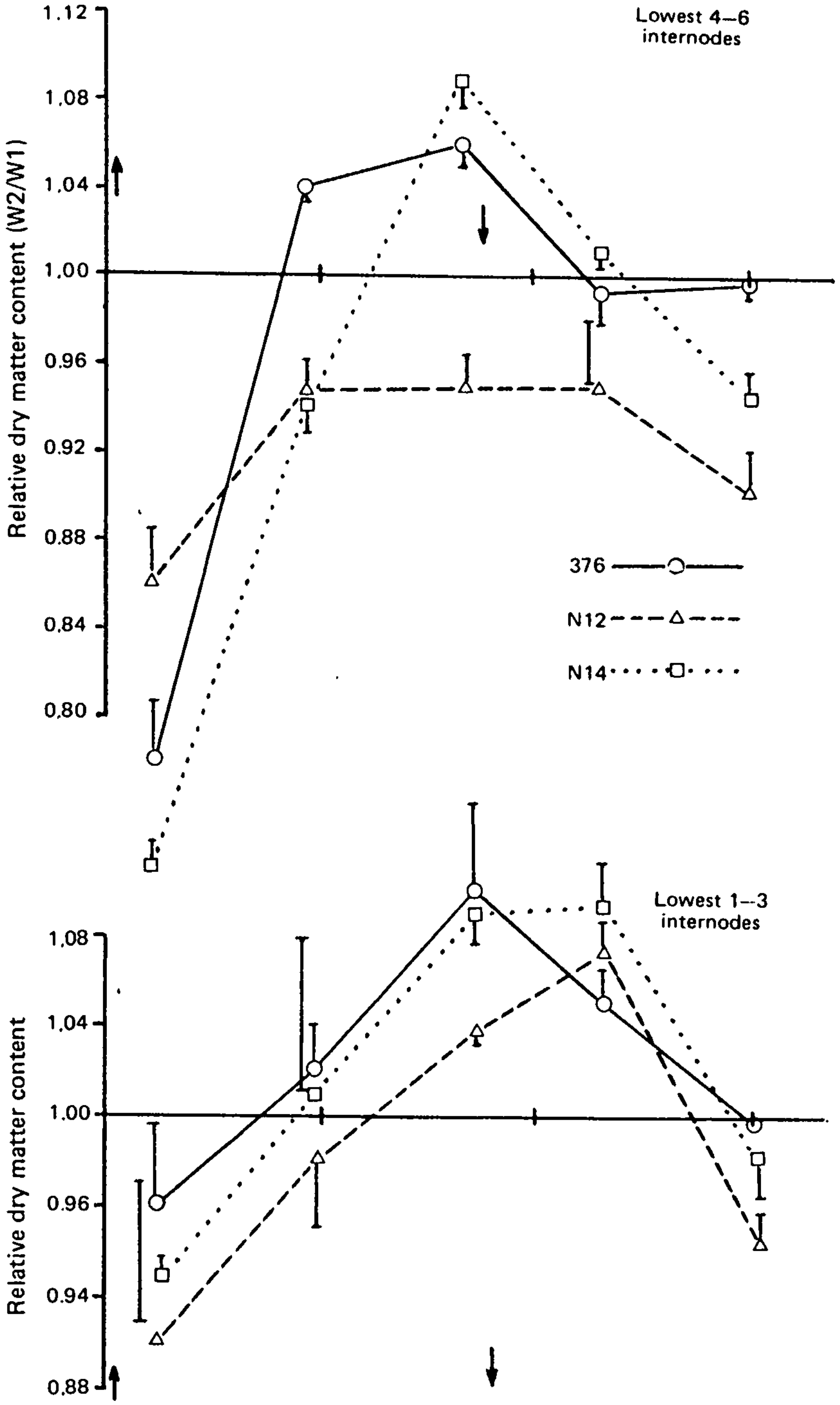

Figure 47. Dry matter content of internodes 1 to 3 and 4 to 6 from base of stressed plants expressed as a ratio of the dry matter content of corresponding internodes of unstressed plants. Bars denote standard errors of means of three internodes. Arrows show when irrigation to stressed plants was suspended (↑) and resumed (↓).

The dry mass and sucrose mass of W2 internodes apparently increased, as did those of W1 internodes, during the first half of the second stress period but remained unchanged during the second half (Fig. 46). Dry mass and sucrose mass of W2 internodes increased as once more when irrigation was resumed. It therefore appeared that water stress did not accelarate the deposition of sucrose in lower portion of the stalk and that sucrose storage ceased when stress became severe. The dry mass and sucrose mass of W2 internodes did not decrease when irrigation was resumed and the decrease in DMP at this stage (Fig. 47) was probably due to rehydration of the stalks.

