Water stress effects on the growth, development and yield of sugarcane

by

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DECLARATION

I, Ryan Louis Rossler, declare that this dissertation, which I hereby submit for the degree M.Sc. (Agric) Agronomy at the University of Pretoria, is my own work and has not previously been submitted by me for a degree at any other tertiary institution.

Signed: …… Date: ……..

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ABSTRACT

Limited research has been conducted and uncertainty exists regarding sugarcane response to water stress during different development phases. This information is necessary to optimize the allocation of limited irrigation water for sugarcane production. The objective of this study was to understand and quantify the response of crop water use (CWU), canopy development, stalk elongation, biomass accumulation and partitioning, and sugarcane yield to mild water stress, imposed through deficit drip irrigation, during different development phases.

A field experiment consisting of a plant and first ratoon crop of cultivar N49 was conducted near Komatipoort. For the three water stress treatments, available soil water (ASW) was maintained between 30 and 60% of capacity during the tillering phase (TP), stalk elongation phase (SEP) and through both phases. ASW was maintained above 60% of capacity in the well-watered control and during periods when stress was not intended.

Rainfall prevented water stress from developing in the TP of the plant crop. In the ratoon crop, 72% less irrigation was applied in the TP, resulting in 50 days of stress (ASW<50%). This did not affect stalk population but reduced CWU by 13%, shortened stalks by 21% and affected the canopy by reducing green leaf number (GLN) and green leaf area index (GLAI). Relieving the stress during SEP allowed the crop to re-establish its canopy, capture adequate photosynthetically active radiation (PAR) and restore rates of photo-assimilation (as suggested by CWU) and stalk elongation to support rapid biomass production. This restoration of plant processes allowed the ratoon crop to attain a cane and stalk dry biomass (SDM) yield that was only 9 and 11% lower (statistically insignificant), respectively, than the well-watered control at lodging (crop age of 286 days).

During the SEP of the plant and ratoon crop, 42 and 85% less irrigation was applied, resulting in the crops experiencing 74 and 39 days of stress and using 7 and 8% less water, respectively. This did not affect stalk population or the crop canopy, but reduced stalk height by about 6 and 14% in the plant and ratoon crops, respectively. In both crops, shorter stalks and a negatively affected CWU which reduced photo-assimilate production, reduced cane yield by 14 and 10% (statically insignificant) and SDM yield by 15 and 5% (statistically insignificant), in the plant and ratoon crops respectively.

Deficit irrigation throughout the TP and SEP of the ratoon crop reduced irrigation amount by 74%, resulting in 110 days of stress and reducing CWU by 16% and stalk height by 14%. PAR capture was reduced through reduced GLAI. This resulted in a significant reduction of 15% in cane yield. SDM yield was reduced by 17%, although this was not statistically significant.

Stalk sucrose content was not influenced by deficit irrigation but was rather dependent on the duration of the drying-off period prior to harvest. Sucrose yields were therefore largely determined by SDM.

Results suggest that the soil water potential (SWP) measured at 0.25 and 0.40 m depths, halfway between drip emitters within a plant or ratoon crop, can drop to about -40 kPa before irrigation is applied, without sacrificing cane or sucrose yield. Lastly, a ratoon crop can rapidly recover from stress during the TP, provided that the SWP during SEP is maintained above -40 kPa.

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LIST OF ACRONYMS

Term	Acronym	Unit
Abscisic Acid	ABA	
Available soil water capacity	ASWC	mm/0.625m
Plant available soil water	ASW	mm/0.625m
Canopy cover	CC	
Carbon dioxide	CO_2	
Crocodile River Major Irrigation Board	CRMIB	
Crop water use	CWU	mm/day
Days after cutback	DAC	
Days after planting	DAP	
Department of Water Affairs and Forestry	DWAF	
Evapotranspiration	ET	mm
Fertilizer Advisory Service	FAS	
Field capacity	FC	mm/0.625m
Fractional interception of PAR	FI_{PAR}	
Green leaf area index	GLAI	m^2/m^2
Green leaf dry mass	GLDM	t/ha
Green leaf number	GLN	
Inkomati Catchment Management Agencies	ICMA	
Inkomati Water Management Area	IWMA	
Irrigation board	IB	
Komati Basin Water Authority	KOBWA	
Komati River Irrigation Board	KRIB	
Leaf elongation rate	LER	cm/day
Leaf water potential	LWP	kPa
Lomati River Irrigation Board	LIB	
National Water Act	NWA	
Neutron water meter	NWM	
Permanent wilting point	PWP	mm/0.625m
Photosynthetically active radiation	PAR	
Phyllochron interval	PI	^oCd
Plant available soil water	ASW	mm/0.625m

Term	Acronym	Unit
Plant available soil water	ASW	mm/0.625m
Plant elongation rate	PER	cm/day
Pyruvate orthophosphate dikinase	PPDK	
Relative available soil water	RASW	
Relative crop water use	RCWU	
Relative stalk elongation rate	RSER	
Soil water potential	SWP	kPa
Soil plant atmospheric continuum	SPAC	
South African Canegrowers' Association	SACGA	
South African Sugar Association	SASA	
South African Sugarcane Research Institute	SASRI	
Stalk dry mass	SDM	t/ha
Stalk dry matter content	SDMC	%
Stalk elongation phase	SEP	
Stalk elongation rate	SER	cm/day
Stalk sucrose content	SSC	%
Tillering phase	TP	
Top visible dewlap	TVD	
Total dry mass	TDM	t/ha
Transvaal Suiker Beperk	TSB	
Trash dry mass	TRDM	t/ha
Treatment: water stress during tillering phase	T	
Treatment: water stress during stalk elongation phase	SE	
Treatment: water stress during tillering and stalk elongation phases	T+SE	
Treatment: well- watered through tillering and stalk elongation phases	WW	
Vapour pressure deficit	VPD	
Water Management Areas	WMA	

CHAPTER 1: INTRODUCTION

South African sugarcane is grown in three main areas, namely the coastal and Midlands regions of Kwa-Zulu Natal, Pongola in northern Kwa-Zulu Natal and in the Lowveld area of Mpumalanga (surrounding the towns of Komatipoort and Malelane). In the 2011/12 season the total production area amounted to 367 302 ha, from which approximately 15.5 million tons of sugarcane was crushed by 14 mills producing more than two million tons of sugar (Personal communication, A. Singels, SASRI).

The climatic conditions, in particular rainfall and potential evapotranspiration under which sugarcane is grown in South Africa varies between production areas. Along the coastal and Midlands production areas water deficits between the potential evapotranspiration (±1200 mm/annum) of sugarcane and rainfall (long term mean (LTM) > 800 mm) are small. In the northern production areas of KwaZulu-Natal (Umfolozi region) deficits are larger because of less rainfall (LTM < 1000 mm) and a higher potential evapotranspiration (±1400 mm/annum). Therefore supplementary irrigation is required in these areas during some months of the year. In the Pongola and Lowveld production areas rainfall (LTM < 700 mm) is not sufficient to satisfy the high potential evaporation (> 1700 mm/annum) of these areas throughout the year and thus sugarcane is fully irrigated in these areas – referred to as the Irrigated North.

Water required for irrigation in the Irrigated North is abstracted from the Komati, Lomati, Crocodile, Umfolozi, Hluhluwe and Pongola rivers. Irrigation water demand for sugarcane production from these rivers has increased over the past 16 seasons (1996/97 to 2011/12) as the total production area increased by 25% from 46 417 ha (Schmidt, 1998) to 61 670 ha (Personal communication, A. Singels, SASRI). Water abstraction from rivers (except the Umfolozi River) is controlled by annual quotas which cannot be exceeded (Olivier & Singels, 2004; ten Napel, 2009). This is in an attempt to ensure that all growers receive their fair share of the available water and to further ensure the availability of water for other economic sectors in the catchment, and to satisfy minimum ecological flow requirements (the ecological reserve) (DWAF, 2004). Komati and Pongola rivers are trans boundary rivers, flowing into neighbouring Swaziland and Mozambique. Due to this, international flow requirements also need to be satisfied (DWAF, 2004).

In the Lowveld production area it is perceived by growers that even with the full utilization of the annual quotas from the Komati River and its tributaries, the Lomati and Crocodile rivers, there are still periods due to the high evaporative demand for water where the crop endures periods of water stress. Therefore the demand for water often exceeds quotas. No further abstraction licences for these rivers will be issued because the rivers fall in the Inkomati Water Management Area (IWMA) which has been classified as a water stressed catchment (DWAF, 2004). The lack of sufficient irrigation water supply leads to the practice of buying or leasing water quotas between users ('water trading') (Bate *et al.*, 1999; Nieuwoudt *et al.*, 2005).

Regardless of whether growers obtain the access to additional water quotas, periods of water stress can still affect yield during dry years. Therefore, irrigation scheduling is an important undertaking which should be adopted in an attempt to minimize water stress and resultant yield loss. Scheduling limited water is however a complex task due to the dynamic nature of the soil water balance. The timing, severity and duration of water stress can vary depending on weather conditions (temperature, humidity, solar radiation and precipitation), soil properties (texture and structure), availability of water (annual quotas), irrigation schedules (frequency and amount of water irrigated) and on the different water demands during each sugarcane development phase (germination, tillering, stalk elongation and maturation). Knowledge is needed regarding the sensitivity of the crop to water stress during different development phases. This will allow growers to tactically allocate available water to achieve the highest yield possible.

According to Doorenbos and Kassam (1979) sugarcane yield is most sensitive to water stress during the germination phase and tillering phase (TP), followed by water stress in the stalk elongation phase (SEP) and least sensitive to water stress in the maturation phase. Pene & Edi (1999) reported results that showed that yield is most sensitive to a water stress during the SEP, as crops can recover from water stress during the TP. Robertson *et al*. (1999) also found that crops were able to recover from water stress during the TP through increased tiller and leaf emergence rates (i.e. re-establishing the canopy), provided that irrigation was not withheld for lengthy periods of time (three months). In a study by Wiedenfeld (2000) yield was affected when irrigation was withheld for six weeks during the SEP. Larger reductions were found when the stress period coincided with periods which had the greatest evapotranspiration (ET) demand and the least rainfall. Robertson *et al.* (1999) also withheld

irrigation during the SEP but for a longer duration (two to three months) and reported significant yield reductions. Pene & Edi (1999) found that a 25 and 50% irrigation water deficit during the SEP of a first ratoon crop had no significant effect on yield but a 75% irrigation deficit did. It was further found that the imposed irrigation water deficits had no effect on the yield of the second ratoon crop. Numerous studies (Inman-Bamber & de Jager, 1988; Robertson & Donaldson, 1998; Singels & Inman-Bamber, 2002; Inman-Bamber, 2004; Inman-Bamber & Smith, 2005; Inman-Bamber *et al*., 2008; Inman-Bamber *et al*., 2009) have shown that water stress during the maturation phase (i.e. the practice of drying-off) increases sucrose yields.

Problem statement

It is clear that considerable uncertainty exists regarding crop response to water stress in different developmental phases and that more research is required, especially on how yield is affected by mild water stress under deficit irrigation during different phases. The widely different crop responses to water stress represented is probably the result of the wide range of water stress severity and durations imposed in each study. The ability to make comparisons between or even within studies to determine which development phase is most sensitive to water stress is difficult because of the different severity and durations of water stress imposed, as well as differences in soil characteristics and atmospheric conditions between study sites. Further research is therefore needed to investigate the sensitivity of a crop to water stress during different development phases. Information is particularly needed on how yield is affected by a mild water stress during different development phases and whether the effects differ between plant and ratoon crops. It is also important to better understand how crop response to water stress relates to soil water supply, plant physiological factors and atmospheric conditions. Obtaining this information would assist growers with optimally allocating limited water to achieve maximum yield.

Objectives

The primary objective of the study was to understand and quantify the response of crop water use (CWU), canopy development, stalk elongation, biomass accumulation and partitioning, and yield of sugarcane to mild water stress, imposed through deficit drip irrigation, during different phases of the growing cycle. Specific objectives included:

- Determining how CWU is affected by water stress during the TP and SEP by monitoring soil and plant water statuses and weather conditions.
- Determining how canopy development is affected by water stress in each phase by measuring leaf and stalk development and the interception of photosynthetically active radiation.
- Determining how growth and biomass accumulation and partitioning are affected by water stress in each phase, by measuring stalk and leaf growth and sucrose accumulation.
- Explaining the mechanisms of sugarcane yield responses to water stress during the different phases in terms of the underlying process responses.
- Determining thresholds (soil water potential (SWP), available soil water (ASW)) for yield reductions due to a water stress for the TP and SEP.

Hypotheses

H_1 Mild water stress imposed through deficit drip irrigation during the TP has neglible influence on yield as the canopy can rapidly re-establish itself in subsequent unstressed conditions.

H_2 Mild stress imposed through deficit drip irrigation during the SEP can significantly reduce yield because a loss in stalk biomass cannot be recuperated once the stress is relieved.

H_3 Yield of a ratoon crop is less sensitive to a TP stress than a plant crop as a ratoon crop has a larger root system.

H_4 Yield of both plant and ratoon crops have the same sensitivity to a water stress during the SEP.

CHAPTER 2: LITERATURE REVIEW

2.1 Irrigation management in the Lowveld

2.1.1 Sources of irrigation water

Annual rainfall (640 mm/annum) in the Lowveld region of the Mpumalanga Province is not sufficient to satisfy sugarcane crop water requirement (1300 mm/annum, calculated using the MyCanesim sugarcane model (Singels, 2007)). Therefore sugarcane growers are dependent on irrigation for profitable sugarcane production in the Lowveld. Irrigation water can be abstracted from the Komati, Lomati and Crocodile rivers and their tributaries.

The Komati, Lomati and Crocodile rivers, from their headwaters to the confluence between the Komati and Crocodile rivers at the border of Mozambique, drain an area in excess of 21 177 km^2 of which 2 590 km^2 is within Swaziland (Carmo Vas & van der Zaag, 2003; KOBWA, 2008; ten Napel, 2009) (Annexure K). This catchment area allows for a total river discharge of 2646 Mm^3/annum, with the Komati-Lomati and Crocodile river systems contributing 1420 and 1226 Mm^3/annum respectively (Carmo Vas & van der Zaag, 2003).

Dams have been constructed on the Komati, Lomati and Crocodile rivers to increase water storage (Table 2.1). The Sand, Kwena, Driekoppies and Maguga Dams stabilize water supply through the year. Weirs have also been constructed on these rivers assisting with water management by retaining excess water and creating a stable water level for the effective operation of pumps (ten Napel, 2009).

2.1.2 Management of water resources

The National Water Act (NWA), which was passed in 1998, divided South Africa into 19 Water Management Areas (WMAs). Each WMA encompassed an individual river catchment. The Komati River and its tributaries fall into the Inkomati Water Management Area (IWMA) (Brown & Woodhouse, 2004; ten Napel, 2009). Management of the water resource in the IWMA was undertaken by the Department of Water Affairs and Forestry (DWAF). DWAF was responsible for reviewing and registering all water licence applications, verifying registered water use, maintenance of dams and other infrastructure and managing water resource so as to comply with international flow requirements between South Africa, Swaziland and Mozambique (Table 2.2) (DWAF, 2004). However as part of the NWA, the

decentralisation of authority from DWAF to the Inkomati Catchment Management Agencies (ICMA) occurred. DWAF still maintains the responsibility of reviewing and registering water licence applications (Brown & Woodhouse, 2004).

Table 2.1: Dams constructed in different catchments (Carmo Vas & van der Zaag, 2003; Brown & Woodhouse, 2004; ten Napel, 2009; eWISA, 2008).

Dam Name	Year of Commissioning	Catchment	Capacity (Mm^3)	Primary Function
Nooitgedacht	1962	Komati	81	Cooling water for electricity
Sand River	1966	Komati	49	Irrigation
Vygeboom	1971	Komati	84	Cooling water for electricity, municipal & industrial use
Maguga	2002	Komati	332	Irrigation
Driekoppies	1998	Lomati	251	Irrigation
Kwena	1984	Crocodile	161	Irrigation

Table 2.2: Minimum water flow requirements of river systems from Swaziland and South Africa to Mozambique (DWAF, 2004)

River	Flow requirements (Mm^3/annum)		Total
	Swaziland	South Africa	Mm^3/annum
Crocodile	-	49	49
Komati	18	42	60
Total	18	91	109

Apart from DWAF and the ICMA, the Komati Basin Water Authority (KOBWA) is an additional structure aiding water management in the Komati and Lomati river catchments. KOBWA, which was established in 1993, was in charge of the design and construction of the Driekoppies Dam in South Africa and the Maguga Dam in Swaziland (KOBWA, 2008; ten Napel, 2009). KOBWA manages both dams and controls daily water releases. Water releases are dependent on the water levels of the respective dams, water demands by users and international flow requirements (Table 2.2) (Brown & Woodhouse, 2004; KOBWA, 2008).

Irrigation boards (IB) were additionally established to control water abstraction by agriculture. The Lomati (LIB) and the Komati (KRIB) IBs manage the water allocation

within their respective catchments (ten Napel, 2009) by announcing weekly allocations applicable to individual growers. The accumulation of weekly allocations over time cannot exceed the annual quota (Table 2.3). Importantly the weekly allocations vary depending on the water levels of rivers and dams. During dry years water restrictions are imposed and thus weekly allocation are reduced.

Table 2.3: Irrigation quota allocations within the Inkomati Catchment Management Agency (Olivier & Singels, 2004; ten Napel, 2009).

River	Quota (m^3/ha/annum)
Komati	9950
Lomati	8500
Crocodile	13000

The Crocodile River Major Irrigation Board (CRMIB) is responsible for determining weekly allocations out of the Crocodile River and the accumulation of these allocations cannot exceed the annual quota (Table 2.3). The timely release of water from the Kwena Dam is determined by the CRMIB, but the release needs to be approved by the dam bailiff and chief engineer of water resource management within the DWAF (Schoch, 2007).

In the Komati, Lomati and Crocodile river catchments pumps are fitted with flow meters. Growers are required to fax/sms the number of hours they pumped to the respective IB's. The IB's also do spot checks to verify grower's sms's/faxes. The abstraction by growers is also monitored at specific control stations (i.e. weirs) along the rivers by measuring flow rates (Schoch, 2007). This allows the IB to identify river sections where over abstraction is taking place and identify which grower/s are responsible. If a grower exceeds the allocation, an official warning is issued and the quota for the following week is proportionally reduced. If growers continue to over abstract, the IB can take legal action (Schoch, 2007).

2.2 Sugarcane development and growth

Sugarcane develops through four phases namely, the germination phase, tillering phase (TP), stalk elongation phase (SEP) and maturation phases. The primary driving force behind the development through these phases is temperature. Temperature increases metabolic activity rates, leading to an increased development rate of each phase (Hay & Porter, 2006). The temperature effect on development is quantified using the concept of thermal time. Thermal

time (in ^{o}Cd) is defined as the summation of the difference between mean daily temperature (Tmean in ^{o}C) and the base temperature (in ^{o}C) (Smit & Singels, 2006; Zhou *et al*., 2006). Base temperature is the temperature below which the rate of development or growth is zero (Zhou *et al*., 2006). The theory states that a certain amount of thermal time is required to complete each development phase.

2.2.1 Germination

Sugarcane is propagated vegetatively by planting cuttings, known as setts. Setts are sections of a stalk which comprise of a number of nodes and internodes. At each node a bud which is an embryonic shoot consisting of a miniature stem and leaves can be found within the root band (van Dillewjn, 1952). These buds sprout under favourable conditions (warm, moist, aerated soil) and give rise to primary shoots. A similar procedure occurs in a ratoon crop, but after harvest primary shoots emerge from the buds found at the nodes of the remaining stalk below ground. Therefore the germination phase commences after planting or harvest and ends once the primary shoots have emerged from the soil. The thermal time required to complete this phase is cultivar dependant (Zhou *et al*., 2006) and is shorter in the ratoon crop than the plant crop (450 ^{o}Cd vs 700 ^{o}Cd using a base temperature of 16 ^{o}Cd, according to Singels & Smit, 2009).

2.2.2 Tillering

Vegetative buds found at the nodes of the primary shoot give rise to 6 – 8 secondary shoots (i.e. tillers), which may in turn produce tertiary shoots (van Dillewjn, 1952). This process continues until a peak tiller population is reached. The thermal time taken to reach peak tiller population has been found to be cultivar specific, for example 576 ^{o}Cd and 774 ^{o}Cd (base temperature of 16 ^{o}Cd) for cultivars ZN7 and NCo376, respectively (Inman-Bamber, 1994; Zhou *et al*., 2003; Smit & Singels, 2006). The TP therefore can be defined as the period between the emergence of primary shoots and occurrence of maximum tiller population.

2.2.3 Stalk elongation and maturation

Due to the high tiller population and the competition for solar radiation (Inman-Bamber, 1994; Bakker, 1999) some tillers senesce, others remain immature and the remaining tillers elongate into harvestable stalks. Tiller senescence decreases the tiller population from the maximum to a stabilized cultivar specific stalk population (Inman-Bamber, 1994; Smit & Singels, 2006).

