MICROMETEOROLOGY AND PHYSIOLOGY OF SUGARCANE CROP DURING WATER STRESS

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by

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This dissertation represents my own work.

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DECLARATION

This thesis prepared for the Master of Science in Agriculture was submitted by me to the University of Free State. I hereby declare that it is my own work and has not been submitted to any other university.

I also agree that the University of Free State has the sole right to publication of this thesis.

Signed :

S.S Koonjah

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Micrometeorology and physiology of Sugarcane crop during water stress

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ABSTRACT

Water stress is the single most important factor limiting yield in plants. The effects of water stress on the micrometeorology and physiology of sugarcane were investigated using the rainshelter facilities provided at the South African Sugar Association Experiment Station, Mount Edgecombe.

Sugarcane variety NCo376 was stressed at the age of seven months during the first ratoon crop. Plant extension rate (PER) together with microclimatic measurements including radiation interception, and leaf and canopy temperature were measured continuously. Photosynthesis and leaf water potential were also measured on a daily basis together with the volumetric soil water content.

Among the yield-determining processes, plant extension rate was the first to be significantly affected 10 days after onset of water stress. The leaf water potential (Ψ_L) measured at this stage was -0.7 MPa. Leaf area index and radiation interception were the next processes to be affected. A significant decrease in photosynthetic rate occurred 19 days after onset of water stress when the Ψ_L was at -1.0 MPa. More than 50% reduction in radiation use efficiency occurred 24 days after imposing water stress and the Ψ_L measured at this stage was -1.5 MPa.

Recovery from the first stress as far as plant extension rate and photosynthesis were concerned, occurred within 3 to 4 days after irrigation was resumed. When the same sugarcane plants were stressed for a second time, it took fewer days for plant extension rate and photosynthesis to be severely affected as compared to the stress imposed during the first time.

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List of Symbols and Abbreviations

Ψ - Water potential

Ψ_L - Leaf water potential

Ψ_S - Soil water potential

CWSI - Crop water stress index

DAT - Days after onset of water stress

ETo - Reference evapotranspiration

LAI - Leaf area index

PER - Plant extension rate

PN - Photosynthetic rate

R_b - Boundary layer resistance

RUE - Radiation use efficiency

SWC - Soil water content

Ta - Air temperature

Tc - Canopy temperature

VPD - Vapour pressure deficit

ET - Actual evapotranspiration

ET_p - Potential evapotranspiration

CER - Carbon exchange rate

ABA - Abscisic acid

IRT - Infrared thermometer

CHAPTER 1

INTRODUCTION

1.1 General

Sugarcane is a member of the family *gramineae* (monocotyledon) and belongs to the genus *Saccharum*. Sugarcane plants have the unique ability to store sucrose in their stems. Its economic importance lies in the sucrose content in the stalk ranging from 10 to 14%. It is grown mainly in the tropical and sub-tropical areas between 15^0 and 30^0 latitude. Sugarcane and sugar beet contribute to over 90% of world sugar production.

1.2 South African sugar industry

South Africa is a large producer of cane sugar following countries such as Brazil, Cuba, India, Australia, United States, Philippines and China, with an annual production of about 2.2 million tons sugar (South African Sugar Association, 2001).

All the sugarcane cultivation is located in the eastern part of the country specifically to the KwaZulu-Natal (KZN) province. The area under sugarcane in KZN for the cropping year 1999/2000 was 424,444 ha of which 315,753 ha were harvested. Table 1.1 shows the area and production of sugarcane during the past five years. There was a general increase in area cultivated and yield of sugarcane although a slight decrease in sugar yield occurred during the season 1999/2000 compared to the previous season.

1.3 Sugarcane production in KZN.

Within the KZN province, the main sugarcane production areas are located in the Northern Irrigated, Midlands North, Midlands South, North Coast and South Coast regions as shown in Fig.1.1. With decreasing latitude north of 28.5^0S, rainfall decreases rapidly whereas thermal time and evaporation increase leading to frequent water stress

Table 1.1 Crop data for the past 5 years in KZN ***(source : South African Sugar Association, 2001).***

Crop year	Area ('000 ha)		Yield ('000 tons)	
	Cultivated	Harvested	Cane	Sugar
1995/1996	395	273	16,714	1,667
1996/1997	411	300	20,951	2,269
1997/1998	421	297	22,155	2,413
1998/1999	417	316	22,930	2,646
1999/2000	424	316	21,223	2,532

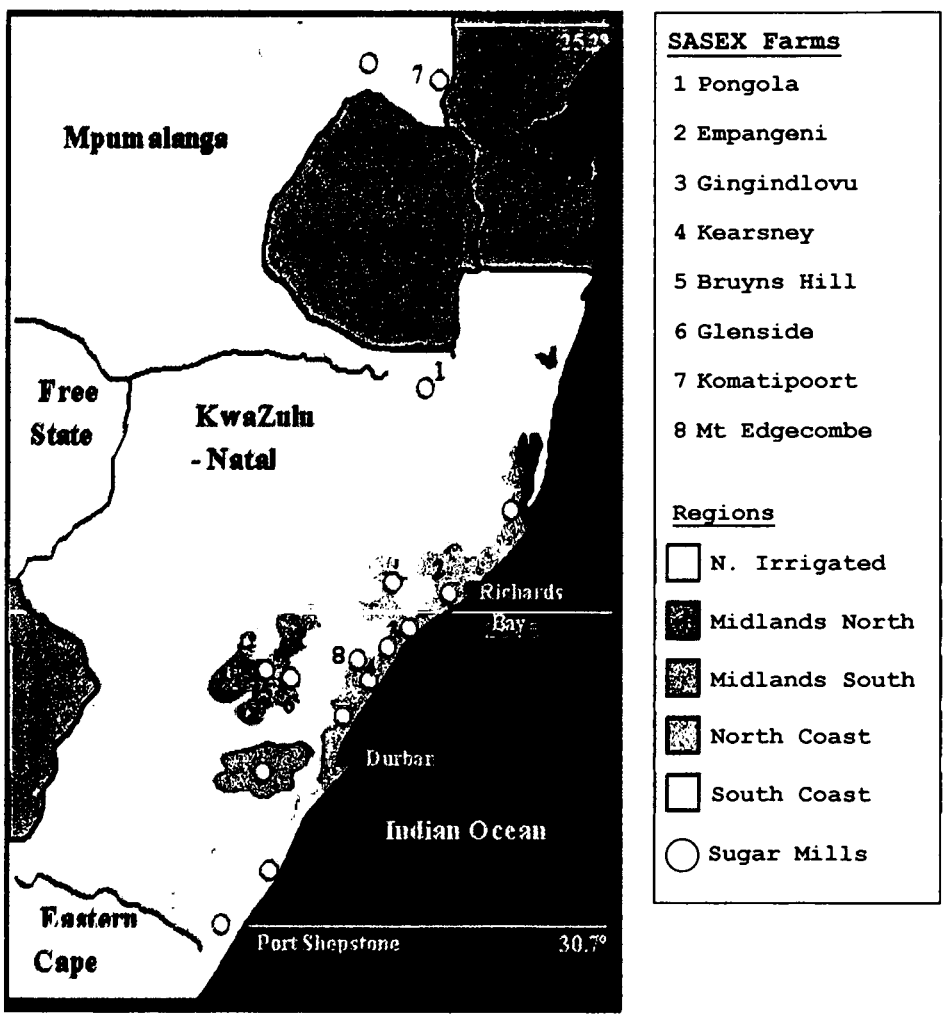

Fig 1.1 Maps showing sugarcane cultivation areas in Kwa-Zulu Natal and location of SASEX experimental farms and the sugar mills

conditions (South African Sugar Association Experiment Station, 2001). Water becomes a limiting factor to yield as

irrigation facilities are not accessible to all the farmers within these regions.

In South Africa, sugarcane grown under dryland conditions amounts to 86% of which around 45% is located on shallow soils less than 600 mm deep (Beater, 1970 as quoted by Van Antwerpen, 1998). Therefore, water stress is a frequent phenomenon occurring in a large part of the South African sugarcane growing area.

1.4 Purpose of study

Water stress is the single most important factor limiting crop yield (Begg and Turner, 1976) and it occurs when transpiration exceeds water uptake by the roots. Little is known of the complex effects of water stress on the physiology, particularly photosynthesis and micrometeorology components in sugar cane crop. This study will endeavour to understand how these processes are affected during the onset of water stress and to help farmers to better understand and manage their crops during drought period. The results will also provide additional data to assist in future crop growth modelling to provide better estimates of yield.

CHAPTER 2

GROWTH OF SUGARCANE

2.1 Phenological development stages

The time period from germination to harvest in sugarcane can be categorized into different phenological development phases namely germination, tillering, elongation, and ripening stages. Germination occurs when buds from stem cuttings develop small shoots and roots. This phase depends on the external environment as well as internal factors in the cuttings (Van Dillewijn, 1952). Tillering is the next developmental phase and provides the foundation for the sugarcane crop as it affects yield and varies according to variety, soil status and climate. The duration of this stage can vary from 4 to 6 months after planting. Elongation phase is when the tillers grow in length and contribute to the final yield. This stage is affected by climate and soil water content, and in Mauritius between 70 and 80% of total stalk elongation takes place during 4 to 5 months after completion of tillering (Anonymous, 1999). The ripening process takes place after the vegetative growth phase. During this phase, there is a shift to sucrose accumulation in the stalk rather than growth of the stalk. Conditions conducive for the ripening process to proceed are when environmental conditions are cooler, air humidity is lower and day length is shorter.

2.2 Factors limiting the phenological development stages

The development phases in sugarcane are affected by both plant and non-plant factors. The plant factors include the age of the plant, hormone balance and presence of metabolites whereas the non-plant factors comprised mostly micrometeorological and soil factors. Only the non-plant factors are discussed in this section.

2.2.1 Radiation

According to Van Dillewijn (1952), radiation intensity and day length were considered to be the most important driving forces for tillering. Gosnell (1968) found that in sugarcane, net radiation was highly correlated with crop characteristics such as crop growth rate, stalk elongation rate, foliage production and leaf area index. Photosynthesis rate has generally been found to be proportional to the fraction of intercepted radiation (Monteith, 1972). Extensive research on biomass accumulation and radiation in sugarcane has shown that the higher the incident radiation, the higher the expected biomass and yield (Muchow, Evensen, Osgood, and Robertson, 1997).

Recent work by Muchow, Spillman, Wood, and Thomas (1994) and Robertson, Wood and Muchow (1996) have shown that the increment in aboveground biomass is directly related to the amount of radiation intercepted by the canopy. Radiation use efficiency (RUE) is the ratio of net aboveground biomass at maturity to cumulative radiation intercepted from sowing to maturity. In sugarcane, the maximum RUE appears to be higher than those of maize and grain sorghum with values approaching 2 g MJ^{-1} when the majority of dead leaf is recovered (Sinclair and Muchow, 1999).

2.2.2 Air Temperature

Temperature is a primary factor driving shoot emergence, leaf appearance and stalk elongation of sugarcane (Glasziou, Bull, Hatch and Whiteman, 1965; Ferraris, Chapman, Ludlow, 1992; Inman-Bamber, 1994). The mean daily air temperatures for optimum growth of sugarcane range from 30 to 35^{0}C. Lower temperatures tend to slow the rate of germination, stalk elongation and therefore reduce yields.

Many researchers have worked on the base and optimum temperatures for the different phenological development stages. In Australia, Liu, Kingston and Bull (1998) found that the base temperatures for shoot emergence, stalk appearance, stalk elongation and leaf appearance in cultivar Q138 were 11.6, 12.4, 18.9 and 16.9^{0}C respectively whereas 29, 30, 28 and 29^{0}C were their respective optimum temperatures. In South Africa, Inman-Bamber (1994) found that both sugarcane cultivars N14 and NCo376 have base temperature of 10^{0}C and 16^{0}C for leaf and tiller appearance respectively.

2.2.3 Water

The necessity of an adequate water supply in the root zone for the sugarcane plant to achieve optimum growth is unquestionable. Shortage of water can be the most important detriment to maximum yield even under conditions of high radiation intensity and optimal temperatures (Mongelard and Nickell, 1971).

The potential yield of sugarcane depends on atmospheric and soil factors as well as on the genetic pool of the clone under cultivation. Clements and Kubata (1943) found a positive and linear relationship between the water content of leaf sheaths and growth in sugarcane. Gosnell (1968) found positive responses between soil water and crop factors especially elongation rate, foliage production and leaf area index.

The water requirement of sugarcane is based on the transpiration requirement. During an experiment using the lysimeter at Pongola in South Africa, Thompson (1976) showed that for each 100 mm of water lost through evapotranspiration, approximately 9.7 tons cane or 1.35 tons sucrose could be produced.

It is generally accepted that withholding water during the maturation phase improves cane ripening. Singels, Kennedy, and Bezuidenhout (2000) found that during mild stress the

instantaneous sucrose partition fraction increased by 33%. Drying off at the maturation phase is a usual practice especially in irrigated fields.

CHAPTER 3

EFFECT OF WATER STRESS

3.1 Definition of water stress

Plants are often exposed to various environmental stresses and when the stress factor is water shortage, then the plant is said to suffer from water stress. Usually, several stress factors act simultaneously on the plant such as combined heat load, water deficit and high irradiance during dry, sunny and warm summer periods (Yordanov, Velikova and Tsonev, 2000).

Lichtenthaler (1996) extended the stress concept of plants by differentiating between eu-stress and dis-stress. Eu-stress is an activating, stimulating stress and a positive element for plant development, whereas dis-stress is a severe and real stress that causes damage, and thus negatively affects the plant and its development. Stress is a dose-dependent matter. At fairly low concentrations a stressor can stimulate plant metabolism and plant growth. Real stress shows up when a certain threshold of a stressor, which can no longer be compensated for by the plant, is exceeded. Plants also differ in their stress coping capacity.

3.2 Phases of water stress

There are different phase sequences and responses induced in plants by water stress. There are three stress response phases namely the response, restitution and end phases. If the water stress has been removed before causing severe damage, then a fourth phase known as the regeneration phase occurs. Table 3.1 gives the consecutive four phases and Fig. 3.1 shows the stress syndrome responses of plants.

At the beginning of stress the plants react with a decline of one or several physiological functions. Due to this decrease in metabolic activities, the plants deviate from their normal physiological standard and their vitality declines.

Table 3.1. The different phases induced by stress in crop. ***(source : Lichtenthaler, 1996)***

Phases	Responses
1. Response	Alarm reaction - deviation of the functional norm - decline of vitality - catabolic processes exceed anabolism
2. Restitution	Stage of resistance - adaptation processes - repair processes - hardening (reactivation)
3. End	Stage of exhaustion - stress intensity too high - overcharge of the adaptation capacity - chronic disease or death
4. Regeneration	Partial or full regeneration - when stressor is removed and the damage not too high

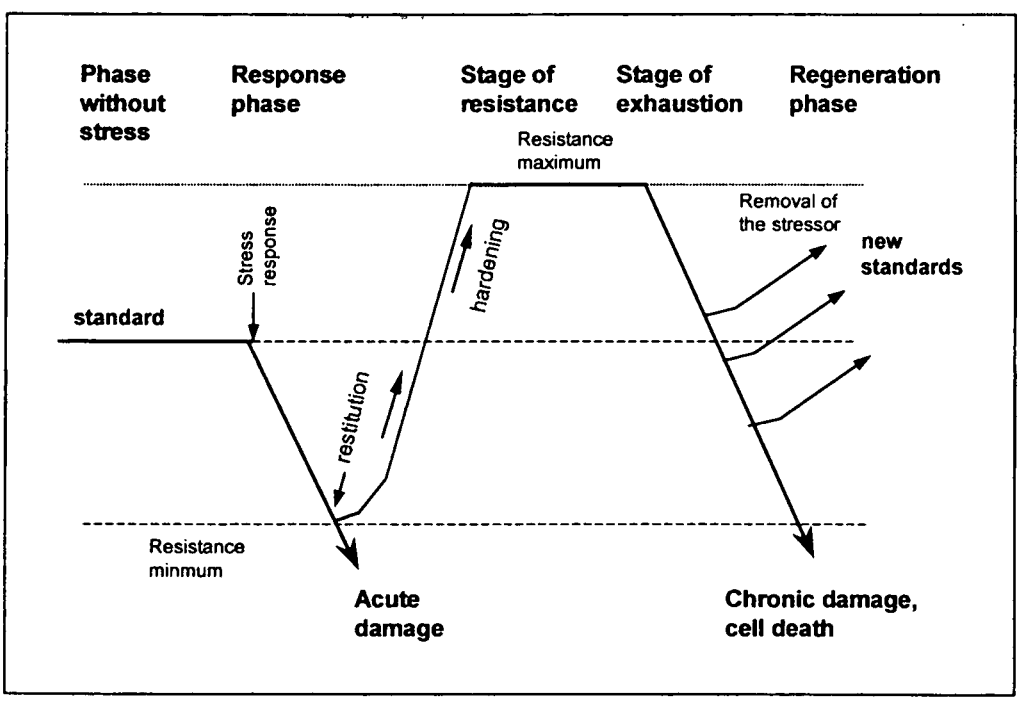

Fig. 3.1. Stress syndrome responses of plants (Lichtenthaler, 1996).

Acute damage will occur fast in those plants which possess no or only low stress tolerance and thus have a low resistance minimum. During this alarm phase most plants will, however, activate their stress coping mechanisms by fast acclimation of their metabolic fluxes as well as activating the repair

processes and long-term metabolic and morphological adaptations. This is also called the general alarm syndrome (GAS).

Repair processes and adaptations will not only lead to a restitution of the previous physiological functions, but also to a hardening of plants by establishing a new operational level, which is an optimum stage of physiology under the changed environmental conditions and which corresponds to the plants' resistance maximum.

During long-term stress when the plants' stress coping mechanisms are overloaded, the stage of exhaustion (end phase) shows up in which physiology and vitality are progressively lost. This causes damage and finally cell death (Lichtenthaler, 1996).

However, when the water stress is removed at the right time before the senescence processes become dominant, the plants will generate and move to new operational levels (regeneration phase). The time and stage of exhaustion at which the stress is removed defines to which new physiological standard within the resistance minimum and maximum the plants will move (Lichtenthaler, 1996).

3.3 Effects of water stress at cellular level

Cell division appears less sensitive to water deficits than cell enlargement (Hsiao, 1973). Gardner and Nieuman (1964, as cited by Begg and Turner, 1976) concluded that cell division continued during stress, though at a reduced rate and thus providing an opportunity for a relatively rapid resumption of growth when stress is removed. However, Tardieu, Reymond, Hamard, Granier and Muller (2000) found that water deficit in maize affected cell division rate in about the same proportion as the sum of relative increases in length and width of cells, so that the cell density per unit leaf length was almost unaffected.

In maize, leaf enlargement was found to decline rapidly at leaf water potential (Ψ_L) below -0.2 MPa and ceased at -0.7

to -0.9 MPa (Boyer, 1970). But, field measurements of leaf extension in maize by Watts (1974) have shown that there was no reduction in leaf extension rate until Ψ_L was below -0.8 or -0.9 MPa.

In general there is a rapid and then more gradual decline in the rates of cell enlargement as water stress develops, with enlargement ceasing when turgor pressures are still positive, for example, as large as 0.6 to 0.8 MPa in sunflower and maize (Boyer, 1970). The extreme sensitivity of growth to water stress has been described by an equation showing the relationship between the relative rate of irreversible increase in volume of a cell to its turgor pressure (Ψ_P) (Lockhart, 1976; Green, 1968) :

$$\frac{dV}{Vdt} = m\left(\psi_p - Y\right)$$

where V - cell volume,

t - time,

m - volumetric extensibility,

Ψ_P - turgor pressure,

Y - threshold turgor pressure.

The equation indicates that growth rate, normalised for the size of the cell, is related by the coefficient m to the turgor pressure above a minimum threshold (Ψ_P-Y), which is termed growth effective turgor. The loosening ability of the cell wall is reflected in both m and Y. The equation emphasizes the fact that Ψ_P must be above the threshold value of Y for the cell to grow. Thus growth may cease well before Ψ_P falls to zero, and can be highly sensitive to water deficits of only a few MPa (Hsiao and Xu, 2001).

3.4 Effects of water stress on plant morphology

3.4.1 Leaf senescence

One of the most important consequences of the sensitivity of cell enlargement to small water deficits is a marked

reduction in leaf growth. Water deficit reduces growth and yield by decreasing both the size and activity of the crop canopy.

Water stress also hastens the rate of leaf senescence which is also the first observable sign of water stress in plants. In maize, it was found that the senesced fraction of leaf area increased exponentially with thermal time (Stone, Wilson, Jamieson and Gillespie, 2001). During water stress, the rate of leaf senescence occurs faster in older leaves than in young leaves (Begg and Turner, 1976).

3.4.2 Leaf area index (LAI)

Reduction in cell enlargement and number of green leaves during water stress usually contribute to a marked decrease in leaf area index. Water stress can also affect leaf area through its effect in hastening the rate of leaf senescence (Begg and Turner, 1976). In maize, the percent reduction of green LAI per mm of soil water deficit decreased exponentially with thermal time (Stone *et al.*, 2001). Inman-Bamber (1986) found that the LAI of three sugarcane varieties decreased at different rates during water stress.

3.4.3 Plant growth rate

Leaf growth defines the canopy size of a plant for capturing and carrying out photosynthesis to gain carbon and energy. In maize, severe reduction in leaf extension rate was found during water deficit as compared to fully irrigated plants (Stone, *et al.*, 2001).

Hudson (1968) studied the sensitivity of sugarcane leaf extension to water stress by recording leaf height continuously. Leaf growth almost ceased when transpiration was only 30% below potential. When the root medium was drenched with a weak sucrose solution having osmotic potential of -0.1 MPa, the plant extension rate (PER) fell below the maximum value. Sugarcane PER ceased when the solution used had an osmotic potential of -0.7 MPa (as quoted by Inman-Bamber, 1986).

Growth rate in sugarcane fell below maximum when 75% of the total available water (TAW) was used in a sandy soil as compared to 25% in a clayey soil (Thompson and de Robillard, 1968). Inman-Bamber and de Jager (1986) found that PER in sugarcane was reduced when Ψ_L was less than -0.2 MPa and ceased when Ψ_L was -0.4 to -0.7 MPa. The initial rapid decline in PER was possibly due to a reduction in the elongation of young cells.

In one of the dry-down experiments in sugarcane, Inman-Bamber (2000) found that leaf extension rate in the stressed plot relative to those of irrigated plots was reduced about 10 days after withholding irrigation. Similarly, relative stalk elongation rate was reduced after 15 days without irrigation.

3.4.4 Plant root growth

Root growth defines the extent to which a plant explores soil for water and mineral nutrients. Growth of roots and leaves are co-coordinated and their sizes relative to each other vary dynamically in response to environmental conditions. Root growth has long been known to be more resistant (Westgate and Boyer, 1984) to water stress than leaf growth (Boyer, 1968).

Hsiao and Xu (2001) found that leaf elongation rate in maize was maximal when water potential (Ψ) of the growth zone was at -0.75 MPa and that elongation stopped when Ψ was reduced to -1.1 MPa. They also found that further reductions in Ψ had less effect on the elongation of maize roots and root elongation continued to grow at more than one-third of the maximum rate even when Ψ was reduced to -1.9 MPa. Therefore, roots are capable of growing at lower Ψ, down to -1.5 MPa and even lower but at a slower rate.

According to a few studies done on sugarcane root system, Van Antwerpen (1998) found that stressed cane (variety NCo376) had smaller root length density compared to fully

irrigated cane and that a strong relationship existed between LAI and root length density.

3.4.5 Biomass and yield

In considering yields in relation to water stress, the most relevant to analyse is the production of total dry matter. The yield will usually depend more on the developmental stages at which stress is applied and on sensitivity to stress in the different development stages. Shoot dry mass accumulation in maize was considerably reduced by soil water deficit (Kang, Shi and Zhang, 2000). Stone *et al.* (2001) found that the biomass of a mature maize crop was significantly and negatively related to soil water deficit.

Despite lack of rainfall and high atmospheric evaporative demand, total fresh weight of sugarcane was reduced 35 days after the last irrigation and cane yield was severely reduced 49 days after irrigation (Inman-Bamber, 2000). During a water stress trial conducted in a rainshelter on sugarcane variety NCo376, Singels *et al.* (2000) reported that biomass accumulation was only affected by water stress after the relative soil water content dropped below 35%. When the soil water content was between 55% and 35%, more biomass was partitioned to sucrose and less to the rest of the stalk. During a trial on deficit irrigation in sugarcane, Pene and Edi (1999) showed that yield decline due to water deficit was significantly higher during stem elongation than during tillering. As a result the cane crop was much more sensitive to water stress at stem elongation.

3.5 Effects of water stress on plant microclimate

3.5.1 Radiation interception and radiation use efficiency

The reduction in crop biomass production and yield due to water deficit are associated with lower radiation interception (Monteith, 1972). In sweet corn, biomass accumulation was reduced by water stress through the

effects on both amount of radiation intercepted (RI) and the radiation use efficiency (RUE) (Stone *et al.*, 2001). Table 3.2 illustrates the severity of water deficits on RI and RUE in maize. For the severely droughted crop, RUE was more affected by water deficit than radiation interception. Water deficit reduced the ability of the crop to accumulate biomass by reducing the capacity to convert intercepted energy to biomass.

Table 3.2 Effect of water deficit treatments on radiation interception (RI, % change), radiation use efficiency (RUE, % change) and maximum leaf area index (LAI, % change) in sweet corn. ***(Source : Stone et al., 2001).***

Treatment	RI	RUE	Max LAI
Fully irrigated	0	0	0
Severe water deficit	-25	-30	-27

Soil water deficits have a major influence on leaf photosynthesis consequently decreasing RUE under drought conditions (Sinclair and Muchow, 1999). Jamieson, Francis, Wilson and Martin (1995) compared RUE of barley subjected to different irrigation treatments and found that there was a linear decrease in RUE with the early droughted crop. Water stress conditions imposed in the middle or end of the growing season did not exhibit a decrease in RUE.

3.5.2 Leaf temperature

Leaf temperature was found to be a good indicator of stress if vapour pressure effects were known (Ehrler, 1973). But the major disadvantage was that many samples had to be taken to represent the leaf temperature of the field. In oats, Sandhu and Horton (1978) found leaf temperature in water-stressed treatments to be 2.5 to 4.0^{0}C warmer than fully irrigated oats and the difference was attributed to reduced transpiration.

3.5.3 Canopy temperature and crop water stress index (CWSI)

Canopy temperature measurement was possible by the development of Infrared thermometer (IRT) which measures emitted thermal radiation. In wheat, Ehrler, Idso, Jackson and Reginato (1978) found that canopy-air temperature difference (Tc-Ta) increases as plant water potential decreases. According to Idso, Jackson, Pinter, Reginato and Hatfield (1981), canopy-air temperature differences of 10-15^{0}C can be expected in a relatively dry environment whereas in a humid region, the differences would be much smaller. In sugarcane, the maximum Tc-Ta values obtained from severely stressed cane were about 6^{0}C (Inman-Bamber and de Jager, 1986).