The rate at which plants became stressed in the ratoon crop was considerably more rapid than in the plant crop when net sucrose accumulation appeared to be enhanced by water stress. In the plant crop, water was withheld for about five months and plants were not stressed as much as they were in the ratoon crop after only eight weeks without water.

Only six internodes had developed when stress was imposed on the plant crop. The mean fresh mass of internode 3 to 6 was variable but there was some indication that water was removed from the stalk as plants became more stressed in May and June (Fig. 48a). Dry mass increased rapidly in the base of stressed stalks during February to April and then remained constant during May and June. The sucrose content of these basal internodes was also increased by water stress and at the end of the prolonged period without irrigation or rain the sucrose mass per internode of this portion of the stalk was significantly greater in stressed than in unstressed plants. At least nine internodes had developed when the plant crop was sampled for the third time (1st May) and data on internodes 7 to 9 could be processed in the same way (Fig. 48b). These results also indicated that water stress resulted in a net increase in the mass of dry matter and sucrose of fully extended internodes. The efficiency with which sucrose is accumulated while plants are moderately stressed was also evident when the plant crop was harvested. The mean cane yields from stressed and unstressed plots were 115 and 134 t ha^{-1} and the sucrose yields were 14.4 and 16.2 t ha^{-1} respectively (Inman-Bamber and de Jager, 198).