Visible elongation of stalks above the ground surface commences after about seven or eight leaves have appeared (Zhou, 2003). For primary tillers this occurs before the peak population is reached, but for many of the lower order tillers this will only occur at, or after, maximum tiller population is reached. Stalk elongation continues until the crop is harvested and thus the SEP commences during the TP and continues until the crop is harvested.

Towards the end of SEP, the elongation rate of stalks slows and thus not all photo-assimilates are metabolised. This results in the accumulation of sucrose in stalks (Carr & Knox, 2011). Therefore the maturation phase and SEP occur in unison. The maturation phase can be affected by the flowering of the crop, application of ripeners (Rostron, 1985; Bakker, 1999; Inman-Bamber, 2004) and/or the deliberate imposing of a water stress (i.e. the practice of drying-off) (Gosnell & Lonsdale, 1964; Robertson and Donaldson, 1998; Inman-Bamber, 2004).

2.3 Water stress effects on plant processes

2.3.1 The Soil-Plant-Atmospheric continuum

Water in the soil is taken up by the plant through its roots and flows through the xylem to the leaves, where it exits the plant in the form of water vapour into the atmosphere (process called transpiration). This flow of water is against a number of resistances in the soil-plant-atmospheric continuum (SPAC) and is achieved through the force generated by a gradient in water potential from the soil, through the different plant organs to the atmosphere (Figure 2.1)

The rate of plant water uptake and transpiration is dynamic and a number of factors regulate it. These include the water status of the soil (soil water content and soil water potential), conditions of the atmosphere (relative humidity, temperature, solar radiation and wind), and plant physiological factors (root, xylem, stomatal and cuticular resistance).

The availability of water for plants to take up can be represented by equation 2.1 (modified from Hensley *et al.*, 2010):

$$LWVT_i = Fsr_i \ln\left(\frac{SWC_i}{LL_i}\right)(\pi Lv_i)^{\frac{1}{2}}\left(SWP\emptyset_{gi} - LWPSWP\emptyset_p\right)Z_i \qquad \text{(Eq. 2.1.)}$$

where $LWVT_i$ is the water supply rate of soil layer i (mm/day), Fsr_i is the soil-root conductance coefficient of soil layer i (mm^2/day/kPa), Lv_i is the root length density of soil layer i (mm/mm^3), LL_i is the lower limit of plant available water of layer i (mm), SWC_i is the volumetric water content of soil layer i (mm), SWP_i is the matric potential of soil layer i (kPa), LWP is the critical leaf water potential (kPa) and z_i is the thickness of soil layer i (mm).

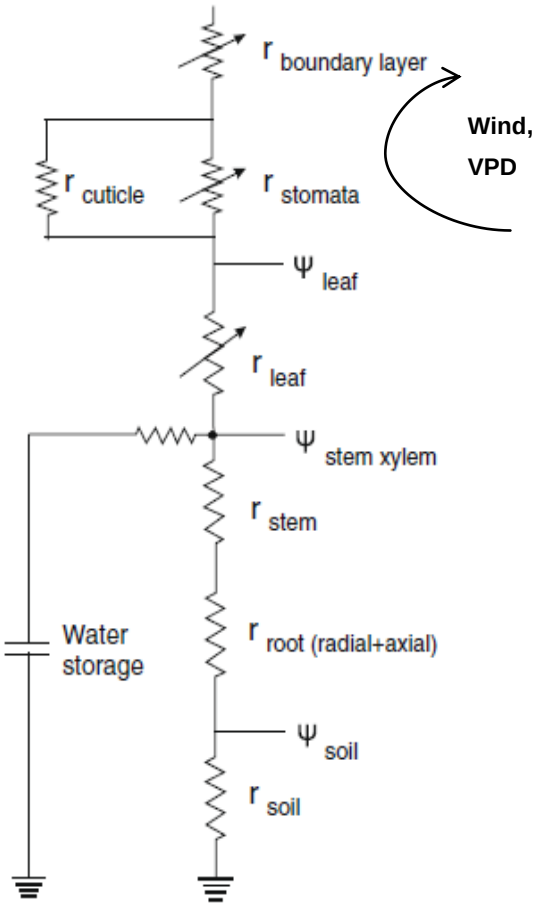

Figure 2.1: A schematic representation of the soil-plant-atmosphere continuum represented using Ohm's Law. Arrows on resistance icons represent where resistance is variable, ψ represents water potential and r indicates resistance (modified from Blum, 2011).

Eq. 2.1 reflects the fact that high soil water content (SWC_i) and root length density (Lv_i) will increase soil water availability, while a soil water potential gradient is required for water uptake.

The Penman-Monteith equation (Allen *et al.*,1998) describes the effects of atmospheric (and canopy) factors on water flow from the crop canopy to the atmosphere:

$$\lambda ET = \frac{\Delta(Rn - G) + \rho a\, cp \frac{(es - ea)}{ra}}{\Delta + \gamma\left(1 - \frac{ra}{rs}\right)} \quad \text{(Eq. 2.2)}$$

where ET is evapotranspiration (mm/day), R_n is net radiation (MJ/m^2/day), G is the soil heat flux (MJ/m^2/day), (e_s-e_a) is the difference between the saturated and actual vapour pressure of the air (i.e. vapour pressure deficit, VPD in kPa), ρa is the mean air density at a constant pressure (kg/m^3), cp is the specific heat capacity of air (MJ/kg/°C), Δ represents the slope of saturated vapour pressure curve at a given temperature (kPa/°C), γ is the psychrometric constant (kPa/°C), λ is the coefficient of latent heat conversion (MJ/kg) , and r_s and r_a are the canopy (mostly stomatal) resistance and aerodynamic resistance against the flow of water (in s/m). The term Rn-G is the energy available at the surface (to evaporate water or heat the air), while the term (es-ea)/ra captures the aerodynamic (air humidity and wind) effect on evaporation.

An increase in solar radiation increases the energy available at the surface (Rn-G) as well as atmospheric temperature, raising the vapour holding capacity of air (increased e_s) and thus increasing the vapour pressure gradient between the leaf and the atmosphere. The presence of wind can assist in increasing the atmospheric evaporative demand by reducing aerodynamic resistance (r_a) because humid air surrounding leaves is carried away and replaced with drier air (Forbes & Watson, 1992).

In conditions where the VPD is relatively low the water potential gradient in the plant will be relatively small. When adequate soil water is available around the roots (high SWP) leaf water potential (LWP) will be relatively high. This will allow guard cells to maintain their turgidity and enabling stomatal apertures to remain wide open, implying low stomatal resistance (r_s), or high stomatal conductance for water vapour transfer to the atmosphere (Blum, 2011).

When VPD is relatively high and the availability of water around roots is relatively low (low SWP), the water potential gradient in the plant will be relatively large. Under these conditions potential transpiration rate may exceed the rate of water uptake by roots. This imbalance lowers the LWP, leading to a reduction in the size of stomatal apertures and hence reduced

stomatal conductance (increased r_s). This situation can even occur when the soil is relatively wet when VPD is extremely high (Bunce, 2006).

Apart from stomatal aperture being regulated by a hydraulic process, chemical signals (hormones) also play a role. Abscisic acid (ABA) is released by dehydrated roots before the water potential gradient affects the turgidity of guard cells (Hsiao, 1973; Grantz & Meinzer, 1990; Chaves *et al*., 2009; Blum, 2011). ABA is therefore an early warning preparing the plant for water stress.

According to Inman-Bamber (1986b), stomata on sugarcane leaves begin to loose their turgidity when LWP drops below -800 kPa, and stomata almost close completely when LWP reaches -1500 kPa.

Prior to the closure of stomata, the diurnal trend in transpiration and hence water uptake of a well-watered crop follows a similar trend to solar radiation (R_n) (Figure 2.2a, b). A water stressed crop transpires and takes up water following evaporative demand as driven by solar radiation (Figure 2.2; 06:00 – 09:00) until the potential transpiration rate exceeds the amount of water that can be taken up, resulting in the closure of stomata (Figure 2.2c and d) (Forbes & Watson, 1992).

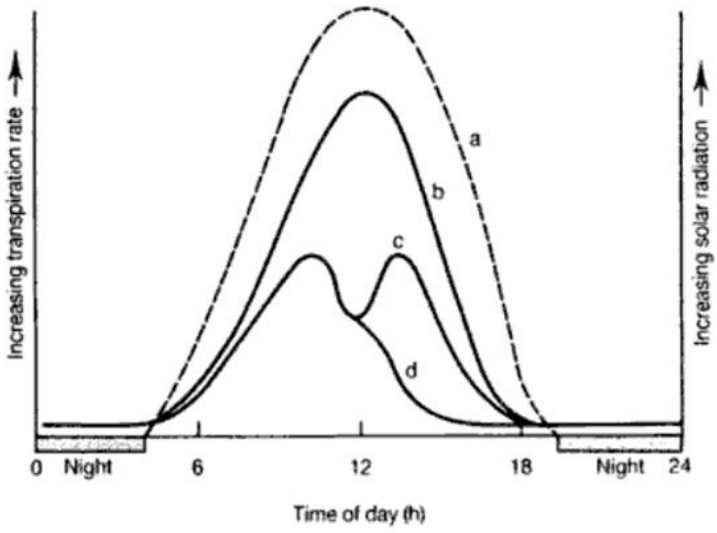

Figure 2.2. Diurnal trends in (a) solar radiation and transpiration of three hypothetical crops (a – solar radiation; b – transpiration rate of a well-watered crop growing with open stomata for the full daylight period in soil at field capacity; c – transpiration rate of a crop growing under mild water stress showing closure and reopening of stomata; d – transpiration rate of a crop growing under severe water stress showing closure of stomata and no reopening of stomata) (Forbes & Watson, 1992).

In some instances crops keep their stomata closed for the remainder of the day (Figure 2.2 d) while in others instances crops reopen their stomata as guard cells regain turgor when VPD declines again later in the day (Figure 2.2, c).

2.3.2 Photosynthesis

Photosynthesis occurs in the green leaves of a sugarcane plant and the photo-assimilates produced are metabolised during cell division and maintenance or stored as sucrose in stalks (van Dillewijn, 1952; Atwell *et al*., 1999). Sucrose is a 'reservoir' of energy and can be metabolised when photosynthesis cannot fulfil the demands from a growing crop.

Water stress decreases the rate of photosynthesis because decreased stomatal conductance reduces the availability of CO_2 required in the process of photosynthesis (Chaves *et al*., 2002; Chaves *et al*., 2009). Koonjah *et al*. (2006) found that the rate of photosynthesis started to decline at a LWP of -720 kPa and was at its lowest when the LWP dropped below -1500 kPa. These thresholds are similar to that reported by Inman-Bamber & de Jager (1986b) for stomatal conductance.

Photosynthesis is also affected by decreased enzyme activity within the mesophyll and bundle sheath cells of leaves, when water stress is severe. The activity of pyruvate orthophosphate dikinase (PPDK) is only affected once the LWP drops below -1200 kPa (Inman-Bamber & Smith, 2005).

The rate of photosynthesis can recover after a water stress event as guard cells regain turgidity and stomatal apertures widen. This allows for more rapid diffusion of CO_2 into the mesophyll cells of leaves and the restoration of CO_2 availability for high photosynthetic rate. The severity and duration of the water stress influences the rate and extent of recovery when stress is relieved (Flexas *et al.*, 2006).

2.3.3 Growth

The expansive growth and development of leaves (van Dillewijn, 1952; Inman-Bamber, 2004) and shoots (van Dillewijn, 1952; Inman-Bamber & de Jager, 1986a, b; Koonjah *et al*., 2006) are all dependent on their respective primordia for the production (i.e. cell division) and the expansion of new cells. The occurrence of a water stress affects the growth rate of the

respective plant structures by firstly reducing cell expansion through decreased turgor pressure (Hsiao, 1973).

Expansive growth of leaves and shoots can also be affected by reduced rates of cell division. Meristematic cells in leaf and shoot primordia require a critical water content for cell division. During periods of severe water stress this water content may not be achieved, thereby reducing leaf and/or shoot growth (van Dillewijn, 1952; Panje & Raja Rao, 1964; Hsiao, 1973).

Leaf development and growth

Leaves on a sugarcane plant are frequently renewed with mature fully expanded green leaves senescing and young leaves appearing (van Dillewijn, 1952). The emergence rate of new leaves is regulated by thermal time. The theory is that leaves appear at regular cultivar-specific thermal time intervals, referred to as phyllochron intervals (PI's) (Inman-Bamber, 1994).

The concurrent emergence and senescence of leaves determines the number of green leaves per stalk (GLN), which is considered a cultivar specific trait (van Dillewijn, 1952). However, shortly after the start of water stress, leaf emergence rates typically decrease and leaf senescence rates increase (Inman-Bamber, 2004; Smit & Singels, 2006). This reduces GLN and green leaf area index (GLAI in m^2/m^2) (Smit & Singels, 2006).

Inman-Bamber (1991; 2004) found that when water stress is alleviated the crop rapidly regains leaves, restoring GLN to levels similar to that of a well-watered crop which has not endured any water stress. According to Inman-Bamber & Smith (2005) leaves accumulate within the leaf whorl during periods of water stress, and then rapidly emerge when water stress is relieved.

Leaf expansive growth is restricted to a zone 40-100 mm above the apical meristem (i.e. at the base of the growing leaf) and both cell division and elongation are completed before the emergence of the leaf tissue from the whorl (Dale & Milthorpe, 1983). According to Hsiao and Acevedo (1974) leaf elongation rate (LER) is one of the most sensitive plant processes to water stress. Inman-Bamber & de Jager (1986a) found in a pot experiment that the LER declined from 40 mm/day at a LWP of -500 kPa to almost zero at a LWP of -1300 kPa.

Research done by Inman-Bamber (1991) and Robertson *et al.* (1998) showed that for a well-watered crop the area of successive leaves increases from the first leaf which emerges from a young shoot until about the 18th leaf. Thereafter mature leaves have a reasonably stable leaf area. However, according to the results obtained by Inman-Bamber (2004) the area of emerging leaves is considerably reduced by the occurrence of water stress. Inman-Bamber (2004) also showed that the reduction in leaf area of individual leaves is the primary cause of a reduced GLAI and that decreased leaf appearance and increased leaf senescence rates play a secondary role.

Stalk development and growth

The development and expansive growth of shoots into harvestable stalks is a continuous process that commences with the emergence of primary shoots after planting or harvest and ends at harvest. Therefore, for the development of stalks the processes of cell division and expansion are required throughout each of sugarcanes development phases.

Shoot emergence rate (which has been found to be cultivar specific, Zhou *et al.*, 2003; Singels *et al.*, 2005a) and subsequent growth of shoots, commences once buds achieve the critical water content required for cell division to commence (van Dillewijn, 1952; Panje & Raja Rao, 1964). According to Jain *et al*. (2009) the moisture level of the buds should be greater than 65% for them to germinate.

It has been reported that water stress during the TP reduces the rate of shoot emergence and peak tiller population (Moreira and Cardoso, 1998; Robertson *et al.*, 1999), while water stress during the SEP increases stalk senescence rates and reduces stalk population (Smit & Singels, 2006).

Cell division and expansion are affected by water stress and can therefore reduce plant elongation rate (PER in cm/day). Inman-Bamber & de Jager (1986a) found that the PER (sum of leaf and stalk elongation rate) began to decrease once the LWP dropped below -200 kPa and stalks ceased to elongate when LWP was between -400 and -700 kPa. Koonjah *et al*. (2006) found higher threshold values as they found that the PER began to decrease once a LWP of -800 kPa was reached and that PER declined to almost zero once the LWP declined below -1200 kPa. It has been reported that stalks compensate somewhat for slow growth when water stress is relieved (Inman-Bamber, 1994; Robertson *et al.*, 1999).

2.3.4 Sucrose accumulation

Sucrose accumulates in stalks when the photo-assimilates are not all metabolised during the processes of cell division, elongation and maintenance (Thompson, 1977; Inman-Bamber *et al*., 2002; Carr & Knox, 2011). The process of sucrose accumulation (i.e. ripening) commences in the older internodes lower down the sugarcane stalk as growth rates decline with age (van Dillewijn, 1952).

It has been reported widely that sucrose yields increase with the occurrence of a water stress and thus growers tend to hold back irrigation prior to harvesting, a procedure known as drying-off (Inman-Bamber, 1988; Robertson & Donaldson, 1998; Singels & Inman-Bamber, 2002; Inman-Bamber, 2004; Inman-Bamber & Smith, 2005; Inman-Bamber *et al*., 2008; Inman-Bamber *et al*., 2009). Sucrose accumulates within stalks because the expansive growth of sugarcane is more sensitive (LWP thresholds between -200 and -700 kPa) to water stress than photosynthesis (LWP threshold between -720 and -1000 kPa, Inman-Bamber & de Jager, 1986a, b; Koonjah *et al.,* 2006). Therefore stomata respond slower to water stress than the turgor regulated expansion of cells and thus the photo-assimilates, which are usually metabolised for expansive growth and cell maintenance, are stored as sucrose in stalks. The increase in sucrose mass due to drying off vary (0.5 to 2.5 t/ha) depending on the drying-off procedure and soil and climatic conditions (Robertson & Donaldson, 1998).

Sucrose accumulation during periods of severe water stress can be limited and possibly reversed as a decreased water supply can limit photosynthesis and the quantity of photo-assimilates produced (Chaves *et al.,* 2009). If it decreases to below the amount which is required to maintain the functioning of cells, stored sucrose reserves are metabolised and hence the sucrose content of stalks could be reduced.

2.3.5 Modelling sugarcane growth and the crop water balance

There are a number of crop models developed for sugarcane (Singels, 2013) but for the purpose of this review the focus will be on APSIM-sugar (Keating *et al.*, 1999), Canegro (Singels & Bezuidenhout, 2002; Singels *et al.*, 2008) and Canesim (Singels, 2007; Singels, 2013) sugarcane crop models.

These three models simulate daily increments of biomass production by converting intercepted solar radiation using efficiency factors. These factors are affected by water stress,

which is represented by a soil water deficit factor ($SWDF_i$) which is calculated from soil water supply and atmospheric demand. Radiation interception is determined by canopy cover, which is calculated directly from thermal time (Canesim) or indirectly through the simulation of shoot and leaf emergence and senescence (APSIM-sugar and Canegro). Each model partitions the daily biomass produced towards roots and aerial parts (leaves and stalks) depending on a partitioning coefficient which depends on the development phase of the crop. Phenological development of a crop is simulated using thermal time. The models maintain a daily soil water balance to determine soil water supply.

Selected aspects of these models relevant to this study are now discussed in more detail below.

Phenological development

All three models simulate phenological development phases (germination, tillering and stalk elongation) using thermal time. Each model uses different thermal time requirements (TTR) for the completion of the germination phase in a plant and ratoon crop. Models also use a cultivar specific TTR to simulate the duration of the TP. In APSIM-sugar and Canesim successive development phases only commence once the TTR of the previous phase has been achieved. In Canegro the TP and SEP may overlap in the simulations (Singels, 2013).

Methods used in these models to calculate thermal time are different. The Canegro and Canesim models both use the summation of the difference between mean daily temperature and a base temperature. APSIM-sugar uses three cardinal temperatures (base, optimal and maximum temperatures) in the thermal time calculation. Temperatures are estimated every three hours using a function fitted to daily maximum and minimum temperatures. Thermal time in APSIM-sugar does not accumulate if temperatures are below the base temperature or above the maximum temperature. Canegro and Canesim use different base temperatures for leaf and stalk development while APSIM-sugar uses constant temperatures for all processes.

Canopy development

Two different approaches to simulating canopy development are adopted by the three models being compared. The first approach, used by APSIM-sugar and Canegro, involves the simulation of individual leaves and shoots. Leaves emerge and senescence at specified phyllochron intervals, and expand at rates determined by temperature and crop water status.

The second, simpler approach used by Canesim is to calculate canopy development as a function of thermal time (Singels & Donaldson, 2000).

Biomass accumulation and partitioning

All three models use Beer's Law of radiation extinction to calculate the interception of solar radiation (APSIM-sugar) or photosynthetically active radiation (PAR, Canegro and Canesim). Daily biomass production is calculated by converting intercepted radiation using a radiation use efficiency parameter.

Biomass produced is partitioned to roots, stalks and leaves. The partitioning fraction to each component changes as the crop develops. The root partitioning fraction is high initially and rapidly declines with crop age. Biomass is only partitioned to stalks after the stalk elongation phase has commenced.

APSIM-sugar and Canegro compute the extension of the rooting depth and root density per soil layer until the maximum rooting depth is reached. This is done by converting daily biomass partitioned to roots into root length. Canesim on the other hand assumes a fully developed root system that occupies the full soil profile at the start of the crop.

Water stress

The three models simulate the impact of water stress on different plant processes (canopy development, biomass accumulation, water uptake and the expansive growth of shoots and roots) by using different water stress factors ($SWDF_i$). The stress factors represent the rate of the different processes relative to the potential rate (Singels *et al.*, 2010).

$SWDF_i$ in APSIM-sugar and Canegro is calculated using the following equation:

$$SWDF_i = fi \times \frac{Ws}{Tmax} \; [bound\ by\ 0.0 < SWDF_i < 1.0] \qquad \text{(Eq. 2.3.)}$$

where f_i represents the process-specific parameter which ranges between 0.0 and 1.0, Ws is soil water supply (mm) and Tmax is potential transpiration (mm) (Jones & Kiniry, 1986).