Under non-limiting water conditions, a crop will transpire at the potential rate (ET_p). But as water becomes limiting, the actual evapotranspiration (ET) will fall below the potential rate. The ratio of actual to potential evapotranspiration gives an index of crop water status (Jackson, 1982). The ratio ET/ET_p ranges from 1 to 0 and the crop water stress index (CWSI) is defined as

$$CWSI = 1 - \frac{ET}{ET_p}$$

CWSI can also be calculated from canopy temperature which was first described by Idso *et al.*(1981). Fig 3.2 shows the linear regression of air-canopy temperature difference and vapour pressure deficit (VPD) in the case of water-stressed (line PQ) and the well-watered crop (line XY). CWSI can then be computed as the ratio of actual measured difference (B-A) over the maximum difference between stressed to well-watered crop (C-A).

$$CWSI = \frac{B - A}{C - A} \quad , \qquad \text{(see figure 3.2 for A,B,C)}$$

where B : measured point lying between stressed and unstressed regression lines

B-A : Vertical distance between point B and point A on unstressed regression line

C-A : Vertical distance between point C on stressed line and A on unstressed regression line

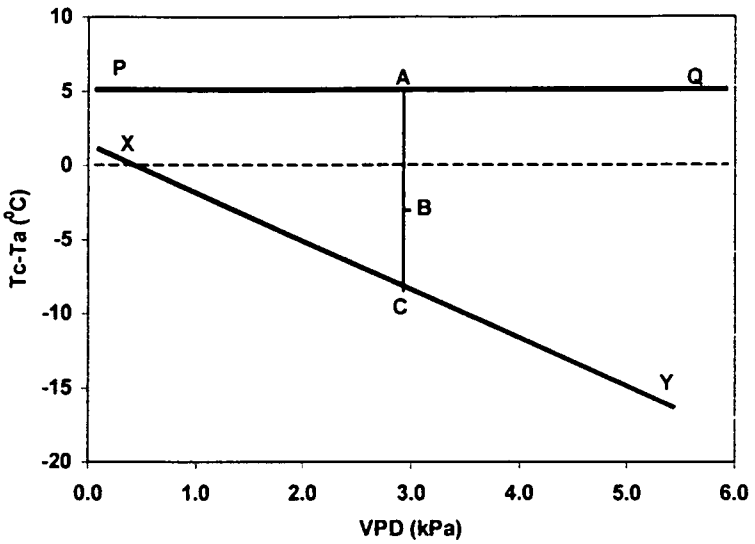

Figure 3.2. Effect of vapour pressure deficit (VPD) on the difference between air (Ta) and canopy (Tc) of the well-watered (line XY) and stressed (line PQ) crop.

CWSI can be used as a tool for either monitoring water status or be used in irrigation scheduling. In fact, in an experiment during the vegetative stage of wheat, Jackson (1982) found out that if CWSI becomes greater than 0.3, a reduction in growth rate occurs. If it reaches 0.5, then net growth will cease and therefore the crop should be irrigated when the CWSI is between 0.3 and 0.5. These limits may not apply for other crops.

In sugarcane variety N12, Inman-Bamber and de Jager (1986) found that CWSI was well correlated with midday Ψ_L which accounted for 88% of the variation.

3.6 Effects of water stress on plant physiology

3.6.1 Photosynthesis

At the whole-plant level, the effect of stress is usually perceived as a decrease in photosynthesis and growth, and is associated with the alterations in carbon and nitrogen metabolism. Contents of photosynthetic pigments

(chlorophyll a and b, and carotenoids) in the leaves is depressed at moderate leaf water deficits or even before leaf water status is changed in response to a drop in air humidity (Bunce, 1981) or in soil water potential (Gollan, Passioura and Munns, 1986). A water deficit of 17-20% in bean plants caused a significant decrease in rates of carbon dioxide uptake and oxygen evolution, whereas a 40 to 44% water deficit coupled with a leaf temperature of 45^0C led to an almost complete inhibition of both processes, but these were capable to recover (Yordanov *et al.*, 2000).

There is variation in the sensitivity of photosynthesis to water stress in different species. In maize and wheat the initial inhibitions of photosynthesis were observed at leaf water potential (Ψ_L) of -0.3 MPa (Beadle, Stevenson, Neumann, Thurtell and King, 1973) and -1.0 MPa (Johnson, Frey and Moss, 1974) respectively. In soybean, it was observed that when the leaf water potential (Ψ_L) ranged between -0.32 to -0.39 MPa, the carbon dioxide assimilation rate was 80% lower than that of well-watered control plants (Ohashi, Saneoka and Fujita, 2000). The response of photosynthetic rate to vapour pressure deficit in rice (*Oryza sativa*) decreased linearly from 25 to 15 $\mu molm^{-2}s^{-1}$ with increasing VPD from 0.5 to 2.5 kPa (He and Edwards, 1996).

In sugarcane, Du, Kawamitsu, Nose, Hiyane, Murayama, Wasano and Uchida (1996) found that when midday Ψ_L decreased from -0.37 MPa to about -0.85 MPa, the carbon exchange rate (CER) decreased almost linearly from 40 to 20 $\mu mol\ m^{-2}\ s^{-1}$. As Ψ_L decreased further, the decline in CER slowed and appeared to be non-linearly related to Ψ_L. At about -1.61 MPa, CER was at 1.3 $\mu mol\ m^{-2}\ s^{-1}$.

3.6.2 Stomatal and non-stomatal limitations

A decrease of photosynthesis due to water deficit has been attributed to both stomatal and non-stomatal limitations (Yordanov *et al.*, 2000; Du *et al.*, 1996).

Stomatal response is probably the most important factor controlling carbon fixation. Stomatal closure is the first line of defence against desiccation as it is a quicker response when compared to other morphological changes. The relative part of stomatal limitation of photosynthesis depends on the severity of water deficit. At mild stress it is a primal event.

Stomatal closure in wheat and barley has been reported to occur at Ψ_L of -0.7 and -3.0 MPa respectively (Begg and Turner, 1976). However, there is not a unique value of Ψ_L for stomatal closure as the latter varies with position of leaf in the canopy, plant age, growth conditions and stress cycles.

In sugarcane, Saliendra and Meinzer (1989) showed that in drying soil, stomata were closed at a soil water potential of -0.1 MPa. Du *et al.* (1996) reported that there was a positive linear relationship between stomatal conductance and CER in sugarcane. Above Ψ_L of -0.85 MPa, the decline in CER was caused by stomatal closure whereas below -0.85 MPa, the decline in CER was due to non-stomatal limitations. The non-stomatal components were attributed to photosynthetic enzyme activities which decreased linearly as Ψ_L became less than -0.85 MPa.

3.6.3 Respiration and transpiration rate

Dark respiration is depressed in crop species whenever the water deficit is sufficiently great to close stomata and decrease photosynthesis. Boyer (1970) showed that the dark respiration rate of shoots in soybean, sunflower and maize decreased steadily between values of Ψ_L from -0.8 to -1.8 MPa. Under fully dry conditions, Huang and Fu (2000) observed a decrease in canopy respiration rate compared to

the well-watered control in perennial grasses, namely tall fescue and kentucky bluegrass.

As water stress develops, the closing of the stomata is the main cause for transpiration decline. Transpiration is directly proportional to the gradient of water vapour concentration from the internal evaporation surface to the bulk air outside the leaf, and inversely proportional to the total resistance to water vapour transport of the air boundary layer and of the leaf (Hsiao, 1973).

Gupta and Kumar (2001) studied the effect of water stress on wheat cultivars in the boot and anthesis stages. They found that water stress decreased leaf transpiration rate at both stages but the reduction was higher during the anthesis stage. The ratio of diffusive resistance of the adaxial to abaxial surface was usually higher during water stress conditions, suggesting greater stomatal closure on the adaxial surface as a result of water stress imposed at the boot stage. But when water stress was imposed at the anthesis stage, the situation was almost reversed.

3.7 Biochemical activities during water deficits

The contrasts between roots and leaves in their growth responses to water stress are also under the influence of biochemical changes. Under water stress, abscisic acid (ABA) increases both in leaves and roots (Hsiao, 1973) and more ABA is transported from roots to leaves (Davies and Zhang, 1991). In maize at low ψ_L, Sharp, Wu, Voetberg, Saab and LeNoble (1994) showed that ABA maintained root growth while inhibiting shoot growth. After water was withheld from the soil, ABA increased in sugarcane leaves before wilting appeared (Most, 1971), thus showing that mild to moderate stress is necessary for the increased production of ABA. Therefore, ABA plays a central role in orchestrating the differential long-term growth responses to water stress of root and shoot.

Ethylene has long been known for its ability to induce abscission and abscission is a known response to water stress in some plants. Abscission induced by water stress may be mediated through internal ethylene production. Ethylene production by petioles in intact cotton plants tended to increase within hours when water deficits developed (McMichael, Jordan and Powell, 1972). Water stress seemed to predispose the leaves to ethylene action.

When severe water stress lasts for several days, total free amino acids in leaves are often increased with proline showing a pronounced rise. Stressed plants commonly accumulate proline as an osmoregulant. Osmoregulation involves the active accumulation of solutes in response to water loss and results in a decline in leaf water potential which in turns leads to an increase in the ability of the plant to extract water from a drying soil. Apart from acting as an osmoregulant, proline accumulation may act as a reservoir of nitrogen and energy storage for recovery after the stress is relieved (Steward, Bogess, Aspinall and Paleg, 1977). Rutherford (1989) tested several sugarcane varieties for their ability to produce proline and found that there was a variation in proline accumulation by leaf segments depending on the severity of stress imposed. Leaf segments soaked in solution having a potential of -3.7 MPa was necessary to maximise proline accumulation in sugarcane.

Much of the injury to plants caused by stress exposure is associated with oxidative damage at the cellular level. It is apparent that water stress induces an increase in hydrogen peroxide content and consequently lipid peroxidation and membrane injury. Hydrogen peroxide accumulation increased under water stress as well as with age. Sairam and Srivastava (2001) studied the effect of water stress on different wheat varieties. They observed that tolerant genotypes had lower hydrogen peroxide content and lipid peroxidation together with higher levels of antioxidant enzymes than susceptible varieties under water stress. The degree of oxidative stress

and antioxidant activity seems to be closely associated with the tolerance or susceptibility of a genotype to water stress.

3.8 Mechanism of adaptation during water stress

Many stress-coping mechanisms exist which show up depending on the type and strength of stress. The mechanism of adaptation employed by crops against water stress can be further divided into morphological and physiological aspects.

3.8.1 Morphological Mechanism

Water deficits usually lead to morphological changes in the plants. A reduction in leaf expansion provides a mechanism for reducing water loss from the soil and delaying the development of more severe stress. Similarly, leaf shedding or accelerated senescence of physiologically older leaves is also an adaptive mechanism for reducing water use (Begg and Turner, 1976).

Positive leaf movement to orient the leaf parallel to the incident radiation and the flagging or rolling of the leaves when wilted are additional adaptive mechanisms that reduce the effective leaf area and hence the energy load upon the plant. O'Toole and Cruz (1980) found that sugarcane leaves behaved more like leaves of rice. Leaf rolling in sugarcane started when Ψ_L was -0.8 to -1.0 MPa and were fully rolled when Ψ_L was -2.0 to -2.5 MPa.

The wax bloom on sorghum leaves has been known to increase the reflection of radiation while reducing net radiation, boundary layer conductance and transpiration (Chatterton, Hanna, Powell and Lee, 1975).

During water deficit, root growth is favoured above shoot growth and is an adaptive mechanism that enables the crop to explore a greater soil volume for available water. Varietal differences in rooting depth have been shown in wheat (Derera, Marshall and Balaam, 1969 as quoted by Begg and Turner, 1974). A decrease in hydraulic conductivity in

wheat has also been attributed to an adaptive mechanism to water stress whereby water loss is reduced.

3.8.2 Physiological Mechanisms

For plants grown under water deficit conditions, it is important to create physiological mechanisms of stress resistance in terms of stress avoidance or stress tolerance.

Stomatal closure in response to stress is a powerful and reversible mechanism for regulating water loss and reducing the development of further stress (Szeicz, Van Bavel and Takami, 1973; Inman-Bamber and De Jager, 1986). Stomata usually closed when the Ψ_L reached a threshold during a stress period. Turner (1974) found that stomata frequently start to open as radiation increases during the morning and then quickly close when the Ψ_L threshold is reached. This adaptive mechanism enables the plant to carry out photosynthesis during the morning to keep the plant in a positive carbon balance and to conserve water during the remainder of the day (Begg and Turner, 1976)

The accumulation of "compatible solutes" or osmolytes leading to osmotic adjustment is the response of plants to water deficit conditions (Bohnert and Shen, 1999). Osmolytes are metabolites whose high cellular concentration increases the osmotic potential significantly. Plant transformation leading to the presence of "compatible solutes" has resulted in significant increases in whole plant tolerance to osmotic stress. Crops originating in favourable climates, as does sugarcane, tend to have less ability to osmoregulate and therefore would be expected to show avoidance characteristics in drought resistant genotypes (Rutherford, 1989).

3.9 Recovery from water stress

Once water stress is alleviated, there is a rapid rise in Ψ_L and recovery in turgor but there is still a delay in the

opening of stomata and recovery in photosynthesis (Loveys and Kriedemann, 1973 as quoted by Begg and Turner, 1976).

A frequently observed effect on recovery from stress is a more rapid rate of growth and development than in unstressed controls. Upon rewatering previously stressed tomato plants, Gates (1968) showed that the growth rates were higher than those in unstressed controls. In both sunflower and maize, relief of stress resulted in transitory greater rates of leaf enlargement (Boyer, 1970; Acevedo, Hsiao and Henderson, 1971).

MATERIAL AND METHODS

4.1 Rainshelter

The experiment was carried out under the rainshelter at the South African Sugar Association Experiment Station (SASEX), Mount Edgecombe ($29^0 43' 20"S$, $31^0 04' 29"E$, elevation 96 m). The purpose of using the rainshelter was to ensure that no rain interfere with the treatments during the water stressed period. The rainshelter consisted of 19 dome shaped ribs made of 50 mm light steel tubing and spaced 1.5 m apart (see plate 4.1). Translucent plastic sheets with a thickness of 200 micrometer were used and fasten onto the tubular frame of the rainshelter to effectively excluded rain.

Plate 4.1 The SASEX rainshelter in the open position.

At the base of each rib was a grooved wheel that ran between two 25 mm iron pipes welded to the top and lower flanges of a channel iron to facilitate as rails. The width of the rainshelter between the rails was 8.5 m. The rainshelter was

driven by means of cables pulled by rotors on either end, and it was automatically activated by a moisture sensor. The successful operation of the shelter was partly due to the location of cables, which were inside the rails and directly in line with the wheels. The rainshelter moved northwards when closing and southwards when opening.

The control room housed a 12 V battery to ensure continual power during interruptions of the electricity supply and electronics to control signals to the rotors and thus movement of the shelter. Rain wetting the sensor was the signal for the shelter to close. A time relay switch was simultaneously activated to test the sensor after 20 minutes. If the sensor was dry a signal was send to the rotor at the opposite end to pull the shelter open. A delay of 20 minutes was enough to prevent unnecessary movement of the shelter on days when rain was intermittent. A small 12 V globe underneath the sensor prevented dew from activating the rotor.

The area covered by the rainshelter was 27 m x 8.5 m. Rainwater falling on the shelter was directed away from the trial by concrete gutters.

4.2 Trial layout and soil type

Fig 4.1 shows the field layout under the rainshelter. There were 24 rows of sugarcane, each 6.5 m long. The interrow spacing was 1.2 m. Thirteen rows were used as the stress plot where water was withheld and the rest was under drip irrigation. Three rows on each plot were demarcated for biomass sampling. Three one-metre row strips were also allotted as the agronomic plots where regular non-destructive measurements about the plant characteristics were taken.

The soil was an orthic topsoil with a 24% clay content and a rooting depth of 950 mm. The drained upper and lower limits of plant available water were 26% (i.e. 0.26 m^3m^{-3}) and 13% (i.e. 0.13 m^3m^{-3}) respectively. The plant available water capacity was 126 mm.

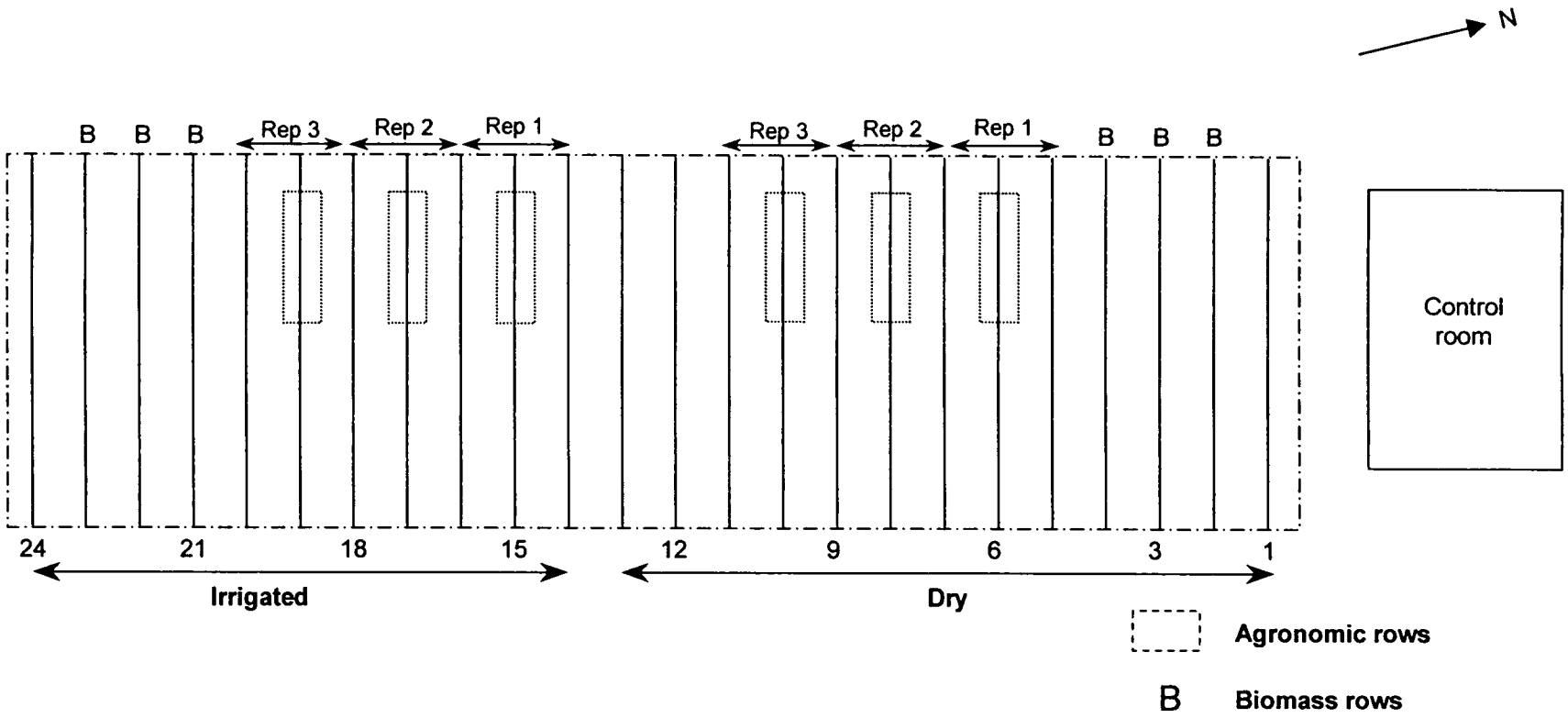

Fig. 4.1 Field layout under the rainshelter

4.3 Varieties and crop status

The variety used in the trial was NCo376. It is a cross between Co421 and Co312. NCo376 is a very common variety among farmers in KwaZulu-Natal and also the most well researched one. It is susceptible to drought and has a high stalk population of 120,000 per ha.

The crop was in its first ratoon and aged seven months old when the water stress treatment started. The crop showed no sign of any deficiencies or attack by pests and diseases at the start of the trial.

4.4 Water stress treatment

After harvest of the plant cane in August 2000, the whole field was drip-irrigated to prevent water stress until the first week of January 2001.

On 8th January water was withheld from 13 rows of the trial that constituted the stress plot (see figure 4.1). The remaining rows became the well-watered plot and drip irrigation continued at regular time intervals. In fact, the volumetric soil water content in the wet plot was monitored so that it never decreased below 21% (102mm) throughout the trial.

4.5 Cultural practices

After harvest of the plant cane in August 2000, gap filling using sprouted plant cane was carried out on 3rd October. The equivalent of 400 g of compound NPK fertilizer 5:1:5 was applied per row followed by light overhead irrigation.

Manual weeding was done on 27th October and the same amount of fertilizer was applied once more per row of cane on 14th November. The whole trial was irrigated immediately after fertilizing. The whole management of the trial in terms of cultural practices and maintenance of the rainshelter was executed by the staff of SASEX.

4.6 Equipment used

Table 4.1 gives the list of equipment used during the trial. Most of the equipment was obtained from SASEX. Only the infrared thermometers were borrowed from the Department of Agrometeorology, University of the Free State and from the Agricultural Research Council, Institute of Soil, Climate and Water, Pretoria.

Table 4.1 Equipment used and measurements taken during the trial

Equipment	Measurements
Pyranometers	Incoming radiant flux density
Tube solarimeters	Intercepted irradiance by placing one on top and one at bottom of canopy
Vaisala RH sensors	Air temperature and relative humidity
Three-cup anemometer	Wind speed
Infrared thermometers	Canopy temperature
Leaf thermocouples	Leaf temperature
Growth transducers	Plant extension rate
Sunscan canopy analysis System	PAR interception and leaf area index
Scholander pressure chamber	Leaf water potential
Infrared gas analyser (IRGA)	Photosynthetic and transpiration rate, stomatal conductance
Neutron probe	Soil water content
Aquaflex sensors	Soil water content
Automatic porometer	Stomatal resistance
Dataloggers CR10X	Continuous collection of data

4.7 Calibration of Equipment

4.7.1 Tube Solarimeters

Three tube solarimeters, model TSL from Delta-T Devices Ltd, were used during the trial and they were calibrated against a recently calibrated LI-200SZ pyranometer sensor. Dry air was passed inside each tube solarimeter to remove any moisture and the surface was wiped clean before calibration was carried out. The sensors were placed in a large open space and in such a way that no physical obstructions come in between the sunrays and sensors. The

tube solarimeters were oriented in the north-south direction.

The three tube solarimeters together with the pyranometer were connected to the CR10X datalogger and the sensors sampled at 3 minutes interval. The programming used on the datalogger is listed in Appendix I. The set up was allowed to run during two consecutive days. The data collected were downloaded and processed.

The readings from the tube solarimeters were regressed against those from the pyranometer and the results are summarized in table 4.2. Strong correlation more than 0.95 was obtained for each regression and the gradient factor ranged from 73.59 to 74.38. These values were used in the datalogger when the tube solarimeters were placed in the field.

Table 4.2 Summarised regression result obtained between tube solarimeters(X) and pyranometer(Y) readings both in W m^{-2}.

Tube Solarimeter	Regression Equation	R^2
1	$Y = 74.38\ X_1$	0.96
2	$Y = 73.73\ X_2$	0.97
3	$Y = 73.59\ X_3$	0.97

4.7.2 Leaf thermocouple

Thermocouple T-type (copper-constantan) wire with diameter 0.22mm was used to measure leaf temperature. The leaf thermocouple wires (8 in all) were calibrated using a waterbath with temperature ranging from 0 to 65^{0}C. Ice was used to get the lower temperature range. The readings from the thermocouple wires were logged on a CR10X datalogger.

Table 4.3 gives the results obtained when the waterbath temperature (measured with mercury glass thermometer) was regressed against the thermocouple output. A strong correlation was obtained between the waterbath temperature and the thermocouple readings.

Table 4.3 Summarized regression results obtained between voltage output from leaf thermocouple (X) and waterbath temperature (Y)

Leaf thermocouple	Regression Equation	R^2
1	$Y = 1.005\ X_1$	0.999
2	$Y = 1.007\ X_2$	0.999
3	$Y = 1.007\ X_3$	0.999
4	$Y = 1.011\ X_4$	0.999
5	$Y = 1.011\ X_5$	0.999
6	$Y = 1.016\ X_6$	0.999
7	$Y = 1.013\ X_7$	0.999
8	$Y = 1.012\ X_8$	0.999

N.B. Y : Water bath temperature (°C)

X : Leaf thermocouple readings

4.7.3 Infrared Thermometer

Two Telatemp AG-42 infrared thermometers (IRT) were used in the trial for measuring canopy temperature. The calibration procedure was similar to that used by Fuchs and Tanner (1966) and repeated by Berliner, Oosterhuis and Green (1984). The IRT was held at an angle of 30^0 to the horizontal and at a distance of 100 mm above the waterbath during the calibration procedure. The IRT and waterbath temperatures were recorded and the calibration temperature ranged from 10 to 60^0 C.

Fig. 4.2a and 4.2b show the regression for the two infrared thermometers respectively. Strong correlations (0.97 and 0.99) were obtained for both IRT. Deviations were observed for temperature below 16^0C and above 45^0C especially in the case of the IRT1. This could be due to the fact that water temperature was measured with an immersed mercury glass thermometer, while the IRT measured the surface temperature of the waterbath, which could be affected by evaporative cooling and sensible heat exchange with the environment.

4.7.4 Relative Humidity (RH) Sensors

Two Vaisala (CS 500) relative humidity sensors were used in the trial. Calibration of the RH sensors was first done by using saturated salt solution in a fully sealed container.

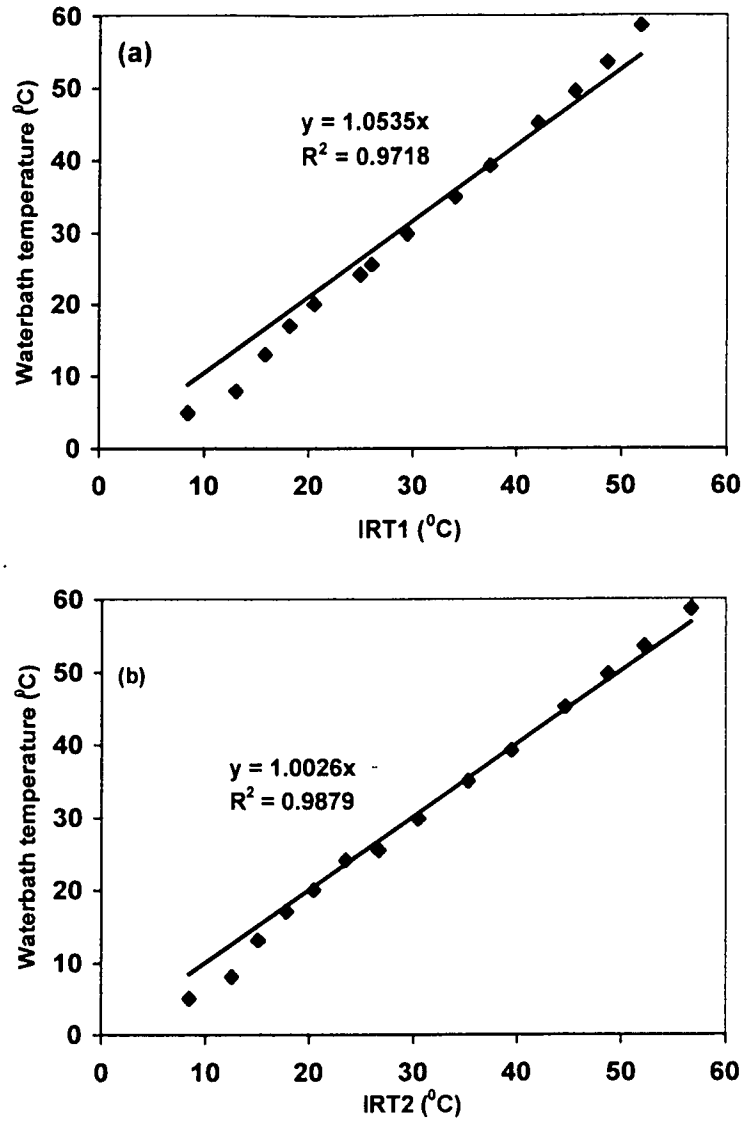

Figure 4.2 a and b. Graphs of regression between waterbath temperature and the respective IRT.