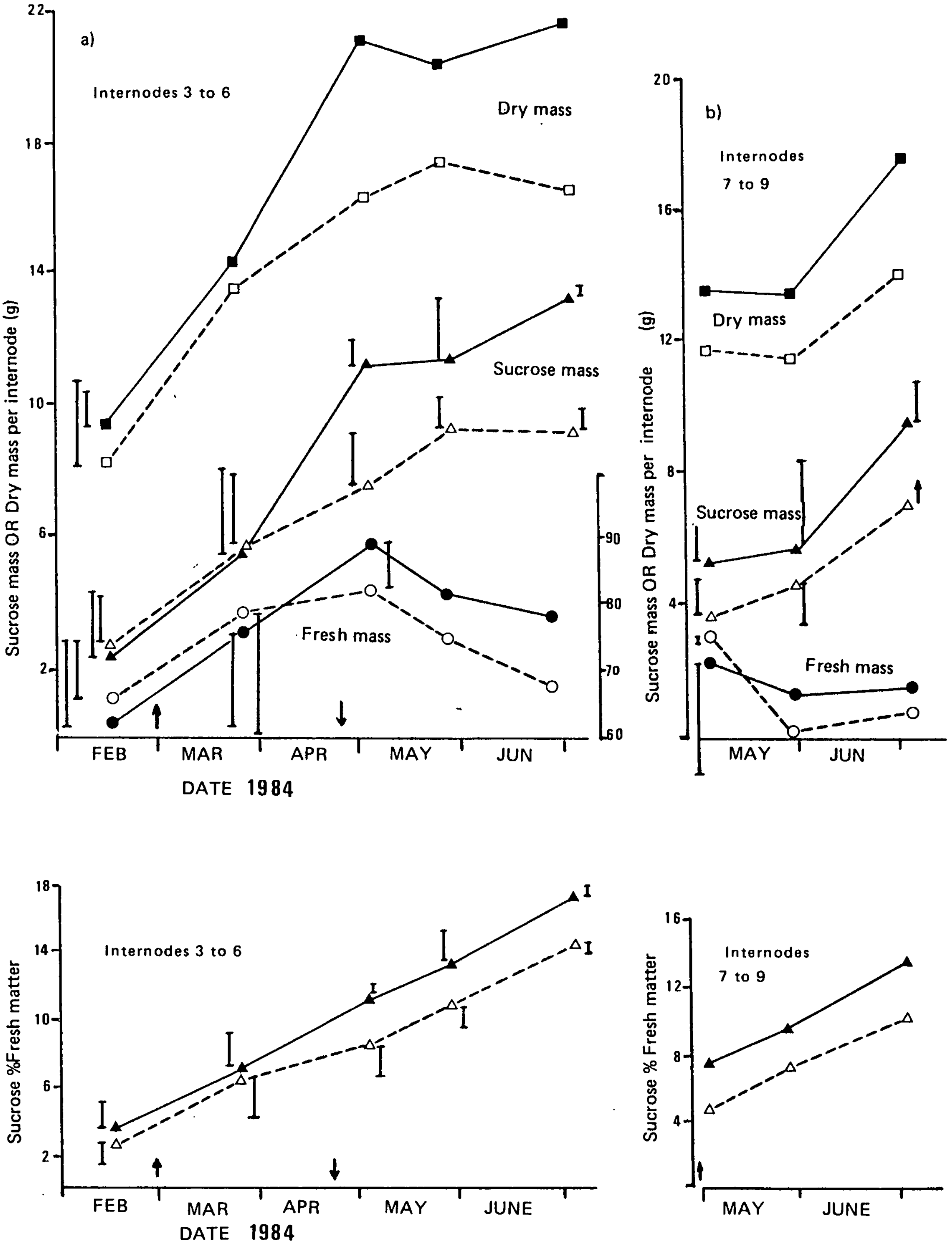

Figure 48. Mean sucrose content and mean mass of sucrose, dry matter and fresh matter of internodes 3 to 6 (a) and 7 to 9 (b) of well watered plants (W1) and plants subjected to stress in 1984 (W2) during the plant crop. Arrows show when irrigation was suspended (↑) and resumed (↓). Bars denote standard errors of means.

Glaziou and Gayler (1972) concluded that "sucrose storage in mature sections of sugarcane stalks is a system in a state of dynamic flux by which sucrose can be moblized as required". A negative correlation was obtained between the rate of stalk elongation and the rate of change of sugar content when temperatures were altered in a controlled environment (Hatch and Glaziou, 1963). In a similar experiment plants growing in constant temperature of 17°C were transferred to a 30°C environment which favoured rapid stalk elongation and sucrose content of basal internodes fell from 16.0 to 6.5 % of fresh mass over a period of 35 days (Glaziou et al, 1965). Changes in growing conditions as large as this probably do not often occur in the field. The marked change in growth rate of stalks after water stress in W2 plants was relieved had a comparatively small effect on the concentrations of dry matter and sucrose in fully extended portion of the stalk. In a recent study on tall fescue by Volenec (1985) only about 50% of sugars stored in stem bases was removed to support leaf growth following total defoliation. The concentration of sugars was restored after 24 days of regrowth.

Conclusions

The dry matter and sucrose content of internodes of sugarcane stalks depended largely on the amount of radiation intercepted by the foliage after formation of the internode and the rate of stalk growth.

Sucrose accumulation in the fully extended portion of the stalk was enhanced when water stress increased gradually and was not reduced in more rapidly stressed plants until stomatal resistance started to increase rapidly.

Sucrose is not readily removed from the fully extended portion of the sugarcane stalk to support new growth following relief from water stress provided three or more green leaves remain.

Chapter 9 FINAL DISCUSSION AND CONCLUSIONS

The objectives of the investigation on the reaction of sugarcane to water stress were satisfactorily achieved during the four years of experimentation.

Methods

Some of the new techniques were particularly useful and they may be of use in future when related problems are investigated. Some techniques were deficient in certain respects and ideas for improvements can be offered.

1. The rail and roller system for moving the 80 kg pots around the experiment site and to and from the balance worked well. Twelve pots could be weighed with minimal disturbance in about 30 minutes.

2. The 10g resolution of the balance was suitable for hourly measurements on water use although daily water use was of more concern in this experiment.

3. While the soil used in the pots had desirable water release characteristics for the imposition of stress it would have been better for the unstressed plants to have had a better drained rooting medium.

4. The mechanics of the rainshelter worked almost faultlessly because of the placement of the cables and chains. The roll up doors adequately solved the problem of sealing the ends.

5. The advantages of locating the rainshelter on a light textured soil were a) the ease of maintaining an even soil surface, b) rapid infiltration of water, c) successful insertion of access tubes and d) rapid recovery of root samples. The precision of neutron probe measurements was almost inadequate to determine the relatively small amount of water removed per unit of soil depth when roots had ready access to water throughout the 3 m profile of this freely

draining soil. This great depth of soil also frustrated the attempt to impose stress repeatedly on the plant crop.

6. The combination of destructive and non-destructive growth measurements provided satisfactory estimates of fresh mass gain by the small plots of crop inside and outside the rainshelter. The rapid location of the top of the stalk overcame the difficulty of accounting for variable sheath length when using the top most leaf collar as a measure of stalk height (Gosnell, 1967). With the high variation from one plot to the next it would have been desirable to have had more replication. The differences in growth rate and water use between varieties may have been clearer had this been possible. The restricted area of the rainshelter and the laborious nature of the measurements limited the amount of replication.