APSIM-sugar and Canegro both use the CERES-Maize equation (Jones & Kiniry, 1986) to calculate Ws using root length density and water availability in each soil layer, not unlike Eq. 2.1.

$SWDF_i$ in Canesim is calculated from relative available soil water content of the rooting zone (RASWC) as a measure of Ws:

$$SWDF_i = \frac{1}{pi} \times RASWC \ [bound\ by\ 0.0 < SWDF_i < 1.0] \quad \text{(Eq. 2.4)}$$

$$RASWC = \frac{SWC - LL}{DUL - LL} \quad \text{(Eq. 2.5)}$$

where p_i is the RASWC where process i is reduced below the potential rate, SWC is the root zones average soil water content (in mm), DUL is the drained upper limit (in mm) and LL is the lower limit of plant available water (in mm).

Crop water use

The Penman-Monteith equation (Eq. 2.2.) is used to calculate daily potential evapotranspiration in the Canegro and Canesim models. Potential evapotranspiration is partitioned into potential evaporation and transpiration (Tmax) depending on canopy cover. Actual evaporation is calculated as a function of the potential rate and the soil water status of the top soil layer, while actual transpiration is a function of the potential rate and SWDFi. APSIM-sugar uses a transpiration efficiency parameter to convert biomass production to evapotranspiration

Canegro and APSIM-sugar simulate the soil water balance using the multi-layered tipping bucket approach, whereby rainfall and irrigation enters the top layer and free water infiltrates down the different layers and out of the bottom layer as drainage. Water can also be redistributed between layers depending on soil water status. Canesim, however, uses only one layer to represent the entire root zone, with rainfall and irrigation entering the root zone and free water draining out of it.

2.4 Yield response to water stress

This section of the literature review will focus on the effects of water stress during the TP (early season), SEP (mid-season) and maturation phase (late season) on yield.

2.4.1 Early season

Robertson *et al*. (1999) conducted water stress trials on a plant and ratoon crop in a field which had a clay loam soil. Early season water stress was imposed on a plant crop by withholding irrigation for 110 days (4 months). ASW was close to the 75 mm capacity at the start of the water stress period and thereafter declined gradually to about 0 mm over the next 77 days. Rainfall then relieved the water stress and for the remainder of the intended water stress period, intermittent rainfall, amounting to 108 mm, prevented ASW from declining below 40 mm. Therefore the severity of the water stress was not as severe as intended. Nevertheless total biomass, GLAI, radiation interception and tiller population were significantly reduced to half that of the values for a well-watered crop (SWP maintained above -60 kPa). During the SEP the water stress was relieved and the SWP was maintained above -60 kPa. Yield at harvest was not affected. The crop therefore recovered from the imposed water stress by re-establishing the canopy through the rapid production and expansive growth of leaves and tillers when supplied with enough water (Robertson *et al.*, 1999). Results from an experiment conducted by Inman-Bamber (1994) on sandy clay soil support the theory of compensatory growth by showing that the PER of plants recovering from water stress was 1 to 6 times greater than a well-watered plant. Inman-Bamber & de Jager (1986a) also found that it took 3 to 4 days for LER to recover and exceed the rates of well-watered plants.

In the study by Robertson *et al.* (1999) irrigation was withheld for 104 days (3½ months) during the TP in the ratoon crop. ASW declined from slightly above capacity at the start of the stress period, to about 0 mm at the end of the stress period. During this period six small rainfall events (each <20 mm) occurred, totalling 48 mm and hence having a minor influence on the severity of the imposed water stress. The imposed water stress reduced GLAI, radiation interception and total biomass to one third of the values found for a well-watered crop. Unlike the plant crop the ratoon crop did not recover during a well-watered SEP and thus final yield was significantly reduced by 24.6 t/ha. Robertson *et al.* (1999) explained that the inability to recover was because the imposed stress extended into a period with higher temperatures which promoted faster canopy development and thus a higher ET rate than the plant crop, leading to a more severe stress.

Ellis & Lankford (1990) in their study irrigated a ratoon crop once after cutback and then withheld irrigation during the TP, during which only 15 mm of rain occurred. Results from

this study suggested that irrigation can be partially withheld until the onset of the SEP without affecting yield, provided the soil profile was filled at the commencement of the phase. Pene and Edi (1999) also found that imposing a water stress through deficit irrigation (25, 50 and 75% of Class A Pan evaporation) throughout the TP of a plant, first and second ratoon crops had no effect on yield. Results from these studies support Robertson *et al.* (1999) findings in that relieving a crop from TP water stress during the SEP allows the crop to achieve yields similar to an unstressed crop.

Evidently there are contradicting results pertaining to the effects of early season water stress on yield. The wide range of results is possibly due to the range of water stress severities and durations imposed in the different studies.

2.4.2 Mid-season

In the study by Robertson *et al.* (1999) irrigation was withheld during the SEP for 78 days (3 months) and 56 days (2 months) in the plant and ratoon crop respectively. The imposed water stress significantly reduced total biomass, leaf number (green and dead) and the GLAI of both the plant and ratoon crops. Both crops were unable to recover from the imposed stress despite being irrigated (SWP maintained above -60 kPa) for the remainder of the growing period, resulting in significant yield reductions of 36 t/ha (20%) and 47.4 t/ha (40%) in the plant and ratoon crop respectively.

The reduction in yield was attributed to the inability of the crop to re-establish a canopy (Robertson *et al.*, 1999). It was found that after the stress had been relieved, GLN returned to a similar value to that of a well-watered crop but that the GLAI remained significantly lower. This implied that the leaf area of individual leaves were reduced, resulting in a lower radiation interception, reducing biomass production and ultimately decreasing yield as the loss in stalk biomass could not be recuperated.

In a study by Wiedenfeld (2000) irrigation was withheld during one of four 6-week periods during the SEP. The experiments were repeated for five consecutive cropping seasons (plant and 4 ratoon crops). From the study it was concluded that water stress during the SEP reduced yield but these reductions were not large. The greatest yield reductions were found when the stress occurred during periods when the ET demand was the highest and rainfall the lowest. From the study it was concluded that the effects of water stress on yield is primarily

dependent on the degree of stress relative to ET demand, rather than the development phase in which the stress occurs.

In the study by Pene and Edi (1999) the SEP of a first and second ratoon crop were irrigated according to 25, 50, 75 and 100% of Class A pan evaporation. Significant yield reductions of 17.7 t/ha were observed for the 25% treatment in the first ratoon crop. No significant yield reductions were observed in any of the treatments in the second ratoon crop.

The contradicting results from the few studies on mid-season water stress effects is probably because of the different degrees of severity and duration water stress periods, as well as difference in crop class (plant or ratoon) or crop cycle.

2.4.3 Late season

The effect of drying-off as previously mentioned has been studied extensively. Research has shown that water stress can improve sucrose yields but excessively severe stress can be detrimental (refer to section 2.3.3).

CHAPTER 3: MATERIALS AND METHODS

3.1 Determination of irrigation water demand in the Lowveld

There is a perception that the water allocations from the Komati, Lomati and Crocodile rivers are not suffice to satisfy sugarcane water demand. A simulation study was undertaken to investigate this and to identify at what time of the year these water deficiencies occur and how severe they are. Historic water allocations (water availability in m^3/ha) from the Komati, Lomati and Crocodile rivers were compared to estimated irrigation water demand (in mm) by a sugarcane-plant crop on a hypothetical farm in each of three production regions in the Lowveld. Each hypothetical farm comprised of 9 x 1 ha fields planted at the beginning of each month from April to December and allowed to grow for 12 months. Therefore there were nine fields growing sugarcane on the farm at any time during the year, each of a different age and thus in different phases of crop development.

The daily crop water use (CWU, defined as the sum of evaporation from the soil and transpiration from the crop canopy) for each field, for 10 seasons (2001/02 season until 2011/12 season), was calculated using the MyCanesim sugarcane model (Singels, 2007). Weather data required by the model was obtained from three automatic weather stations situated in separate production regions in the Lowveld (see Annexure K for the location of the weather stations). For the Komati River the Coopersdal-SASRI weather station (25° 37’ 0” S, 31° 52’ 0” E, 187 m) was used, for the Lomati River the Kaalrug-Inala weather station (25° 39’ 0” S, 31° 33’ 0” E) and lastly for the Crocodile River the Mhlati-Malelane weather station (25° 28’ 36” S, 31° 32’ 8” E) was used.

The daily irrigation water demand for each field was calculated by subtracting the daily effective rainfall from the simulated daily CWU. Effective rainfall was calculated by assuming an interception loss of 5 mm and a rainfall efficiency of 90%, with a maximum value of 50 mm. The long term average monthly irrigation requirement (mm/month) was calculated from average daily requirements for the nine fields over the 10 seasons.

Average monthly water allocations (mm/month) were calculated from the weekly water allocations, determined from available data (seven seasons 2006/07 to 2012/13) from

Transvaal Suiker Beperk (TSB) Sugar. The sum of the monthly water allocations were not allowed to exceed the annual irrigation quota (Table 2.3).

3.2 Site details

A field trial was conducted on the South African Sugar Association's (SASA) Mpumalanga Research Station near Komatipoort (25°37'S, 31°52'E, 187 m a.s.l.) during the 2011/12 and 2012/13 growing seasons. The research station is in a region which is characterized by very hot summers and mild winters with a long term mean annual rainfall of 640 mm.

The trail was conducted on a field which has been lying fallow since 2009. The soil in the trial is classified as a sandy clay loam soil (based on the root zone average clay, silt and sand content of 36%, 16% and 49% respectively, Annexure A) of the Glenrosa form (Soil Classification Working Group, 1991). Soil texture was determined by taking 20 soil cores at depths of 0.25 and 0.4 m randomly from the field and mixing all sampled soil from a given depth. Eight subsamples were then taken from each depth and analysed separately. Results are given in Annexure A.

The rooting depth was taken as 0.625 m, the average of that determined for a number of cores taken in various locations in the same plots in a previous study by Olivier *et al.* (2009). A layer of rocky material exists below the rooting zone and was considered impermeable to roots but not to water. The actual rooting depth varied somewhat spatially within the trial area. In the assumed rooting depth the soil holds 71 mm of plant available soil water (ASW, defined as the difference between field capacity (FC, also known as the drained upper limit of plant available water following Ratliff *et al.*, 1983) and permanent wilting point (PWP, also known as lower limit of plant available water), similar to the value found for the same field by Olivier *et al.* (2009). The FC value was determined as 165 mm/0.625 m (265 mm/m) by measuring the volumetric soil water content (SWC) in the root zone with a neutron water meter (NWM) two days after a calibration plot was saturated and covered with plastic. PWP value was determined as 94 mm/0.625m (150 mm/m) by measuring the volumetric SWC after all ASW was extracted by a fully canopied crop (negligible change in SWC over time and only 3 to 4 green leaves per stalk).

3.3 Treatments

Four irrigation treatments were applied on a plant crop during the 2011/12 season and on a ratoon crop during the 2012/13 season. Water stressed treatments comprised of aiming to maintain ASW between 30% and 60% of capacity through the (1) tillering phase (T), (2) stalk elongation phase (SE) and (3) through both tillering and stalk elongation phases (T+SE). ASW was maintained above 60% of capacity in the well-watered control (WW) and during development phases in the other treatments when water stress was not imposed. Importantly, irrigation was only applied once the ASW had declined close to the lower ASW limit within the respective treatments. The amount of irrigation applied at each irrigation event was aimed to raise ASW to the upper threshold of the respective treatments.

3.4 Trial design

A 1 ha field was divided into two 0.5 ha blocks (one for the plant crop and the other for the ratoon crop) which were separated by a 3 m pathway. Each 0.5 ha block was further divided into 20 plots, each plot with dimensions of 12 x 20 m. Two 5 m wide pathways split the 20 plots to complement the irrigation system design which allowed for each plot to be irrigated independently (see trial layout in Annexure F).

Individual plots comprised of six dual rows with an inter-row spacing of 0.6 m and a row spacing of 1.4 m (centres of dual rows spaced at 2 m). The four inner dual rows were used for destructive and non-destructive measurements while the outer dual rows acted as guard rows which split adjacent plots (see Annexure G). Pressure compensated surface dripper lines which had emitters spaced a 0.6 m were placed 2 m apart (between the two dual rows) allowing for a water application rate of 1.45 mm/h. Water application rates were continually monitored in both the plant and ratoon crop blocks.

The four irrigation treatments in both the plant and ratoon crops were replicated five times in a randomized completed block design (see Annexure F).

3.5 Crop and trial management

Both the plant and ratoon crop blocks were manually planted with cultivar N49 on the 8th and 9th November 2011. Cultivar N49 was selected because it is not prone to flowering or lodging and there is a growing interest from growers in Mpumalanga to plant this cultivar. All plots in

the ratoon block crop were cut back on the 23rd and 24th April 2012 to shift the crop into the desired growing season. At the time of the cut back the crop was 5½ months old and although this is not the normal harvesting age, stalk population was similar to that of a 12 month crop because the stalk population had declined from its peak and had levelled off. Subsequent shoot emergence and tillering could therefore be expected to represent a typical ratoon crop. The cut back allowed for the evaluation of water stress effects on two sugarcane crops at widely different stages of development at the same time of the year. During September, when the irrigation shortfall often is at its highest (see chapter 2, section 2.2), the plant crop would be 10 months old and in the stalk elongation phase (SEP), while the ratoon crop would be five months old and still in the tillering phase (TP). The block was not burnt prior to the cut back and all biomass was manually removed from the field. All plots in the plant crop lodged on the 8th September 2012 (313 days after planting, DAP) and half the plots in the ratoon crop lodged on the 4th February 2013 (286 days after cut back, DAC; referred to as the 1st lodging event, see Annexure H for a sketch map of the lodging, Annexure I for the lodge rating and Annexure J for photos) and the remaining plots lodged on the 7th March 2013 (317 DAC, referred to as the 2nd lodging event). On days 301 to 313 DAP in the plant crop, adverse weather conditions with 159 mm rainfall saturating the soil profile and strong winds caused the crop to lodge. In the ratoon crop, the 1st lodging event in the T and WW treatments occurred when rain fell a few hours after irrigation was applied on 286 DAC, saturating the soil profile. Strong winds during the night caused these treatments to lodge. The 2nd lodging event (317 DAC) occurred not because the soil was saturated but rather because strong winds blew over a heavy canopy wetted by rain. To avoid the effect lodging could have on cane yield the plant and ratoon crops were burnt and manually harvested on the 10th October 2012 and 19th March 2013 (i.e. 11 month growing cycle) respectively. To prepare the field for harvest (i.e. drying-off period) irrigation was withheld for 23 days in the plant crop and 12 days in the ratoon crop.

Fertilizer was manually applied with Mayfield fertilizer applicators to the plant and ratoon crop blocks in the row on the 16th January 2012 (120 kg/ha of N (LAN) and 100 kg/ha of P (MAP)). Additional fertilizer (160 kg/ha of N (LAN) and 100 kg/ha of K (KCL)) was applied on the ratoon crop shortly after the cut back and again on the 6th December 2012 (45 kg/ha of N (LAN)). All fertilizer applications were done according to the South African Sugarcane Research Institute's (SASRI) Fertilizer Advisory Service's (FAS) recommendations which

were based on soil and leaf analyses (Annexure B and Annexure C). During the trial weeds were removed by hand.

3.6 Non-destructive measurements

3.6.1 Weather data

Daily weather data (maximum and minimum temperature and rainfall) was recorded by a fully automated weather station which is located (< 100 m from the trial) on the Mpumalanga Research Station. This weather station is checked and calibrated annually.

3.6.2 Soil water measurements

(a) Soil water content and crop water use

Volumetric SWC in the assumed rooting depth of 0.625 m was measured three times a week with a NWM (Model 503DR CPN Hydroprobe, Campbell Pacific Nuclear, CA, USA). Aluminium access tubes were installed in three plots per treatment halfway between emitters along the dripper line to best represent the water status of the root zone (Annexure G). All access tubes were placed in the same position, relative to emitters. Measurements were taken at 0.15 m intervals, commencing at a soil depth of 0.25 m to a maximum depth of 0.55 m.

The NWM was calibrated against volumetric SWC (%) (calculated from gravimetrically sampled SWC and the bulk density of undisturbed soil cores) of numerous samples taken at depths of 0.25, 0.4 and 0.55 m. The cores were taken in close proximity to three aluminium access tubes installed in a 2 x 2 m infield calibration plot and from cores taken close to the aluminium access tubes within the plant and ratoon crop fields. The calibration equation established for all data from all soil depths was:

$$SWC = 22.36CR - 8.6246,\ r^2 = 0.51,\ n=58 \qquad \text{(Eq. 3.1)}$$

where SWC is the estimated volumetric SWC (%) and CR the count ratio of the soil reading (16 seconds) to the standard wax reading. Data is provided in Annexure D.

The volumetric SWC (%) at each measurement depth was multiplied by the soil depth to determine the SWC (mm) in each soil layer. The sum of the SWC in all soil layers represented the SWC in the assumed root zone (mm/0.625 m). The amount of ASW in the

root zone was calculated as the difference between measured SWC and permanent wilting point (PWP) (94 mm/0.625m or 150 mm/m).

Daily CWU (sum of evaporation and transpiration in mm) and number of stress days (defined as a day when simulated ASW was below 50% of capacity, following Singels *et al.*, (2010)) was estimated using the MyCanesim sugarcane model (Singels, 2007). It is acknowledged that the ASW threshold for water stress can vary with atmospheric evaporative demand and possibly also with ASW capacity, but due to lack of information a constant threshold was used for this study. Actual irrigation and local weather data were used as inputs, and simulated ASW was corrected with measured values of ASW. This method of determining CWU was preferred over a water balance approach using measured ASW values because frequent drainage events due to rainfall made it impossible to calculate reliable values of CWU.

(b) Soil water potential

Soil water potential (SWP) was measured at depths of 0.25 and 0.4 m in one plot per treatment. Tensiometers (CFM Industries (Pty) Ltd) were installed halfway between emitters along the dripper line and close to the aluminium access tubes (Annexure G). SWP was measured at the same frequency as SWC (3 times a week).

3.6.3 Plant measurements

(a) Stalk population

A 5 m section of a dual row which encompassed the aluminium access tubes and the tensiometers were marked in three plots per treatment (see Annexure F and Annexure G). All stalks with green leaves within the marked sections were counted every two to four weeks. Stalk emergence rate was related to thermal time using base temperature of 16 ^{o}C (Inman-Bamber, 1994).

(b) Stalk height

Eight stalks were marked within the demarcated 5 m sections and the height of these stalks manually measured (mm) twice a week. The height of each stalk represents the distance between the top visible dewlap (TVD) and the ground surface. Senescing stalks were replaced with stalks which were of a similar height to the other marked stalks. After the 1st lodging event in the ratoon crop eight new stalks in two plots of the WW treatment were

marked. These stalks were within a meter from the edge of the plot and this data was considered unrepresentative and hence excluded from further analysis.

Stalk elongation rate (SER) was calculated as the average change in stalk height between two consecutive measurements, divided by the number of days between these measurements. Relative SER (RSER) was calculated as the SER of stalks in the T, SE and T+SE treatments relative to the SER of the WW treatment. The average SER for the TP and SEP was calculated as the average change in stalk height between the first and last measurement done in each phase, divided by the duration of the phase.

(c) Dead and green leaf number

Leaf appearance and the number of fully expanded green leaves (GLN) and senesced leaves (90% of leaf area necrotic) on the eight marked stalks were counted every two to four weeks up to lodging. A base temperature of 10 ^{o}C was used for relating leaf appearance to thermal time (Inman-Bamber, 1994).

(d) Interception of photosynthetically active radiation

Fractional interception of photosynthetically active radiation (FI_{PAR}) by the canopy was determined every two to four weeks in three plots per treatment using a ceptometer (AccuPAR LP-80, Decagon Devices, Pullman, WA, USA). A reference reading above canopy was taken before a series of ten readings below canopy at midday on days with clear skies. The ceptometer was held at ground level (below green and dead leaves) at an angle so that the tip was in the middle of the dual row and the recording unit was between adjacent dual rows. It should be noted that radiation interception by the green, photosynthesizing canopy will be less than FI_{PAR} in older canopies with a substantial number of dead leaves. FI_{PAR} was calculated using the following equation:

$$FI_{PAR} = 1 - (FI_{bottom}/FI_{top}) \qquad \text{(Eq. 3.2)}$$

where FI_{bottom} is the measured PAR below the canopy and FI_{top} is the PAR measured above the canopy.

3.7 Destructive measurements

3.7.1 Leaf water potential

Midday (11h00 – 13h00) leaf water potential (LWP) of three leaf strips (excised from stalks of different plants) from two plots per treatment were measured regularly using a Scholander pressure chamber. A 20 to 30 cm leaf section from one of the three topmost fully expanded leaves was excised and a leaf strip (excluding the midrib) was stripped from the leaf section. The leaf strip was placed into a plastic bag which had a wet cloth in and placed into the pressure chamber so that the cut end protruded through a rubber seal. The chamber was pressurized using compressed air until xylem water appeared on the cut surface and the pressure (kPa) was recorded as the LWP.