Two salt solutions were used namely potassium chloride (KCl) and magnesium chloride ($MgCl_2$). At 25°C, a saturated salt solution of KCl yields a relative humidity of 84.3% whereas 32.7% is obtained with a saturated $MgCl_2$ solution (Pearcy, Ehleringer, Mooney and Rundel, 1989). The two RH sensors were inserted in a plastic container containing the saturated solution together with a thermocouple to record the inside air temperature. With KCl, relative humidity of 83.5 and 81.1 % were obtained for the two RH sensors respectively. With $MgCl_2$, it was difficult to

obtain a relative humidity of less than 55% even though the setup was left overnight to equilibrate.

The two RH sensors were calibrated again at the University of Natal by making use of a water vapour generator. The lowest relative humidity achieved by the water vapour generator was 24%. The calibration was carried out at room temperature and by altering the relative humidity from 24 to 84%.

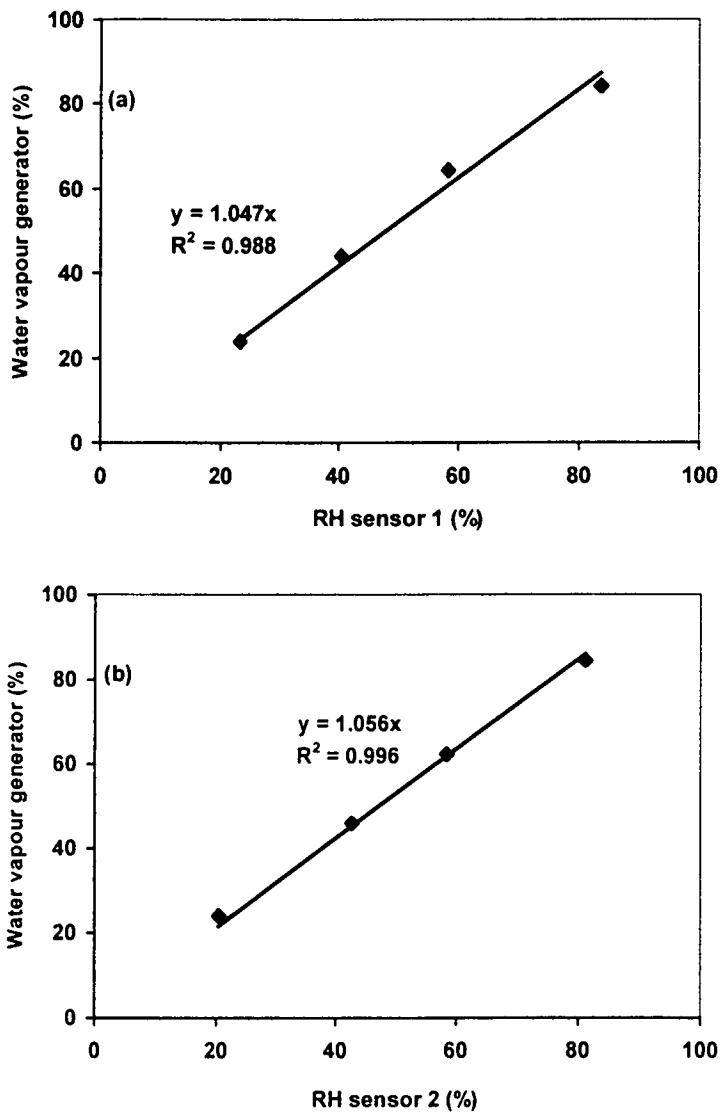

Figure 4.3a and b. Regression between relative humidity from water vapour generator and the respective RH Vaisala CS 500 sensors.

A good correlation was obtained with both RH sensors (see Fig. 4.3a and b).

4.7.5 Infrared Gas Analyser (IRGA)

Photosynthetic rate was measured during the trial by using an infrared gas analyser, LCA3 from Analytical Development Corporation Ltd. The LCA was calibrated by making use of standard compressed air in a cylinder. The procedure stipulated in the manual was followed. The carbon dioxide concentration detected by the LCA3 from the gas cylinder was 375 ppm and was in agreement when the same cylinder was crosschecked with another IRGA model LI-COR 6400 at the University of Natal.

4.7.6 Automatic Porometer

Resistance to gaseous diffusion of water vapour from leaves was measured with the Delta-T MK3 automatic porometer. Since the calibration plate was missing, another one was constructed at the SASEX workshop. The calibration plate consists of groups of holes with the diameter of each hole being 1 mm. By using the formula given below (Campbell, 1975), the resistance for each group could be computed.

$$r = \frac{A.(L + \pi.d/8)}{n.D.(\pi.d/4)} \quad ,$$

where r = resistance (s/cm)

A = cup area (= 0.559 cm^2)

n = number of holes

L = plate thickness (cm)

d = hole diameter (cm)

D = diffusion coefficient (=0.242 cm^2/sec at 20°C)

The calculated resistance values for each group of holes are given in Table 4.4.

The calibration was done by using a strip of filter paper that fits exactly on the calibration plate. The latter was moistened with distilled water at ambient temperature. The damp filter paper was placed on the flat side of the plate so that all the holes were covered. The edges of the plate

Table 4.4 Resistance for each group of holes in the calibration plate at 20° C.

Group of holes	Holes/group	Resistance (cm/s)
1	3	13.6
2	4	10.2
3	6	6.8
4	8	5.1
5	11	3.7

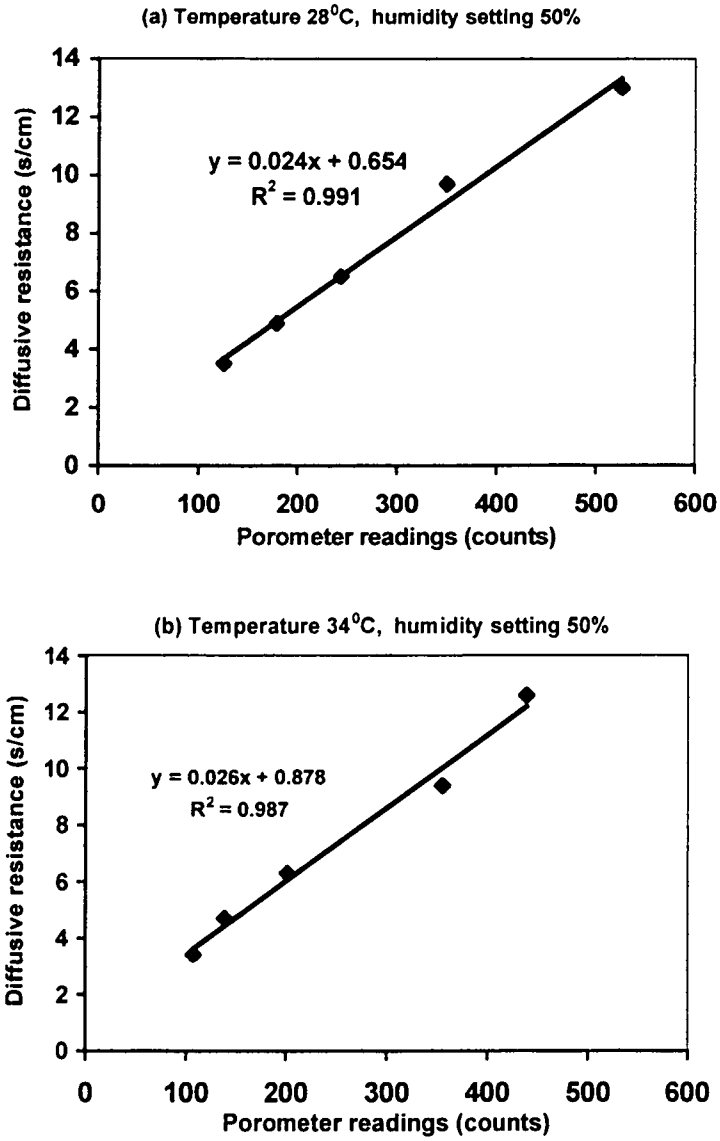

Figure 4.4a and b. Regression obtained between porometer readings (counts) and diffusive resistance at 28°C and 34°C respectively.

were sealed with adhesive tape to minimise evaporation from the pad. Then by carefully placing the cup on each set of holes, the resistance was recorded. The humidity

knob on the porometer was set on 50%. The calibration was carried out at two different temperatures namely at 28°C in the laboratory and at 34°C in the field.

A good fit was obtained when the counts from the porometer was regressed against the calculated diffusion resistance (see figure 4.4a and 4.4b).

4.8 Measurements

The measurements carried out during the trial can be categorized into climatic, microclimatic, agronomic, physiological and edaphic components.

4.8.1 Climate

Incoming solar irradiance, wind speed, air temperature and rainfall data from a standard meteorological station situated within 20 m of the rainshelter were available. A pyranometer and three-cup anemometer were also placed on the top of a central beam running across the centre of the cane rows to measure radiation and wind speed (see plate 4.2). These measurements were important to get data about wind speed and radiation received by the crop canopy with the closed rainshelter during rainfall events. The Penman-Monteith equation (Allen, Pereira, Raes and Smith, 1998) was used to compute the reference evapotranspiration (ET_o).

4.8.2 Microclimate

The microclimatic measurements taken during the trial were radiation interception, relative humidity and temperature of leaf and canopy.

4.8.2.1 Global radiation interception

The amount of solar radiation intercepted by the cane in the stressed and irrigated plots was measured by placing the tube solarimeter just below the lowest green leaves between two rows (Plate 4.3). Another instrument was placed at the top of the canopy to measure the incoming radiation above the canopy (see Plate 4.2).

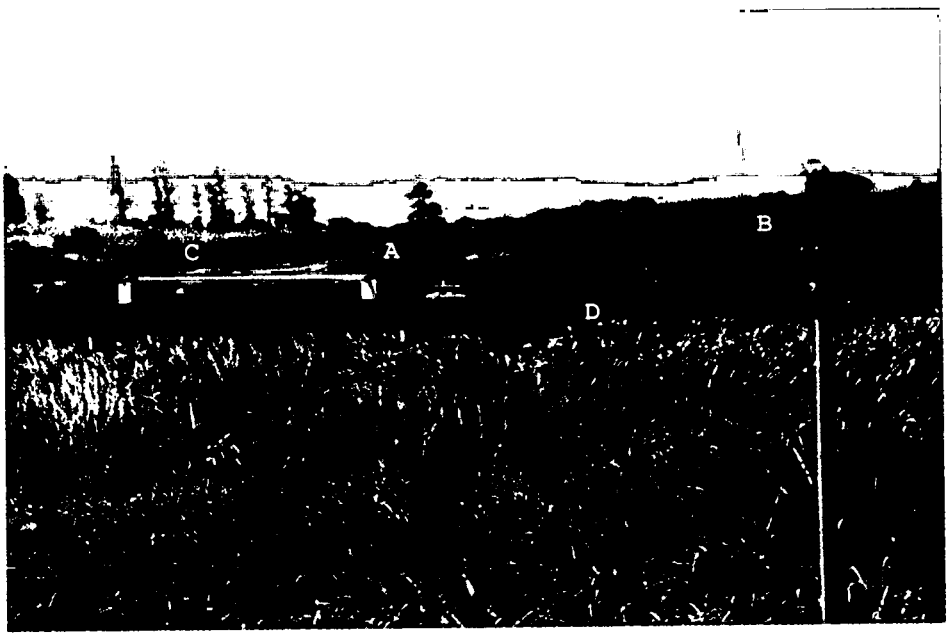

Plate 4.2 The pyranometer (A), three-cup anemometer (B) and tube solarimeter (C) positioned on the beam (D) in the rainshelter area.

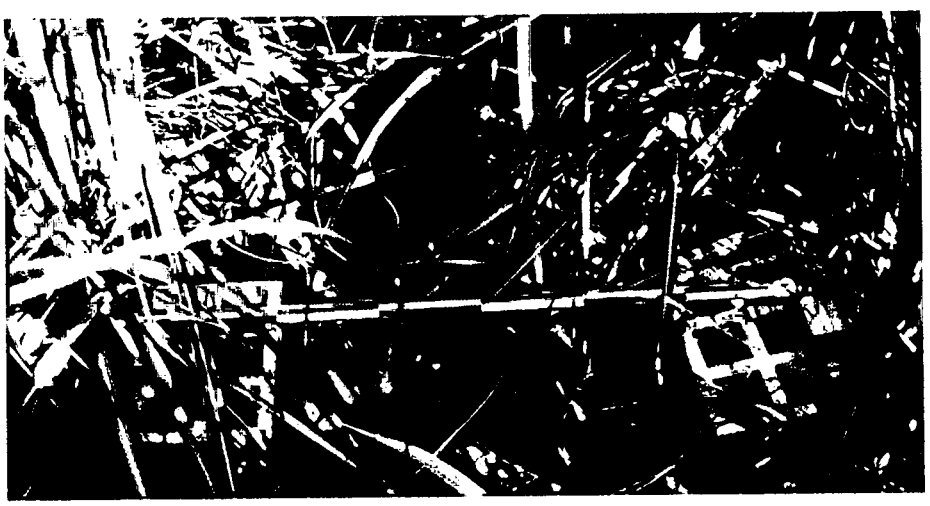

Plate 4.3 Tube solarimeter placed between two cane rows and just below the green leaves.

In the stressed plot as the lowest leaves start to dry out, the tube solarimeter had to be raised so as to maintain it consistently just below the green leaves. The readings from the tube solarimeters were logged by a CR10X datalogger.

4.8.2.2 Photosynthetically active radiation (PAR) interception

The sunscan canopy analysis system was used to measure PAR interception by the canopy and also to determine the

leaf area index. Before taking the readings, two important parameters need to be keyed in the sunscan namely the leaf absorption coefficient and the ellipsoidal leaf angle distribution parameter (ELADP). The leaf absorption was taken as 0.85 whereas the ELADP was determined weekly by counting the number of horizontal and vertical leaves around the rows earmarked for sunscan measurements and by applying the following formula (Wang and Jarvis, 1988; Campbell, 1986).

$$ELADP = \frac{\pi.H}{2.V}$$

where H = number of horizontal leaves

V = number of vertical leaves

The sunscan probe was held just below the bottom green leaves. The instrument was leveled before 12 readings were taken from each agronomic row in both treatments (see fig 4.1). The sunscan measurements were taken around midday at least once a week during clear days and the data were then downloaded to a PC.

4.8.2.3 Relative humidity (RH) within the canopy

Two Vaisala CS500 air temperature and relative humidity sensors were placed in each plot for measuring air temperature and relative humidity within the canopy. The sensor was inserted in a fix Gill plate screen and mounted on a pole so that it is positioned within 200 mm of the topmost leaves in the canopy (see plate 4.4).

4.8.2.4 Leaf temperature

T-type leaf thermocouple was used for measuring leaf temperature. Two plants per plot were chosen for leaf temperature measurements. A leaf thermocouple was attached firmly to the abaxial surface of a green leaf by means of paper clips (plate 4.5). Leaf temperature was measured at two levels on the same plant; one was on the third leaf from the top and another on the lowest green leaf. The readings from the leaf thermocouples were recorded by the CR10X datalogger at 30 minutes intervals.

Plate 4.4 Vaisala CS500 relative humidity sensor mounted inside a fix Gill radiation shield within the top of the crop canopy

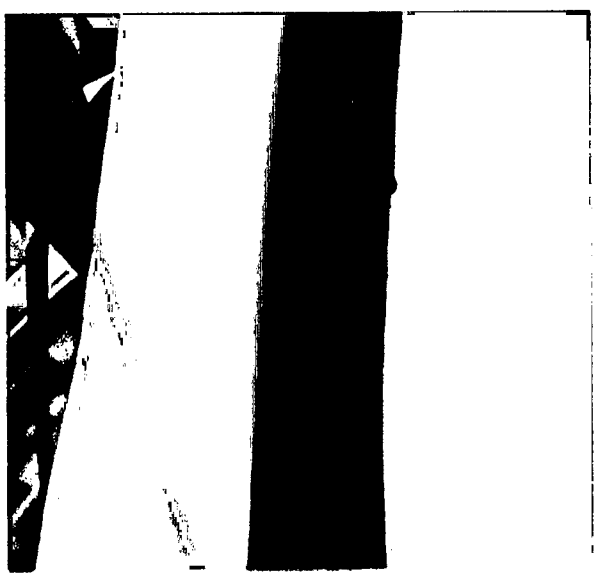

Plate 4.5 Leaf thermocouple attached to the abaxial surface of the leaf

The leaf thermocouple in the stressed plot was checked regularly to ascertain that the curling of the leaf due to water stress does not expose the thermocouple to direct sunlight.

4.8.2.5 Canopy temperature

This was measured continuously with a Teletemp AG-42 infrared thermometer (IRT). In fact, two IRT's were used, one in each treatment. They were positioned about 0.5 m above the canopy at an angle of 30^0 above the western horizon in line with the crop rows which ran from east to west (Plate 4.6). A thin aluminium sheet fitted on top of each IRT provided protection against the first drops of rainfall before the rainshelter could close completely. The two IRTs were connected to the CR10X datalogger and the average of the 60-second readings during 30 minute intervals were recorded.

Plate 4.6 Infrared thermometer (IRT) set up in the field.

4.8.3 Agronomic Parameters

The agronomic parameters taken during the trial consisted of canopy characteristics, plant extension rate and aboveground biomass.

4.8.3.1 Canopy characteristics

Since the area under the rainshelter was limited, the agronomic rows were restricted to 1 m long and replicated three times in each plot (refer to Fig. 4.1).

Stalk density was determined by counting the total number of tillers in each agronomic row. Tillers having less than three green leaves were not counted.

Five tillers were selected at random in each agronomic row and tagged. Stalk height from ground level up to the topmost visible dewlap (TVD) was monitored in these stalks. The total number of green leaves together with the diameter of the bottom, middle and top portion of the tagged stalks were also measured weekly.

The sunscan canopy analysis system was used to measure the leaf area index weekly for each of the agronomic rows.

4.8.3.2 Plant Extension Rate

The growth transducer used in the experiment was designed by Inman-Bamber (1995). A linear potentiometer was used to convert plant extension to electrical resistance. The growth transducer consisted of a drum having a diameter of 10 mm mounted on the potentiometer shaft and the latter was in turn fixed on the top of a central beam in the field. One end of a weak galvanized coil spring of length 100mm was fixed on the beam and a 1.5 m length nylon dial cord (0.5 mm diameter) was attached to the other end. The cord was fixed to a peg that was clamped to the youngest visible leaf (see Fig. 4.5). When the spring was fully extended, it exerted a tension of about 200 g on the leaf and when retracted, it exerted a tension of 50 g. The datalogger CR10X was used to record the data at an hourly interval.

The movement of a microtome was used to calibrate the growth transducers and the calibration factor was 0.409 mm/mV. The staff of SASEX did the set up and calibration of the growth transducers.

Nine growth transducers were used in each plot and the cord together with the peg was reset on the spindle leaf each week after downloading the data. Sometimes the readings from the growth transducers were not good and

some plant extension rate (PER) values had to be rejected whenever it was greater than 10.0 mm/h or less than -0.1 mm/h. Readings were also rejected when the spindle leaf became detached from the pegs.

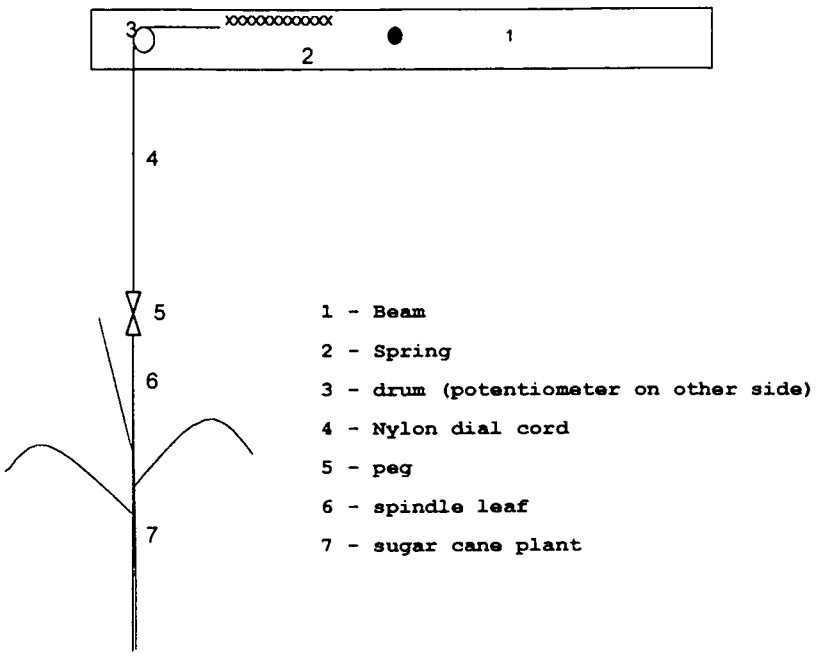

Fig 4.5. Sketch of growth transducer set up in the field

4.8.3.3 Biomass and quality characters

Due to the limited sugarcane rows per plot, total aboveground dry matter was determined only at the start and end of the first and second stress cycle, that is, on 15th January, 5th February, 12th February and 1st March.
On the 15 January, due to the uniformity of the crop, only one replicate from each plot was sampled for biomass determination. For the other sampling dates at least 3 replicates of 1m length of row were removed for dry matter analysis. For each sample taken, the following parameters were recorded,

- number of tillers and number of green leaves;
- leaf area from a sub-sample of three tillers;
- stalk height together with diameter of bottom, middle and top portion from five stalks;

- Fresh weight of senesced leaves (trash), green leaves, stalk (up to the apex) and leaf sheath;

A small sample (200-250 g) of chopped trash, green leaves and leaf sheath were placed in a paper bag, labelled and left in an oven set at 80^0C for 48 hours. Then the mass was measured and dry matter content computed.

The stalks were tied in bundles of 12 and sent to the cane analysis laboratory for determination of sucrose and fibre.

4.8.4 Soil water content

The soil water content was measured hourly by Aquaflex soil water meters which were permanently buried at depths of 250 and 500 mm in each plot (see fig 4.7).

Two equitensiometers were inserted at depths of 250 and 500mm in each plot and hourly measurements of soil water potential (kPa) were automatically recorded on a CR10X datalogger.

A recently calibrated neutron probe was also used to measure soil water content on a daily basis around 10:00 a.m. in both plots. Three aluminium access tubes were inserted in each plot for measurement of soil water content at depths of 250, 400, 550 and 700 mm. All the soil water measurements were undertaken by the SASEX staff.

4.8.5 Physiological measurements of the plant

The physiological parameters measured during the trial were leaf water potential, photosynthesis, stomatal conductance, transpiration and stomatal resistance.

4.8.5.1 Total leaf water potential

Leaf water potential (Ψ_L) was destructively determined on the topmost, fully expanded leaf using a Scholander pressure chamber (Plate 4.7). This was carried out on 5 leaves per plot between 12:00 and 14:00 hours on a daily basis.

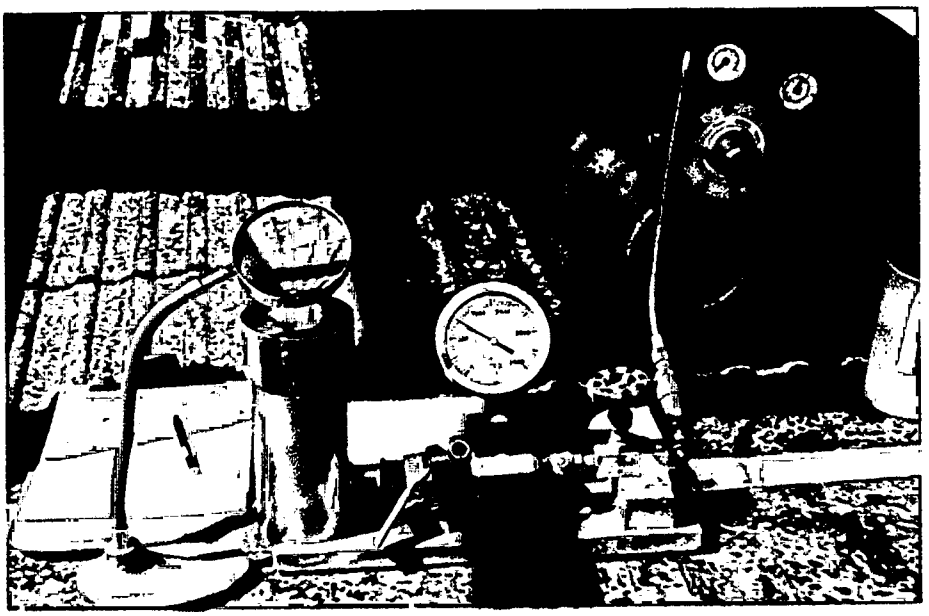

Plate 4.7 Scholander pressure chamber for Ψ_L measurement

The part of the leaf to be used for the Ψ_L determination was wrapped in a damp cloth before being cut about 200 mm from the tip and Ψ_L determined within a minute of the leaf being cut as described by Saliendra, Meinzer and Grantz (1990). The pressure at which leaf sap oozes out of the cut surface represented the Ψ_L, the pressure increase rate in the chamber being about 0.25 MPa s^{-1}.

From 23rd January, Ψ_L was also measured before sunrise and constituted the predawn Ψ_L. The staff of SASEX did most of the Ψ_L measurements.

4.8.5.2 Photosynthesis, stomatal conductance and transpiration

Photosynthesis, stomatal resistance and transpiration were measured using a portable LCA-3 infrared gas analyser (IRGA) from Analytical Development Company (ADC Ltd), England. Before readings could be taken by the IRGA, it was necessary to key in the boundary layer resistance together with the actual leaf area of the leaf section covered in the chamber.

Boundary layer resistance was determined according to the procedure in the instruction manual (Analytical

Development Company (ADC Ltd), 1989) and Parkinson (1984). The following equation was used

$$r_s = \frac{(e_L - e_o)}{(e_o - e_i)} \cdot \frac{(P - e_o)}{P} \cdot \frac{1}{W} - r_b \quad ,$$

where r_s : stomatal resistance (s m^{-1})

r_b : boundary layer resistance (s m^{-1})

e_L : saturated vapour pressure at leaf temp (bar)

e_o : vapour pressure of air flowing out of cuvette (bar)

e_i : vapour pressure of air flowing into cuvette (bar)

P : atmospheric pressure (bar)

W : mass flow of dry air per unit leaf area (m s^{-1})

Since boundary layer resistance changes with leaf area, therefore filter paper of different sizes ranging in area from 3.5 to 21.0 cm^2 were used. Two pieces of the filter paper representing each area were cut and a thermocouple was placed between them to measure the temperature. A piece of overhead projector transparency was cut and inserted between the 2 pieces of filter paper to give rigidity inside the leaf chamber. The filter paper was then dampened in distilled water and put inside the leaf chamber. The relative humidity inside the chamber was recorded. Using the above equation together with measured values of relative humidity, flow rate, area, temperature and atmospheric pressure, the boundary layer resistance was computed assuming that r_s in the case of filter paper is zero.

The relationship between the area of filter paper used (cm^2) and r_b (s m^{-1}) was linear with a coefficient of determination (r^2) of 0.994 (Fig.4.6).