Plant water relations

Threshold leaf water potentials for various attributes have been provided for sugarcane for the first time as far as is known. These may be summarized as follows:

1	-0.2 MPa	Plant extension rate falls below potential
2	-0.3 MPa	Stomatal resistance starts to rise gradually
3	-0.4 to -0.9 MPa	Plant extension ceases
4	-0.8 MPa	Youngest unfurled leaves start to roll
5	-1.0 to -1.7 MPa	Green leaf area is reduced
6	-1.2 to -1.7 MPa	Stomatal resistance rises rapidly
7	-1.4 to -2.3 MPa	Stomata finally close
8	-2.0 MPa	Youngest unfurled leaf rolls fully
9	-2.8 MPa	Apical meristem is permanently damaged

Previous stress history and varietal differences were responsible for the range in threshold values for attributes 3, 5, 6 and 7 above. The decrease in the threshold ψ_l for plant extension during successive stress cycles in the pot experiment corresponded with a general decrease in leaf osmotic potential. In the field experiment the sensitivity of plant extension was apparently greater during the second than during the first stress period imposed upon the ratoon crop at the rainshelter site. This corresponded with a smaller osmotic adjustment in the second than in first stress period. The reduced osmotic adjustment in the second stress period of the field crop may have resulted from a shortage of assimilate (Michelena and Boyer, 1982). Leaf area had been restricted by stress and light competition was severe in whereas competition amongst the potted plants was minimal.

The threshold ψ_l for plant extension applies to decreasing and not increasing ψ_l unless the decrease to the threshold value is rapid and stress is relieved shortly afterwards. Plant extension was not directly linked to leaf water potential after a protracted period of stress.

Sugarcane appears not to be capable of substantial adjustments in the sensitivity of stomata to stress after a period of stress as has been observed in several crop species (Ludlow, 1980). Also the marked reduction with age in threshold ψ_l for stomatal closure that has been observed in other crops (Frank et al, 1973) was not evident in sugarcane. There was however a slight increase in stomatal resistance of unstressed plants as they became older.

The threshold ψ_l for a reduction in leaf area was high when leaf area was high and was lower when leaf area had been reduced by water stress.

The threshold for the rapid increase in stomatal resistance differed between varieties, stress cycles and rates of stress imposition. The drought resistance of N12 was explained at least partially by the relatively high sensitivity of its stomata to decreasing leaf water potential and the converse was true of N14. This type of resistance in sugarcane distinguishes the species as one that avoids rather than endures drought (Kriedermann and Barrs, 1983). The threshold for completion of stomatal closure was reduced slightly by previous occurrences of water stress and it was reduced when the rate of stress development was reduced.

The use of the infra-red thermometer in detecting water stress in sugarcane was reasonably successful despite the relatively low vapour pressure deficits that were prevalent at the coast. A crop water stress index (CWSI) of 0.4 was associated with the threshold leaf water potential for plant extension. This may be a useful criterion for applying irrigation since recovery from stress would be practically immediate at this stage of stress. Further work is required to establish the association between CWSI and yield reduction due to stress.

The data on crop growth rate has again shown that growth potential varies considerably through the year and that cane yield may increase at rates as high as one ton per hectare per day during the hottest months.

Water use efficiency likewise varies during the year and this will need to be considered when growth models based on water use are developed. Variations in water use efficiency may also affect the procedure for assessing the feasibility of irrigation schemes. Water use efficiency may at times be as high as 0.3 t ha^{-1} per millimeter of water used. The data nevertheless supported a general WUE of about 0.1 t ha^{-1} mm^{-1} which is presently used in feasibility studies.

While cane growth rate decreased rapidly with the onset of stress the recovery when stress was relieved prior to stalk death was practically complete within two weeks. Thus an irrigation or rain prior to stalk death would prevent permanent damage to the crop. Growers that are able to apply limited amounts of irrigation to otherwise rainfed crops would be advised to do this before stalks began to die rapidly.

Water use efficiency is reduced slightly during water stress but returns rapidly to normal when stress is relieved.

Water stress promotes ripening in sugarcane when stress is sufficient to reduce plant extension but insufficient to substantially increase stomatal resistance. Thus ripening will occur when leaf water potential is between -0.2 and -1.2 MPa.