3.7.2 Biomass production and partitioning

Biomass components were destructively sampled by cutting all stalks in a 1.5 m section of the dual row (1.5 x 2 m = 3 m^2) in each of the five plots per treatment. Samples were taken at the end of the TP (plant crop: 16th February 2012; ratoon crop: 30th October 2012), shortly after the first lodging event in the ratoon crop (18th February 2013), and at final harvest (plant crop: 5th October 2012; ratoon crop: 19th March 2013). Biomass samples were partitioned into millable stalks, green leaves (defined as green tops – biomass above the stalks natural breaking point, green laminar and sheath) and trash (defined as dead leaves – 90% of leaf area necrotic) and the fresh biomass yield of each component determined.

Load cells were also used at final harvest to determine the biomass of the remaining millable stalks (i.e. cane yield) within the four dual rows of each plot after all plots were burnt and harvested by commercial cane cutters.

The dry matter content of each component was determined by drying a sub-sample of each component (stalks ≈ 1 kg, leaves ≈ 1 kg, trash ≈ 0.5 kg) at 75 to 80 ^{o}C until samples mass remained constant. The dry mass yield of each component (tons/ha) was calculated as the product of the dry matter content and the fresh biomass yield of the same component.

3.7.3 Stalk component yields

At the final harvest five sub-samples from each of the plots, each comprising of 16 stalks were cut and sent to SASRI's Pongola mill room where the sucrose, non-sucrose and fibre

content of each sample was determined using the method described by Singels *et al.* (2005b). Stalk dry matter content (%) determined from the destructive samples taken at final harvest was preferred over the dry matter content determined by the mill room and were hence used to re-calculate stalk sucrose (%), non-sucrose (%) and fibre (%) contents. This preference was because samples were possibly not dry after the short drying period used by the mill room. Sucrose yield (t/ha) was calculated as the product of cane yield and sucrose content (%).

3.7.4 Green leaf area

Sub samples (≈ 1 kg) of green leaves (laminar and sheath) were taken from the green leaf component of each plot at each harvest and the specific leaf area (cm^2/kg) of just the laminar part determined using a belt driven Li-Cor 3100 Area Meter (LI-COR, Nebraska, USA). The biomass of the laminar was determined and the ratio of leaf laminar to sheath was used to calculate the green leaf area index (GLAI) (m^2/m^2) of each sample.

3.8 Data analysis

All data was analysed using the Genstat statistical program. General and one-way analysis of variance (ANOVA) was performed to test for differences between treatments. Fishers' least significance difference (LSD) test was used to determine at the 5% level of significance which treatments were different.

CHAPTER 4: IRRIGATION WATER DEMAND IN THE LOWVELD

Results in Figure 4.1 show that the irrigation water demand is always above zero indicating that irrigation is required throughout the year for sugarcane production in the Lowveld. Irrigation water demand in the Crocodile and Lomati production areas are similar but lower than the demand for the Komati production area.

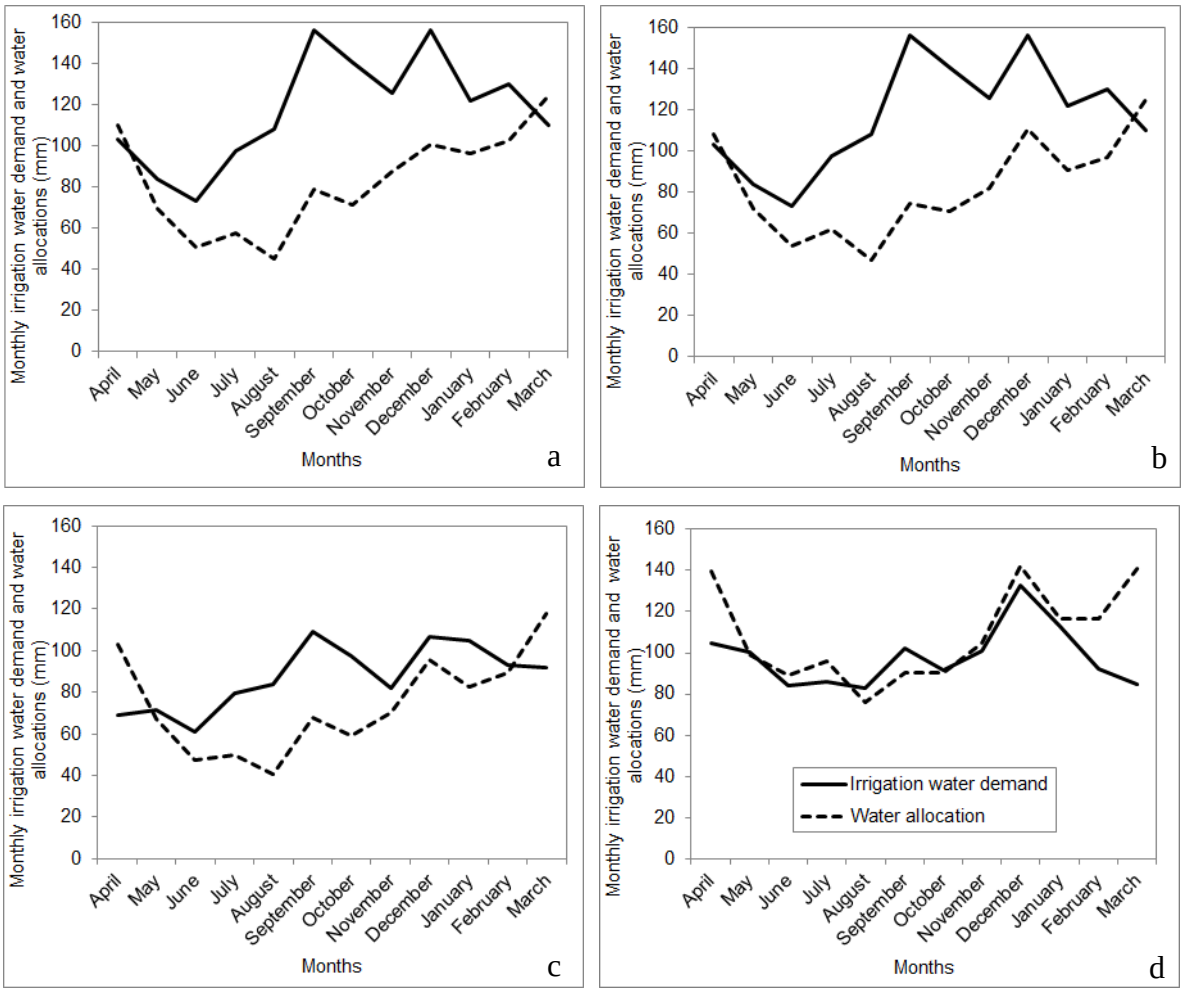

Figure 4.1. Annual trends in irrigation water demand (10 season average) and water allocations (7 season average) for the a) lower Komati and b) middle Komati, c) Lomati and d) Crocodile rivers.

Water allocations for the Komati and Lomati production areas are only sufficient to satisfy the irrigation water demand for three (March to May) and four (February to May) months respectively. Water allocations for the Crocodile production area satisfy the irrigation water demand for all months of the year except for August and September.

Therefore it is concluded that the full water allocations for the respective rivers are not sufficient to satisfy average irrigation water demand through the year; hence there are periods during the year where the sugarcane crop will endure water stress. Irrigation shortfall for the Lomati and Komati river systems shortage is greatest in September and high for the period from August to December. Ideally, field experiments should at least evaluate water stress responses of crops in different development phases during this time of the year.

CHAPTER 5: PLANT CROP RESULTS

5.1 Water relations

5.1.1 Available soil water and soil water potential

Germination phase:

Irrigation commenced in all plots three days after planting (DAP) and continued intermittently through the germination phase to ensure good germination. Available soil water (ASW) trends in all treatments shows that the crop was slightly over irrigated and hence drainage probably occurred (Figure 5.1). All treatments received the same irrigation (105 mm) and rainfall (54 mm) and thus used the same amount of water during this phase (Table 5.1).

Table 5.1: Phase duration, rainfall, irrigation, number of stress days (days when ASW<50% of capacity) and estimated crop water use for each treatment in the plant crop during the tillering phase, stalk elongation phase, the three week dry-off period and for the entire growing season.

	Treatment	Development phases			Drying off	Total
		Germination	Tillering	Stalk elongation		
Duration of each phase in:						
Days		34	65[1]	214	24	337
Thermal time (^{o}Cd, base 10 ^{o}C)		547	1026[1]	2283	305	4162
Thermal time (^{o}Cd, base 16 ^{o}C)		337	636[1]	1025	161	2160
Rainfall (mm)		54	373	267	3	694
Irrigation (mm)	T	105	45	834	0	985
	SE	105	212	491	0	809
	T+SE	105	27	501	0	633
	WW	105	224	813	0	1142
Stress days	T	0	0	10	15	25
	SE	0	0	62	15	77
	T+SE	0	0	86	16	102
	WW	0	0	7	15	22
Crop water use (mm)	T	114	357	745	102	1317
	SE	114	348	706	101	1268
	T+SE	114	358	688	96	1256
	WW	114	355	746	94	1308

[1] These durations were used for imposing water treatments and for analysing data. The true duration of the tillering phase would have been shorter than indicated here, when the end of the tilling phase is taken as the time of peak stalk population.

Tillering phase:

During the tillering phase (TP) the T and T+SE treatments received little irrigation (Table 5.1), but large rainfall events prevented the ASW from declining into the targeted water stress range (Figure 5.1a and b) and the soil water potential (SWP) at 0.4 m deep from declining below -30 kPa (Figure 5.2a and b). Towards the end of the TP there was a slight over irrigation of the SE and WW treatments leading to probable drainage (Figure 5.1c and d). Therefore all treatments used similar amounts of water and experienced no water stress during this phase (Table 5.1).

Stalk elongation phase:

The SE and T+SE treatments received about 320 mm (40%) less irrigation and used 40 and 58 mm (5 and 8%) less water than the unstressed T and WW treatments. ASW fluctuated mostly within the desired regime for these treatments (Figure 5.1b and c) resulting in 62 days and 86 days of water stress, compared to 7 and 10 days for the unstressed treatments (Table 5.1).

It is clear that from Figure 5.1b and c that ASW of stressed treatments occasionally rose above 50% of capacity because of irrigation and rainfall. Therefore the duration of individual stress periods (continuous dry spell of consecutive days of water stress) varied from one to 25 days (See Figure 5.3). The longest dry spells for each treatment were 7, 6, 24 and 25 days for the WW, T, SE and T+SE treatments respectively.

SWP at both depths declined to -90 kPa when ASW in the SE and T+SE treatments dropped to the lower limit of the targeted water regime (30% of available soil water capacity, ASWC) (Figure 5.2b and c). SWP at both depths increased rapidly to between -10 and -20 kPa shortly after irrigations. This fluctuation occurred throughout the phase. SWP in the unstressed treatments fluctuated less and at higher levels than the SE and T+SE treatments, mostly between -10 and -40 kPa, for the duration of the stalk elongation phase (SEP) (Figure 5.2a and d).

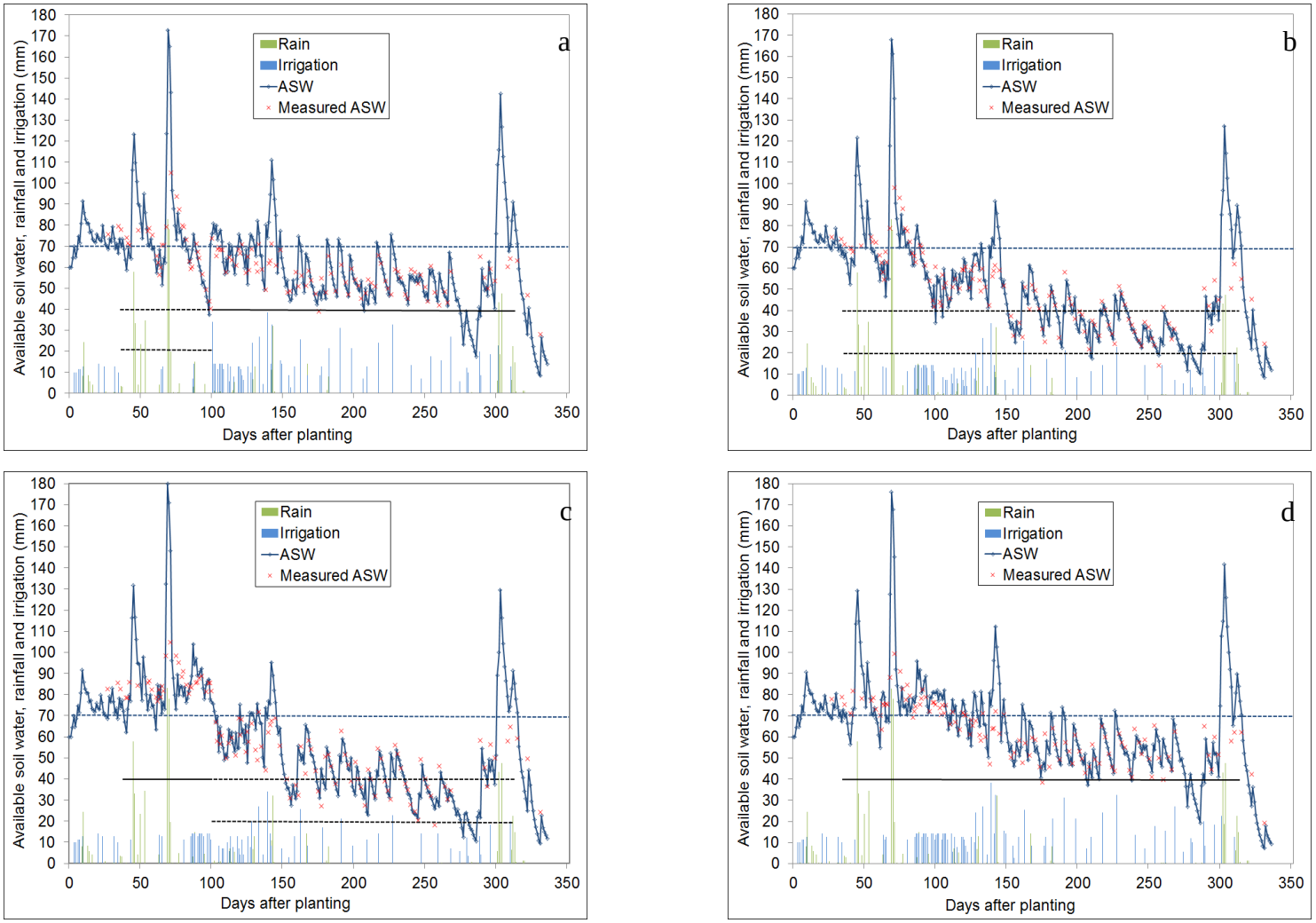

Figure 5.1: Simulated (blue line) available soil water (ASW) corrected with measured (red crosses) ASW in the T (a), T+SE (b), SE (c) and WW (d) treatments of the plant crop. The blue dotted horizontal line represents field capacity (ASWC = 71 mm). The black horizontal lines represent 30 and 60% of the available soil water capacity, when the line is solid no water stress was imposed while the dotted line represents when a water stress was imposed. The green and blue bars represent rainfall and irrigation, respectively.

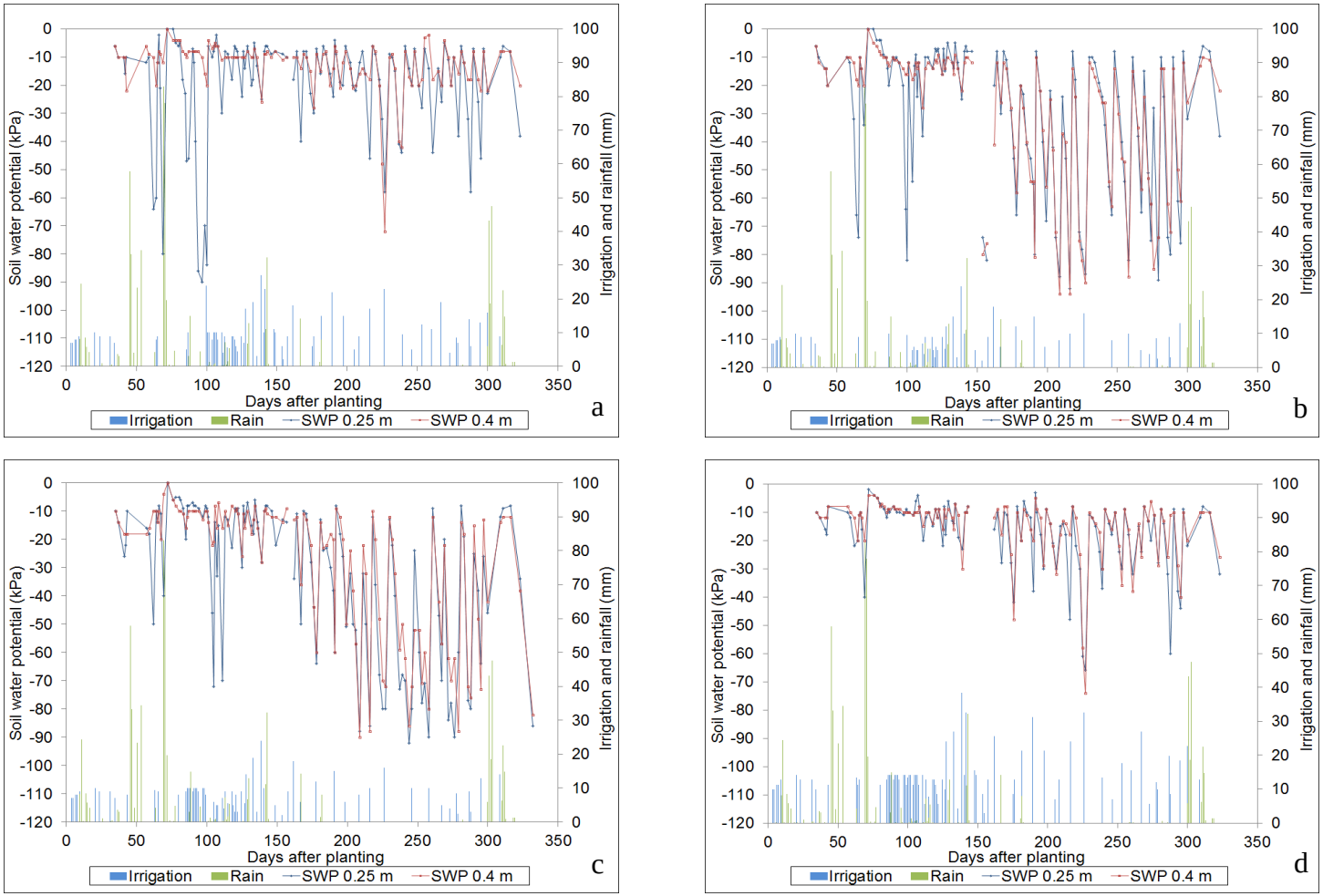

Figure 5.2: Soil water potential measured at a soil depth of 0.25 m (blue line) and 0.4 m (red line) in the T (a), T+SE (b), SE (c) and WW (d) treatments of the plant crop. The green and blue bars represent rainfall and irrigation, respectively. Note: tension acting on the water column in tensiometers placed in the T, T+SE and WW treatments exceeded the devices' capacity shortly before final harvest and hence no readings were recorded.

From 301 to 311 DAP, 169 mm of rainfall refilled the soil profile and also caused lodging in all plots. Water treatments were ceased at this point to minimize the confounding effect of lodging. Lodging could possibly have been avoided through better irrigation management. Irrigation could have been withheld for slightly longer and smaller amount could have been applied. Irrigation was withheld from 313 DAP until harvest (23 day dry-off period) and resulted in all treatments enduring 15 to 16 consecutive days of water stress (Table 5.1).

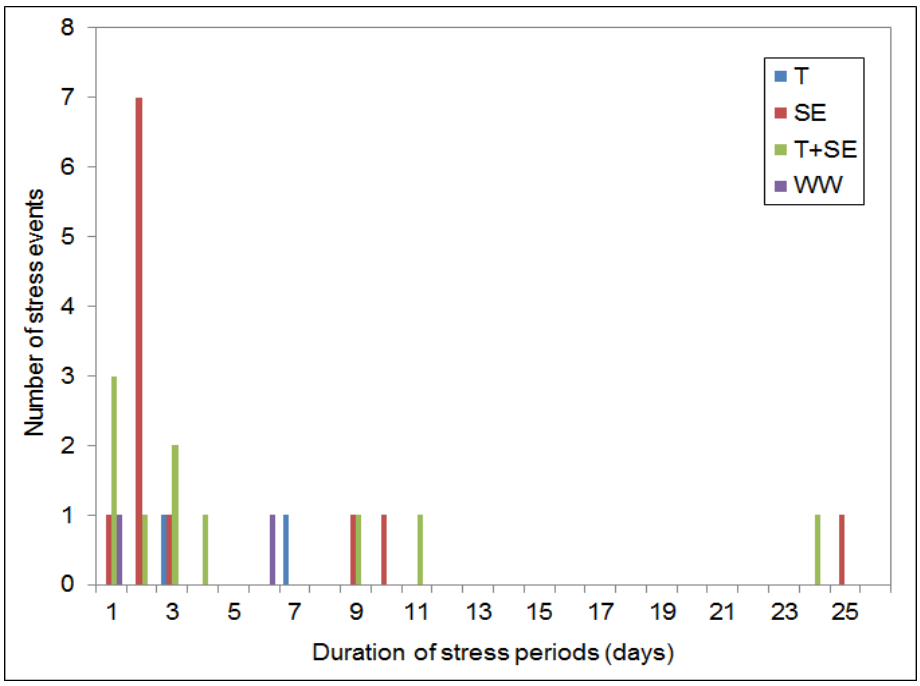

Figure 5.3: The number of dry spells (consecutive days with ASW<50% of capacity) of a given duration for the different treatments during the stalk elongation phase (excluding the drying off period) of the plant crop.