A paper scale was stuck onto the leaf chamber (Plate 4.8) so that the average width could be computed then using a

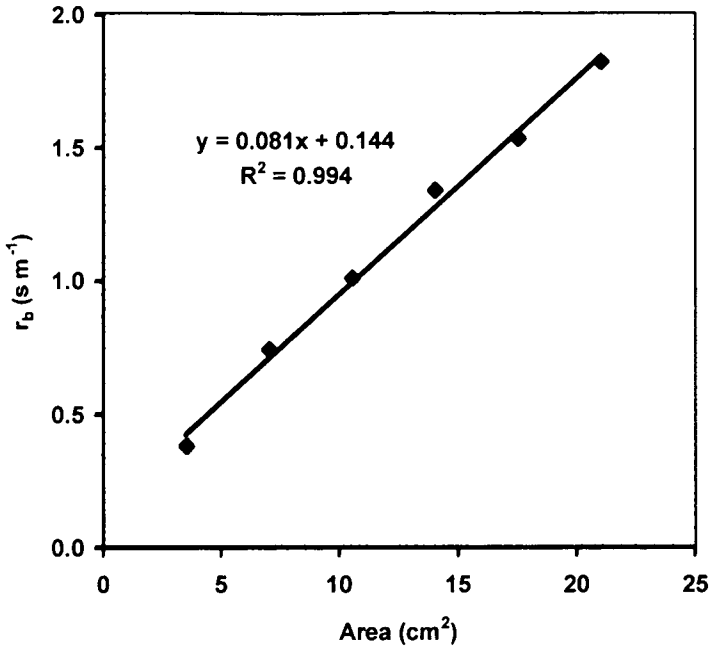

Fig. 4.6. Regression obtained between area and boundary layer resistance (r_b)

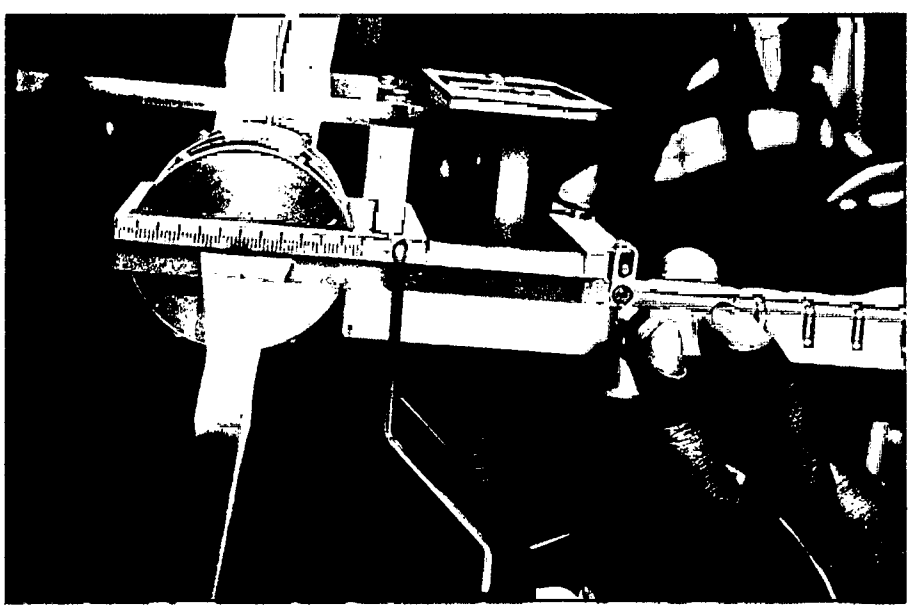

Plate 4.8 Leaf chamber of LCA-3 IRGA showing the scale attached to it to facilitate leaf width reading

conversion table, the corresponding area and r_b were determined. Thus these values were keyed in the IRGA before measuring the photosynthesis, stomatal conductance and transpiration rate of a specific leaf sample. IRGA

readings were taken at the same time as the Ψ_L measurements using the second or third youngest leaf.
The measurements were made on portions of leaves exposed directly to the sunlight, and the leaves were maintained at right angles to incident solar radiation. IRGA readings were taken on 5 plants in each plot and all those measurements could be made within a continuous period of 40 minutes after which the IRGA started to heat up and give erroneous values.
Diurnal readings with the IRGA were also carried out whenever it was sunny at three hour intervals.

4.8.5.3 Leaf stomatal resistance

Resistance to gaseous diffusion of the abaxial surface of the second or third youngest leaf was measured using the Delta-T MK3 automatic porometer. The measurement was only taken during the second stress cycle to provide a means of checking the stomatal conductance measured using the IRGA. Stomatal resistance was measured on leaves from 10 different plants per plot and was done at the same time as Ψ_L readings were taken.

4.9 Experimental Set up and dataloggers

The way all the equipment was set up in the field is shown in Fig. 4.7. Two CR10X dataloggers and one multiplexer were used in the field and were protected inside a metal safe.
All 8 thermocouples were connected to the multiplexer and relayed to the CR10X. The relative humidity sensors and the infrared thermometers were connected to the same datalogger. The program used on this datalogger is listed in Appendix II. The pyranometer, the three tube solarimeters and the anemometer were connected to the second CR10X and the program used is listed in Appendix III. Each sensor was sampled at one minute interval. The data was averaged over 30 minutes and stored in the output location. For relative humidity, a sample value at each 30 minutes interval was recorded. A 12 V

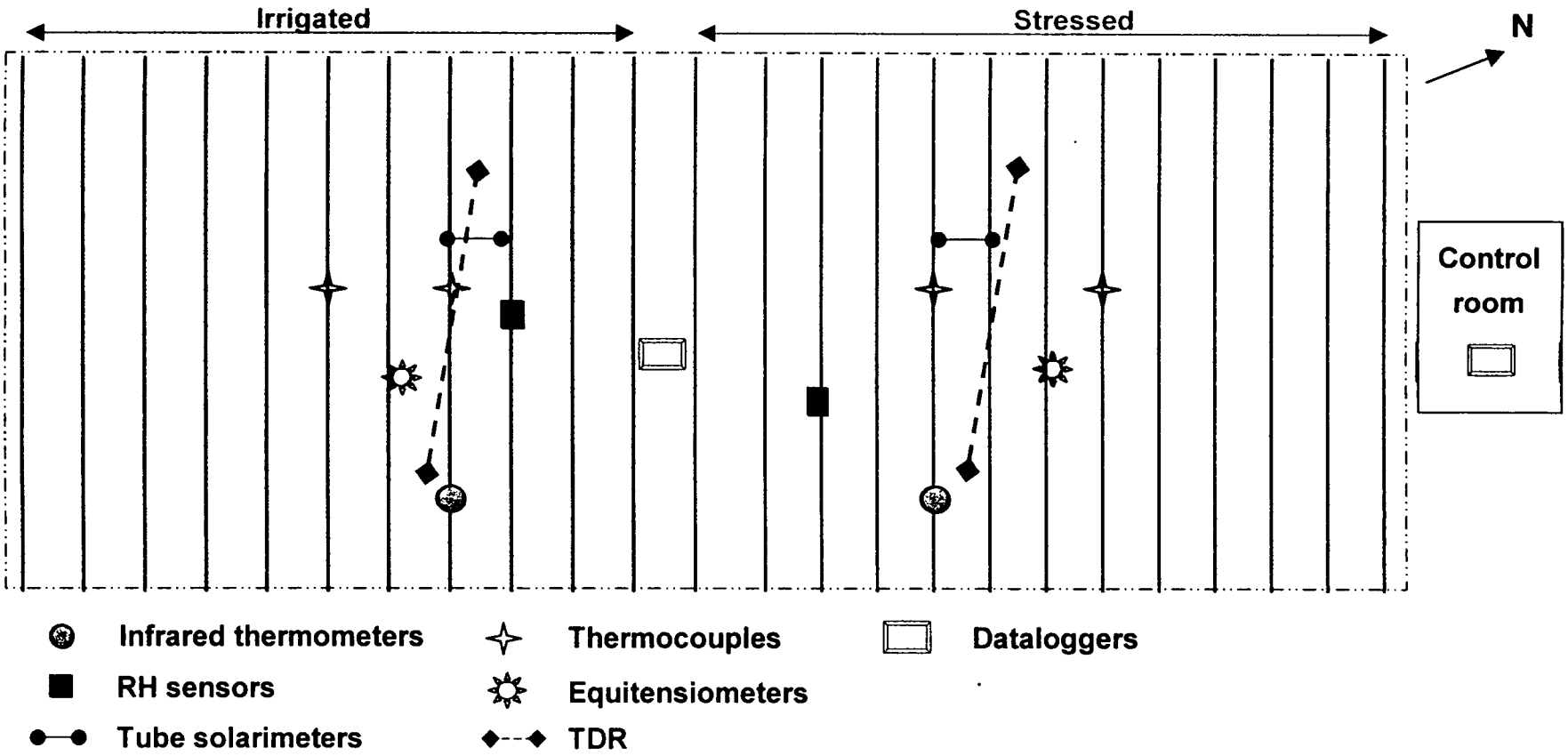

Figure 4.7 Rainshelter layout showing equipment set up.

battery charger was permanently connected to the battery to avoid the later from being depleted.

Another CR10X datalogger located in the control room was used to collect hourly data from the growth transducers and soil moisture sensors. All the dataloggers were downloaded twice a week.

RESULTS AND DISCUSSION : FIRST STRESS CYCLE

The stressed plot in the trial was deprived of water starting from 8th January until 5th February and constituted the first stress cycle. All the results and discussions below are referring to observations and measurements made during that period.

5.1 Climate

Figures 5.1a, b and c give the temperature, radiation, wind speed, relative humidity and computed ETo during the stress cycle. The maximum temperature varied from 23.8 to 32.3^{0}C and was within the optimal range for sugarcane growth (Van Dillewijn, 1952; Fauconnier, 1993; Liu *et al.*, 1998). The average minimum temperature was 20.0^{0}C and was above the base temperature required for stalk elongation (Liu et al., 1998). The relative humidity ranged from 67to 82%. During a growth analysis experiment, Gosnell (1968) found that relative humidity had a significantly positive effect on elongation rate of irrigated cane.

An average wind speed of 1.4 ms^{-1} prevailed during the trial with maximum wind speed of 3.1 and 2.9 ms^{-1} at the start of the trial and on the 23rd January. There were many fluctuations in the incoming radiation throughout the trial due to frequent cloudy days. The mean ET_o computed during the trial was 4.4 ± 1.3 mm/day indicating that regular irrigation had to be provided to maintain the irrigated control plot unstressed.

5.2 Soil characteristics

The soil water content, soil water potential and soil temperature are discussed under this section.

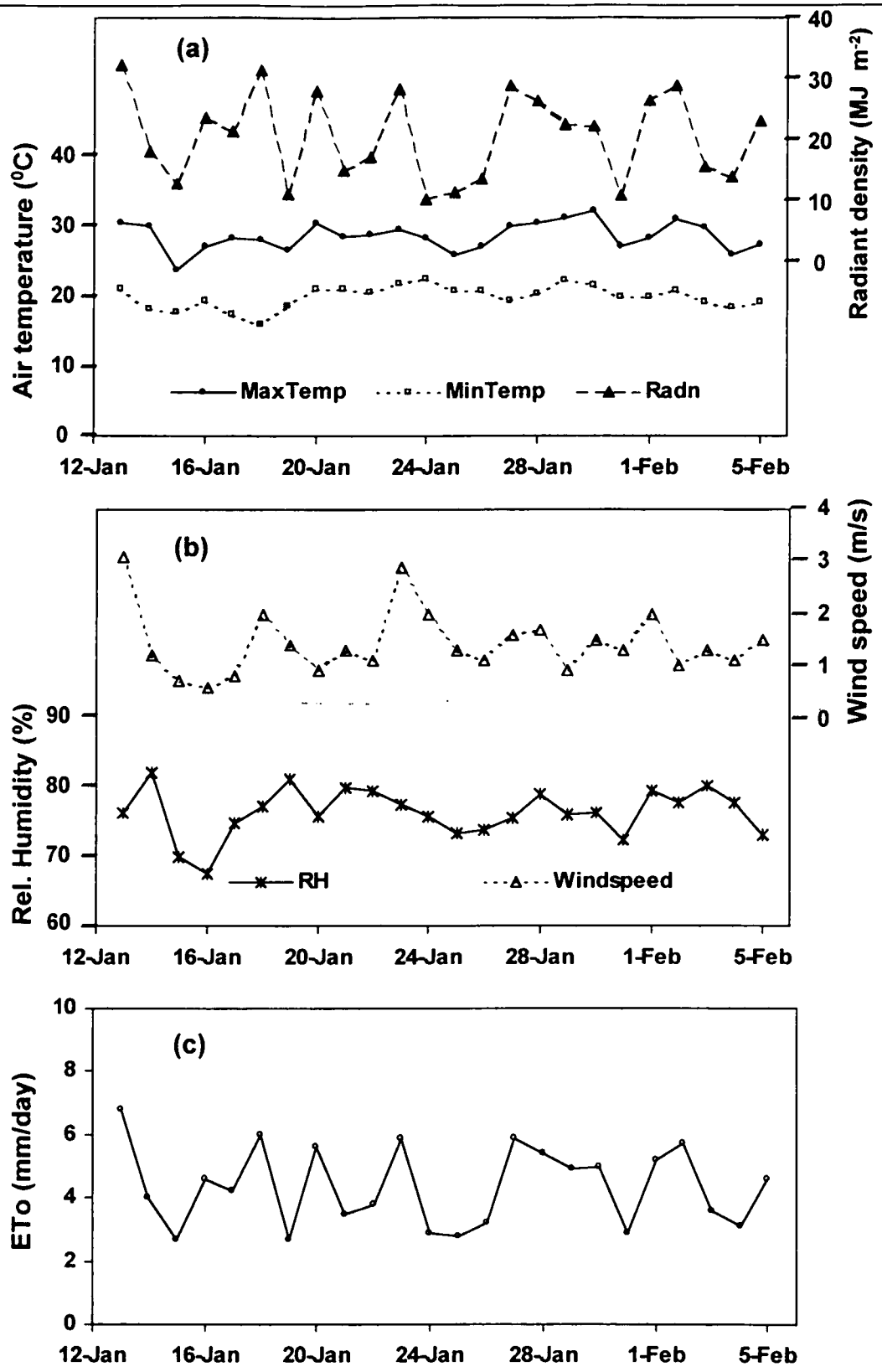

Fig 5.1 a,b and c. Graphs showing air temperature (max and min), radiant density, wind speed, relative humidity and reference evapotranspiration (ETo, Penman-Monteith) prevailing during the first stress cycle.

5.2.1 Soil water content(SWC) and soil water potential(Ψ_s)

The values of SWC obtained from the neutron probe seemed to somewhat underestimate the actual SWC especially in the irrigated plot. The possible explanation being that the access tubes were located more than 20 cm from the cane rows and could not properly detect the water content in the row especially after drip-irrigating along the rows. Hence only the SWC as recorded by aquaflex sensors will be used throughout the discussions. Fig 5.2 and 5.3 show the trend in volumetric soil water content (v/v,%) and soil water potential (kPa) during the trial.

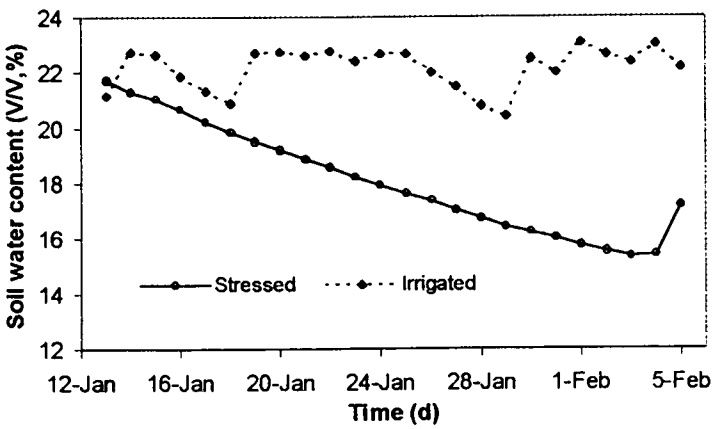

Figure 5.2 Time course of soil water content in the irrigated and stressed soil.

The drained upper and lower limits of freely available water (FAW) were 26% and 13 % respectively. The upper limit of FAW is similar in value to field capacity, which is the maximum amount of water that the soil can hold against the gravitational forces of the earth. The lower limit of FAW is defined as the least amount of water present in the soil whereby plant growth is not affected by water stress. The plant available water capacity (PAWC), that is FAW between upper and lower limit, was 126 mm for the whole profile.

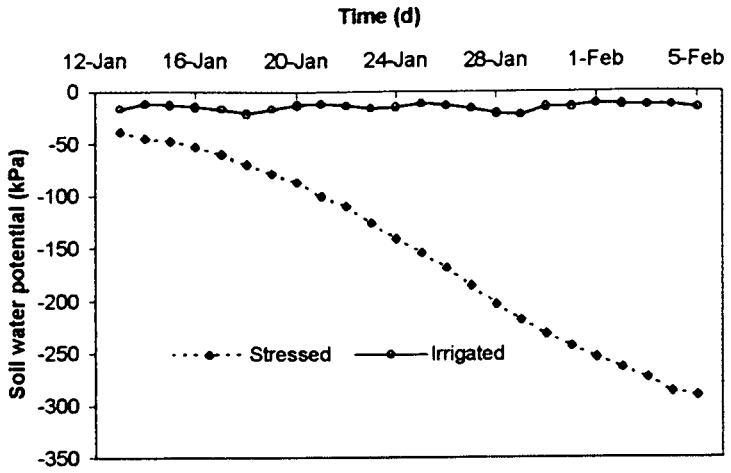

Figure 5.3 Time course of soil water potential in the irrigated and stressed soil.

The SWC in the irrigated plot was maintained above 21% by regular irrigation except on the 28 and 29 January. In the stressed plot, the SWC decreased almost linearly by 0.3% per day starting 6 days after water was withheld. The lowest SWC level of 15.4% was reached on 3rd February, that is 26 days after withholding water. In terms of soil water potential (Ψ_S), a minimum of -290 kPa was reached on 3rd February. In the well-watered plot, the Ψ_S never fell below -22 kPa due to frequent irrigation.

Fig.5.4 gives the relationship between SWC and Ψ_S. A linear regression was fitted by the least square procedure to relate SWC to Ψ_S. In soil having clay content of 25-70%, it has been observed that a Ψ_S of -8 kPa was equivalent to that observed to occur in rain-free periods while a Ψ_S of -20 kPa provided the water requirements of the sugarcane crop (Hodnett, Bell, Ah Koon, Soopramanien and Batchelor, 1990).

5.2.2 Soil temperature

The soil temperature trends as measured by soil thermocouples, are shown in Fig.5.5 at a depth of 25 cm in both treatments. Each temperature value is the mean of the daytime hourly readings.

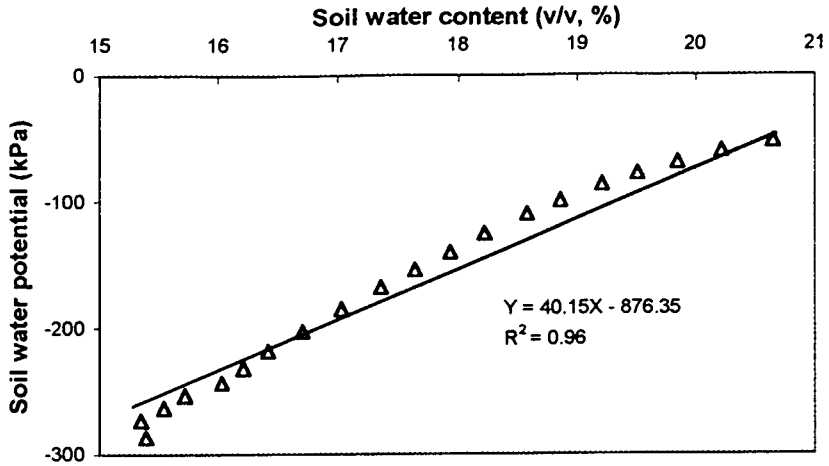

Figure 5.4 Relationship between soil water content (X) and soil water potential (Y) in water stressed plot.

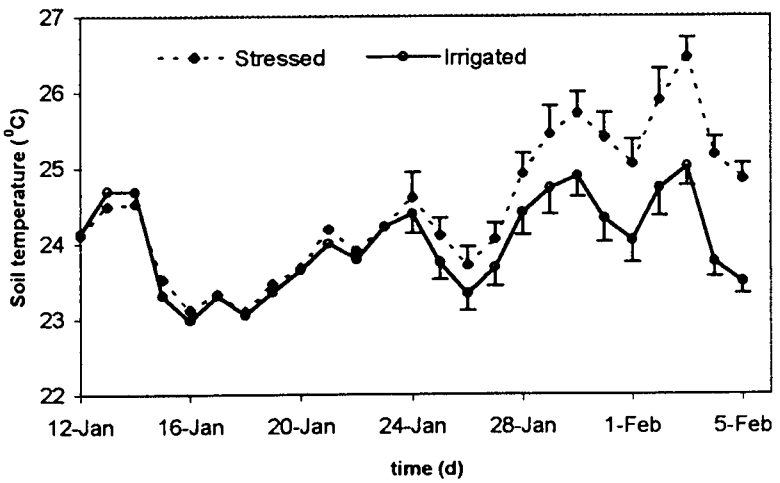

Figure 5.5 Soil temperatures at 250 mm depth in the irrigated and stressed plot.

The soil temperature in the stressed plot was slightly higher than the irrigated plot around 24th January, that is 16 days after withholding water. Significant differences in soil temperatures occurred only after the 29th January and at this stage the canes already had a lower leaf area index (LAI) due to senescencing of the lower leaves (see figure 5.8). The reduction in LAI resulted in more direct radiation reaching the interrow space and consequently more heating as compared to the closed canopy in the well-

watered plot. Wierenga, Hagan, and Gregory (1971) recorded soil temperature in non-irrigated soil to be higher by 2 to 3^{0}C than in irrigated soil.

5.3 Growth analysis

Under this section, the impact of water stress on the morphological development and growth of sugarcane cultivar NCo376 will be discussed.

5.3.1 Tiller density

Figure 5.6 shows the time course of tiller density in both treatments. The adverse effect of water stress on tiller density was observed after the 24th January, that is 16 days after withholding water from the canes.

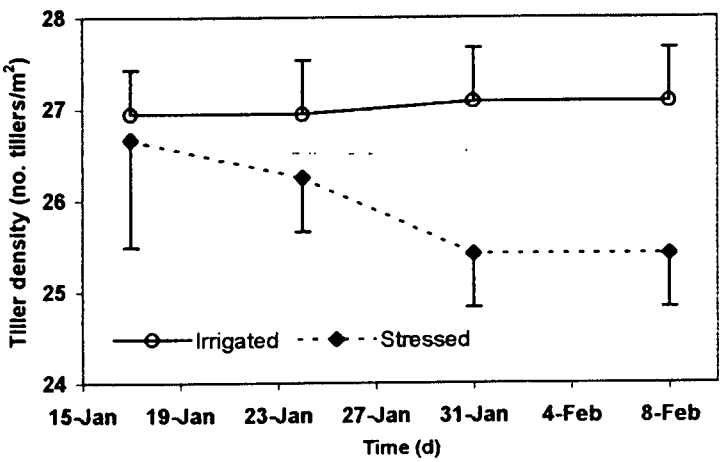

Figure 5.6 Tiller density for the irrigated and water stressed canes.

In the stressed plot, most of the tillers with 2 to 4 leaves started to senescence and became completely dried. Significant difference in tiller density between the treatments was observed on the 31st January (24 days after water stress) and at this stage the soil water content decreased to 16%. For the irrigated canes, a tiller density of 27 per m^2 was maintained throughout the trial. In the water stressed canes, the tiller density dropped to 25 and would have declined below this level had it not been irrigated on the 5th February. Inman-Bamber (1986)

also observed in variety NCo376 that stalk population were substantially lower in stressed plots than in unstressed plots.

5.3.2 Number of green leaves

Yellowing of the lower old leaves is amongst the first visual signs of water stress in canes. This difference is shown on plates 5.1a and 5.1b when the sugarcane plants were deprived of water for 6 and 20 days respectively.

Water stress hastened the rate of leaf senescence and lead to yellowing and drying of older leaves (Begg and Turner, 1976). Figure 5.7 shows the time course for the total number of green leaves recorded per stalk. Sixteen days after withholding water in the sugarcane, the green leaves number per stalk had decreased from 8 to 6. This occurred when the soil water content was 18%. As the water stress became severe, the stalks tend to lose leaves and by 31st January, the green leaf number was 5. In the fully irrigated sugarcane, the green leaf number was maintained around 9.

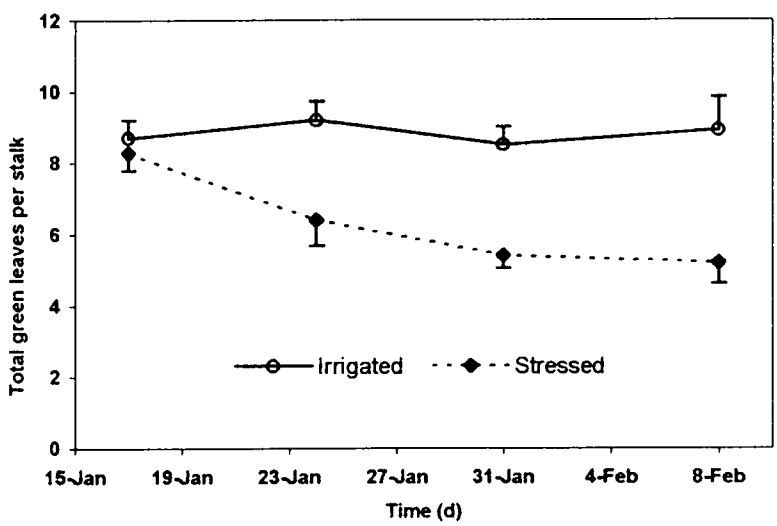

Figure 5.7 Total green leaves per stalk for both treatments.

Plate 5.1a. Leaf status for the stressed and irrigated canes 6 days after withholding water.

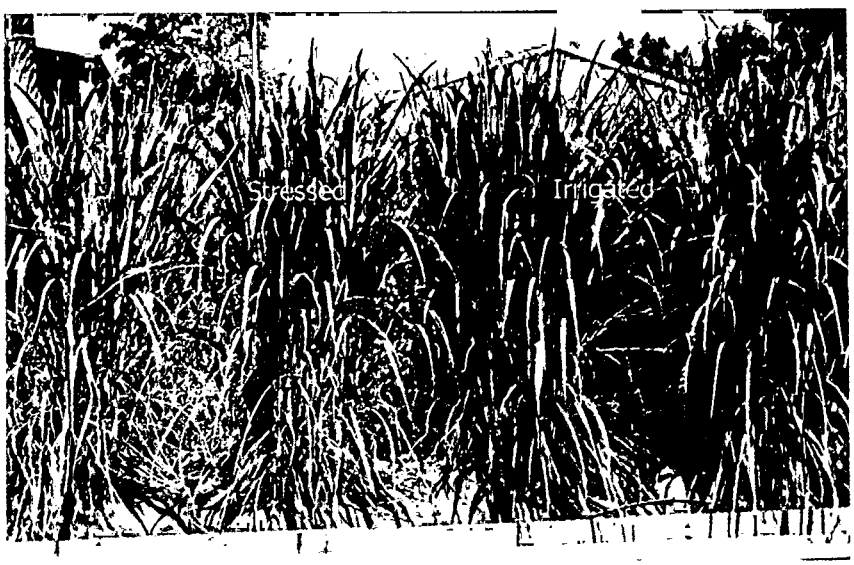

Plate 5.1b. Leaf status for the stressed and irrigated canes 20 days after withholding water.