Ripening implies not only an increase in dry matter and sucrose content of the fully extended portion of the stalk but also a net increase in the mass of these components. It appears that more than 10 days of this type of stress are required before sucrose mass of stressed stalks will increase more rapidly than that of unstressed stalks.

It appears that sucrose is not readily removed from the lower internodes to support new growth when water stress is relieved.

SUMMARY

The effects of water stress on plant water relations, growth, water use and sucrose accumulation were investigated with the aid rainshelters. In the first experiment various aspects of the water status of cane growing in large pots were measured. The pots were weighed to determine water use. In the second experiment similar measurements were made on cane grown in the field. Crop growth was measured non-destructively and water use was determined with a neutron probe.

The threshold leaf water potentials for various attributes were determined as follows: 1) at -0.2 MPa, plant extension rate fell below potential, 2) at -0.3 MPa, stomatal resistance started to increase, 3) at -0.4 to -0.9 MPa plant extension ceased, 4) at -0.8 MPa, leaves started to roll, 5) at -1.0 to -1.7 MPa, green leaf area was reduced, 6) at -1.2 to -1.7 MPa, stomatal resistance rose rapidly, 7) at -1.4 to -2.3 MPa, stomata finally closed, 8) at -2.0 MPa, young leaves were fully rolled and 9) at -2.8 MPa, the apical meristem was permanently damaged.

Osmotic adjustments during stress were reversed when plants recovered and there was no evidence of osmotic hardening. Stomata became more, rather than less sensitive to stress after a stress period in the field. The drought resistance of N12 was evidently due to its relatively low stress threshold for stomatal closure. This behaviour of stomata distinguished the species as one that avoids rather than endures drought. A crop water stress index (CWSI) based on infra-red thermometry correlated reasonably well with plant extension rate, leaf water potential and canopy resistance.

Crop growth potential and water use efficiency appeared to vary considerably through the year. Cane yield increased by more than 1.0 t ha d^{-1} during the hottest months. Water stress appeared to have no permanent effect on cane growth rate provided stalk death did not result from stress. Water stress promoted ripening when plant extension was reduced and before stomata finally closed. Sucrose was apparently not readily removed from the lower internodes to support new growth when water stress was relieved.

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APPENDIX 1a CALIBRATION OF POROMETER

A porometer sensitive to diffusive resistance of leaves was first described by van Bavel, Nakayama and Ehrler (1965). When a porometer cup is attached to a leaf, water vapour continues to diffuse through the stomata and cuticle and the humidity increases within the cup at a rate uniquely related to the resistance of the epidermis. A Delta-T Mk3 porometer based on the design of Stiles, Monteith and Bull (1970) was acquired. Salient features of the Delta-T porometer and of its operation were as follows:

1. Relative humidity (RH) of the cup was displayed continuously and ambient RH was measured before selecting the RH range over which readings were to be taken. The porometer had seven such range settings thus allowing a good match between humidity of the cup and that of the air. Relative humidity was mostly between 50 % and 60 % at midday when readings were taken and the porometer was set to cycle between 45 and 55 % and between 55 and 65 % on most occasions.

2. The transit time required for relative humidity in the porometer cup to return from 5% below the selected humidity setting to 5% above this setting was displayed while dry air was pumped into the cup.

3. Automatic pumping of dry air into the sensor cup ensured repeatable readings within 4 or 5 cycles each 3 to 10 s in duration. Pumping time was adjusted to about 2 s.

4. The temperature of air inside the cup and the difference in temperature between cup and leaf or calibration plate were displayed alternately.

5. A calibration plate with resistances of 40, 130, 290, 650, 1090 and 2250 s m^{-1} was provided.

Calibration of the porometer was carried out in a temperature controlled germination cabinet. Relative humidity in the cabinet was kept above 80% in order to prevent excessive cooling of the moist filter paper attached to the calibration plate. Differences in temperature between the evaporating surface and the sensor may affect the calibration substantially (McCree and van Bavel, 1977). The difference in temperature of the thermistor inside the porometer cup and the thermistor against the adhesive tape securing the moist paper was less than 0.3 °C when the plate resistance was greater than 130 s m^{-1} . This temperature difference rose to as much as 1.0°C when the plate resistance was 40 s m^{-1} and these data were excluded from the calibration equations.