5.1.2 Leaf water potential

No significant differences in midday leaf water potential (LWP) between treatments were found due to the large variation between measurements (Figure 5.4). These large discrepancies were possibly due to differences in the water status of the soil in which the selected stalks were growing in. The water status of the soil along a dripper line is wetter (less negative SWP) below emitters than between emitters and thus LWP could have varied depending on the selected stalks proximity to emitters. It is therefore recommended that in future studies the LWP of leaves from a greater number of stalks at varied proximities to emitters be determined per plot in an attempt to reduce the standard deviation. Another possible cause of variation could be the measurement time range (11h00 – 13h00).

Relationship between LWP and vapour pressure deficit (VPD) or reference evapotranspiration was investigated but these correlated poorly (not shown). LWP and relative ASW correlated significantly, although the R^2 was low due to the large variability in the data (Figure 5.4).

LWP of unstressed plants (ASW > 50% of capacity) ranged between -970 and -1400 kPa, compared to between -1400 and -1600 kPa for stressed plants (ASW < 50% of capacity) (Figure 5.4). The LWP values of the unstressed plants were similar to the findings of Smit & Singels (2006) who found that LWP values at midday ranged from -700 to -1200 kPa and considerably lower the minimum value of -500 kPa for unstressed plants quoted by Inman-Bamber & de Jager (1986a). These differences in LWP values between studies could be due to differences in evaporative demand, rather than differences in SWC because similar irrigation strategies were adopted.

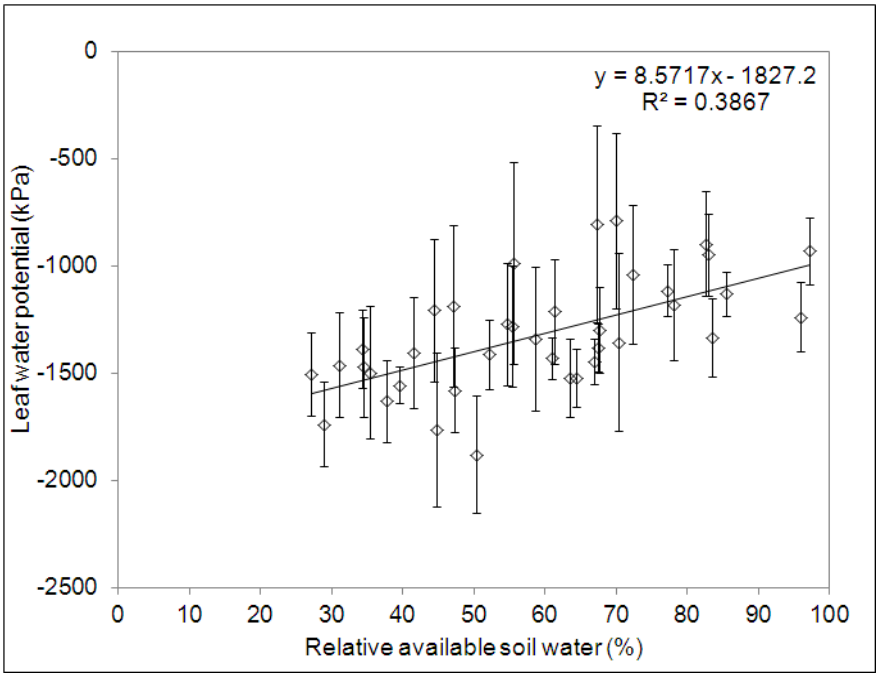

Figure 5.4: Leaf water potential measured at approximately midday in relation to available soil water expressed as a percentage of the available soil water capacity. Vertical bars represent the standard deviation of the mean.

LWP values for the stressed plants in the current study was slightly higher (less negative) than the -1300 to -1700 kPa range reported by Inman-Bamber & de Jager (1986a) and considerably higher than the -1200 to -2300 kPa range reported by Smit & Singels (2006).

The lower LWP values found in these studies was due to irrigation being withheld for longer periods, leading to more severe stress than in the current study.

Lastly, Inman-Bamber & de Jager (1986a) reported cultivar differences in LWP. It was found that cultivar N14 reached a LWP of -1800 kPa 7 days earlier than cultivars N12 and NCo376. Therefore the differences in LWP threshold values reported in different studies could also be because different cultivars were used.

5.2 Growth and development

5.2.1 Shoot emergence and senescence

Primary shoots began to emerge 174 ^{o}Cd after the crop was planted (Figure 5.5) and all primary shoots were deemed to have emerged at 337 ^{o}Cd. This point was taken as the start of the TP. Secondary shoots rapidly emerged during the TP, reaching a peak stalk population of about 23 stalk/m^2 at 835 ^{o}Cd after planting. Due to the measurement interval peak stalk population was only identified two weeks after it actually occurred (at 986 ^{o}Cd) and this point had to be taken as the end of the TP and the start of the SEP for the implementation of water treatments and for data processing.

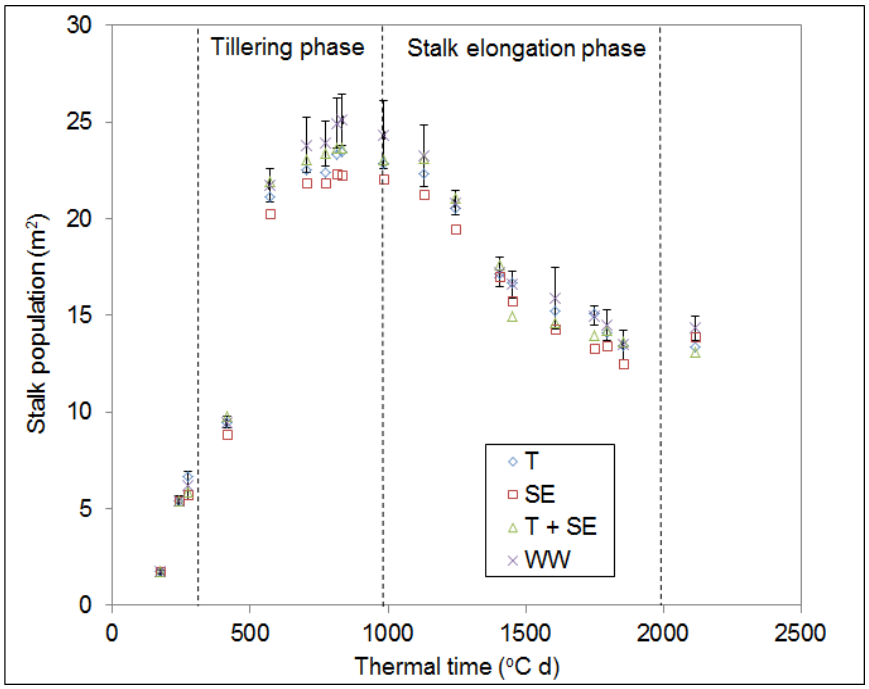

Figure 5.5: Stalk population as a function of thermal time using a base temperature of 16 ^{o}C for the different treatments. Vertical bars represent the standard deviation of mean values for the WW treatment.

Rapid shoot senescence started as the competition for photosynthetically active radiation (PAR) increased, which in this study was when about 88% of PAR (at a thermal time of 974 ^{o}Cd after planting) was intercepted by the canopy (Figure 5.8). Senescence rates in all treatments slowed after 1451 ^{o}Cd, resulting in the stabilization of the stalk population. All treatments had a stalk population of about 13 stalks/m^2 at the last measurement before lodging. The lodging marked the end of the SEP and thus the phase was 1025 ^{o}Cd or 214 days long (Table 5.1). After the 24 day (161 ^{o}Cd) long drying off period (i.e. at final harvest) all treatments had a stalk population of about 14 stalks/m^2.

Evidently, during the SEP, the imposed water stress had no effect on stalk senescence rates. This result is different to that found by Smit & Singels (2006) where severe water stress during the SEP (irrigation and rainfall withheld for 42 consecutive days) increased stalk senescence and reduced the stalk population by 8.05 and 4.44 stalks/m^2 for cultivars NCo376 and N22, respectively. Therefore it can be concluded that the mild water stress imposed through deficit irrigation in this study maintained the longevity of the stalks.

5.2.2 Leaf emergence and senescence

The emergence and senescence rates of leaves and hence the number of green leaves per stalk (GLN) was not significantly different between treatments at the end of the TP due to no water stress being imposed during this phase (Figure 5.6a and b, Figure 5.7 and Table 5.2).

Water stress during the SEP (from 3212 to 3888 ^{o}Cd) caused a slight reduction in the rate of leaf emergence relative to the unstressed treatments (Figure 5.6a). This however had no significant effect on the number of leaves per stalk in comparison to the WW treatment (Figure 5.6a). In other studies, Inman-Bamber (2004) and Smit & Singels (2006) also found that withholding water reduced the leaf emergence rate shortly after irrigation was withheld. It has further been reported by Inman-Bamber (1991, 2004) and Inman-Bamber & Smith (2005) that leaves tend to accumulate within the leaf whorl during stress periods and then rapidly emerge once the stress is relieved, restoring the number of leaves relative to an unstressed plant. This could explain why leaf number was not affected by water stress in this study.

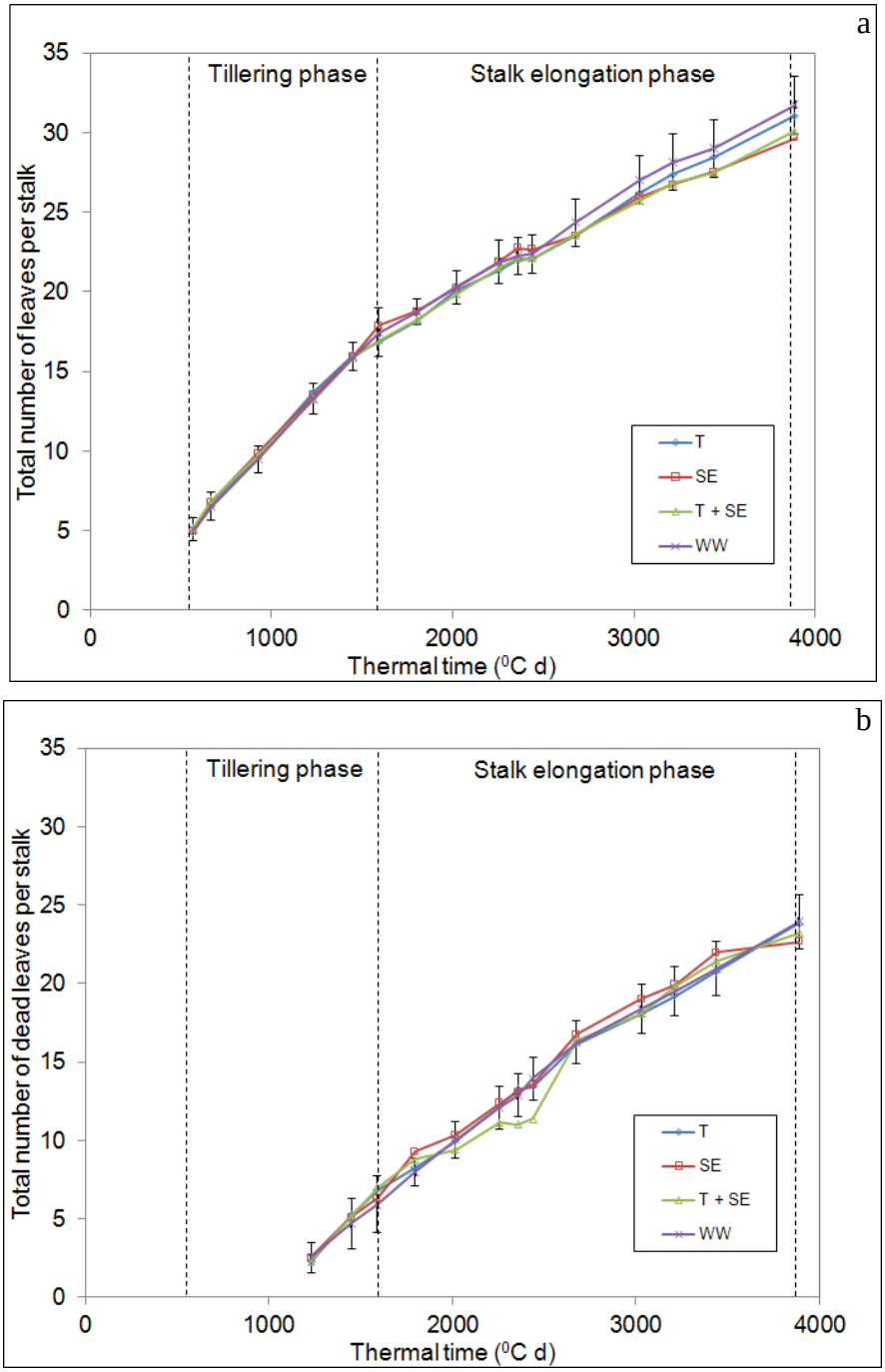

Figure 5.6: Total number of fully expanded leaves (a) and dead leaves (b) per stalk as a function of thermal time using a base temperature of 10 ^{o}C for the different treatments. Vertical bars represent the standard deviation of the WW treatment.

Water stress also increased rates of leaf senescence slightly during the SEP (from 2440 to 2677 ^{o}Cd and from 3029 to 3438 ^{o}Cd), leading to a slightly higher number of senesced leaves on stalks in the SE and T+SE treatments in comparison to the WW treatment (Figure 5.6b). Smit & Singels (2006) also reported accelerated leaf senescence rates due to water stress.

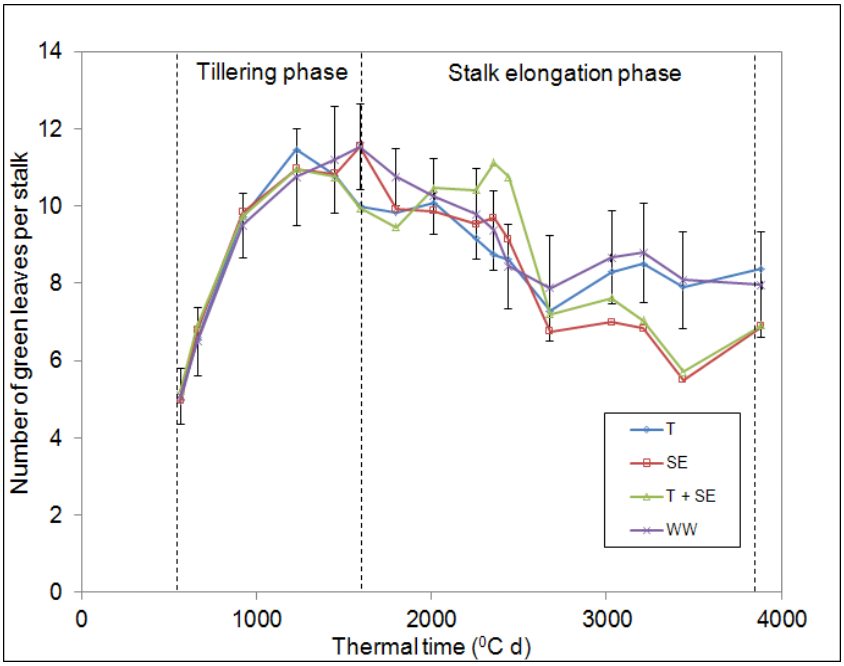

Figure 5.7: Green leaves per stalk as a function of thermal time using a base temperature of 10 ^{o}C for the different treatments. Vertical bars represent the standard deviation of the WW treatment.

Table 5.2: Crop growth parameters (mean ± standard deviation) for the different treatments at the end of the tillering and stalk elongation phases.

Growth indicators	Treatments				Significance
	T	SE	T+SE	WW	
Total number of green leaves per stalk (GLN)					
End of tillering phase	10.0±3.0	11.5±1.7	10.0±1.4	11.5±1.1	NS
End of stalk elongation phase	8.4±2.3	6.9±1.2	6.9±0.7	8.0±1.4	NS
Green leaf area index (GLAI) (m^2/m^2)					
End of tillering phase	3.96±0.70	3.75±0.78	3.10±0.66	4.04±0.28	NS
End of stalk elongation phase	3.38±0.51	2.72±0.49	2.78±0.39	3.42±0.46	NS
Stalk elongation rate (SER) per development phase (cm/day)					
Tillering phase	1.41 ± 0.25	1.60 ± 0.20	1.41 ± 0.26	1.68±0.13	NS
Stalk elongation phase	0.70±0.07^{a}	0.52±0.08^{c}	0.58±0.06^{c}	0.63±0.07^{b}	*
Stalk height (cm)					
End of tillering phase	103±14.9	116±12.7	105±14.6	120±8.30	NS
End of stalk elongation phase	245±21.4^{a}	222±18.6^{b}	222±14.8^{b}	248±14.5^{a}	*
At harvest	258±26.2	236±18.7	237±14.7	254±15.2	NS

* indicate significance at $P \leq 0.05$ and NS indicated non-significance of treatment difference.

Decreased leaf appearance and increased leaf senescence rates resulted in the SE and T+SE treatments having significantly lower GLN (6.4 and 6.8 leaves) from 3029 to 3438 ^{o}Cd after planting compared to the WW treatment (8.5 leaves) (Figure 5.7). At the end of the phase

(before commencing the drying-off period) the stress treatments had about one less green leaf than the unstressed treatments but this difference was not significant (Table 5.2).

5.2.3 Green leaf area

The green leaf area index (GLAI) at the end of the TP did not differ significantly between treatments, as can be expected, because no water stress occurred during this phase (Table 5.2). At the end of the SEP the GLAI of stressed treatments were 0.64 to 0.70 m^2/m^2 lower than the unstressed treatments but these differences were not significant. The result contradicts that of Inman-Bamber (2004) who found that the leaf area of mature leaves decreases shortly after irrigation was withheld. The large rainfall event on 302 to 304 DAP (Figure 5.1b and c) probably relieved the water stress and enabled rapid leaf growth in the stressed crops.

5.2.4 Interception of photosynthetically active radiation

PAR capture increased rapidly in conjunction with the rapid emergence of shoots, reaching a fractional PAR capture of 50% at 639 ^{o}Cd after planting. This was 114 and 39 ^{o}Cd (base temperature = 16 ^{o}C) slower than the values reported by Singels & Donaldson (2000) for cultivars N14 and N26, respectively. At peak stalk population (835 ^{o}Cd) 83 to 87% of PAR was intercepted by the canopy and almost 100% was captured at 1198 ^{o}Cd after planting (Figure 5.8).

With the imposed water stress not having a major effect on stalk population, GLN or on the GLAI it was expected that differences in canopy development between treatments throughout the crop would be negligible (Figure 5.8). Through both the TP and SEP no differences in PAR capture between treatments was apparent on any day of measurement (Figure 5.8) and thus a similar amount of PAR was captured through both phases (Table 5.3). This result contradicts Robertson *et al.* (1999) who found that a more severe water stress, imposed by withholding irrigation for longer periods, significantly affected canopy development by reducing GLN and GLAI and as a result significantly reduced the interception of PAR.

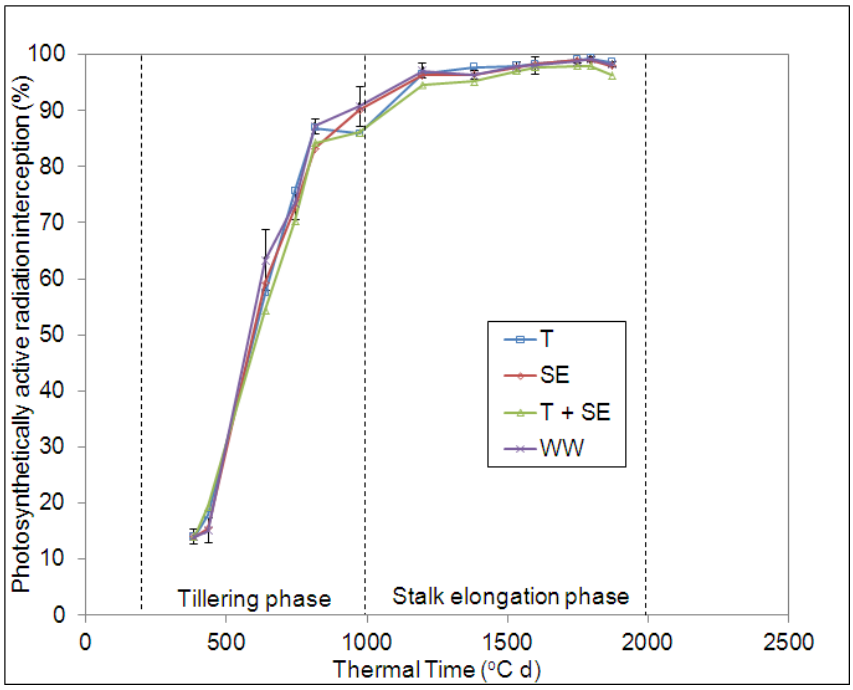

Figure 5.8: Photosynthetically active radiation interception as a function of thermal time using a base temperature of 16 ^{o}C for all treatments. Vertical bars represent the standard deviation of the WW treatment.