5.3.3 Leaf Area Index

Rapid leaf senescence in the water stressed plot led to a marked reduction in leaf area index (Figure 5.8). LAI measurement started on 20th January, i.e. 12 days after withholding water. There was already significant difference in LAI between the irrigated and stressed sugarcane at this stage. The soil water content was 19.2%. After 23 days of water stressed conditions (31st January),

the soil water content decreased to 16% and the difference in LAI between the two treatments was of the order of 4.8. In fact, at this stage the tiller had at most 5 green leaves compared to 9 green leaves in the fully irrigated plot.

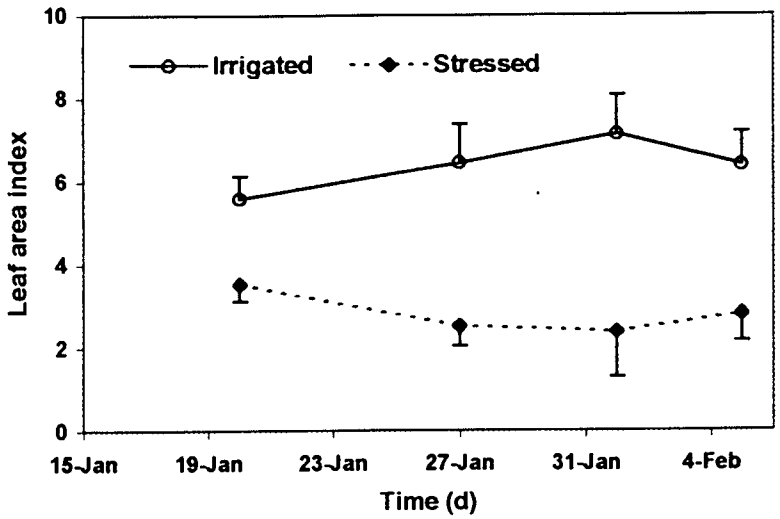

Figure 5.8 Leaf area index for stressed and irrigated canes.

The slight decrease in LAI for the fully irrigated cane after the period of 1st February was attributed to the normal senescence of the lower leaves.

5.3.4 Stalk height and estimated weight

The trend observed from measurements made on stalk height in the agronomic rows is shown in figure 5.9. Ten days after imposing water stress, stalk elongation rate in the water stressed cane seemed to have slowed down completely compared to irrigated canes. Significant difference in height between the treatments showed up as from 31st January (i.e., 23 days after imposing water deficit) when the soil water content was 16%. The crop was in the boom stage of elongation rate and water deficit during this stage has been shown to be more detrimental than when it occurs during tillering phase (Pene and Edi, 1999). The depressing effect of water stress on stem elongation is also reflected in the final cane yield.

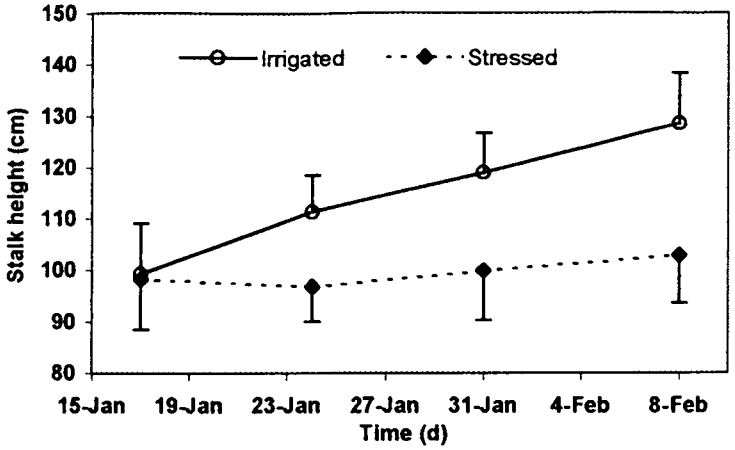

Figure 5.9 Time course of stalk height for stressed and irrigated canes.

Stalk mass was estimated non-destructively by combining stalk elongation and diameter with stalk density obtained during biomass determination. Figure 5.10 shows the time course of estimated stalk mass for each treatment.

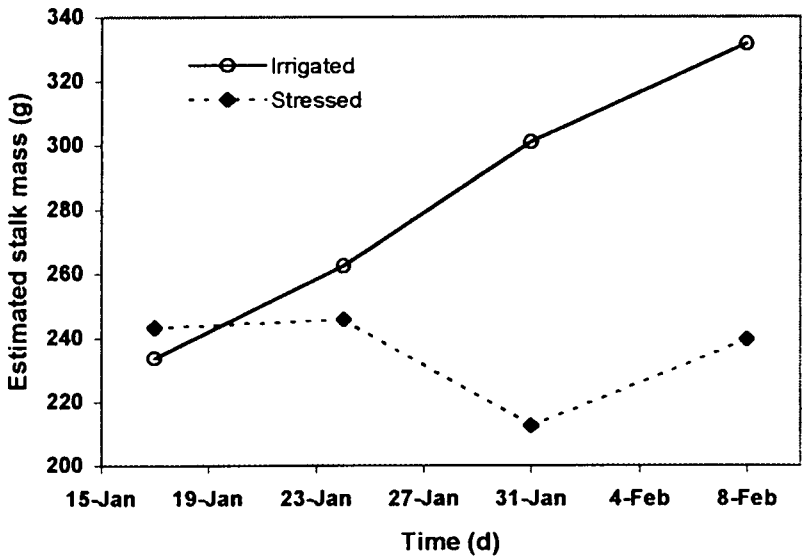

Figure 5.10 Estimated stalk mass for stressed and irrigated canes.

A reduction in stalk mass on the water stressed cane occurred 16 days after withholding water when the soil water content was around 17.9%. The maximum depression in cane mass, about 90 g/stalk as compared to the irrigated

treatment, was obtained when the soil water content reached 16%, i.e. on 31st January. A slight increase was noted thereafter due to resumption of irrigation on the 5th February. During an experiment on water stress in sugarcane, Inman-Bamber (1986) observed that fresh mass per internode decreased from 50 to 40g when irrigation was suspended during two consecutive months.

5.3.5 Plant extension rate

Figure 5.11 shows the time course for the daily plant extension rate (PER) in the irrigated and stressed plot. The cane in both plots grew at the same rate up to 20th January, that is, 12 days after withholding water in the stressed plot. After this time, significant differences started to show up between the plots. During dry-down experiments on sugarcane in Australia, Inman-Bamber (2000) also found that leaf extension rate and stalk elongation rate of stressed plants fell behind that of irrigated plants about 10 and 15 days after suspending irrigation respectively.

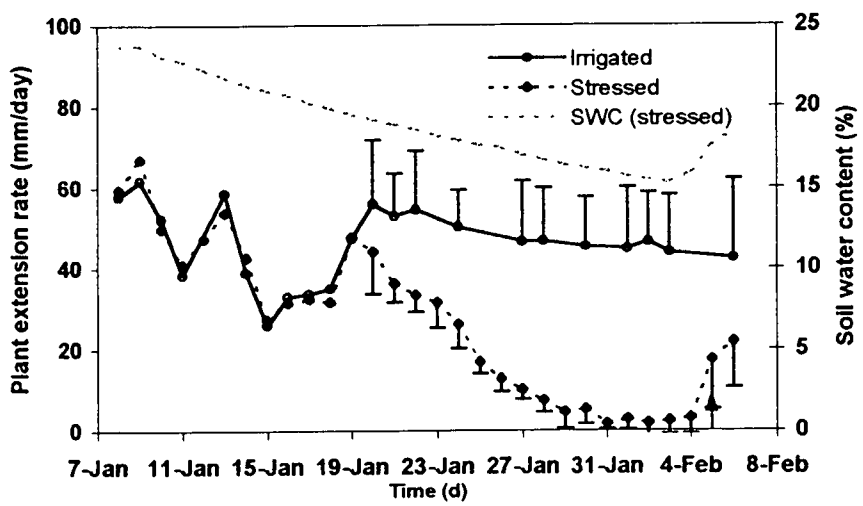

Figure 5.11 Trends in plant extension rate for stressed and irrigated canes. Arrow indicates irrigation applied to stress crops.

The plant extension rate was affected when the soil water content (SWC) fell to 19% and this decline in extension

rate continued to a value of almost zero when the SWC was around 15-16%. The rapid decline in PER was possibly due to a reduction in the elongation of young cells as was observed in maize by Boyer (1970). During the period 19th January to 4th February the PER of the irrigated plants was maintained around 45mm/day with fluctuations of 10mm/day. The fluctuation can be explained by variation in incoming radiation received and windy conditions experienced during that period (fig 5.1a).

Irrigation was applied to the dry plot in the evening of the 4th February and it is interesting to note the quick recovery after watering within 24 hours in PER.

Figure 5.12a shows the diurnal variation in PER (mm/h) for both plots on 17th January, i.e., before the difference in PER started showing. Both plots had almost the same hourly extension during the day. It should be noted that PER in both plots were higher in the morning and in the afternoon as compared to that during midday period. Even Inman-Bamber (1986) found that PER in variety NCo376 was highest in the late afternoon and lowest at midday. One possible explanation was that the stomata were closed during the high radiation and wind speed recorded at midday thus minimizing photosynthesis and reducing growth as was shown by Ludlow and Ng (1976) in Panicum *maximum*.

On 2nd February, i.e. 25 days after withholding water from the dry plot, the PER was zero. Figure 5.12b shows the diurnal variation in PER (mm/hr) for both plots on 2 February. The hourly PER for the canes in the well-irrigated plot was higher by more than 1.2 mm/hr than those in the water stressed plot. In variety NCo376, Inman-Bamber (1986) also observed that PER was reduced to 0.4 mm/hr around 20 days after withholding irrigation (fig 5.12b). The hourly PER in the irrigated plot was 1.8 ± 0.4 mm/hr. In the fully irrigated plot, the hourly extension was again slightly higher during early morning and late evening which was due to the lower radiation and wind

speed. A similar pattern though of lower magnitude was discernible in the stressed canes.

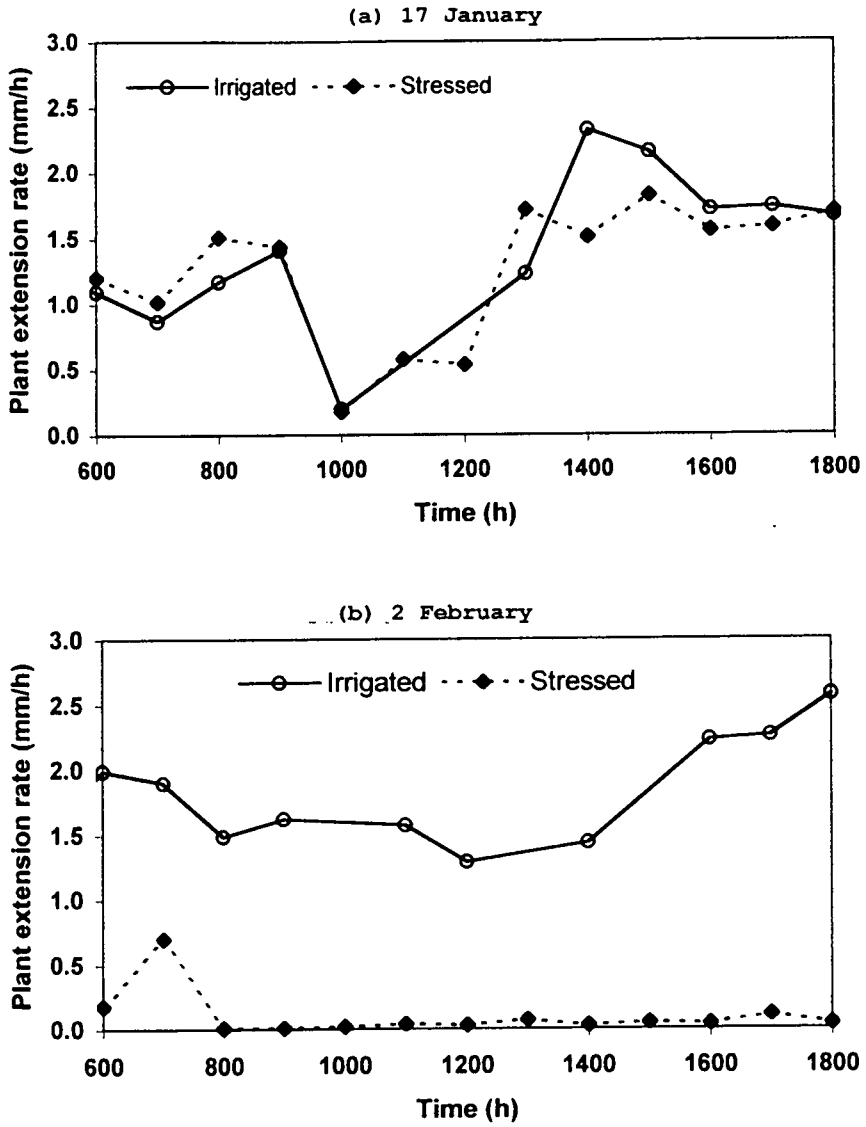

Figure 5.12a and b. Diurnal plant extension rate in the irrigated and stressed canes on (a) 17 January and (b) 2 February respectively.

5.3.6 Biomass and partitioning

Due to the limited rows available under the rainshelter, aboveground biomass determination could only be done at the start and end of the stress cycle. Figure 5.13 shows the total biomass in the stressed and irrigated canes on 15th January, 30th January and 5th February. The sampling done on 15th and 30th January was limited to one repetition

in each plot whereas on the 5th February a full sampling consisting of 6 replicates was carried out together with full statistical analysis.

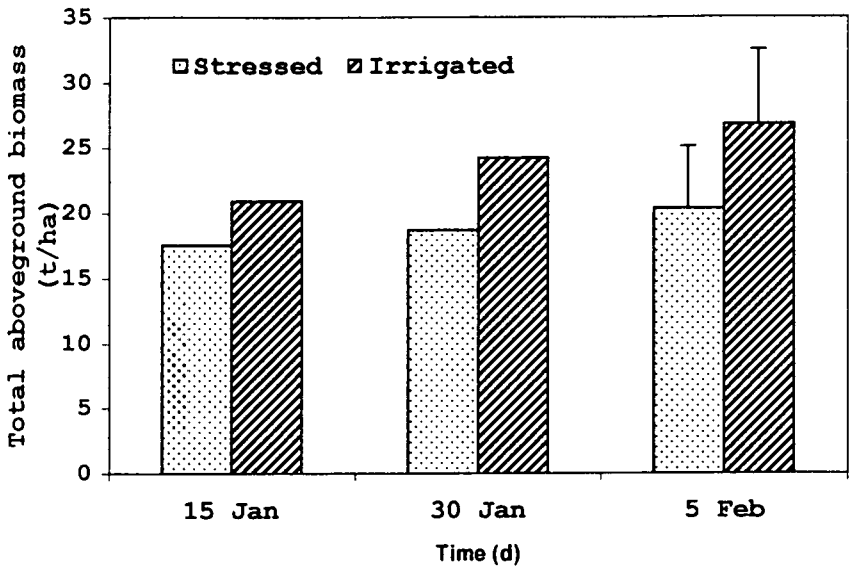

Figure 5.13. Aboveground biomass in stressed and irrigated canes.

Total dry matter accumulation in the irrigated plot was always higher than in the water stressed crop. The difference in dry matter between the treatments on 15th January, i.e. 7 days after water was withheld, was 3.3 t/ha. This difference increased up to 6.5 t/ha at the end of the stress cycle (30 days after withholding water) although it was not significant at the 5% level. The relative soil water content (RSWC) at this stage was 23%. Singels *et al.* (2000) found during a similar experiment in 2000 that biomass accumulation in variety NCo376 was reduced when RSWC dropped below 35% of available soil water capacity. Inman-Bamber (2000) reported that total fresh biomass of sugarcane was reduced 35 days after last irrigation.

The cane was devoid of water during its elongation phase and it has been showed that water stress during elongation

phase was more detrimental to growth rate and cane yield than during tillering phase (Pene and Edi, 1999).

During dry matter determination, the sugarcane plant was separated into green leaves (GL), dry leaves (DL), leaf sheath (LS) and cane. Figure 5.14 gives the dry matter partitioning for 15th and 30th January.

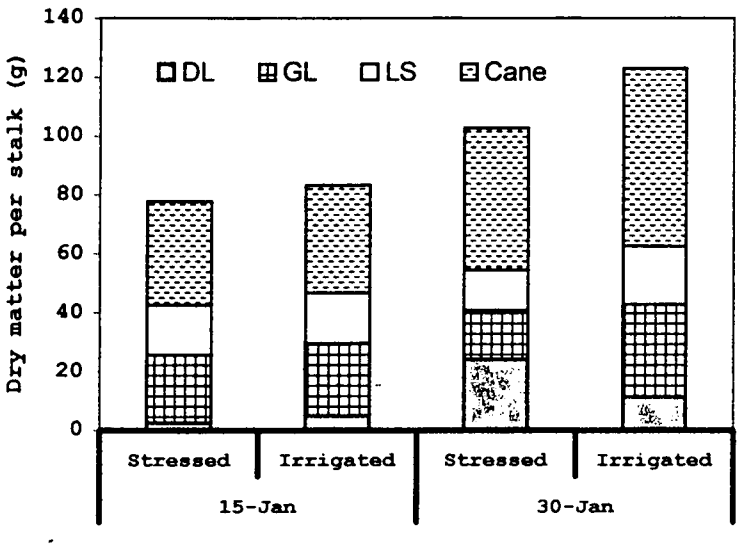

Figure 5.14. Dry matter partitioning in stressed and irrigated canes (DL-dry leaves, GL-green leaves, LS-leaf sheath).

When comparing the components of dry matter for the two treatments at the two time intervals, it is evident that 22 days after suppressing water (30th January) the dry leaves constituted about 23% of the total dry matter in the stalk whereas in fully irrigated crop it represented just 9%. In the case of green leaves, unstressed cane stalk biomass consisted of 40% green leaves compared to 21% in water stressed cane. Since the irrigated canes had more green leaves, it meant that they had higher photosynthetic capacity and grew at a faster rate than stressed cane. This was reflected in the higher partitioning of biomass into cane component in the irrigated crop (60 g/stalk) as compared to the water stressed crop (48 g/stalk). The fraction of millable stalk

in the aboveground biomass was 0.47 and 0.49 for the stressed and fully irrigated canes respectively. Thompson (1978) reported higher fraction of millable stalk in irrigated sugarcane variety NCo376 which was in the range of 0.59 to 0.71.

5.3.7 Quality character

Water deficit is known to affect the sucrose content in the stalk and pol%cane can be used as a measure of the sucrose content. Figure 5.15 shows the pol%cane obtained when cane was sampled for dry matter determination.

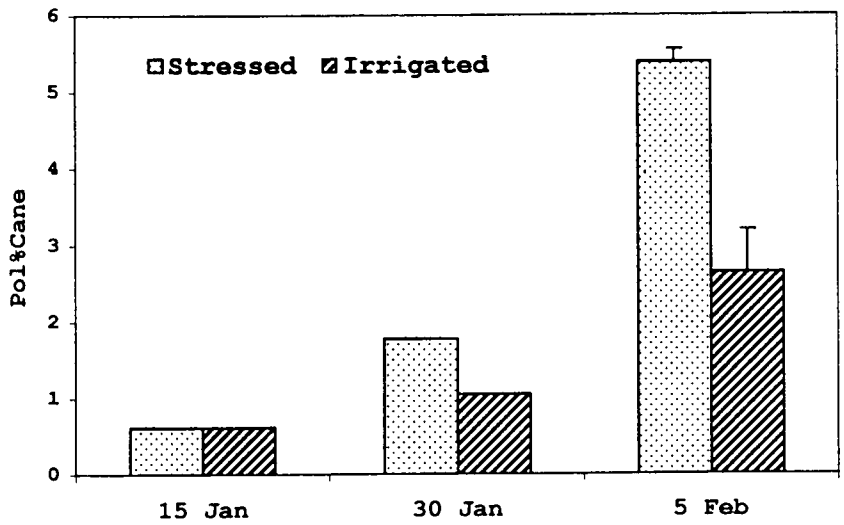

Figure 5.15. Pol%cane in stressed and irrigated canes.

As the crop was still in the elongation phase, the pol%cane in both treatments was quite low. On a comparative basis, it was evident that as water stress became more severe, the sucrose content in the stalk increased. At the end of the stress cycle the pol%cane of the stressed cane was significantly higher and more than double the value obtained in the irrigated cane. Similar trends were observed by Inman-Bamber (1986). Robertson and Donaldson (1998) reported significant increase (up to 10%) in sucrose yield in sugarcane during drying-off trials. But under severe water deficit, both sucrose dry weight concentration and dry matter concentration have been

observed to decline. In sweet sorghum, Massacci, Battistelli and Loreto (1996) found that drought stress slightly increased sugar accumulation on a fresh weight basis

5.4 Plant microclimate

Water stress also influences the plant microclimate and under this section, radiation interception and leaf temperature together with canopy temperature will be discussed.

5.4.1 Radiation interception

Growth of sugarcane is largely determined by the amount of radiation intercepted by the crop canopy. Water deficit will have depressing effect on radiation intercepted by the crop. The effects of water stress on the interception of global radiation and Photosynthetically Active Radiation (PAR) together with radiation use efficiency are discussed below.

5.4.1.1Global radiation interception

Figure 5.16 depicts the time course for the percentage global radiation intercepted by the stressed and fully irrigated plot as measured by the tube solarimeters. The soil water content is also given for the stressed canes. There was no clear-cut difference in radiation interception between the treatments up to the 20th January, i.e. 12 days after withholding water. Thereafter difference in radiation interception could be seen between the plots and at this stage the soil water content was about 19%.

The canes under water stress condition suffered mild stress up to 28th January where the difference in radiation interception compared to irrigated canes was of the order of 10%. Following this during the period 31st January up to 4th February the canes in the dry plot were under severe stress and the reduction in radiation interception from the fully irrigated plot was about 25% (figure 5.16). At this stage the soil water content was

just below 16% and most of the lower leaves in the stressed canes were dead. The stressed plants had on average only 4 to 5 green leaves. The lower green LAI in the stressed crop (refer fig 5.8) accounted for the low radiation interception as compared to the fully irrigated crop. Monteith (1972) associated lower radiation interception due to water deficit with the reduction in crop biomass and yield.

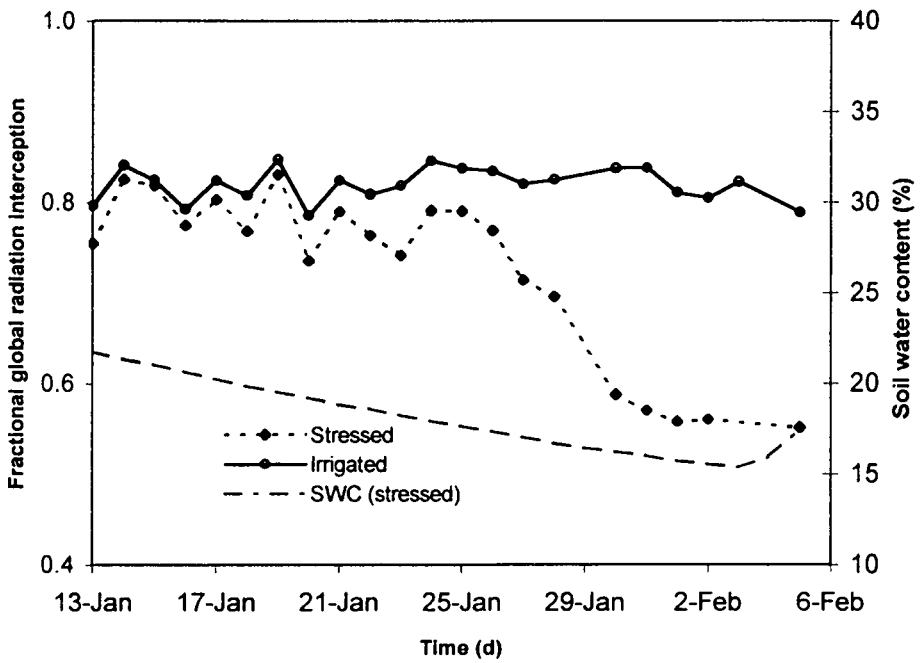

Figure 5.16. Time course of global radiation interception in stressed and irrigated cane treatments.

The fractional radiation interception in the fully irrigated crop fluctuated from 0.79 to 0.85 and each plant had about 9 fully expanded green leaves. In Australia, the fractional interception of fully irrigated sugarcane varieties Q117 and Q138 stayed above 0.8 once full cover had been reached (Robertson *et al.*, 1996) which is a similar result to this.

5.4.1.2 PAR interception

Figure 5.17 gives the PAR interception by the cane canopy in both plots. The values were obtained from the sunscan canopy analysis system and measurements were taken once a

week. For the fully irrigated plot, the % PAR interception was above 95% throughout the measurement period and was higher than the interception measured by the tube solarimeters. This is because plants intercept more radiation in the wavelength of 400 to 700nm (PAR) than in the broadband of solar radiation as measured by the tube solarimeters.

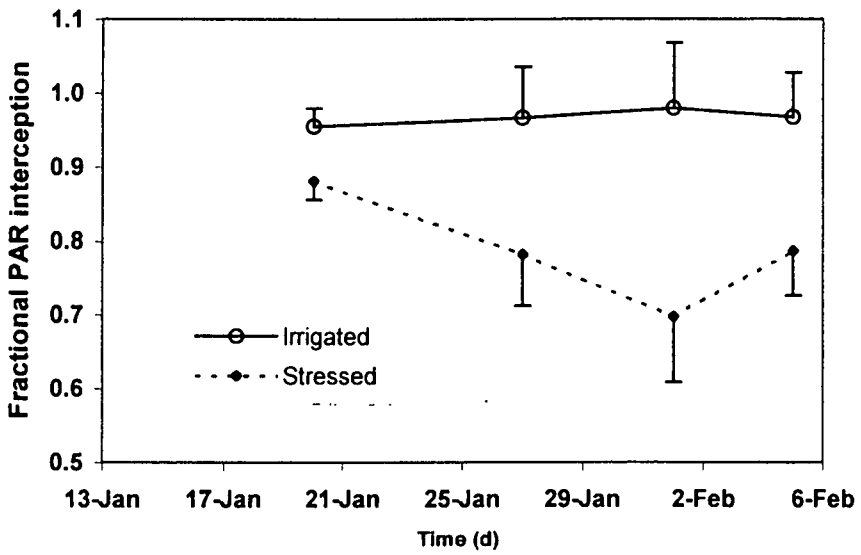

Figure 5.17. PAR interception in stressed and irrigated canes.

PAR interception by the stressed canes decreased from 88% on 20th January down to 70% on the 1st February and at this stage the soil water content was 16%. When compared to the unstressed cane, the PAR interception by the water stressed canes was significantly reduced by almost 28%. Inman-Bamber (1986) found that stressed plots under varieties NCo376 intercepted less than 60% of incident PAR when the plants were severely stressed. The decrease in PAR interception is attributed to the reduction in green LAI in the stressed plants. The rapid increase in PAR interception in the dry plot after resumption of irrigation on 5th February was due to the quick recovery of the plant in terms of turgidity of the leaves during the day and also a regain in green colour of the young leaves.

5.4.1.3 Radiation Use Efficiency (RUE)

Radiation use efficiency was computed from radiation interception measured by the tube solarimeters and total aboveground biomass. Figure 5.18 gives the radiation use efficiency of the fully irrigated and stressed treatments for 30th January and 5th February. It should be emphasized here that the computation of RUE was based on the global radiation interception and biomass accumulation from 15th January. The RUE is a measure of photosynthetic performance of the leaves.