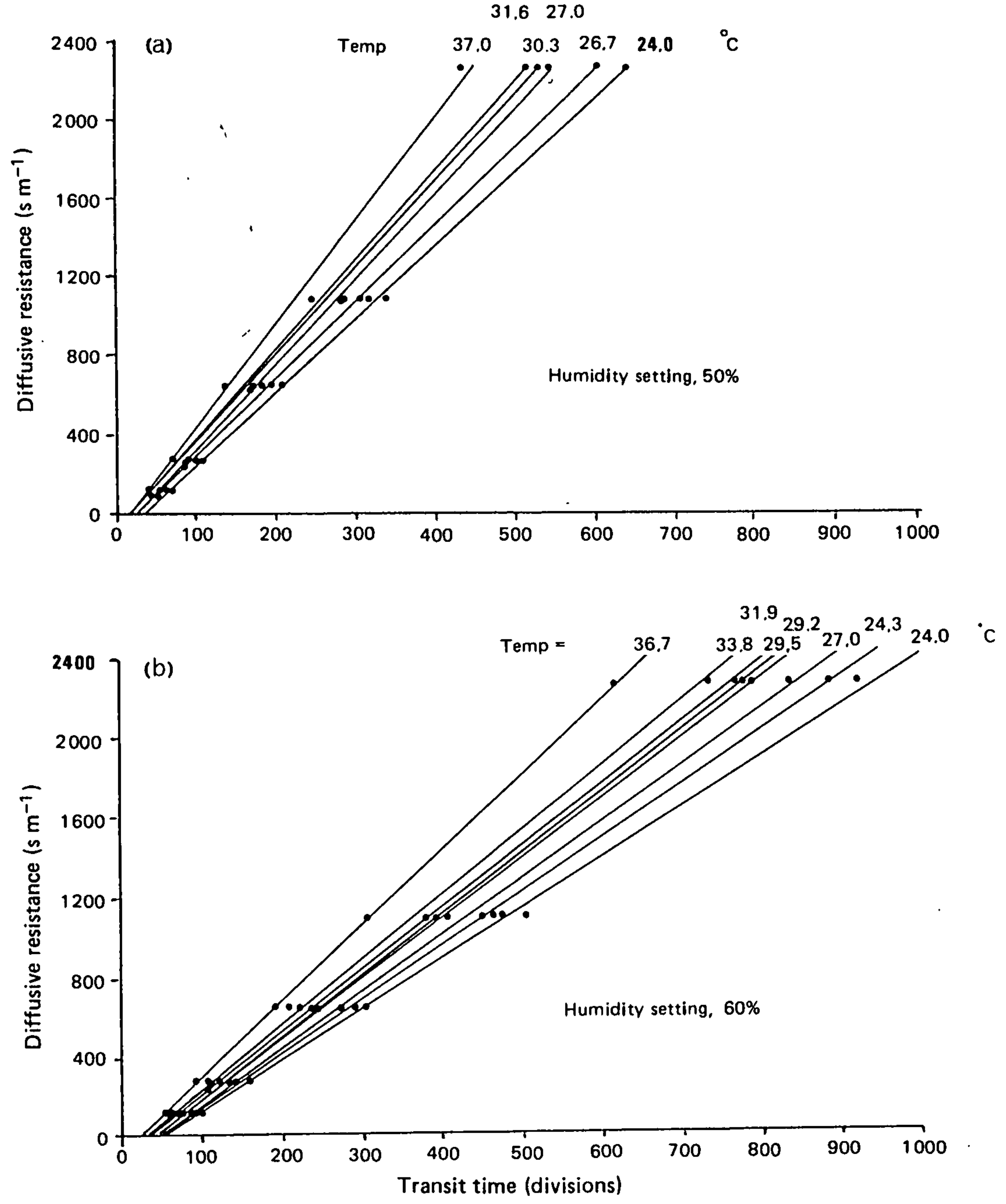

Figure A1. Resistance to gaseous diffusion through a perforated calibration plate, versus transit time at two humidity settings and various cup temperatures. Lines fitted by least squares.

Regression equations were fitted to the resistance and transit time data (Fig. A1) so that transit times might be converted to resistances conveniently. The constants in the equations were independent of temperature but the slopes and temperature were highly correlated. Intercepts in the equations for 50 % and 60 % RH settings were -115 ± 3.6 and -76 ± 5.9 s m^{-1} respectively.

The slopes were computed as follows from the cup temperatures recorded in the field.