Table 5.3: Photosynthetically active radiation (PAR) captured, expressed as a percentage of incoming PAR (%, mean ± standard deviation) during the tillering phase, stalk elongation phase and for the entire season.

Treatments	Tillering phase	Stalk elongation phase	Season
T	56.3±3.7^{NS}	98.2±0.7^{NS}	77.3±2.2^{NS}
SE	55.8±2.1^{NS}	97.8±0.7^{NS}	76.8±1.4^{NS}
T+SE	54.7±2.8^{NS}	96.7±1.2^{NS}	75.7±2.0^{NS}
WW	57.3±2.8^{NS}	97.9±0.8^{NS}	77.6±1.8^{NS}

NS indicated non-significance of treatment differences

5.2.5 Stalk elongation

Stalk elongation rate (SER in cm/day) of stressed treatments were expressed as a fraction of the WW treatment, and named relative stalk elongation rate (RSER). RSER of the three stress treatments all declined to values of less than one with declining ASW, and often increased to values close to one when ASW increased due to rainfall and/or irrigation (Figure 5.9a and b and Figure 5.10).

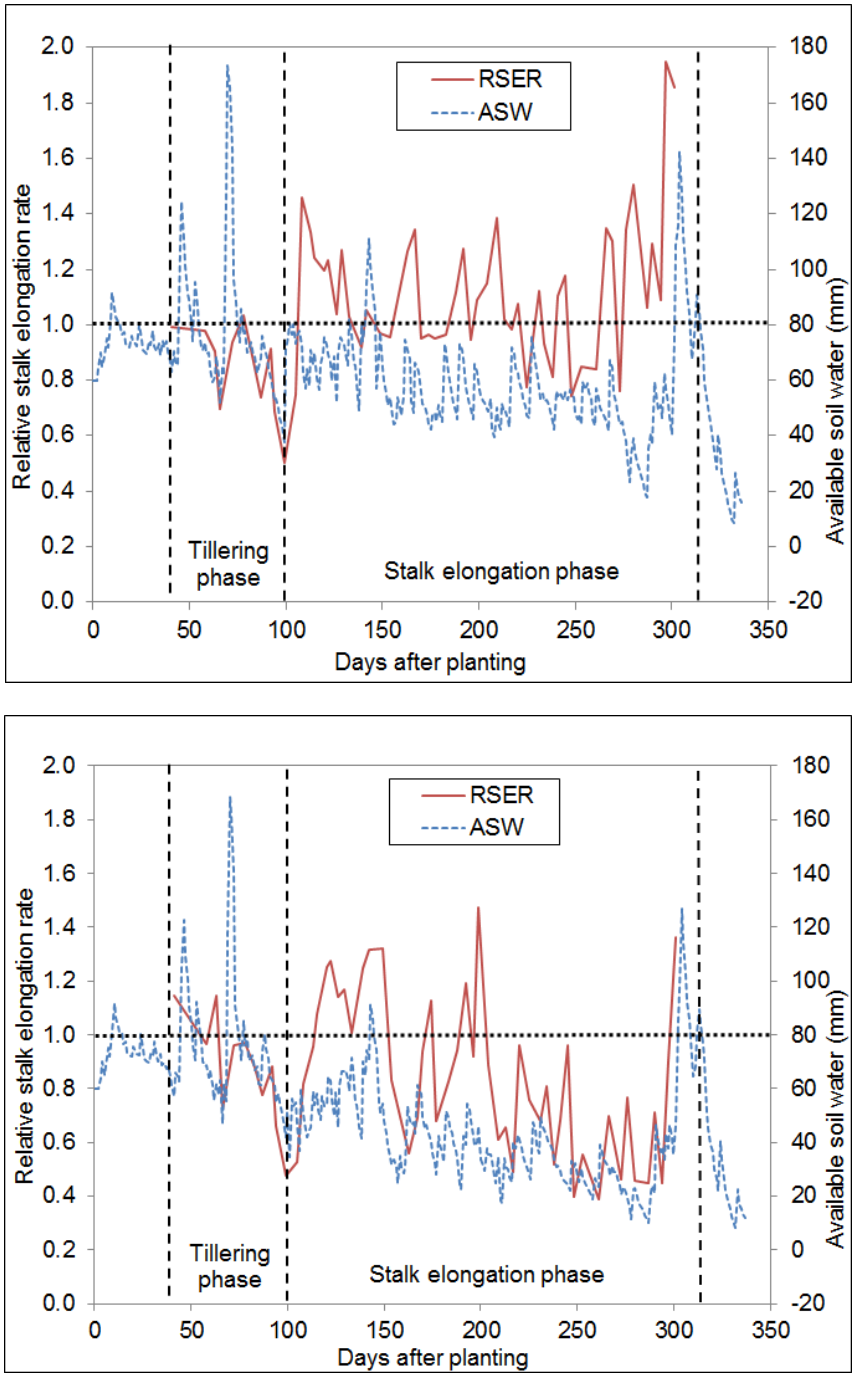

Figure 5.9: Relative stalk elongation rate as affected by available soil water (ASW) for the T (a) and T+SE (b) treatments during the tillering and stalk elongation phases. The black horizontal dotted line indicate RSER = 1.

During the TP the RSER of the different treatments were similar (RSER≈1), except towards the end of the phase when ASW declined to a value of 43 mm, causing RSER of the T and T+SE treatments to drop to about 0.5 (Figure 5.9a and b). Although the average SER of the stress treatments during the TP was slightly lower than that of the unstressed treatments, this difference was not significant (Table 5.2). Stalk height of the T and T+SE treatments were 15

to 17 cm shorter than the WW treatment at the end of the TP but these differences were not significant (Table 5.2 and Figure 5.11).

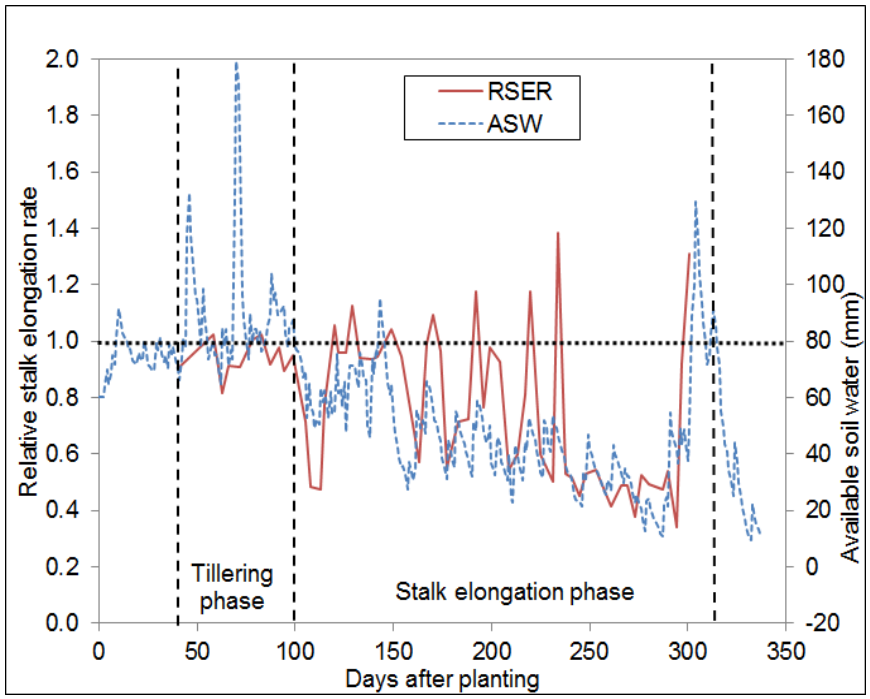

Figure 5.10: Relative stalk elongation rate as affected by available soil water (ASW) for the SE treatment during the tillering and stalks elongation phases. The black horizontal dotted line indicate RSER = 1.

During the SEP RSER declined rapidly with declining ASW to values of between 0.4 and 0.6 when ASW was low (Figure 5.9b and Figure 5.10). RSER rose rapidly and sometimes exceeded a value of 1, when ASW was increased by rainfall and/or irrigation, even for small increases in ASW. This suggests that stalks were able to compensate for the slow growth during stress periods (Figure 5.9b and Figure 5.10). Inman-Bamber and de Jager (1986a) reported similar results in a potted sugarcane trial. Compensatory growth was made possible by cells regaining turgor pressure quickly (Inman-Bamber, 1995). RSER did not fully recover after smallish wetting events later in the SEP, after about 250 DAP for the SE treatment and after about 200 DAP for the T+SE treatment. However, refilling the profile with rainfall (304 DAP) allowed stressed treatments to regain RSER levels close to 1 (Figure 5.9b and Figure 5.10).

Average SER in the SEP of stressed treatments was about 0.1 cm/day (8 to 17%) slower than that of the unstressed treatments (Table 5.2). This slower growth rate gradually affected stalk height with the first significant differences between the stressed and unstressed treatments

detected 132 days after the start of the SEP (231 DAP) (Figure 5.11). Stalks in the stressed treatments remained significantly shorter from 231 DAP until 301 DAP and at the end of the phase were 26 cm (10%) shorter than that of the unstressed treatments (Table 5.2). At final harvest, after the drying-off period stalks in the stressed treatments were 17 cm (7%) shorter than stalks in the unstressed treatments, but this difference was not significant (Table 5.2).

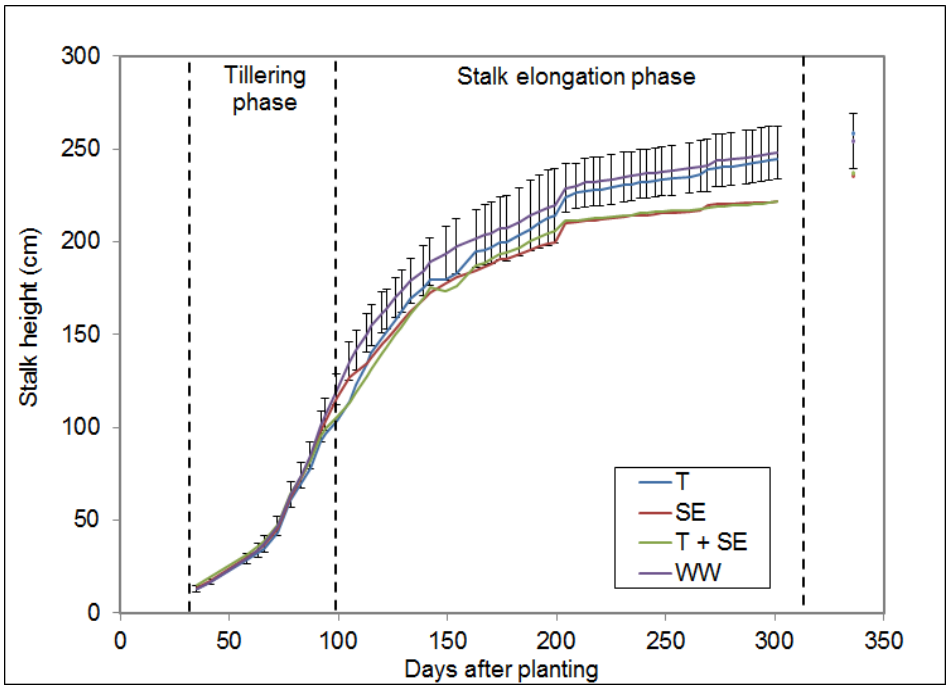

Figure 5.11: Stalk height over time for the different treatments. Vertical bars represent the standard deviation of the WW treatment.

5.3 Biomass production and partitioning

At the end of the TP, the T+SE treatment had significantly lower green leaf dry mass (GLDM) and higher trash dry mass (TRDM) than the other treatments (Table 5.4). This is unexpected because no stress occurred in this treatment and reasons for this are unclear.

Total dry mass (TDM) at final harvest was similar for all treatments. The water stress imposed during the SEP reduced the GLDM by 1.4 to 1.5 t/ha, stalk dry mass (SDM) by 4.4 and 6.1 t/ha and TRDM by 0.6 to 1.7 t/ha. Only the reduction in GLDM was statistically significant (Table 5.4).

Table 5.4: Dry mass of different biomass components (in t/ha and as percentage of the total; mean ± standard deviation) for each treatment at the end of the tillering phase and at final harvest, cane quality and final cane and sucrose yields (in t/ha) determined using the load cell and destructive sampling techniques.

Crop stage	Component	Treatments				Significance
		T	SE	T+SE	WW	
End of tillering phase (t/ha)						
	Stalk	3.84±0.70	3.56±0.65	3.09±0.55	4.00±0.64	NS
	Green leaves	6.07±0.86^{b}	5.77±0.84^{ab}	4.73±0.76^{a}	6.64±0.88^{b}	*
	Trash	0.19±0.06^{ab}	0.12±0.03^{a}	0.25±0.09^{b}	0.14±0.03^{a}	*
	Total	10.09±1.54	9.49±1.42	8.07±1.25	10.77±1.40	NS
End of tillering phase (%)						
	Stalk	37.8±2.01	37.6±2.62	38.2±3.67	37.0±3.26	NS
	Green leaves	60.2±1.70	61.1±2.38	58.7±3.58	61.7±3.25	NS
	Trash	1.92±0.59^{a}	1.31±0.28^{a}	3.1±0.86^{b}	1.28±0.15^{a}	*
Final harvest (t/ha)						
	Stalk	34.5±3.10	30.9±5.63	29.2±4.05	35.3±3.32	NS
	Green leaves	6.77±1.24^{b}	5.08±1.36^{a}	5.13±0.75^{a}	6.57±0.60^{b}	*
	Trash	10.54±1.73	9.63±1.83	8.44±1.87	10.18±2.14	NS
	Total	51.8±4.85	45.7±8.23	42.8±5.29	52.0±5.54	NS
Final harvest (%)						
	Stalk	66.7±2.99	67.8±1.99	68.2±2.42	67.9±2.33	NS
	Green leaves	13.0±1.55	11.1±2.04	12.1±1.80	12.6±0.48	NS
	Trash	20.3±2.62	21.1±1.09	19.7±3.81	19.5±2.45	NS
Cane quality (%)						
Sucrose Content		13.0±1.21	12.6±0.63	14.2±1.05	12.9±1.52	NS
Non-sucrose Content		1.53±0.38	1.78±1.00	1.59±1.46	1.10±0.10	NS
Fibre Content		13.7±2.14	13.4±1.52	12.6±1.94	14.2±0.45	NS
Stalk dry matter content (%)						
Final harvest		28.1±0.74	27.8±0.84	28.3±2.11	28.3±1.63	NS
Cane yield (t/ha)						
Load cells		124±5.27^{b}	117±7.23^{a}	112±6.05^{a}	123±1.67^{b}	*
Sampling		123±12.6	112±20.9	103±10.6	125±11.4	NS
Sucrose yield (t/ha)						
Load cells		16.0±1.43	14.8±1.47	15.8±0.84	16.0±1.95	NS
Sampling		15.9±2.18	14.1±2.99	14.5±1.25	16.1±1.75	NS

* indicate significance at $P \leq 0.05$, and NS indicated non-significance of treatment differences.

Partitioning of biomass was not affected by water stress and about 68% was partitioned to stalks, 12% to green leaves and 20% to trash (Table 5.4). In a study done by Robertson *et al.* (1999) significantly less (3%) biomass was partitioned to stalks in response to prolonged water stress during SEP. It is concluded that mild water stress imposed through deficit drip

irrigation did not alter biomass partitioning and that the lower SDM was solely due to a lower TDM of stress treatments.

Cane yield, as determined using the load cell and destructive sampling techniques, was reduced by SEP water stress (Table 5.4). The load cell technique indicated a statistically significant reduction in cane yield of 6 and 11 t/ha in comparison to the WW treatment. The destructive sampling technique indicated larger yield reductions (13 to 22 t/ha) but these were not significant. Taking all this information into account, it is concluded that yield was significantly reduced by the water stress imposed during the SEP.

Dry matter, sucrose, non-sucrose and fibre contents of stalks did not differ between treatments because all treatments were exposed to a 24 day long dry-off period, causing similar stress levels during this period (Table 5.1 and Table 5.4). Therefore the reductions in sucrose yield (by 0.2 to 1.2 t/ha determined using the load cell cane yield and by 1.6 to 2 t/ha determined using destructive sampling cane yield) are largely due to reductions in SDM (Table 5.4).

Much greater cane and sucrose yield losses in response to prolonged and severe water stress in SEP, were observed in the study by Robertson *et al.* (1999).

It is concluded that mild water stress during the SEP imposed through deficit drip irrigation, allowed the crop to maintain growth and development processes close to the potential rates and hence limited cane and sucrose yield losses. .

5.4 Summary

- Rainfall during the TP prevented ASW in the T and T+SE treatments from declining into the intended water stress regime and thus these treatments endured no water stress during this phase.
- In addition to the 267 mm of rain, the SE and T+SE treatments received 312 to 322 mm (40%) less irrigation and used only 40 to 58 mm (5 to 8%) less water during the SEP, than the unstressed T and WW treatments. Consequently the stressed treatments endured 62 and 86 days of water stress, respectively.
- The SWP at 0.25 and 0.40 m depths fluctuated between -10 and -90 kPa in the stressed treatments, while it fluctuated above -40 kPa in the unstressed treatments.

- Water stress in the SEP temporarily affected GLN but had no effect on the GLAI, stalk population or PAR capture.
- SER was highly sensitive to changes in ASW, declining rapidly with declining ASW. However plants appear to have the ability to compensate somewhat for the reduced growth during short period of water stress through accelerated growth when water stress was relieved. However, on average, SER was reduced by about 0.1 cm/day, resulting in the stalks of water stressed plants being 18 cm (7%) shorter than stalks of the unstressed treatments at final harvest.
- The imposed water stress slightly lowered SDM, GDM, TRDM and TDM but had no effect on the partitioning fractions.
- Cane yield, as determined with the load cell technique, was reduced by the water stress during SE phase by 8.5 t/ha (6%), while sucrose yield was reduced by about 0.7 t/ha (4%). Destructive sampling technique suggests a larger reduction but these were statistically insignificant. .

It can finally be concluded that irrigating the plant crop with 40% less water during the SEP (will vary depending on rainfall) in an attempt to maintain the ASW between 30 and 60% of capacity, only reduced CWU by 7%, stalk height by 7%, SDM by 15%, cane yield by 6% and sucrose yield by 4%. Therefore adopting a similar deficit drip irrigation strategy would allow for water to be saved during cropping seasons where water is limited while still achieving more than 90% of potential cane and sucrose yields.

CHAPTER 6: RATOON CROP RESULTS

6.1 Water relations

6.1.1 Available soil water and soil water potential

Germination phase:

The ratoon crop was irrigated six days after cutback (DAC) and thereafter irrigation was applied intermittently until 24 DAC to ensure the sprouting and establishment of primary shoots (Figure 6.1). During this phase all treatments received the same amount of irrigation (37 mm) and rainfall (10 mm), and presumably used the same amount of water (Table 6.1). All treatments endured negligible stress during this phase.

Table 6.1: Phase duration, rainfall, irrigation, number of stress days and estimated crop water use for each treatment in the ratoon crop during the tillering phase, stalk elongation phase, the two week dry-off period and for the entire growing season.

	Treatment	Development phases			Drying-off	Total
		Germination	Tillering	Stalk elongation		
Duration of each phase in:						
Days		24	165[1]	128	12	329
Thermal time (^{o}Cd, base 10 ^{o}C)		299	1548[1]	1981	181	4009
Thermal time (^{o}Cd, base 16 ^{o}C)		149	584[1]	1213	109	2055
Rainfall (mm)		10	358	439	1	808
Irrigation (mm)	T	37	48	384	0	468
	SE	37	175	77	0	289
	T+SE	37	49	84	0	170
	WW	37	175	384	0	595
Stress days	T	2	50	1	1	54
	SE	0	3	56	11	70
	T+SE	2	53	67	12	134
	WW	0	6	1	5	12
Crop water use (mm)	T	22	343	685	58	1107
	SE	22	392	616	44	1075
	T+SE	22	331	584	41	977
	WW	22	393	685	53	1152

[1] These durations were used for imposing water treatments and for analysing data. The true duration of the tillering phase would have been shorter than indicated here, when the end of the tilling phase is taken as the time of peak tiller population.