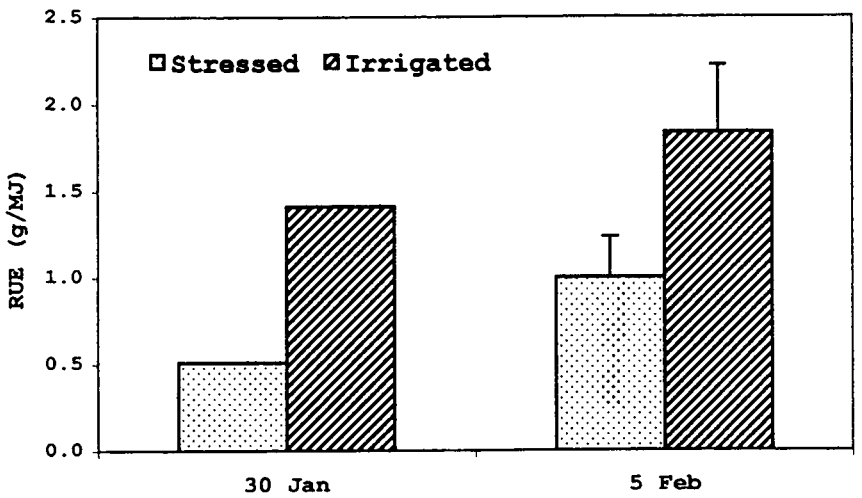

Figure 5.18. Radiation use efficiency in stressed and irrigated canes.

Considering the period from 15th January up to 5th February, there was significant difference in RUE between the stressed and irrigated plants. The stressed canes gave a RUE of 1.0 g/MJ whereas from the fully irrigated crop, the RUE was 1.84 g/MJ. Therefore, under water stress condition when the soil water content was at 16%, RUE in sugarcane was reduced to about 50% of its optimum potential. Water stress reduced the ability of the crop to accumulate biomass by reducing the capacity to convert intercepted energy to biomass.

On a sugarcane crop grown in an irrigated tropical environment, Muchow *et al.* (1994) obtained a maximum RUE

of 1.75 g/MJ which was below that obtained for the unstressed crop in this study. But based on a 0.4 g/MJ standard error, the RUE of 1.84 g/MJ was not different from that obtained by Muchow *et al.* (1994). It should be noted that all the trash was recovered during the trial and included in the calculation of RUE.

5.4.2 Leaf Temperature

Leaf temperature fluctuates throughout the day and has been used as an indicator of water stress (Ehrler, 1973). The diurnal leaf temperature in sugarcane together with the vapour pressure fluctuations on 13th January, 18th January and 2nd February is given in figure 5.19.

The leaf temperature was low in the early morning and late evening and high during the period 1000 and 1400 hours. Diurnal variation in incoming radiation and vapour pressure deficit has an influence on leaf temperature fluctuations.

At the initial stage of water stress, i.e. on 13th January, slight difference of 0.87 ± 0.12 °C in leaf temperature between stressed and irrigated plant was obtained between 1000 and 1430 hours. At this stage the soil water content in the stressed plot was around 21 % and there was no observable sign of water stress in the crop. When the SWC decreased to 19.2% on 18th January, the leaf temperature difference became 1.33 ± 0.17 °C and lasted for a period of 7 hours. The crop was under mild stress.

Under severe water stress which occurred on 2nd February when the SWC was 15.3% (i.e. 0.153 m^3m^{-3}), the leaf temperature difference increased to 2.0 ± 0.28 °C and occurred throughout most of the day.

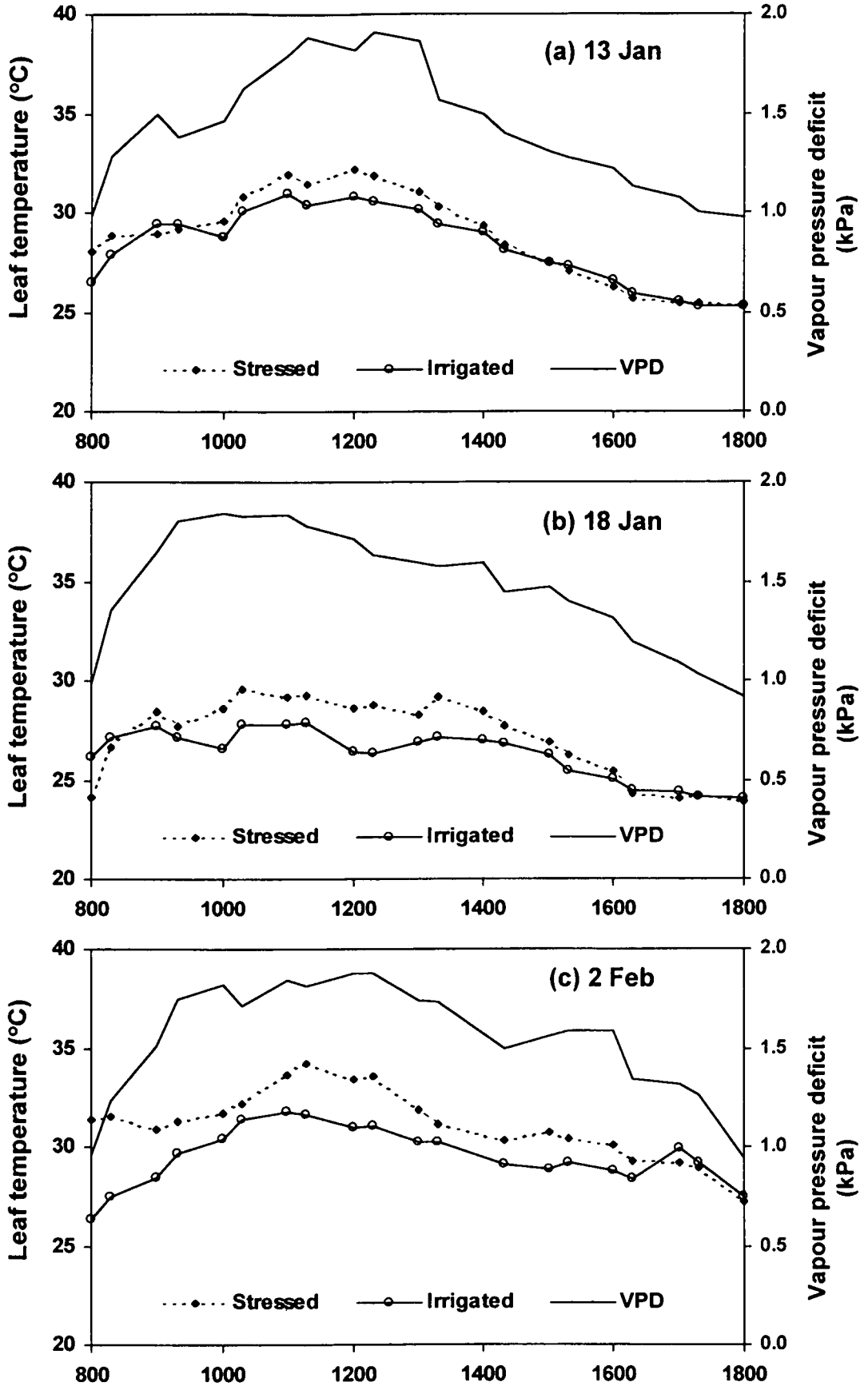

Fig 5.19a,b and c. Graphs showing diurnal leaf temperature (using leaf thermocouples) fluctuation together with vapour pressure deficit (VPD) on 13 Jan, 18 Jan and 2 Feb respectively.

The high leaf temperature recorded in the water stressed sugarcane plant can be attributed to the closure of the stomata so as to limit the loss of water through transpiration (Farquhar and Sharkey, 1982; Sandhu and Horton, 1978). Reduction in transpiration meant that the cooling of the leaf surfaces was decreased resulting in a rise in leaf temperature as compared to a plant under irrigation and transpiring at a normal pace. In wheat, Ehrler *et al.* (1978) found that the temperature difference between plant canopy and air increased as drought conditions became severe.

The relationship between leaf temperature and vapour pressure deficit is given in figure 5.20. Leaf temperature was strongly correlated with VPD. Ehler (1973) found that leaf-air temperature differences in cotton decreased linearly about 1.3°C for each kPa increase in vapour pressure deficit. In kidney beans, a strong dependence of leaf-air temperature differences on VPD was reported (Walker and Hatfield, 1983).

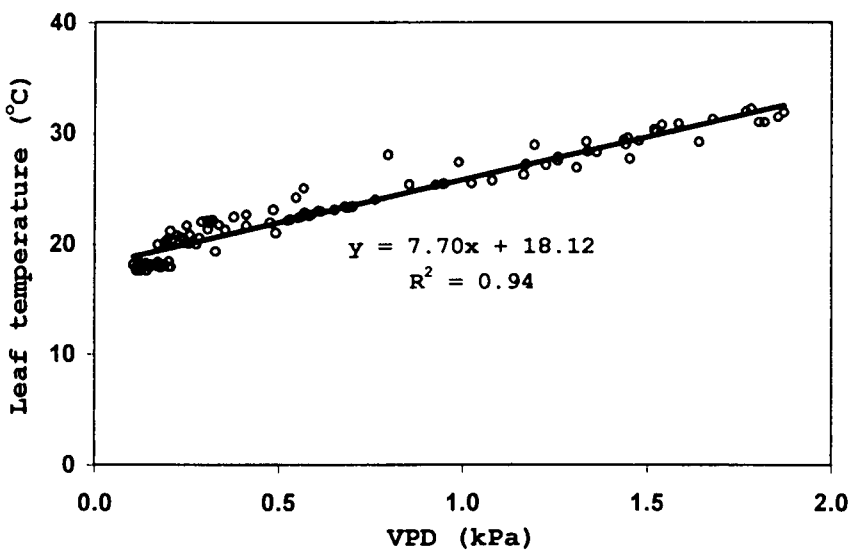

Figure 5.20. Regression of leaf temperature against vapour pressure deficit in stressed crop.

The measurement of individual leaf temperature using thermocouples is cumbersome and many leaves must be sampled in order to obtain a reasonable average for an

entire field. A better method would be to use infrared thermometry to measure canopy temperature.

5.4.3 Canopy temperature and Crop Water Stress Index

The scaling up of leaf temperature to canopy was made possible by the use of infrared thermometer. Figure 5.21 gives the linear regression of the difference between air and canopy temperature against the vapour pressure deficit for both the irrigated and stressed canes.

The regression line for unstressed crop was obtained by screening canopy temperatures measured during sunny and calm (windspeed < 2.0 m s^{-1}) days. Air temperatures ranged from 15 to 32°C. The slope of the line was -3.67 °C kPa^{-1} and slightly less negative than that (-4 ^{0}C kPa^{-1}) obtained by Inman-Bamber (1986), but of the same order of magnitude.

For the stressed crop, the canopy-air difference obtained was around 6.8^{0}C irrespective of VPD fluctuation and was higher than 4.16^{0}C obtained by Inman-Bamber (1986).

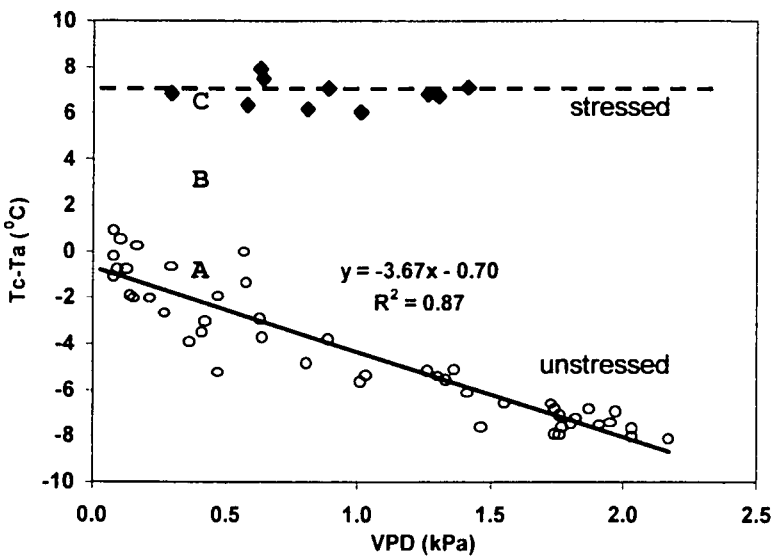

Figure 5.21. Effect of vapour pressure deficit (VPD) on the difference between air (Ta) and canopy (Tc) temperatures of the unstressed and stressed crop.

The scatter of data around the regression lines could have been due to changes in radiation, wind speed and experimental errors during measurements of canopy

temperatures and vapour pressure deficit as reported in other trials (Berliner *et al.*,1984; O'Toole and Hatfield, 1983; Jackson, 1982; Inman-Bamber, 1986).

A crop water stress index (CWSI) was computed from linear regression of air-canopy temperature difference and VPD using the stressed and unstressed lines (Fig 5.21). CWSI was described by Idso *et al* (1981) and Jackson (1982).

$$CWSI = \frac{B - A}{C - A} \quad , \qquad \text{(see Fig 5.21 for A,B,C)}$$

where B : measured point lying between stressed and unstressed regression lines

B-A : Vertical distance between point B and point A on unstressed regression line

C-A : Vertical distance between point C on stressed line and A on unstressed regression line

Figure 5.22 shows the regression of CWSI against soil water potential in the stressed canes.

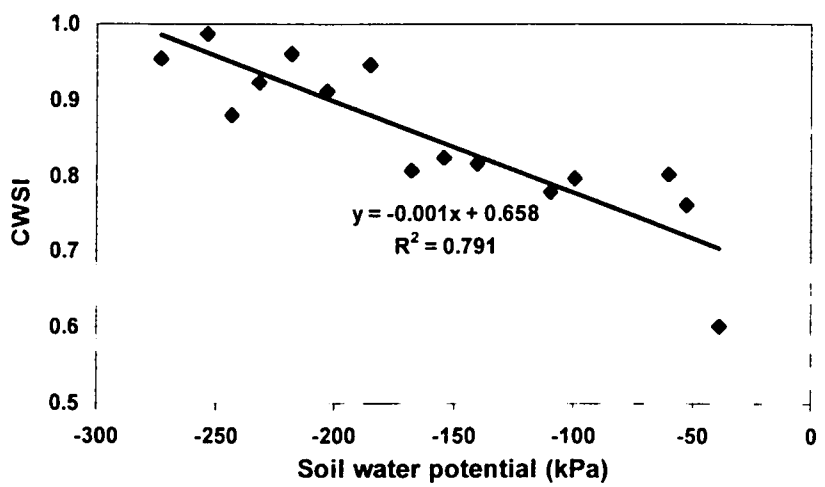

Figure 5.22. Regression of CWSI against soil water potential for stressed cane

Soil water potential(SWP) accounted for 79% of the variation in CWSI. A SWP of -0.1 MPa corresponded to a CWSI of -0.8. CWSI has been used to quantify the extent of water stress in many crops and was used in irrigation

scheduling. Inman-Bamber and de Jager (1986) found in sugarcane variety N 12 that CWSI was well correlated with midday Ψ_L which accounted for 88% of the variation in CWSI. In wheat, Jackson (1982) reported a reasonably strong correlation existing between CWSI and extractable water used.

5.5 Plant physiological factors

The effects of water stress on the physiological behaviour of sugarcane were also assessed. Leaf water potential and photosynthetic rate as affected by water stress will be discussed in more detail.

5.5.1 Leaf water potential

Figure 5.23 shows the time course for the midday leaf water potential (Ψ_L) under full sun conditions in both treatments. Cloudy days during which Ψ_L was determined are excluded from the graph.

Significant difference in Ψ_L between the stressed and irrigated canes occurred on 16th January, which is 8 days after water was suspended in the stressed plot. At this stage the soil water content (SWC) was 20% and the Ψ_L of

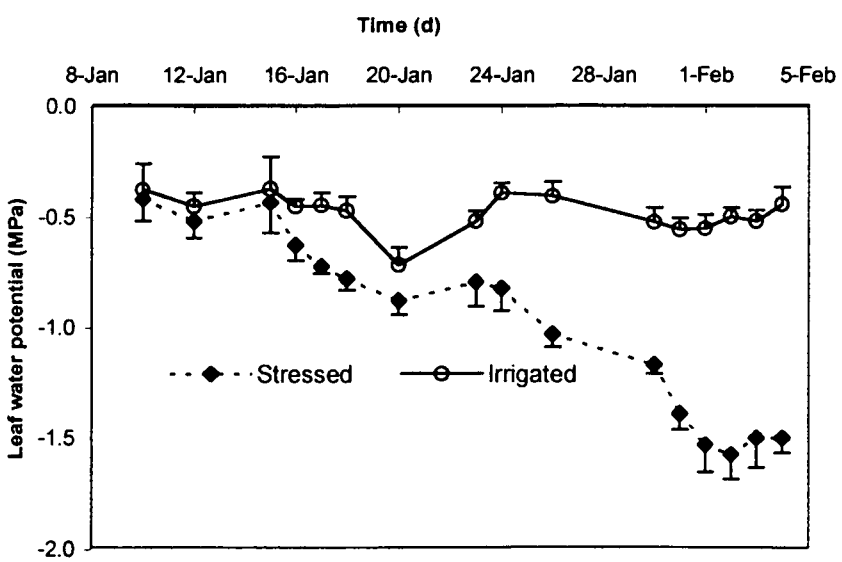

Figure 5.23. Full sun midday leaf water potential in water stressed and fully-irrigated canes.

the stressed and irrigated plant were -0.63 and -0.45 MPa respectively. Up until 24th January, the water stress can be categorized as mild with a difference of 0.27 MPa existing between the stressed and well-watered canes. On 24th January when water had been withheld for 16 days, the SWC was 18%.

As this SWC level dropped to 16%, the sugarcane plants were under major water stressed condition. The lowest Ψ_L was -1.57 MPa and occurred 24 days after water was suspended. The difference in Ψ_L between the two treatments during the major water stressed condition was 0.83 ± 0.24 MPa and was significant at the 5% level. At this stage, the plant extension rate of the stressed plant was zero and each stalk had less than five green leaves. Inman-Bamber (1986) reported that PER in sugarcane grown in pots ceased when midday Ψ_L fell below -1.3 MPa during the first stress cycle and that the apical meristem was permanently damaged at -2.8 MPa. In maize, leaf elongation rate stopped when midday Ψ_L was reduced to -1.1 MPa (Hsiao and Xu, 2000).

Pre-dawn Ψ_L was measured from 23rd January onwards and there were significant differences between stressed and well-watered canes till the end of the water stress cycle (fig 5.24).

The pre-dawn Ψ_L in stressed plant dropped to -0.98 MPa when the SWC was around 16%, that is after water was suspended for 27 days. The low values of the pre-dawn Ψ_L in the stressed plot as compared to the wet plot confirmed the damaging effect of water stress on the canes which was due entirely to the shortage of water in the soil.

From figure 5.25, a fairly strong linear correlation (R^2 = 0.85) existed between soil water potential (Ψ_S) and Ψ_L. Soil water potential has a strong influence on the Ψ_L of the canes.

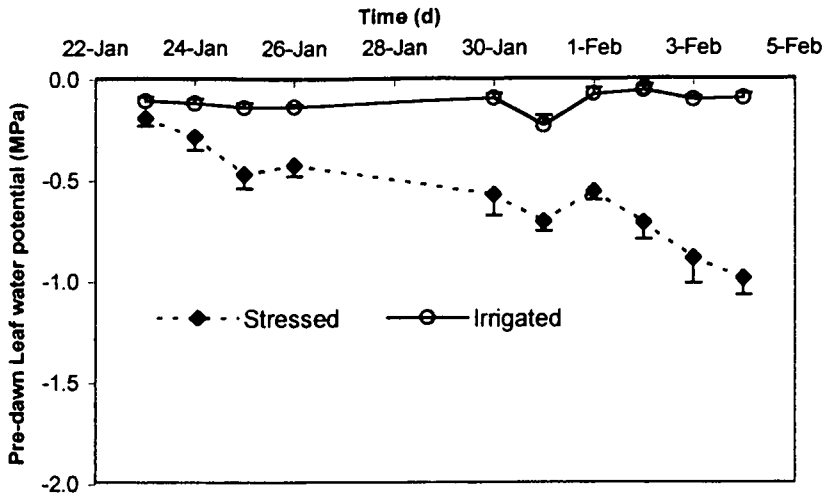

Figure 5.24. Pre-dawn leaf water potential in water stressed and fully-irrigated canes.

Plant extension was also affected by changes in leaf water potential. Figure 5.26 shows the relation obtained between plant extension rate (PER) and leaf water potential with a line fitted by eye. PER of stressed and irrigated cane plants was reduced when midday Ψ_L fell below -0.4 MPa. Inman-Bamber (1986) found that PER decreased when Ψ_L fell below -0.5 MPa.

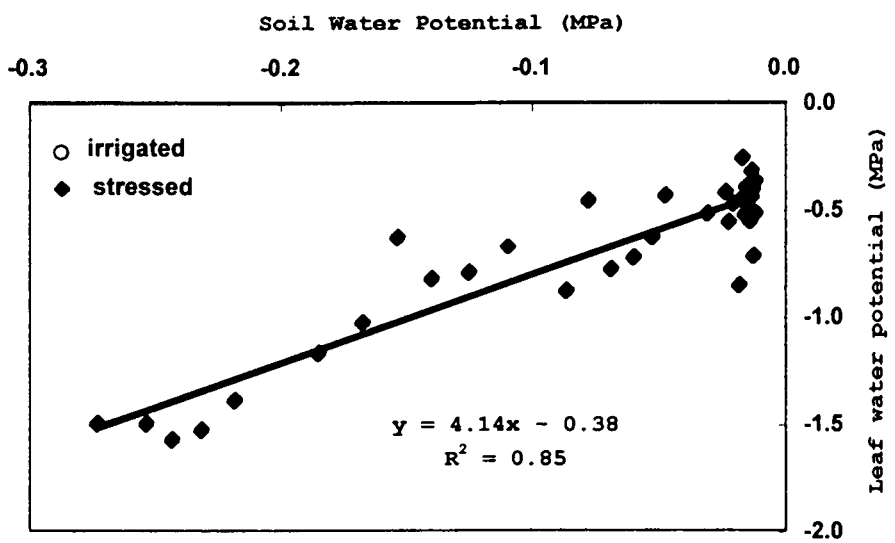

Figure 5.25. Regression of soil water potential against midday leaf water potential (values taken from both treatments).

Plant extension rate almost ceased when the Ψ_L fell below -1.2 MPa (fig 5.26) which was in agreement with that obtained by Inman-Bamber (1986). In maize, Hsiao and Xu (2000) reported that leaf elongation rate stopped when Ψ_L was reduced to about -1.1 MPa. Therefore, sugarcane sensitivity to water deficit appears to be similar to maize.

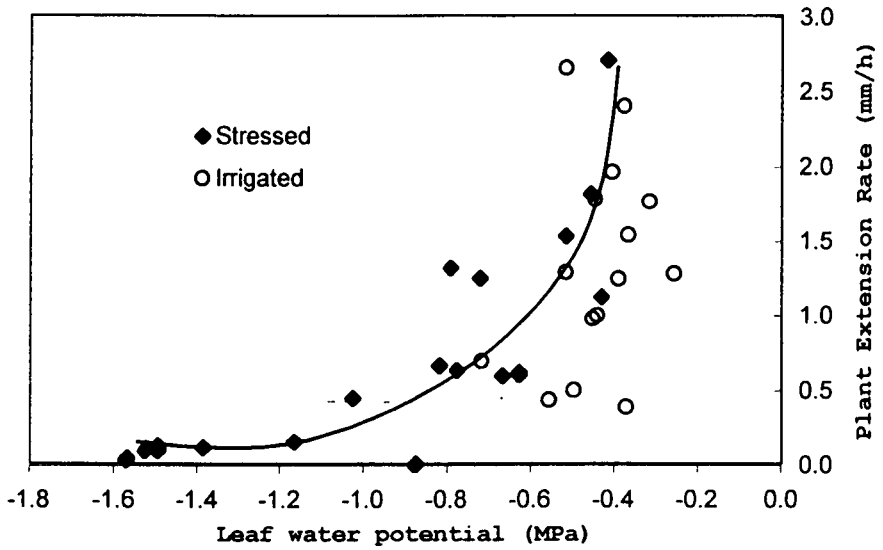

Figure 5.26. Plant extension rate measured from 1200 to 1400 hours and the midday leaf water potential (curve fitted by eye).

5.5.2 Photosynthesis during stress

5.5.2.1 Photosynthetic rate

The photosynthetic rate was measured around midday on a daily basis on the upper fully expanded leaves and exposed to sun in the stressed and irrigated canes. Figure 5.27 shows the time course of photosynthetic rate for both treatments on sunny days.

Photosynthetic rate (PN) in the stressed plants started to be affected after the 20th January, i.e. 12 days after onset of stress, when soil water content was around 19%. The rate of photosynthesis decreased significantly to an average value of 2.2 $\mu molm^{-2}s^{-1}$ when the soil water content reached 16% on 2nd February, i.e. 25 days after water

stress. This could be due to stomatal and non-stomatal limitations (Du, *et al.*, 1996). In bean, a soil water deficit of 17-20% caused a significant decrease in rates of carbon dioxide uptake whereas a 40 to 44% soil water deficit led to an almost complete inhibition of photosynthesis (Yordanov *et al.*, 2000).

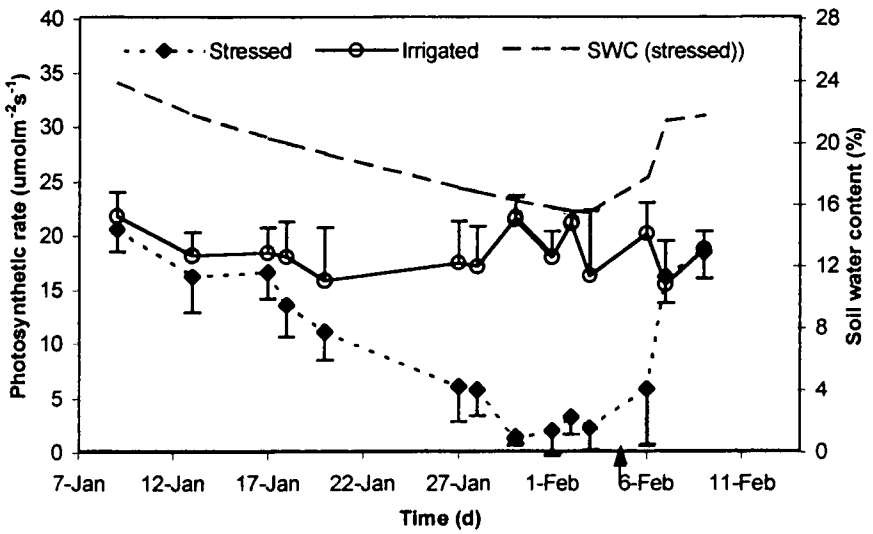

Figure 5.27. Time course of photosynthetic rate in stressed and fully irrigated sugarcane plants. Arrow indicates time of irrigation to stressed plot.

In the well-watered plants, the PN was maintained at 18.4 ± 1.8 μmol $m^{-2}s^{-1}$. It is worth noting that when irrigation was applied to the stressed plot on 5th February, recovery in PN occurred within 2 to 3 days.

5.5.2.2 Photosynthesis and leaf water potential

The relationship between net photosynthesis and leaf water potential measured in the stressed and irrigated sugarcane plants is given in figure 5.28.