RH= 50 % : Slope = $1.62 + .0849 \times T^{o}C \pm 0.144$
r = 0.94
n = 7
RH= 60 % : Slope = $1.25 + .0514 \times T^{o}C \pm 0.113$
r = 0.92
n = 10

The difference in temperature between leaf and cup during field use was often greater than 0.5 ^{o}C but usually less than 1.2 ^{o}C when resistances were low. A correction for the effect of this gradient on diffusion of water vapour, based on work of Monteith & Bull (1970) was applied. When humidity settings were 50, 60 and 70%, the recorded transit time was reduced by 1.2, 1.5 and 2.0% respectively for each 0.1% increase in the temperature gradient above zero.

APPENDIX 1b SELECTION OF STANDARD SURFACES FOR RESISTANCE MEASUREMENT.

Resistances of ad- and abaxial surfaces of leaves 1 to 6 of unstressed plants were measured before the start of the pot experiment in order to establish which of these should be measured during the experiments. Leaves 2, 3 and 4 provided the most consistent readings and were selected as the representative leaves for the duration of the pot and field experiments. Leaf 1 was defined as the youngest half unfurled leaf and leaf 3 was the youngest fully expanded leaf. Leaves 1 to 4 were the most exposed leaves in the canopy.

Table A1. Stomatal resistance (s m^{-1}) of leaves 1 to 6 of well watered plants of varieties NCo376 and N11 (means of both surfaces).

Leaf number	1	2	3	4	5	6
No. readings	7	10	10	10	10	9
Mean r_s	620	350	380	340	470	300
SE of mean	120	40	50	50	70	70

On another occasion several resistance measurements were made on ad- (upper) and abaxial surfaces in order to establish which surface should be routinely measured. The adaxial (upper) surface had twice the resistance of the abaxial surface ($p=0.01$, Table A2) probably because of a lower frequency of stomata on the ad- than on the abaxial surface Dunlop (1913).

Table A2. Stomatal resistance (r_s) of ad- and abaxial surfaces of leaves 2,3 and 4 of unstressed plants of NCo376 and N11 (s m^{-1}).

	Variety		Leaf number			Surface	
Factor	NCo376	N11	2	3	4	Ad-	Ab-
N	216	216	144	144	144	216	216
r_s	410	410	480	370	380	540	270
SE	16	12	22	31	32	14	8

The abaxial surface was preferred for routine measurements because of its comparatively low resistance and variability.

APPENDIX 2. CALIBRATION OF NEUTRON PROBE

Surface calibration.

Since the radius of response of the neutron moisture meter may extend above the soil surface when the neutron source is less than 150 mm deep it is customary to measure the water content of the soil above this depth gravimetrically (Greacen, 1981). This method was not suited to the water stress project on sugarcane because the plots were small and the repeated sampling required for this method would have caused unacceptable disturbance.

Water from a 300 l tank was allowed to drip overnight on portions of the field at the rainshelter site shortly after planting in August 1983. A section of access tubing was inserted to a depth of 400 mm and counts were taken when the neutron source was 50, 150, and 250 mm below the surface. Disturbed soil cores 100 x 50 mm were removed from three positions adjacent to the access tubes to a depth of 300 mm. A similar procedure was carried out on dry portions of the field. Data from fifteen portions of the field was obtained in this way.

Volumetric water content of the top 100 mm of soil was best correlated with count ratio (CR) when the neutron source was 150 mm deep (Fig. A2). The water content (WC) of this layer was estimated by the following regression equation:

$$\begin{aligned} WC &= (91.5 \times CR) - 10.2 \pm 1.17\ \% \\ r^2 &= 0.93 \\ n &= 13 \end{aligned}$$

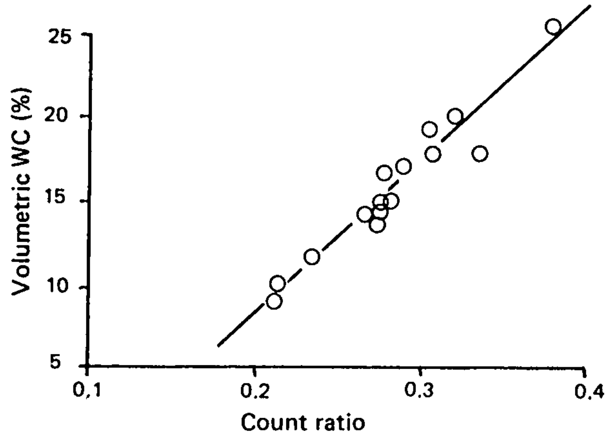

Figure A2. Neutron count ratio (CR) of neutron source at 150mm and volumetric water content (WC) of soil 0 to 100 mm deep.