Tillering phase:

Available soil water (ASW) in the T and T+SE treatments declined into the targeted water regime from 90 to 132 DAC and again from 158 to 170 DAC (Figure 6.1a and b). The T and T+SE treatments received 127 mm (73%) less irrigation than the WW and SE treatments and endured 50 and 53 days of water stress, compared to 3 and 6 days of stress for the WW and SE treatments, respectively (Table 6.1). Therefore the T and T+SE treatment endured water stress for 17 and 26% of the duration of the tillering phase (TP). Interestingly, crop water use (CWU) in the T and T+SE treatment was only reduced by 50 to 62 mm (13 to 16%) when compared to the unstressed treatments (Table 6.1).

During the TP when the ASW declined into the targeted regime, the soil water potential (SWP) (at 0.25 and 0.4 m soil depths) fluctuated between -40 and -90 kPa (Figure 6.1a and b). The SWP of the WW and SE treatments, which were unstressed during the TP, mostly fluctuated between -10 and -40 kPa (0.25 m depth) and between -10 and -30 kPa at a depth of 0.4 m (Figure 6.2c and d).

Stalk elongation phase:

The SE and T+SE treatments were only irrigated on eight occasions, totalling 77 and 89 mm, respectively, because of frequent, substantial rainfall occurring during the stalk elongation phase (SEP). This was 300 and 307 mm (78 to 80%) less irrigation than the WW treatment (Table 6.1). SWP (at 0.25 and 0.4 m soil depth) of the SE and T+SE treatments fluctuated between -10 to -90 kPa when ASW was in the targeted regime (Figure 6.2b and c). ASW in the WW and T treatments was mostly maintained above 60% of capacity, while SWP at both depths in the T treatment fluctuated between -10 and -30 kPa while the SWP in the WW treatment fluctuated between -10 and -60 kPa (Figure 6.2a and d). The SE and T+SE treatments endured 55 and 66 more days of water stress than the unstressed WW and T treatments, and endured water stress for 44% and 53% of the SEP (Table 6.1). The imposed water stress only reduced CWU by 69 to 101 mm (10 to 15%), compared to the unstressed treatments.

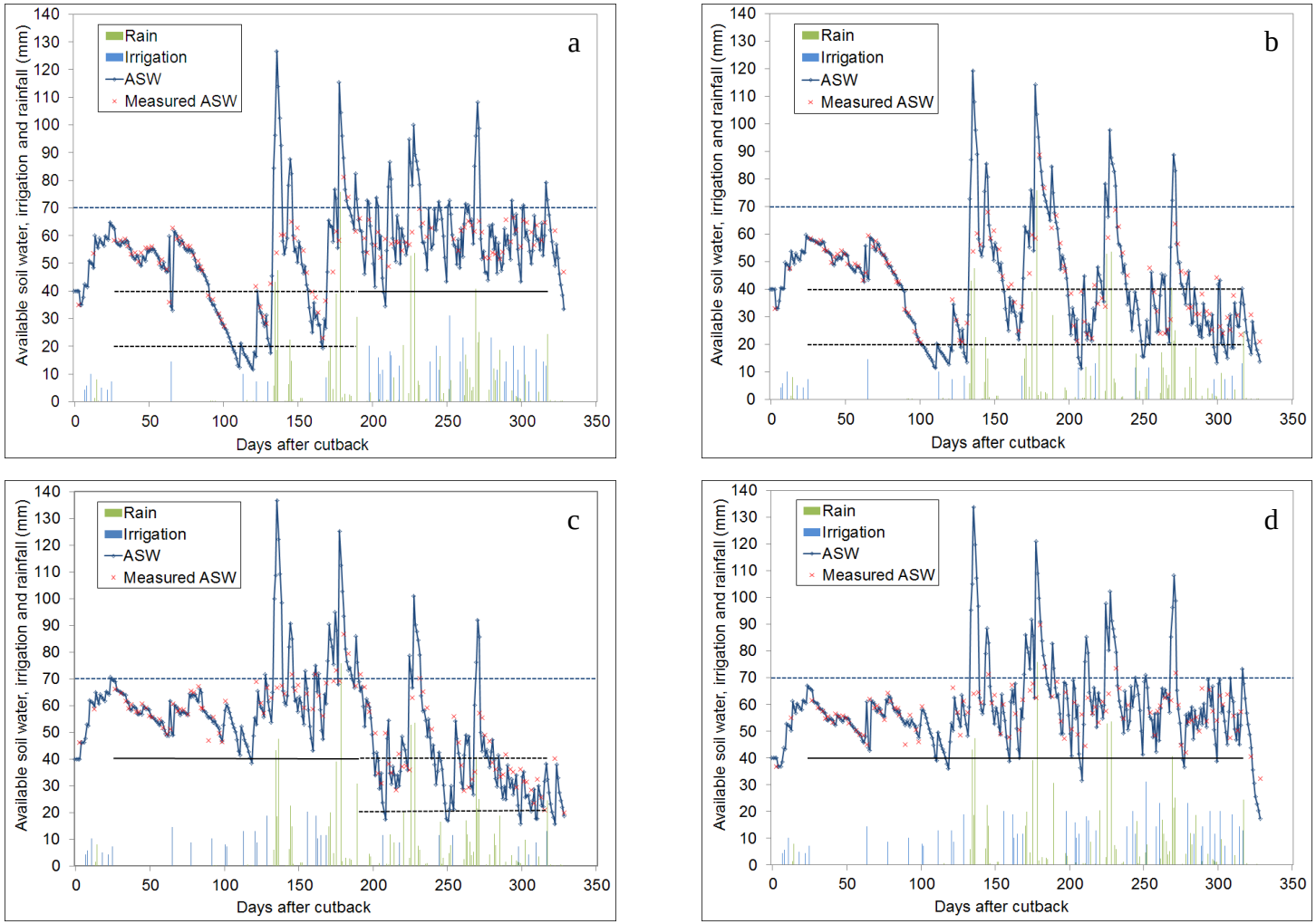

Figure 6.1: Simulated (blue line) available soil water (ASW) corrected with measured (red crosses) ASW in the T (a), T+SE (b), SE (c) and WW (d) treatments in the ratoon crop. The blue dotted horizontal line represents field capacity (ASWC = 71 mm). The black horizontal lines represent 30 and 60% of the available soil water capacity. Where the line is solid no water stress was imposed while the dotted line represents imposed water stress periods. The green and blue bars represent rainfall and irrigation, respectively.

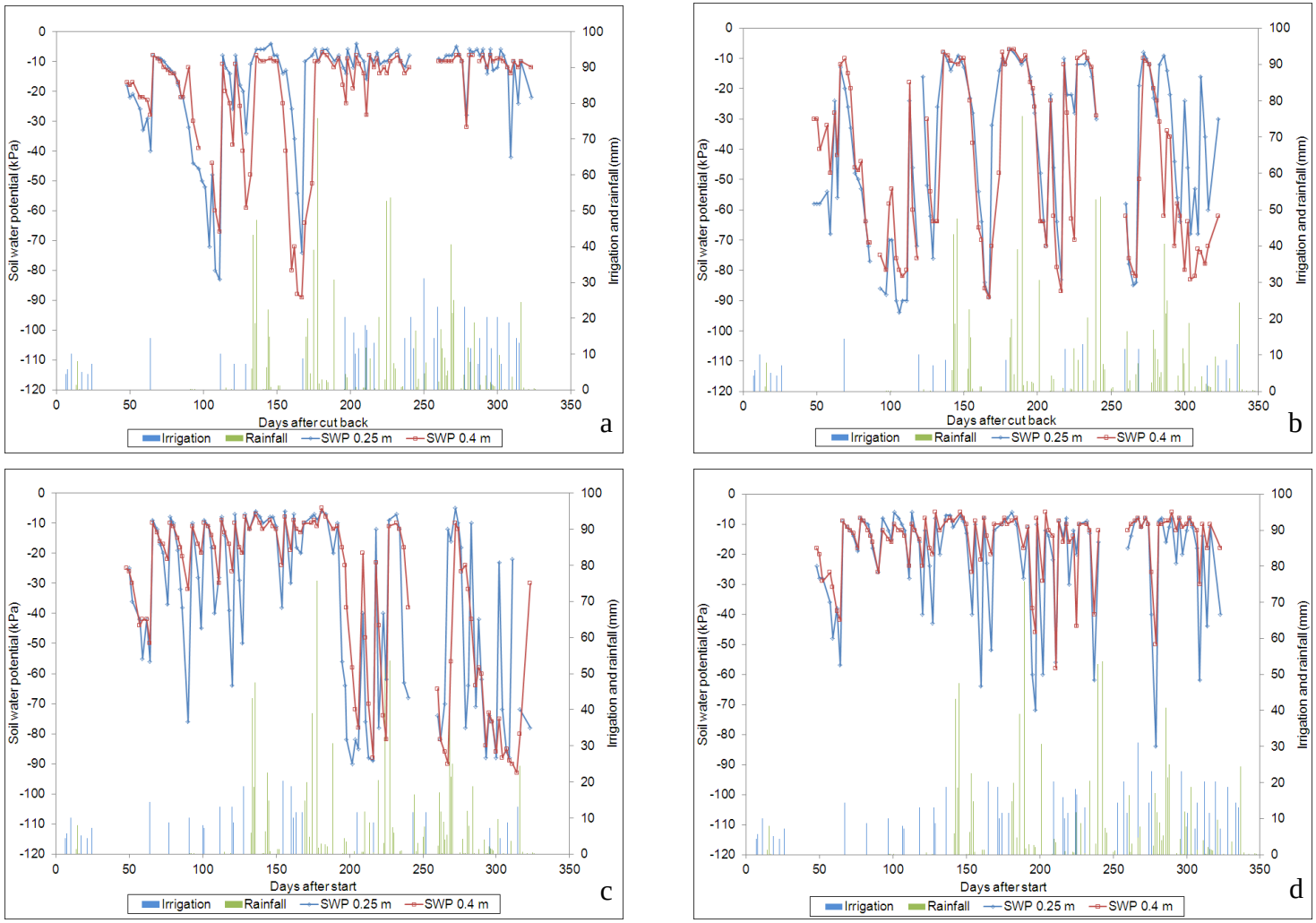

Figure 6.2: Soil water potential measured at a soil depth of 0.25 m (blue line) and 0.4 m (red line) in the T (a), T+SE (b), SE (c) and WW (d) treatments in the ratoon crop. The green and blue bars represent rainfall and irrigation respectively.

It is clear from Figure 6.1 that the ASW at times was above 50% of capacity during intended stress periods. This was due to rainfall and irrigations that were applied to prevent ASW from dropping below the lower threshold of 30% of ASWC. Therefore the duration of individual stress periods (ASW<50% of capacity) ranged from one to 43 days in the TP and from one to 15 days in the SEP (Figure 6.3a and b).

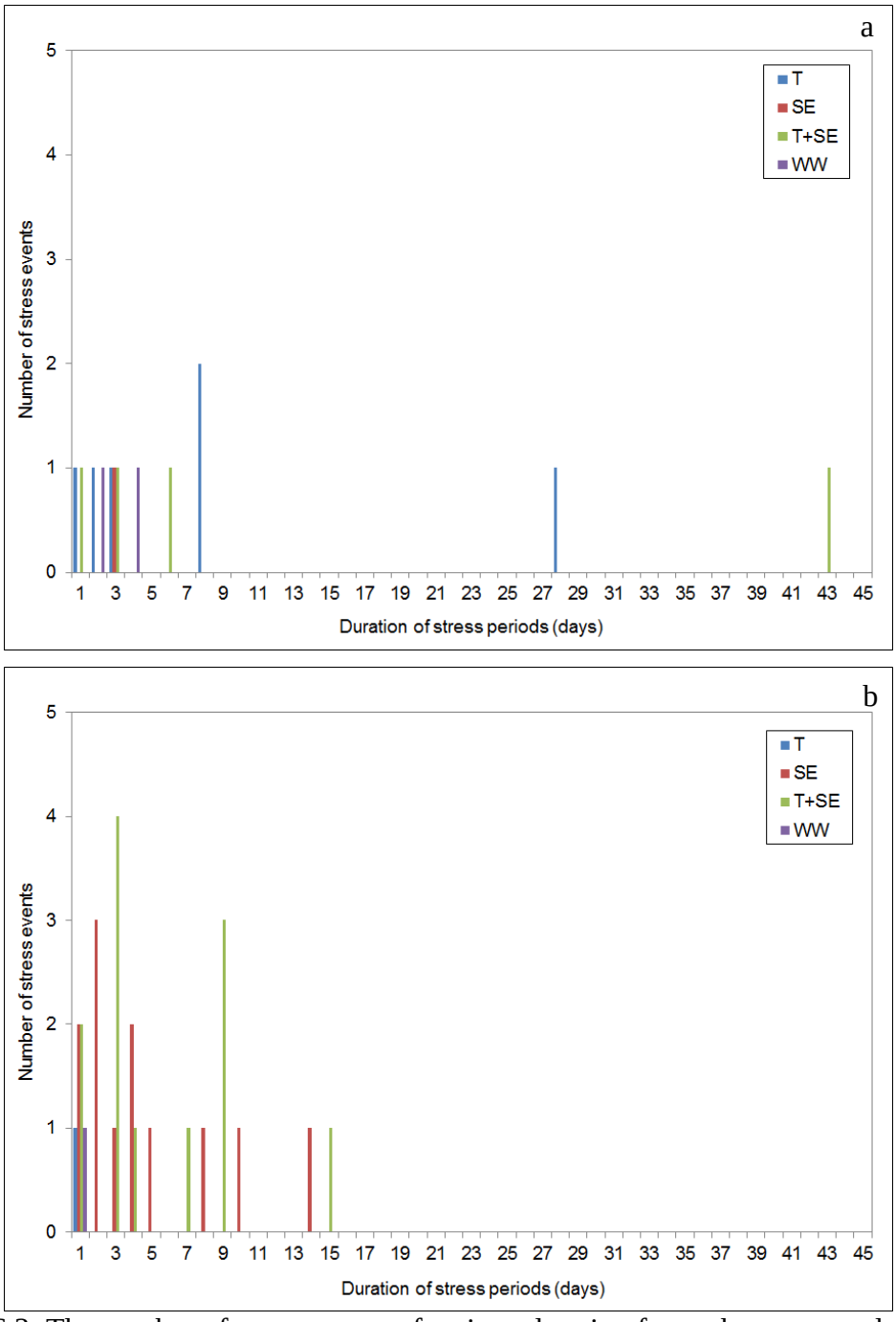

Figure 6.3: The number of stress events of a given duration for each treatment during the tillering (a) and stalk elongation (b) phases of the ratoon crop.

A storm on 286 DAC, with 19 mm of rain and strong winds, caused sugarcane to lodge in 80% of the plots in the T treatment, all plots in the WW treatment and one plot in the T+SE treatment (i.e. 1st lodging event; see sketch map in Annexure H, lodge ratings in Annexure I and photos in Annexure J). Destructive samples from all the plots were taken two weeks after lodging, 301 DAC, to minimize the confounding impact of lodging on results. At this point the SE and T+SE treatments had received 279 and 275 mm (83 and 85%) less irrigation, endured 41 and 54 more days of stress and used 47 and 80 mm (8 and 13%) less water than the T and WW treatments, respectively.

A second storm on 317 DAC, with 25 mm of rain and strong winds, caused lodging of sugarcane in all the remaining plots (lodge ratings in Annexure I). At this point irrigation was ceased in all treatments.

6.1.2 Leaf water potential

Midday leaf water potential (LWP) measurements showed huge variation, causing non-significance of treatment differences (Figure 6.4). It is recommended that in future studies a greater number of leaves per plot be sampled to reduce the sampling error.

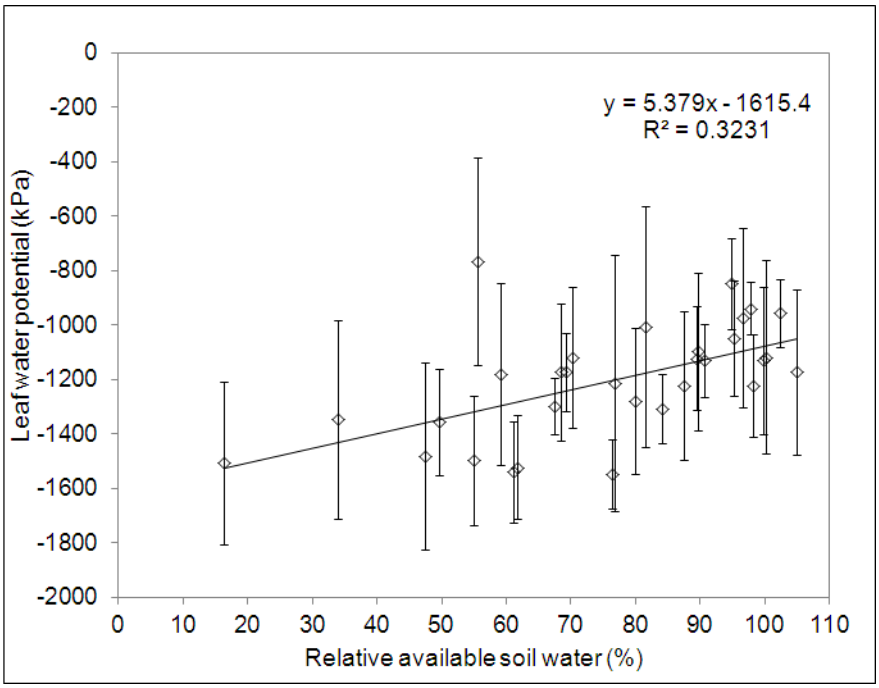

Figure 6.4: Leaf water potential at approximately midday in relation to the available soil water expresses as a percentage of the available soil water capacity. Vertical bars represent the standard deviation amongst the measurements done in each treatment.

LWP was poorly correlated to daily mean vapour pressure deficit (VPD) and to daily mean reference evapotranspiration (not shown). LWP did however correlate significantly with relative ASW (Figure 6.4), although the R^2 was low.

LWP of unstressed plants (ASW > 50% of capacity) ranged between -1078 and -1346 kPa and between -1346 and -1529 kPa for stressed plants (ASW < 50% of capacity) (Figure 6.4). These values are similar to those found in the plant crop. The LWP range of unstressed plants was similar to the range found by Smit & Singels (2006) (-700 to -1200 kPa) but lower than the LWP range found by Inman-Bamber & de Jager (1986a) (>-500 kPa). As explained in Chapter 4 the variation in the LWP of unstressed plants between studies is likely to be due to differences in the atmospheric evaporative demand between study sites.

The LWP range of stressed plants was higher (less negative) than previously found by Inman-Bamber & de Jager (1986a) (-1300 to -1700 kPa) and by Smit & Singels (2006) (-1200 to -2300 kPa). The lower LWP of stressed plants in previous studies is due to a more severe water stress as irrigation was withheld for longer periods than in the current study. Lastly, differences in LWP between studies may also be due to cultivar specific differences (Inman-Bamber & de Jager, 1986a).

6.2 Growth and development

6.2.1 Shoot emergence and senescence

Primary shoots in all treatments began to emerge after 117 ^{o}Cd have accumulated since the crop was cut back. All primary shoots were deemed to have emerged by 149 ^{o}Cd (24 DAC, Table 6.1) and thus marked the end of the germination phase and the start of the TP. Secondary shoots (i.e. tillers) emerged rapidly thereafter, reaching a peak stalk population of about 43 stalks/m^2 after 581 ^{o}Cd since the cut back (Figure 6.5). The destructive samples for the end of the TP were only taken 22 days after the actual peak stalk population occurred (at 733 ^{o}Cd or 189 DAC). This was taken as the end of the phase and the start of the next phase for the implementation of treatments and for the processing of data. Therefore the duration of the TP in this study was 584 ^{o}Cd or 165 days long (Table 6.1).

Shoot senescence commenced at about 581 ^{o}Cd after the cut back and coincided with a photosynthetically active radiation (PAR) interception of 70 to 80% (Figure 6.8). Shoot

senescence ceased for all practical purposes after 1350 °Cd since the cut back, resulting in a stable stalk population of about 16 stalks/m^2. The 2nd lodging event at 1946 °Cd (317 DAC) after the cut back marked the end of the SEP and thus this phase was 1213 °Cd or 128 days long. After the 12 day drying off period (109 °Cd long) the stalk population across all treatments remained at about 16 stalks/m^2.