In well-watered sugarcane, the Ψ_L was within -0.4 and -0.75 MPa and the net photosynthesis measured was above 15 μmol $m^{-2}s^{-1}$. In the stressed sugarcane plant, the net photosynthesis measured decreased linearly as the Ψ_L became more negative. From the linear regression line,

the leaf photosynthetic rate was first affected at a Ψ_L of -0.6 to -0.7 MPa and reduced to zero at -1.5 MPa. It was reported that when midday Ψ_L in sugarcane decreased from -0.37 to -0.85 MPa, the carbon exchange rate declined linearly from 40 to 20 $\mu molm^{-2}s^{-1}$ (Du *et al.*, 1996). The same authors observed that photosynthetic rate was severely affected when Ψ_L was about -1.61 MPa which is in line to that observed in the present study.

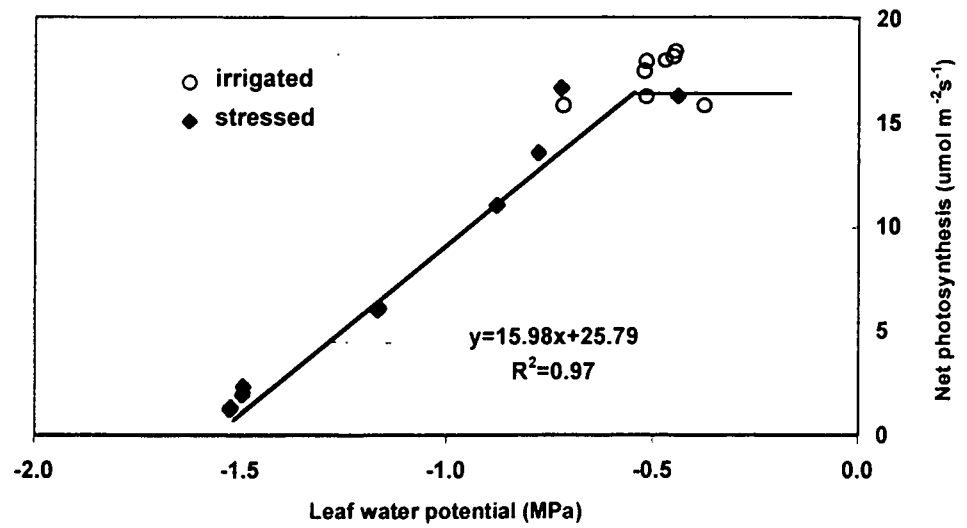

Figure 5.28. Regression of net photosynthesis and leaf water potential (values taken from both treatments).

In maize and wheat, photosynthesis was initially inhibited at Ψ_L of -0.3 MPa (Beadle *et al.*, 1973) and -1.0 MPa (Johnson *et al.*, 1974). Ludlow *et al.* (1985) found that in buffel, green and spear grasses, the rate of leaf photosynthesis ceased when Ψ_L reached -3.0 and -4.0 MPa which is much lower than measured here for sugarcane. This would indicate that sugarcane is more susceptible to water stress than these grasses.

5.5.2.3 Photosynthesis and leaf temperature

Figure 5.29 shows the response of leaf temperature and photosynthesis in irrigated and water stressed sugarcane plants.

Photosynthetic rate in the irrigated canes increased rapidly when leaf temperature was in the range of 26 to 32°C after which it stabilised around 17 µmol $m^{-2}s^{-1}$. A probable explanation for the very high leaf temperature recorded in the irrigated canes could be due to the enclosure of leaves in the IRGA cuvette for too long during photosynthesis measurements.

In stressed canes, a decrease in photosynthetic rate was measured with increasing leaf temperature in the range 26 to 40°C. Stomatal closure during water deficit reduces the carbon dioxide exchange rate required in the process of photosynthesis and also decreases the rate of transpiration which is important for cooling the leaves. Thus, explaining the trend of increasing leaf temperature and decreasing photosynthetic rate in the stressed canes.

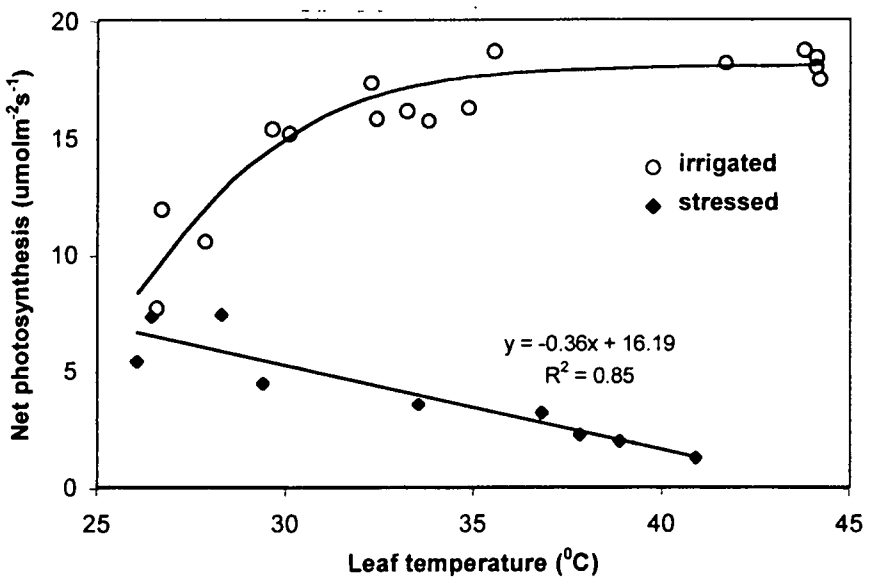

Figure 5.29. Net photosynthesis (including diurnal readings) and leaf temperature as measured in irrigated canes (line fitted by eye) and stressed canes.

5.5.2.4 Diurnal variation in photosynthesis

Figure 5.30a and b show the diurnal variation in net photosynthesis for the stressed and irrigated plants 20 and 25 days after withholding water.

Twenty days after withholding water from the stressed plot, the photosynthetic rate measured before noon was

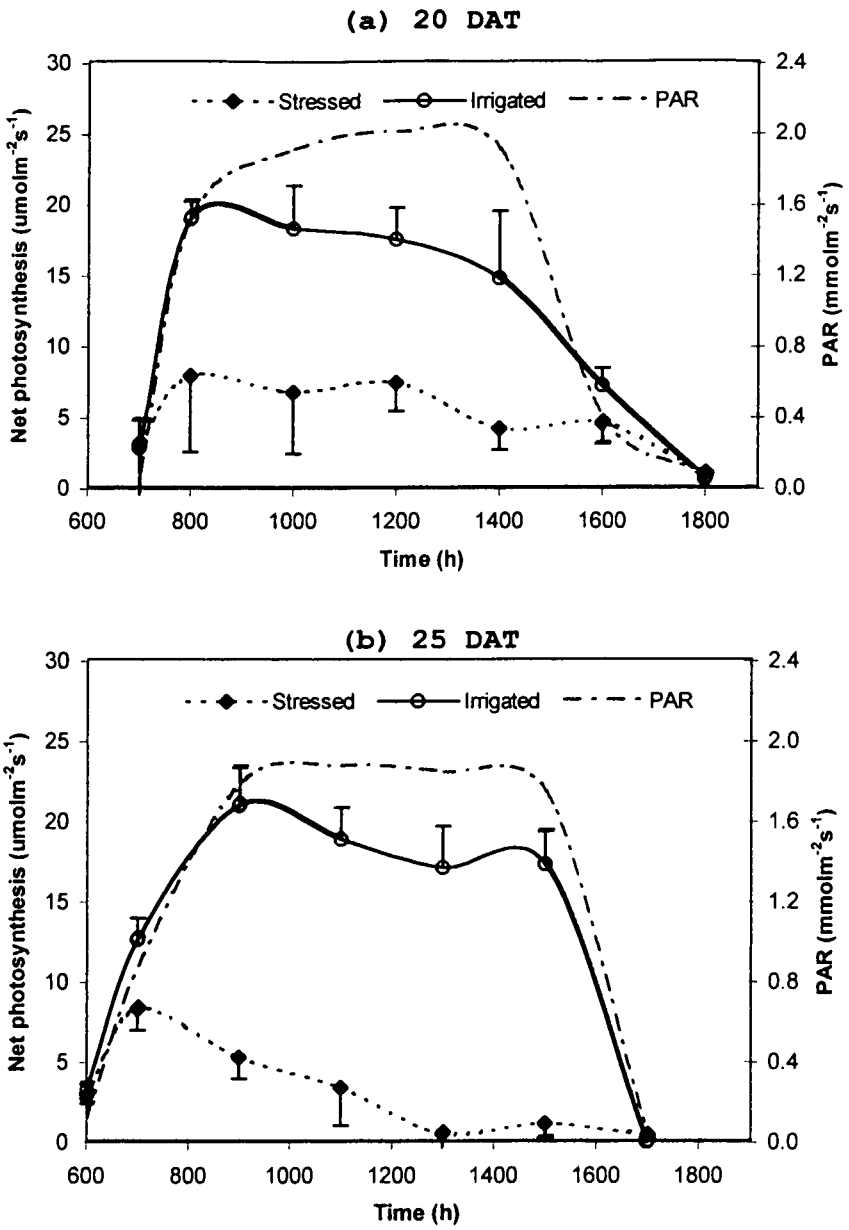

Figure 5.30a and b. Diurnal variation in net photosynthesis and PAR 20 days and 25 days after withholding water.

7.5 $\mu molm^{-2}s^{-1}$ as compared to 18.0 $\mu molm^{-2}s^{-1}$ in the well-watered canes. In the stressed plants, low photosynthetic rate was recorded at high PAR whereas in irrigated plants, high photosynthesis occurred at high PAR. The response of net photosynthesis to increasing PAR was significantly higher in the irrigated canes than in the stressed plants suggesting that the stomata in the latter may be partially closed at relatively lower PAR (figure

5.31). During this period, the soil water content was at 17% with a midday Ψ_L of -1.0 MPa.

At 25 days after withholding water, the soil water content was 15.5% and the midday Ψ_L of the stressed plants was -1.5 MPa. At low PAR (0.8 $mmolm^{-2}s^{-1}$), the rate of photosynthesis in the stressed plant increased to 8 $\mu molm^{-2}s^{-1}$ and then decreased to almost zero by noon (fig 5.30b). Due to the severe water stress conditions, the stomata in the stressed sugarcane plant are closed at high PAR, thus limiting any flux of carbon dioxide into the leaf and minimizing the rate of photosynthesis.

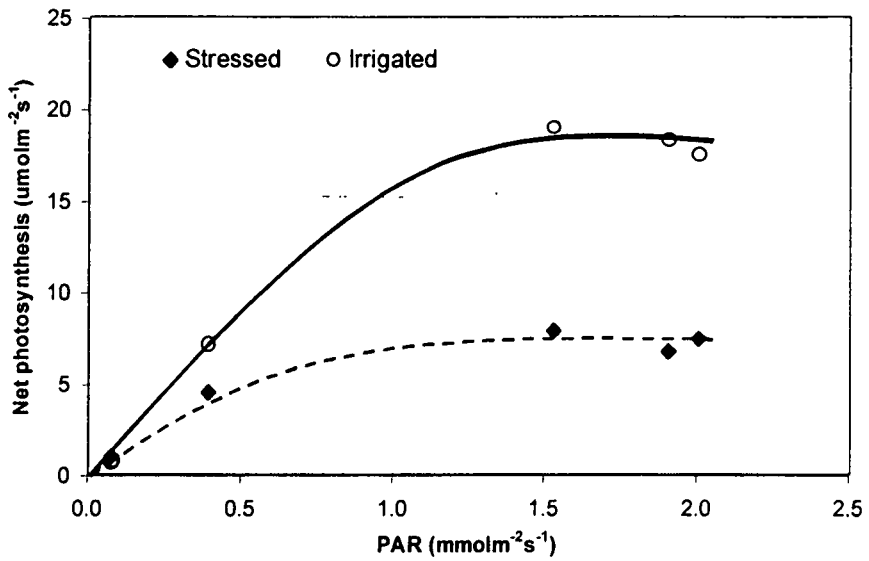

Figure 5.31. Light response of photosynthesis for sugarcane under irrigated and after suppressing water for 20 days. (lines fitted by eye)

In the well-watered plants, the photosynthetic rate followed the diurnal variation in PAR and was at 18.6 ± 0.9 $\mu molm^{-2}s^{-1}$ during 1000 and 1400 hr. This could explain the higher growth rate and biomass in the irrigated crops.

The amount of carbon dioxide fixed per m^2 green leaf area during the day was estimated by integrating the area under the curves in figure 5.30a and b. Daily total CO_2 fixation and photosynthetic efficiency by the irrigated

and water stressed plants during daylight hours on 20 and 25 days after stress are given in table 5.1.

Twenty days after water stress, the sugarcane plant was able to fix only 10.91 mg CO_2 m^{-2} representing about 43% of its potential amount under irrigation. This amount decreased further 25 days after stress and represented only 20% of the irrigated crops. The low LAI measured in the stressed canes was responsible for the inferior carbon dioxide fixation as compared to the fully irrigated crop.

Table 5.1 Leaf area index, daily carbon dioxide fixation and photosynthetic efficiency (%) in irrigated and water stressed sugarcane plants

Parameters	DAT*	Stressed	Irrigated	Relative (%)
Leaf area index	20	2.50	6.40	39
	25	2.40	7.10	33
CO_2 fixation (mg CO_2 m^{-2})	20	10.91	25.34	43
	25	6.34	31.36	20
Photosynthetic efficiency (%)	20	0.44	1.01	44
	25	0.22	1.09	20

* Days after onset stress

Photosynthetic efficiency (PE) was computed as a percentage of total amount of carbon dioxide fixed over total amount of incoming PAR. In stressed cane, PE of 0.44 and 0.22% was obtained at 20 and 25 days after withholding water. The PE in the well-watered canes was above 1% (Table 5.1).

Vapour pressure deficit and photosynthetic rate obtained during diurnal measurements are plotted in figure 5.32 for both treatments.

From the graphs, it was evident that the rate of photosynthesis in the irrigated sugarcane was high even when the vapour pressure deficit (VPD) reached 1.6 kPa. It could be deduced that the stomata remained open for

gaseous exchange and photosynthesis although the VPD was high.

Contrary to the irrigated crops, photosynthesis in the water stressed canes (after more than 20 days without irrigation) were severely affected with increases in VPD. At a VPD above 1.5 kPa, the rate of photosynthesis was below the 2 μmol $m^{-2}s^{-1}$ level.

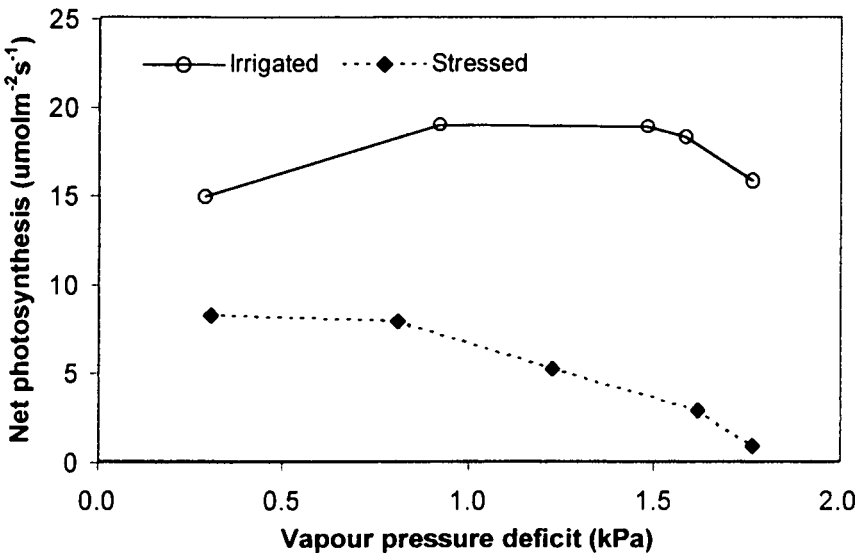

Figure 5.32. Net photosynthesis and vapour pressure deficit in the irrigated and stressed sugarcane plants.

5.5.3 Stomatal conductance

The infrared gas analyser used to measure photosynthesis also gave readings for stomatal conductance and transpiration. Figure 5.33 shows the time course of stomatal conductance measured in stressed and fully irrigated sugarcane. From 8th to 20th January, the stomatal conductance for both treatments decreased slightly but they were not significantly different. The low stomatal conductance may be explained by partial closure of the stomata due to the high PAR, (1.91 ± 0.06) mmol $m^{-2}s^{-1}$, recorded during the measurement.

Significant difference in stomatal conductance between the treatments was observed after 27th January (i.e., 20 days after withholding water in the stressed plot). The PAR

measured during this period was 1.29 ± 0.14 mmol $m^{-2}s^{-1}$ and was lower than that recorded before 27th January. The comparatively lower PAR was favourable for the opening of stomata in the irrigated canes whereas in the stressed canes the stomata were closed due to low soil water content (below 17%). Meinzer and Grantz (1989) also observed a steady decrease in stomatal conductance when irrigation was withheld in sugarcane.

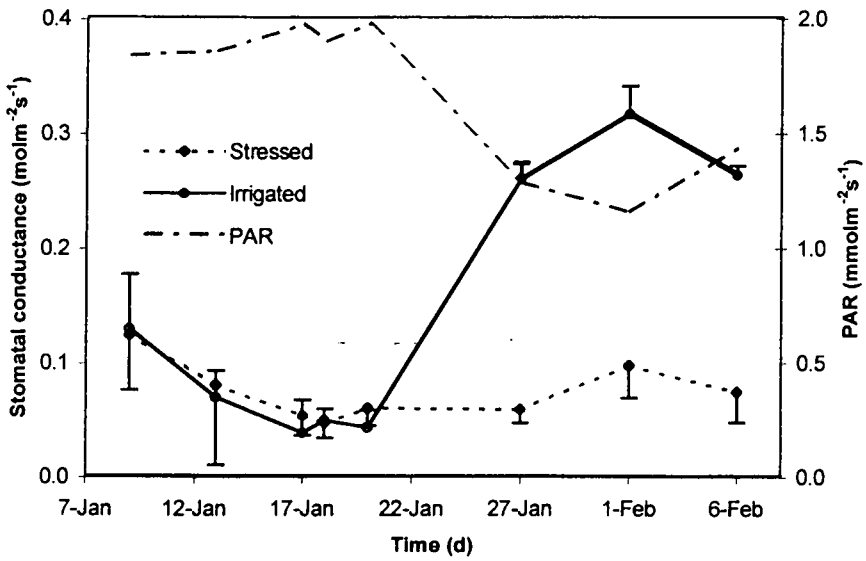

Figure 5.33. Time course of stomatal conductance for stressed and fully irrigated sugarcane plants.

5.6 Summary of first stress cycle

(a) In terms of midday Ψ_L, the stress phase can be categorized into minor and major stress as given in Table 5.2.

(b) Table 5.3 summarises the effect of water stress on growth and physiological parameters of sugarcane variety NCo376.

During water stress, the sequence in which sugarcane plant processes are affected is plant extension rate,

Table 5.2 Summary of the different stress period in terms of DAT (days after onset of stress) and leaf water potential (Ψ_L).

Stress	Period	DAT	Ψ_L(MPa)
Minor	Start	8	-0.5
	End	16	-0.8
Major	Start	16	-0.8
	End*	25	-1.6

* after which irrigation was resumed

Table 5.3 Summary of the different processes affected by water stress in sugarcane.

Parameters	DAT		SWC (%)		Ψ_L(MPa)		Ψ_S(MPa)	
	A	B	A	B	A	B	A	B
Tiller density	24		16		-1.4		-0.23	
Green leaf no.	16	24	18	16	-0.8	-1.4	-0.15	-0.23
Leaf area index	12	20-24	19	17-16	-0.7	-1.4	-0.11	-0.23
Stalk height	16		18		-0.8		-0.15	
Stalk weight	16	24	18	16	-0.8	-1.4	-0.15	-0.23
Plant extn rate	10	24	20	16	-0.7	-1.4	-0.07	-0.23
PAR interception	12	24	19	16	-0.7	-1.4	-0.11	-0.23
Photosynthesis	19	23	17	16	-1.0	-1.2	-0.19	-0.23
Stom. conductance	19	20	17	16	-1.0	-1.4	-0.19	-0.23

DAT - days after water stress SWC - soil water content

A - significant difference observed B - process very low/ceased

LAI, radiation interception, then green leaf number together with stalk height and weight, followed by photosynthesis, stomatal conductance and tiller density.

(c) Total above ground biomass together with radiation use efficiency are drastically affected when soil water content reached 16% and the Ψ_L at -1.5 MPa.

(d) With decreasing soil water content, an increase in the crop water stress index was observed and can be used as an indicator of water stress in sugarcane.

RESULTS AND DISCUSSION : SECOND STRESS CYCLE

Water was applied to the stressed plot on the 5th February, that is, after withholding water for 28 days. At this stage, the stressed sugarcane plants had 4 to 5 green leaves, the daily plant extension rate was very low (2.5 mm/day) and the midday photosynthetic rate was only 3 $\mu molm^{-2}s^{-1}$.

6.1 Recovery from first stress cycle

The response to water application was fast in terms of plant extension rate (figure 6.1). Within 48 hours, the PER rose from 3.2 to 21.8 mm/day. Total recovery in PER occurred between 8 and 9 February where the PER was around 40 mm/day. It is interesting to note that the PER during recovery was more rapid in the stressed crop than in the unstressed controls. Gates (1968) observed higher growth rates in stressed tomato plants upon rewatering than in unstressed controls.

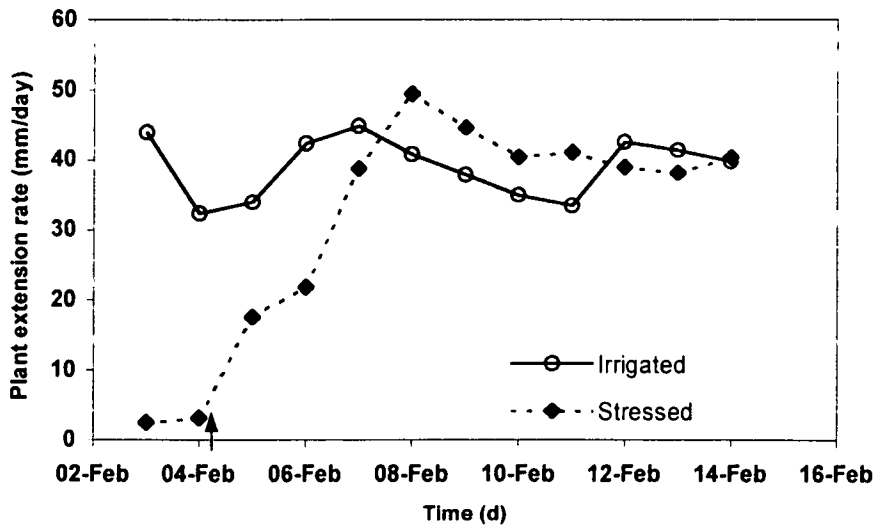

Figure 6.1 Trends in plant extension rate for stressed and irrigated canes. Arrow indicates irrigation applied to stress crop.

Within two days after irrigating the stressed canes, the rate of photosynthesis increased from 2.3 to 16.2 μmol $m^{-2}s^{-1}$ (figure 6.2). The rate of increase in the stressed crop was greater than in the irrigated during one day only. Begg and Turner (1976) also reported higher leaf photosynthetic rate on plants undergoing recovery from previous stress than on unstressed leaves of similar chronological age.

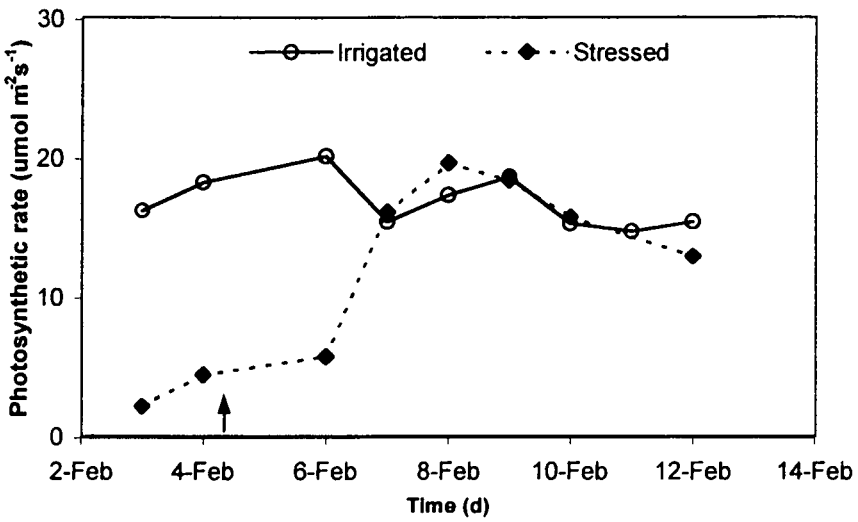

Figure 6.2. Time course of midday photosynthetic rate in stressed and irrigated plants. Arrow indicates time of irrigation.

6.2 Objectives of second stress cycle

The stomatal conductance measured in the sugarcane leaves using the IRGA was not giving clear cut differences between the stressed and irrigated crop although significant differences in photosynthetic rates were observed. The objectives of stressing the plant once more were to

(i) compare the stomatal conductance measured in both plots using the IRGA and the automatic porometer; and

(ii) assess the effect of a second stress on sugarcane plants.

When the previously stressed canes fully recovered in terms of PER and photosynthetic rate, water was withheld for a second time starting on 8th February. Discussions for the

second stress cycle will be restricted to PER, photosynthetic rate and stomatal conductance.

6.3 Climatic conditions

Figures 6.3a, b and c give the temperature, radiation, wind speed, relative humidity and computed reference evapotranspiration (ETo) during the second stress cycle. The maximum temperature varied from 26.4 to 31.9^{0}C whereas the average minimum temperature was 20.0^{0}C. The relative humidity ranged from 64.1 to 89.8%. The average wind speed was 1.2 ms^{-1} during the trial with maximum wind speed of 2.4 and 2.7 ms^{-1} occurring on 7th and 12th February.

The daily incoming radiation and ETo varied around 19.6 ± 7.2 MJ m^{-2} and 4.1 ± 1.2 mm respectively during the second stress period.

6.4 Plant extension rate

Figure 6.4 shows the time course for the daily plant extension rate (PER) in the irrigated and stressed plot. The PER in the stressed canes started declining on 14th February (6 days after withholding water) when the soil water content was at 19 %. The leaf water potential (Ψ_L) measured in the stressed cane was at -0.8 MPa. Compared to the first stress cycle, the response of the plant in terms of decreasing PER was quicker during the second water stress. Within 24 hr, the PER was reduced from 40.4 to 17.9 mm d^{-1}.

As the soil water content fell to 15 %, the PER in the stressed canes became very low to a value of 4.4 mm d^{-1}. This was definitely the result of a reduction in the enlargement of the cells in the growth zones. Moreover, at this stage, most of the green leaves in the stressed canes remained roll up during most of the day, thus reducing the leaf area exposed for capture of radiation and leading to lower growth of leaf and stalk.