Depth calibration.

Calibration of the probe at depths greater than 300 mm, was carried out between the 12th and 28th October 1983, shortly after the surface calibration had been completed, and between the 5th and 12th July 1984, after the plant crop was harvested. Access tubes for the depth calibration were inserted as in the small plots and neutron counts were taken at the same depth intervals as those used during the experiment. The gravimetric water content of three disturbed soil cores from each depth at which counts had been taken, was obtained. Interference with the neutron scatter was avoided by taking counts while the neutron source was at least 400 mm deeper than the adjacent sampling holes. During the first calibration period, four tubes were inserted in portions of the field which had been irrigated the day before. Another four tubes were inserted in unirrigated soil although this was not much drier than the irrigated portion. During the second depth calibration period three access tubes were inserted in the irrigated area and three in the dry area under the rainshelter which, at that stage, had excluded rain for five months.

The water content (WC) of the three cores alongside each count position often differed considerably and it was necessary to group WC data in order to reduce standard errors to acceptible levels. This was done by grouping WC values into classes in which the corresponding count ratios differed by 0.01 or less. The results of multiple linear regression analysis on volumetric soil water content, count ratio and soil depth are shown Table A3. The depth variable became statistically insignificant ($p=0.01$) when the analysis was conducted independantly on the top 300 to 1200 mm of soil and the underlying 1350 to 2700 mm layer. These two layers differed substantially in clay content (Table 5) and a separate calibration for each was logical.

Means of water content and count ratio for each group are shown in Fig. A3. The following regression equations obtained from this grouped data were then used to estimate water content of soil 300 mm below the surface:

300 to 1200 mm : $WC = (60.0 \times CR) - 2.1$ $(R = 0.96)$
1350 to 2700 mm : $WC = (51.2 \times CR) - 1.5$ $(R = 0.91)$

where WC = volumetric water content
CR = Neutron count ratio

Table A3. Results of multiple linear regression of volumetric soil water content on count ratio and soil depth interval.

Depth Class	Independ. Variable	Mean square	F value	Total no. of observations
30 to	CR	731642	1608.8	269
270 mm	Depth	9251	20.3	
30 to	CR	176907	588.4	127
120 mm	Depth	1263	4.4	
135 to	CR	294748	580.9	142
270 mm	Depth	1253	2.4	

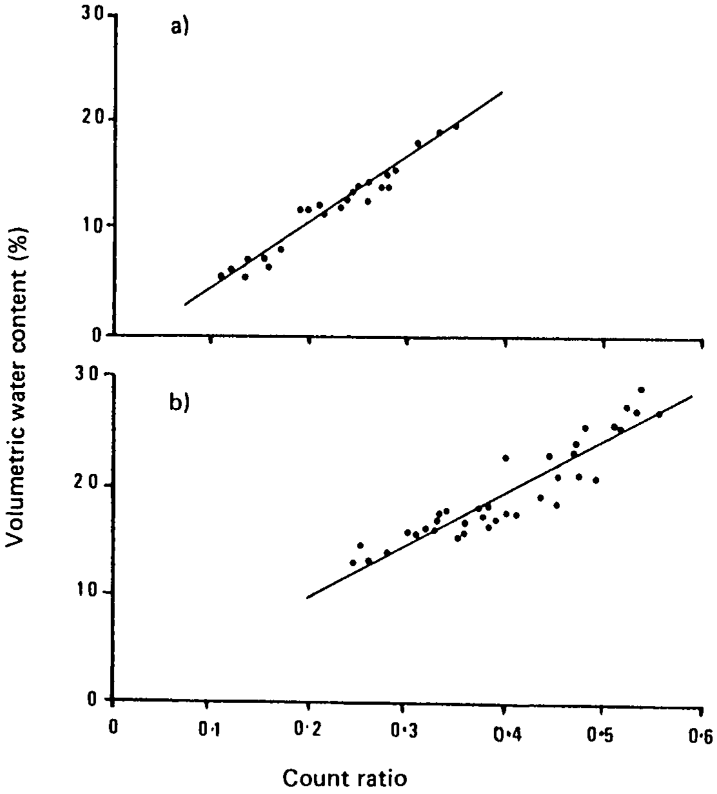

Figure A3. Relationship between neutron count ratio (CR) and volumetric water content (WC) of soil (a) 300 to 1200 mm and (b) 1350 to 2700 mm deep. Each point is the mean water content associated with count ratios differing by less than ,01.