In the irrigated canes, a PER of 36.9 ± 2.9 mm d^{-1} was measured from 14th to 21st February. Afterwards, a slight

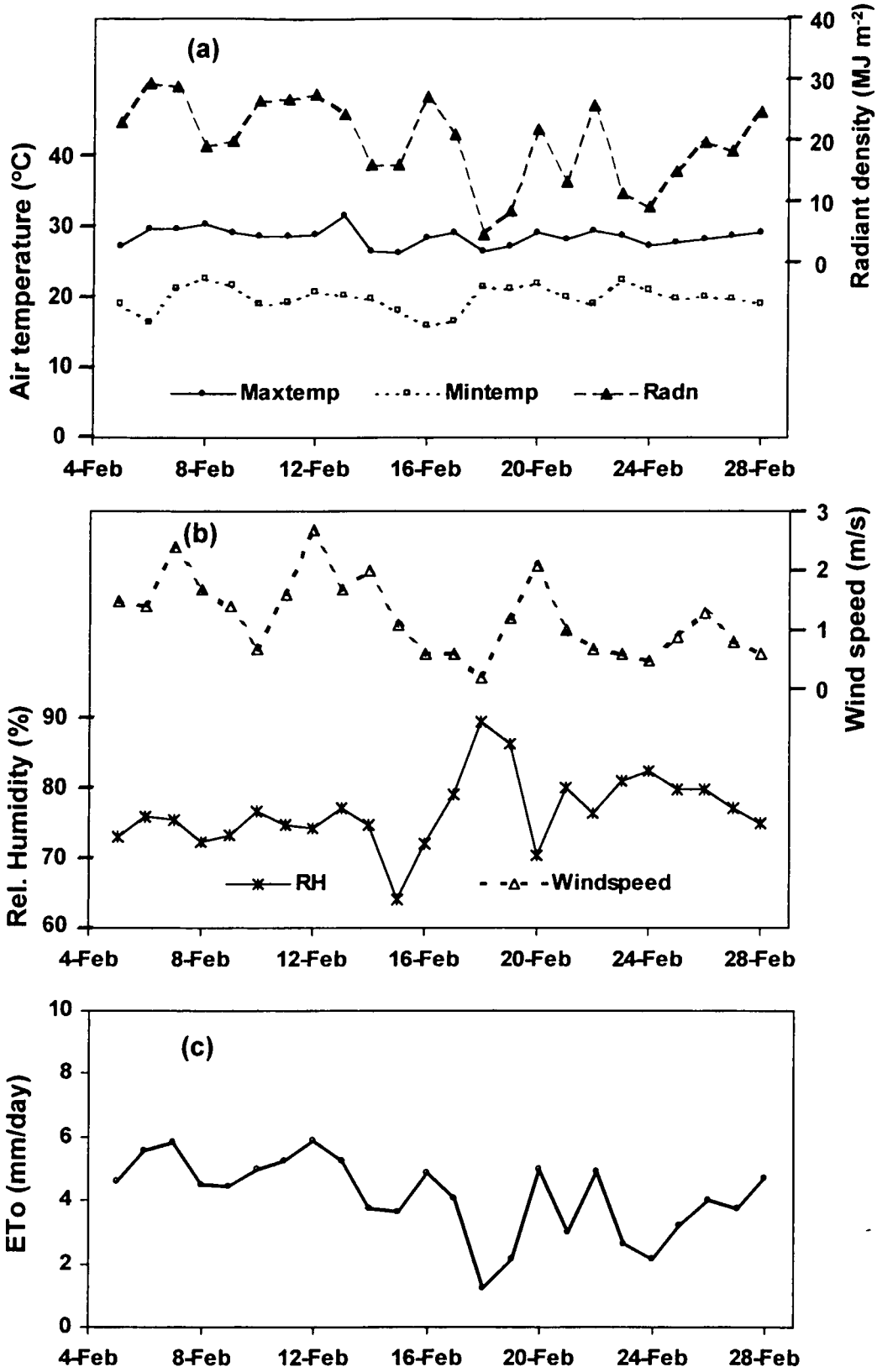

Fig 6.3 a,b and c. Graphs showing air temperature (max and min), radiant density, wind speed, relative humidity and reference evapotranspiration (ETo,Penman-Monteith) prevailing during the second stress cycle.

decrease in daily PER was observed although the soil water content was above 21%. As a reduction in size of the upper emerging leaves was observed in the plants, this could explain the slight decrease in daily PER.

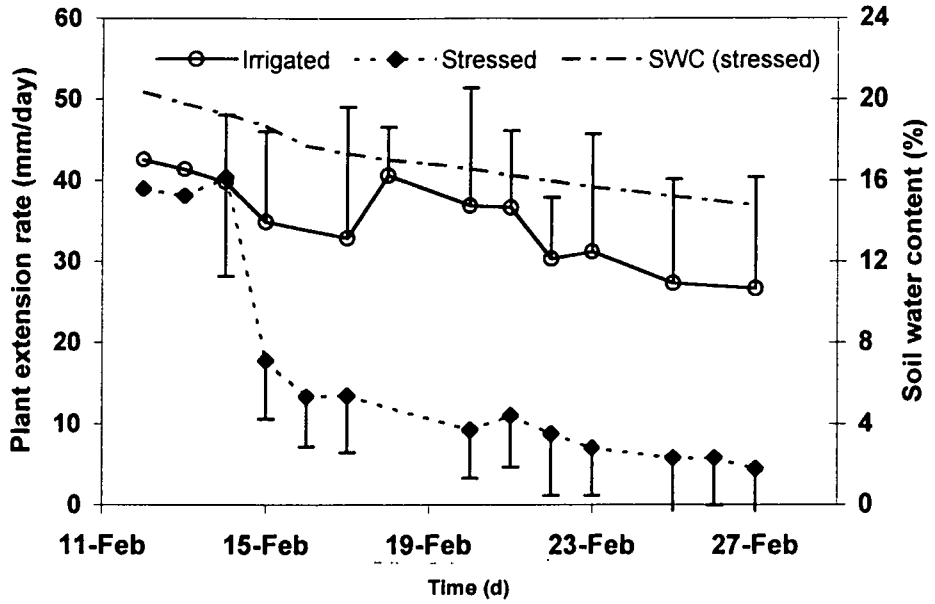

Figure 6.4 Trends in plant extension rate for stressed and irrigated canes.

6.5 Total aboveground biomass

The total aboveground dry matter obtained during the second stress period together with that obtained at the end of the first stress cycle are shown in figure 6.5.

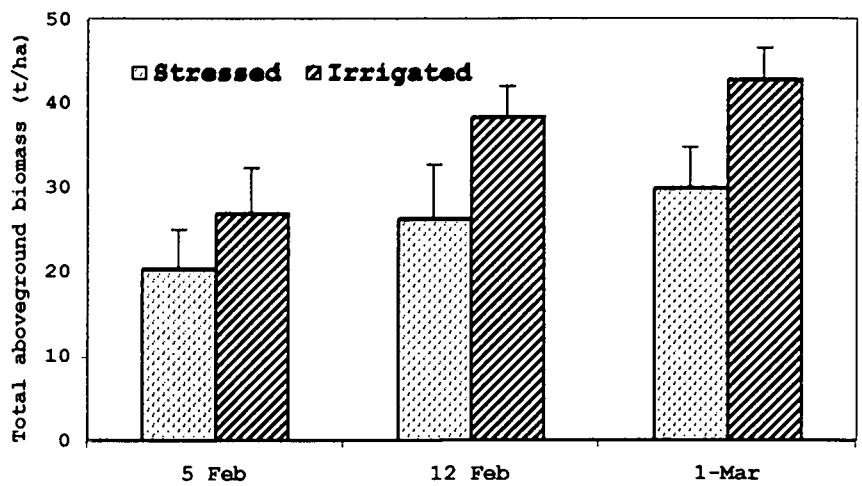

Figure 6.5 Total aboveground biomass in stressed and irrigated canes.

Total dry matter accumulation of the stressed crop on 12th February (4 days after withholding water during the second stress period) was higher than that measured on the 5th February (end of the first stress period). This was due to crop recovery in terms of plant extension rate and growth after the application of water. On 12th February, the soil water content was at 20% and the Ψ_L at -0.8 MPa.

On 1st March (21 days after withholding water), there were significant differences in total biomass between the stressed and irrigated canes. The total aboveground biomass of the stressed canes was 70% of the fully irrigated one. Soil water content of 14.5% and a Ψ_L of -1.6 MPa were measured in the stressed plants. The lower biomass in the stressed plants was due to low PER and low photosynthesis rate.

In the unstressed control, the rate of aboveground dry matter accumulation from 5th to 12th February was higher than from 12th February to 1st March. This probably indicated that the sugarcane plants were at the end of their elongation period.

6.6 Photosynthetic rate

The midday photosynthesis rate measured during the second stress period is shown in figure 6.6. Photosynthesis rate in the stressed plants was affected after 16th February, i.e. 8 days after withholding water. The soil water content at this period was around 18%. The rate of photosynthesis decreased significantly afterwards to reach the lowest level of 1.0 $\mu molm^{-2}s^{-1}$ on 22nd February. At this stage, the midday Ψ_L was at -1.5 MPa. The reduction in leaf area due to leaf rolling and stomatal closure could explain the low photosynthetic rate in the stressed plants.

In the irrigated plants, the photosynthetic rate was maintained at the level of 15 $\mu mol\ m^{-2}s^{-1}$ with deviation of 2.2 $\mu mol\ m^{-2}s^{-1}$ after 16th February.

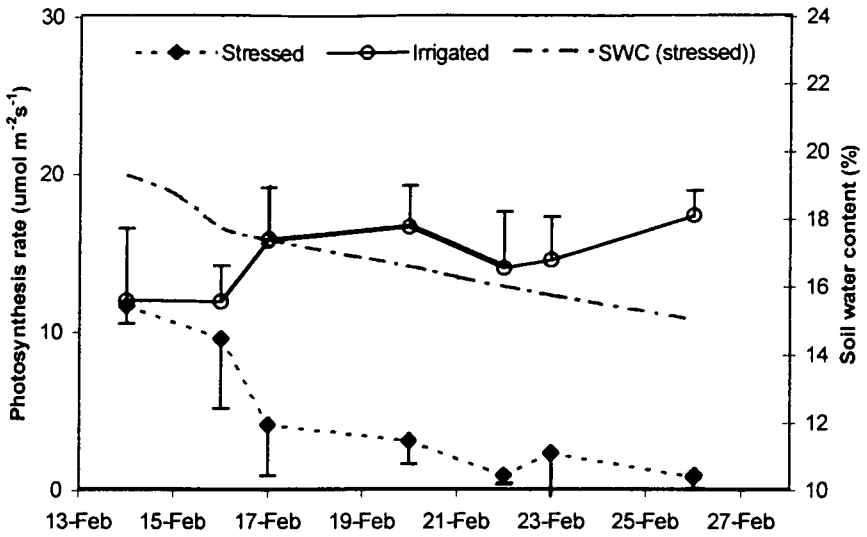

Figure 6.6. Time course of midday photosynthetic rate in stressed and fully irrigated sugarcane plants.

6.7 Stomatal resistance

Stomatal resistance using an automatic porometer was also measured in both plots during the second stress period (figure 6.7). Significant differences in stomatal resistance between the stressed and irrigated sugarcane plants occurred after 16th February. At this stage, the soil water content of the stressed plot was in the range 17 to 18% while the measured midday Ψ_L was at -1.0 MPa.

From 16th to 20th February, an increase in stomatal resistance in the stressed plants was observed reaching a peak of 18 scm^{-1}. Afterwards, there was a decrease in stomatal resistance which could be explained by a lower leaf temperature recorded by the porometer and a reduction in the level of incoming radiation. Diffusive resistance of irrigated plants remained at about 4.2 ± 1.1 s cm^{-1} during the second stress period. Inman-Bamber (1986) found that stomatal resistance in irrigated canes to be about 5 s cm^{-1}. At the time when the difference in stomatal resistance between stressed and unstressed canes became significant, the soil water potential in the stressed plot was in the range of -80 to -90 kPa (figure 6.7). This probably indicated the

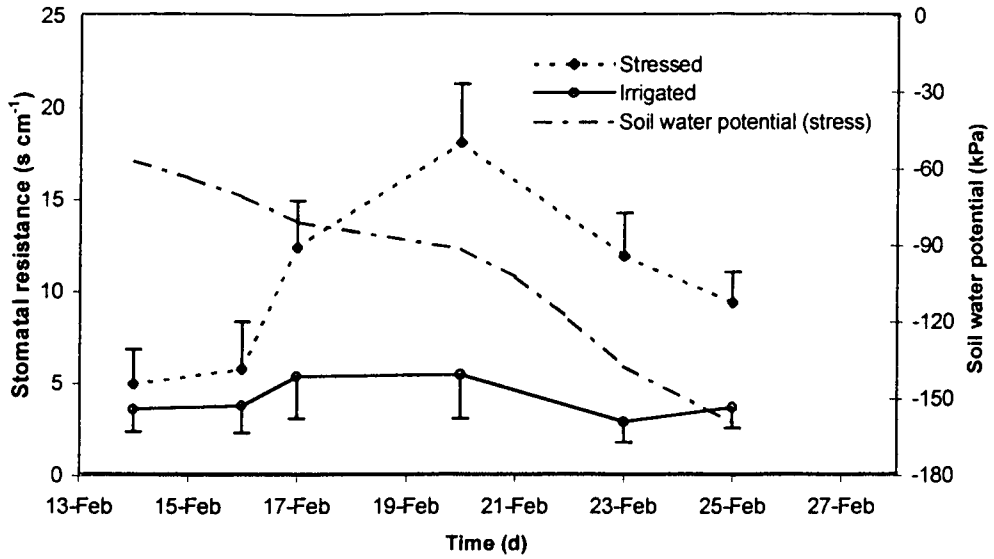

Figure 6.7. Time course of stomatal resistance measured using the automatic porometer in stressed and fully irrigated sugarcane plants.

range of soil water potential when stomata in sugarcane (var NCo376) become affected. Similarly, in soil drying trials on three sugarcane cultivars, Saliendra and Meinzer (1989) found that stomatal conductance came close to zero as soil water potential approached -90 kPa.

6.8 Summary of second stress cycle

(a) In previously stressed sugarcane where the lowest Ψ_L was -1.5 MPa, full recovery in terms of plant extension rate (PER) and photosynthesis rate occurred 3 to 4 days after irrigation was resumed.

(b) During the second stress period, PER started to decline 6 days after withholding water when the soil water content was around 19% and Ψ_L was at -0.8 MPa compared to 10 days after withholding water when SWC was 20% and Ψ_L at -0.8 MPa during the first stress period.

(c) Leaf photosynthesis rate was affected 8 days following water suppression and a further 6 days led to very low photosynthetic rate of 1.0 μmol $m^{-2}s^{-1}$. The latter occurred at a soil water content of 16% and a Ψ_L of -1.5 MPa.

The IRGA was not able to detect differences in stomatal conductance between the treatments. But the use of automatic porometer showed significant difference to occur in stomatal resistance 9 days after withholding water when the soil water potential was in the range -80 to -90 kPa.

CONCLUSION

Water stress is one of the most important causes of decreased productivity of plants. Crops have to exhibit both morphological and physiological changes in response to crop water deficits. From literature gathered so far, only a few studies have been conducted in sugarcane to look at the effect of water stress on the micrometeorological and physiological components in particular radiation interception and photosynthesis. The present study was done to assess the effects of water deficits on the commercial sugarcane variety NCo376.

During the onset of water stress, the various yield-determining processes in sugarcane were significantly affected in the following order. Plant extension rate (PER) was the first factor directly affected as there was less water available. Then this reduced leaf growth which decreased the leaf area index and consequently radiation interception by the canopy was severely affected. Thereafter it was the green leaf number together with stalk height and stalk mass that were affected, followed by photosynthesis, stomatal conductance and tiller density. This confirms findings for other crops (Hsiao, 1973).

A significant reduction in PER of the stressed canes occurred when the Ψ_L was at -0.7 MPa and ceased at -1.4 MPa. This was in conformity with Inman-Bamber (1986) who found that PER in potted sugarcane was affected at -0.8 MPa and ceased at -1.3 to -1.7 MPa. At a Ψ_L of -0.8 MPa, green leaf number together with leaf area index was reduced with a similar depressing effect on stalk height and stalk mass. Photosynthesis and stomatal conductance was significantly reduced at Ψ_L of -1.0 MPa and ceased at Ψ_L of -1.4 MPa. Inman-Bamber (1986) also found that stomatal conductance reached a minimum at -1.3 to -1.7 MPa. Similar results on photosynthesis were obtained by

Du *et al.*(1996) where a reduction in the rate occurred at Ψ_L of -0.85 MPa and decreased considerably at about -1.61 MPa.

Radiation interception by the canopy in the stressed plot was affected at Ψ_L of -0.8 MPa. This was due to a reduction in the effective leaf area of the stressed crop. Total biomass of sugarcane was lower by about 6.5 t/ha in the stressed plots at the end of the stress period. A 50% reduction in radiation use efficiency was observed at Ψ_L of -1.5 MPa in the stressed crop. Water deficit reduced the ability of the crop to accumulate biomass by reducing the capacity to convert intercepted energy to biomass. Even the photosynthetic efficiency was below that of the irrigated crop by more than 56% when the Ψ_L was at -1.3 MPa.

During this study, diurnal variation in PER, leaf temperature and photosynthesis were carried out during the stressed period. It was found that when the water stress was severe and the Ψ_L around -1.4 MPa, the differences between irrigated and stressed canes in term of PER, leaf temperature and photosynthesis recorded during the day were 1.2 mmh^{-1}, 2°C and 10 $\mu molm^{-2}s^{-1}$ respectively.

The use of the infra-red thermometers in detecting water stress in sugarcane was done despite the relatively low vapour pressure deficits prevailing at the coast. A linear relationship was found between crop water stress index(CWSI) and the soil water potential(SWP) such that a SWP of -0.1 MPa corresponded to a CWSI of -0.8. This can be used as a criterion for the application of irrigation since recovery from stress would be immediate at this stage of stress.

When irrigation was resumed prior to the drying up of all the green leaves and death of the stalks, full recovery in terms of PER and photosynthetic rate occurred 3 to 4 days after irrigation was resumed. Thus an irrigation or rain prior to stalk death would prevent permanent damage to the crop. Cane growers having limited water resources at their disposal

would be advised to apply water before stalks began to die rapidly. It was also observed that during the second stress cycle, PER and photosynthesis was affected within a short period of a few days after withholding water as compared to the longer delay during the first stress cycle.

The stress syndrome response of plants as described by Lichtendthaler (1996) was also applicable to sugarcane. When water stress condition was imposed on sugarcane, the crop responded to the stress by reducing its vitality and physiological activities. Thus, there was a decline in the number of green leaves by the senescence of older leaves together with a decrease in growth rate leading to a reduction in the leaf area index. At the same time as the stress became severe, the crop had most of its leaves curled due to loss in turgidity of the cells. Hence, the low leaf area index and leaf curling contributed to the decrease in the rate of photosynthesis and stomatal conductance. As the water stress condition intensified, the plant extension rate and the rate of photosynthesis was reduced to zero. The crop was at this stage in the exhaustion phase. Without rewatering at this stage, the sugarcane crop would have suffered chronic damage leading to the death of cells and the crop. When the stressed crop was irrigated again, a rapid recovery in terms of plant extension rate and photosynthesis rate was recorded. Thus the operational level in terms of vitality and physiological processes were restituted.

During the study, the different yield determining processes in sugarcane affected by water stress have been categorised in the order in which they are affected starting from the most sensitive one to the least sensitive. This will help researchers and farmers to better understand the response of sugarcane to water stress and to develop better strategies in terms of irrigation scheduling during drought period. The results from this study especially photosynthesis and radiation interception can be used to assist in crop growth modelling to provide better estimates of yield. Many models

are based on incoming radiation for the simulation of crop growth but not all radiation received by the crop is used in crop growth. By including the photosynthesis reduction during water stress in crop models, simulation of crop growth would be more precise and yield forecasting more accurate.

The present study should be extended to other commercial sugarcane varieties in South Africa so that the results can be used to develop drought-management strategies and to fine tune existing crop growth models for better prediction of sugarcane yield at the country level.

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Appendix I

CR10X program used during calibration of tube solarimeter

```
*Table 1 Program
  01: 5.0000    Execution Interval (seconds)
1:  Batt Voltage (P10)
 1: 1          Loc [ _________ ]
2:  Internal Temperature (P17)
 1: 7          Loc [ _________ ]
3:  Volt (Diff) (P2)
 1: 2          Reps
 2: 24         25 mV 50 Hz Rejection Range
 3: 1          DIFF Channel
 4: 2          Loc [ _________ ]
 5: 200        Mult
 6: 0          Offset
4:  Volt (Diff) (P2)
 1: 3          Reps
 2: 34         250 mV 50 Hz Rejection Range
 3: 3          DIFF Channel
 4: 4          Loc [ _________ ]
 5: 1          Mult
 6: 0          Offset
5:  If time is (P92)
 1: 0          Minutes (Seconds --) into a
 2: 3          Interval (same units as above)
 3: 10         Set Output Flag High (Flag 0)
6:  Real Time (P77)
 1: 1120       (Same as 1220) Y,D,Hr/Mn
7:  Average (P71)
 1: 4          Reps
 2: 1          Loc [ _________ ]
8:  Sample (P70)
 1: 3          Reps
 2: 5          Loc [ _________ ]
```

Appendix II

CR10X program used for logging data from leaf thermocouple, RH sensors and Infrared thermometers

```
*Table 1 Program
  01: 60.0000    Execution Interval (seconds)

1:  Batt Voltage (P10)
 1: 2           Loc [ _________ ]

2:  Temp (107) (P11)
 1: 1           Reps
 2: 12          SE Channel
 3: 1           Excite all reps w/E1
 4: 3           Loc [ _________ ]
 5: 1           Mult
 6: 0           Offset

3:  Internal Temperature (P17)
 1: 1           Loc [ _________ ]

4:  Volts (SE) (P1)
 1: 1           Reps
 2: 35          2500 mV 50 Hz Rejection Range
 3: 10          SE Channel
 4: 22          Loc [ _________ ]
 5: .09005      Mult
 6: 0           Offset

5:  Volts (SE) (P1)
 1: 1           Reps
 2: 35          2500 mV 50 Hz Rejection Range
 3: 11          SE Channel
 4: 23          Loc [ _________ ]
 5: .10025      Mult
 6: 0           Offset

6:  Do (P86)
 1: 44          Set Port 4 High

7:  Excitation with Delay (P22)
 1: 3           Ex Channel
 2: 0           Delay W/Ex (units = 0.01 sec)
 3: 10          Delay After Ex (units = 0.01 sec)
 4: 0           mV Excitation

8:  Volts (SE) (P1)
 1: 2           Reps
 2: 25          2500 mV 60 Hz Rejection Range
 3: 3           SE Channel
 4: 12          Loc [ _________ ]
 5: .1          Mult
```

```
 6: -40       Offset

 9:  Volts (SE) (P1)
 1: 2         Reps
 2: 25        2500 mV 60 Hz Rejection Range
 3: 5         SE Channel
 4: 14        Loc [ _________ ]
 5: .001      Mult
 6: 0         Offset

10:  Saturation Vapor Pressure (P56)
 1: 12        Temperature Loc [ _________ ]
 2: 16        Loc [ _________ ]

11:  Saturation Vapor Pressure (P56)
 1: 13        Temperature Loc [ _________ ]
 2: 17        Loc [ _________ ]

12:  Z=X*Y (P36)
 1: 16        X Loc [ _________ ]
 2: 14        Y Loc [ _________ ]
 3: 18        Z Loc [ _________ ]

13:  Z=X*Y (P36)
 1: 17        X Loc [ _________ ]
 2: 15        Y Loc [ _________ ]
 3: 19        Z Loc [ _________ ]

14:  Z=X*F (P37)
 1: 14        X Loc [ _________ ]
 2: 100       F
 3: 14        Z Loc [ _________ ]

15:  Z=X*F (P37)
 1: 15        X Loc [ _________ ]
 2: 100       F
 3: 15        Z Loc [ _________ ]

16:  Z=X-Y (P35)
 1: 16        X Loc [ _________ ]
 2: 18        Y Loc [ _________ ]
 3: 20        Z Loc [ _________ ]

17:  Z=X-Y (P35)
 1: 17        X Loc [ _________ ]
 2: 19        Y Loc [ _________ ]
 3: 21        Z Loc [ _________ ]

18:  Do (P86)
 1: 54        Set Port 4 Low

19:  Do (P86)
 1: 41        Set Port 1 High
```

```
20:  Beginning of Loop (P87)
 1: 0          Delay
 2: 8          Loop Count

21:  Do (P86)
 1: 72         Pulse Port 2

22:  Excitation with Delay (P22)
 1: 1          Ex Channel
 2: 0          Delay W/Ex (units = 0.01 sec)
 3: 1          Delay After Ex (units = 0.01 sec)
 4: 0          mV Excitation

23:  Thermocouple Temp (DIFF) (P14)
 1: 1          Reps
 2: 21         2.5 mV 60 Hz Rejection Range
 3: 1          DIFF Channel
 4: 1          Type T (Copper-Constantan)
 5: 3          Ref Temp Loc [ _________ ]
 6: 4       -- Loc [ _________ ]
 7: 1          Mult
 8: 0          Offset

24:  End (P95)

25:  Do (P86)
 1: 51         Set Port 1 Low

26:  If time is (P92)
 1: 0          Minutes (Seconds --) into a
 2: 60         Interval (same units as above)
 3: 10         Set Output Flag High (Flag 0)

27:  Real Time (P77)
 1: 1120       (Same as 1220) Y,D,Hr/Mn

28:  Average (P71)
 1: 13         Reps
 2: 1          Loc [ _________ ]

29:  Average (P71)
 1: 8          Reps
 2: 16         Loc [ _________ ]

30:  Sample (P70)
 1: 2          Reps
 2: 14         Loc [ _________ ]

*Table 2 Program
  01: 0.0000    Execution Interval (seconds)

*Table 3 Subroutines
End Program
```

Appendix III

CR10X program used for logging data from tube solarimeters, pyranometer, and anemometer

```
*Table 1 Program
  01: 2.0000    Execution Interval (seconds)

1:  Batt Voltage (P10)
 1: 1          Loc [ _________ ]

2:  Internal Temperature (P17)
 1: 2          Loc [ _________ ]

3:  Volt (Diff) (P2)
 1: 1          Reps
 2: 23         25 mV 60 Hz Rejection Range
 3: 1          DIFF Channel
 4: 3          Loc [ _________ ]
 5: 200        Mult
 6: 0          Offset

4:  Volt (Diff) (P2)
 1: 1          Reps
 2: 34         250 mV 50 Hz Rejection Range
 3: 2          DIFF Channel
 4: 4          Loc [ _________ ]
 5: 74.38      Mult
 6: 0          Offset

5:  Volt (Diff) (P2)
 1: 1          Reps
 2: 34         250 mV 50 Hz Rejection Range
 3: 3          DIFF Channel
 4: 5          Loc [ _________ ]
 5: 73.73      Mult
 6: 0          Offset

6:  Volt (Diff) (P2)
 1: 1          Reps
 2: 34         250 mV 50 Hz Rejection Range
 3: 4          DIFF Channel
 4: 6          Loc [ _________ ]
 5: 73.59      Mult
 6: 0          Offset

7:  Pulse (P3)
 1: 1          Reps
 2: 1          Pulse Channel 1
 3: 21         Low Level AC, Output Hz
 4: 7          Loc [ _________ ]
 5: .75        Mult
```

```
 6: .2        Offset

8:  If time is (P92)
 1: 0         Minutes (Seconds --) into a
 2: 1         Interval (same units as above)
 3: 10        Set Output Flag High (Flag 0)

9:  Real Time (P77)
 1: 1120      (Same as 1220) Y,D,Hr/Mn

10:  Average (P71)
 1: 7         Reps
 2: 1         Loc [ _________ ]

*Table 2 Program
  01: 0.0000    Execution Interval (seconds)

*Table 3 Subroutines

End Program
```