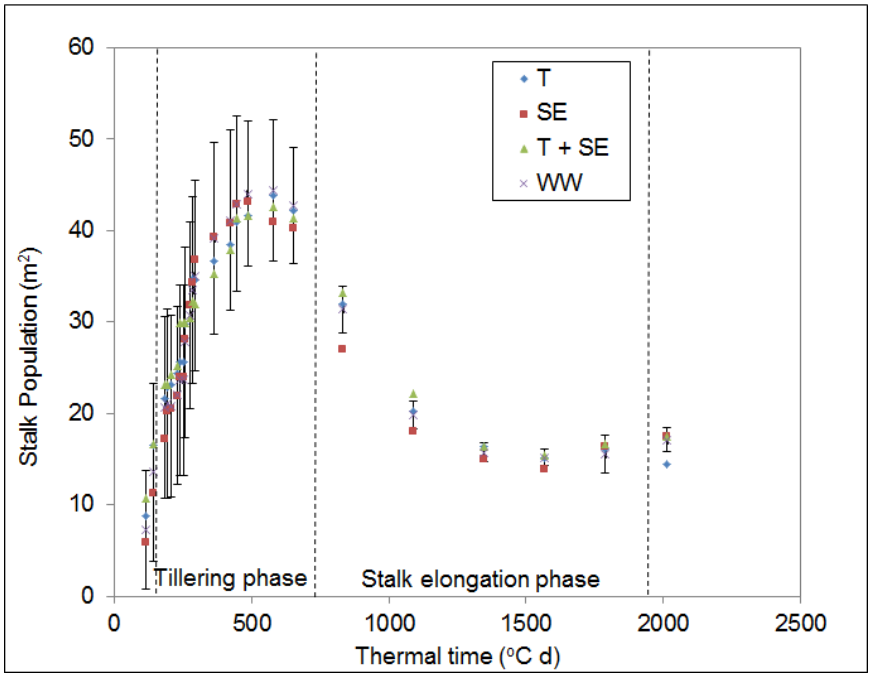

Figure 6.5: Stalk population of the different treatments of the ratoon crop as a function of thermal time using a base temperature of 16 °C. Vertical bars represent the standard deviation of the mean values for the WW treatment.

Evidently the imposed water stress had no effect on the emergence or senescence rates of shoots throughout the crop growing cycle. This result is different to that found by Smit & Singels (2006), who reported that stalk senescence rate increased under severe water stress, reducing stalk population. The severity of the imposed stress therefore seems to play a significant role in influencing stalk senescence, with mild intermittent stress as imposed in this study, having no effect on stalk development.

6.2.2 Leaf emergence and senescence

Tillering phase:

Leaf emergence rate of the stressed T and T+SE treatments were slightly lower than that of the unstressed SE and WW treatments for the period between 764 to 1114 °Cd after the cut back (Figure 6.6). Thereafter leaf emergence rates of all treatments were similar for the

remainder of the phase. The initial slower rate of leaf emergence in the stressed treatments caused them to have on average 1.1 and 1.6 fewer green leaves per stalk at the end of the phase, than the unstressed treatments (Figure 6.7b and Table 6.2).

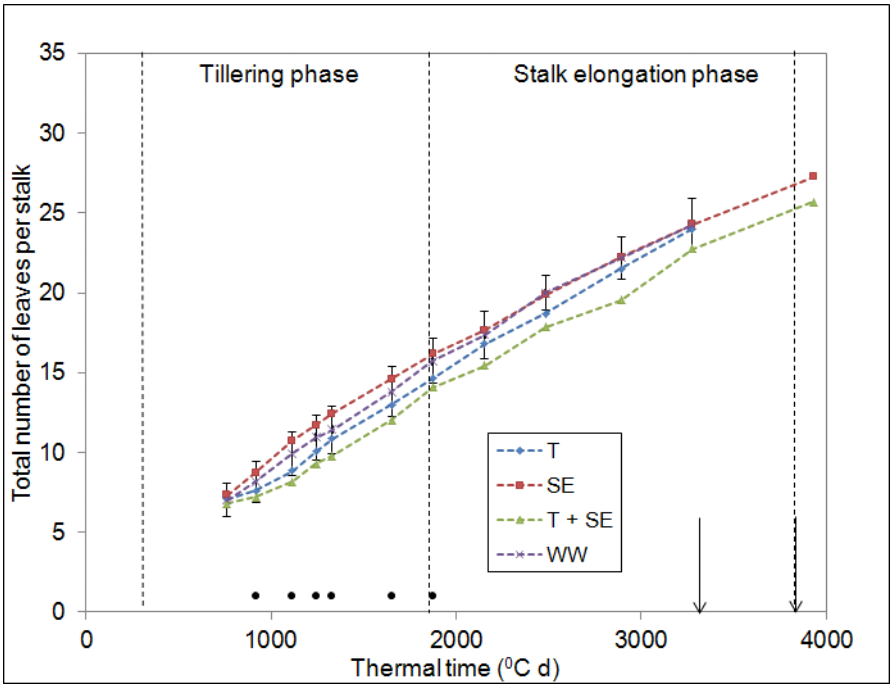

Figure 6.6: Total number of fully expanded leaves per stalk as a function of thermal time (base temperature 10 ^{o}C). Black dots represent times when significant differences occurred and vertical arrows indicate lodging events. Vertical bars represent the standard deviation of the WW treatment.

Leaf senescence rates were not affected by the water stress and the number of dead leaves was similar for all treatments throughout the phase (Figure 6.7a and Table 6.2). Therefore the significantly lower number of green leaves per stalk (GLN, 2 to 3 fewer leaves, Figure 6.7b) of the stressed treatments compared to the unstressed treatments was primarily the result of the reduced leaf emergence rate. No significant differences between the unstressed treatments in the total, dead and green leaf numbers per stalk were apparent during or at the end of the phase (Figure 6.6, Figure 6.7a and b and Table 6.2).

Stalk elongation phase:

Leaf emergence rates in the T treatment recovered shortly after the SEP commenced when water stress was relieved (see Figure 6.6). This allowed stalks to produce a similar number of leaves as the WW treatment. Senescence rates of leaves of the T treatment, and hence GLN, were similar to that of the WW treatment for the duration of the phase (Figure 6.7a and b).

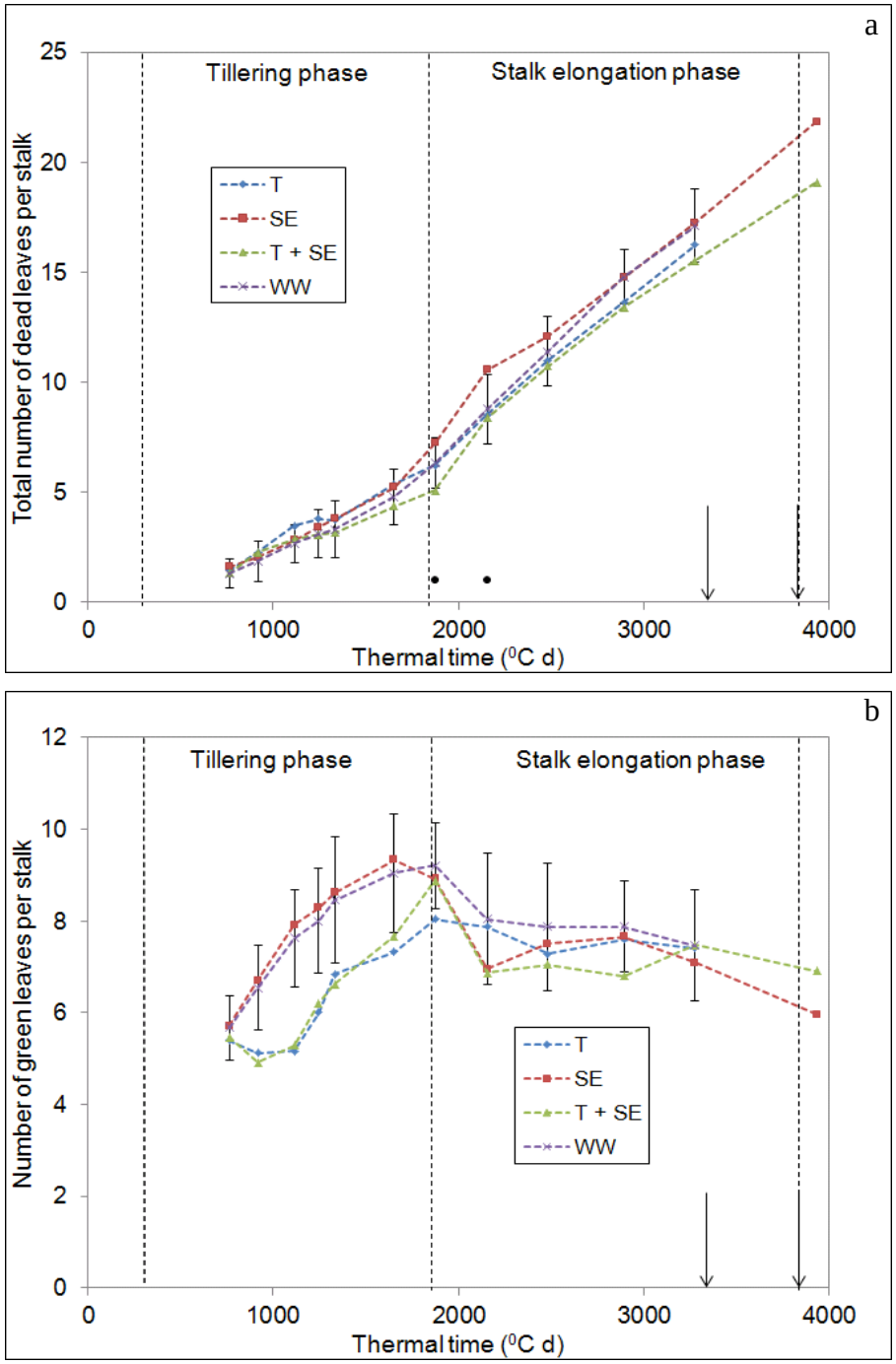

Figure 6.7: Total number of dead leaves (a) and green leaves (b) per stalk as a function of thermal time (base temperature 10 °C). Black dots represent times when significant differences occurred and vertical arrows indicate lodging events. Vertical bars represent the standard deviation of the WW treatment.

Water stress during the SEP had no effect on leaf emergence rates of the SE and T+SE treatments (Figure 6.6). Water stresses in other studies (Inman-Bamber, 2004; Smit & Singels, 2006) have been found to reduce leaf emergence rates shortly after irrigation is withheld. This contradictory result is likely to be due to the rapid emergence of leaves once

the stress was relieved because of rainfall and/or irrigation (Figure 6.1b and c), a phenomenon which has previously been reported by Inman-Bamber (1991; 2004) and Inman-Bamber & Smith (2005). The number of emerged leaves per stalk at the 1st lodging event was therefore similar to that of the WW treatment (Figure 6.6 and Table 6.2). The T+SE treatment had a slightly lower number of emerged leaves because this treatment started the phase with a lower number (Table 6.2).

Table 6.2: Crop growth parameters (mean ± standard deviation) for the different treatments at the end of the tillering phase, after the 1st lodging event and at the end of the stalk elongation phase.

Growth indicators	Treatments				Significance
	T	SE	T+SE	WW	
Total number of fully emerged leaves					
End of tillering phase	14.6±1.8^{a}	16.2±1.5^{b}	14.1±1.3^{a}	15.7±1.4^{b}	*
1st lodging event	24.0±2.0	24.3±1.7	22.8±1.8	24.2±1.7	NS
End of stalk elongation phase	-	27.3±3.4	25.7±1.8	-	NS
Total number of dead leaves					
End of tillering phase	6.3±1.5^{b}	7.3±1.4^{b}	5.1±1.3^{a}	6.3±1.1^{b}	*
1st lodging event	16.3±1.7^{ab}	17.3±1.3^{b}	15.5±1.5^{a}	17.1±1.7^{b}	*
End of stalk elongation phase	-	21.9±1.6	19.1±1.8	-	NS
Total number of green leaves per stalk (GLN)					
End of tillering phase	8.0±1.3	8.9±1.4	8.9±1.0	9.2±0.9	NS
1st lodging event	7.4±1.0	7.1±1.1	7.5±1.2	7.5±1.2	NS
End of stalk elongation phase	-	6.0±1.4	6.9±1.4	-	NS
Green leaf area index (GLAI) (m^2m^2)					
End of tillering phase	3.93±0.62^{a}	4.93±0.66^{b}	3.56±0.66^{a}	5.29±0.67^{b}	*
1st lodging event	8.00±0.93^{c}	6.49±0.55^{ab}	6.02±0.49^{a}	7.40±0.90^{bc}	*
End of stalk elongation phase	4.41±0.42	4.31±0.43	4.64±0.83	4.76±0.76	NS
Stalk elongation rate (SER) per development phase (cm/day)					
Tillering phase	0.32±0.10^{a}	0.54±0.14^{b}	0.34±0.09^{a}	0.46±0.12^{b}	*
Stalk elongation phase	1.66±0.23^{b}	1.38±0.33^{a}	1.48±0.29^{a}	1.63±0.36^{b}	*
Stalk height (cm)					
End of tillering phase	56±14.6^{a}	82±20.5^{c}	53±12.9^{a}	71±17.2^{b}	*
At 1st lodging event	212±25.0^{b}	210±30.9^{b}	191±25.3^{a}	223±31.5^{b}	*
At harvest	260±23.3	246±15.7	221±25.5	264±16.0	-

* indicate significance at $P \leq 0.05$, and NS indicated non-significance of treatment differences, - significance could not be determined because only one replication in the WW treatment was available after others lodged

Shortly after the commencement of the SEP (from 1873 to 2155 ^{o}Cd after cut back) the water stress increased leaf senescence rates of the SE and T+SE treatments in comparison to the WW treatment but thereafter the senescence rates were similar for the remainder of the phase (Figure 6.7a). This resulted in a similar GLN during and at the end of the phase, compared to the WW treatment (Figure 6.7b and Table 6.2). This result suggests that relieving the water stress through irrigation or because of rainfall allowed the growth and development processes of leaves to continue at similar rates to that of an unstressed plant.

6.2.3 Green leaf area

Tillering phase:

Water stress during the TP significantly reduced GLAI of the T and T+SE by 1.73 and 1.35 m^2/m^2 respectively, compared to the WW treatment (Table 6.2). This is ascribed to a reduction in the leaf area of individual leaves because all treatments had a similar GLN and stalk population. Inman-Bamber (2004) previously reported that water stress can decrease leaf area.

GLAI of the unstressed WW and SE treatments did not differ significantly, as expected.

Stalk elongation phase:

At the end of the SEP the T treatment had similar GLN and GLAI to that of the WW treatment (Table 6.2). This suggests that individual leaves regained a similar leaf area to leaves in the WW treatment.

At the 1st lodging event, water stress during the SEP significantly reduced GLAI of the SE and T+SE treatments by 0.91 to 1.38 m^2/m^2, respectively, compared to the WW treatment (Table 6.2). These treatments had a similar GLN (Table 6.2) and lower green leaf dry mass (GLDM) (Table 6.4) than the WW treatment, suggesting that the GLAI reduction is due to decreased area of individual leaves. GLAI of the T+SE treatment did not differ significantly from that of SE treatment, indicating that the length of the imposed water stress had no long term effect on leaf growth.

GLN of all treatments decreased by about 0.6 to 1.8 leaves, while GLAI increased by about 1.56 to 4.07 m^2/m^2 from the end of the TP up to the 1st lodging event (Table 6.2). The

increase in GLAI is therefore ascribed to an increase in the area of individual leaves. Inman-Bamber (1991) and Robertson *et al.* (1998) have shown that the area of successive leaves increases with increasing leaf number until about the 18th leaf and thereafter have a reasonably stable area. In the current study 12 to 15 leaves had already emerged by the end of the TP, suggesting that the area of leaves appearing thereafter were still increasing with increasing leaf number.

GLAI of the SE and T+SE treatments declined by 1.38 and 2.18 m^2/m^2 from the 1st lodging event to final harvest (28 days), due to fewer leaves and less GLDM compared to unstressed treatments (Table 6.2 and Table 6.4). This reduction could be resultant of the ASW remaining in the desired water regime (ASW between 30 to 60% of capacity) continuously for the 28 days between 1st lodging and final harvest.

6.2.4 Interception of photosynthetically active radiation

PAR capture increased rapidly in all treatments in conjunction with the rapid emergence of shoots and leaves reached a PAR capture of 50% 280 ^{o}Cd after the cut back (Figure 6.8). This was 45 and 120 ^{o}Cd (base temperature = 16 ^{o}C) quicker than the values reported by Olivier *et al.* (2009) for cultivars N14 and N26, respectively. Interestingly, Singels & Donaldson (2000) reported a quicker canopy development to 50% PAR capture (30 ^{o}Cd faster than the current study) for different cultivars (NCo376, N25 and N26) which were planted in single rows.

At peak stalk population (581^{o}Cd, Figure 6.5) 75 to 85% PAR was captured and almost 100% of PAR was captured after about 944 ^{o}Cd (Figure 6.8).

Tillering phase

At the end of the TP the reduced GLAI of the T and T+SE treatments caused the canopy to intercept 4 to 5% less PAR compared to the WW treatment (Figure 6.8). However, these reductions had no significant effect on the PAR captured through the phase (Table 6.3). PAR capture in the SE and WW treatments did not differ significantly.

Stalk elongation phase

Shortly after the start of the SEP the rapid emergence of leaves in the T treatment restored the GLAI to a similar value to that of the WW treatment, resulting in a similar amount of PAR

captured during the SEP (Figure 6.8 and Table 6.3). It can therefore be concluded that water stress during the TP had no lasting effect on the interception of PAR.

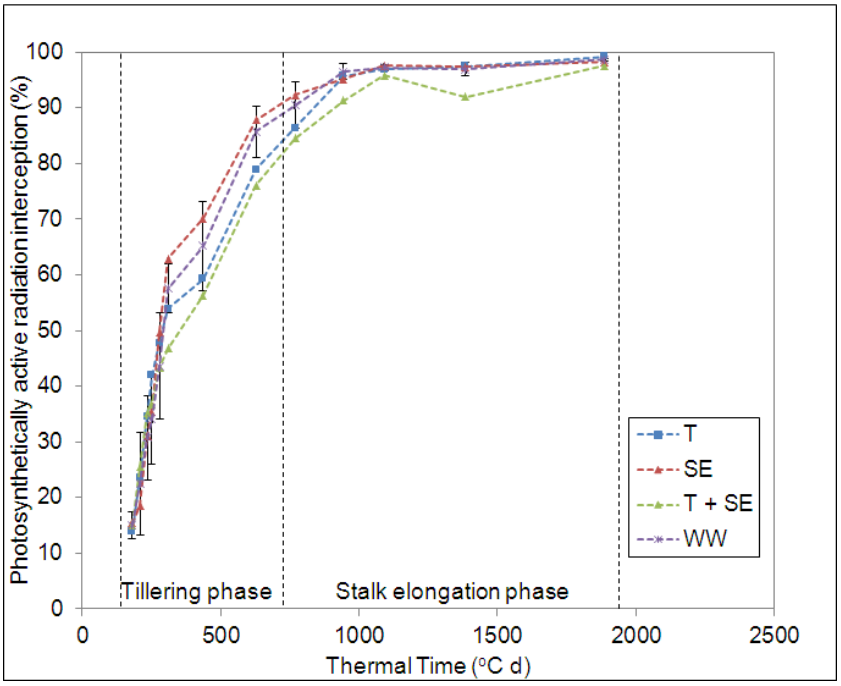

Figure 6.8: Photosynthetically active radiation (PAR) interception as a function of thermal time (base temperature of 16 ^{o}C) for the different treatments of the ratoon crop. Vertical bars represent the standard deviation of the mean values for the WW treatment.

Table 6.3: Photosynthetically active radiation (PAR) captured, expressed as a percentage of incoming PAR (%, mean ± standard deviation) during the tillering phase, stalk elongation phase and for the entire growing season.

Treatments	Tillering phase	Stalk elongation phase	Season
T	44.2±7.6^{NS}	95.1±0.8^{NS}	69.7±4.2^{NS}
SE	46.4±3.8^{NS}	96.1±1.1^{NS}	71.3±2.4^{NS}
T+SE	41.9±5.0^{NS}	92.2±0.9^{NS}	67.1±3.0^{NS}
WW	44.3±6.7^{NS}	95.9±1.6^{NS}	70.1±4.1^{NS}

NS indicated non-significance of treatment difference

Water stress during the SEP only (SE treatment), expectedly did not affect PAR capture, because GLAI was not affected (Figure 6.8 and Table 6.3).

GLAI of the T+SE treatment, however, was significantly lower than that of the WW treatment, resulting in a 3.7% reduction in PAR captured through the SEP (Figure 6.8 and

Table 6.3). Therefore through the season (i.e. TP and SEP) 3% less PAR was captured (Table 6.3).

6.2.5 Stalk elongation

Tillering phase:

RSER values of the T and T+SE treatments dropped sharply when ASW dropped below 40 mm (60% of ASWC), reaching values as low as 0.1 (Figure 6.9a and b). RSER rapidly increased when rainfall refilled the soil profile, and in some cases exceeded a value of one, suggesting that stalks briefly grew at rates faster than the WW treatment. This suggests that the crop was able to compensate for slow growth during short periods of mild water stress. This response is due to cells regaining turgor pressure after re-watering (Hsiao, 1973; Inman-Bamber, 1995).

The average SER for the TP phase of the T and T+SE treatments were between 0.12 and 0.14 cm/day lower than that of the WW treatment (Table 6.2). This eventually affected stalk height with the first significant difference between these treatments and the WW treatment detected 105 DAC (Figure 6.10). At the end of the phase the T and T+SE treatments were 15 to 18 cm (21 to 25%) shorter than the WW treatment (Table 6.2).

For reasons unknown, the SE treatment had a higher average SER (0.08 cm/day) than the WW treatment, resulting 11 cm (15%) taller stalks at the end of the TP, even though it received the same amount of water (Figure 6.10, Figure 6.11 and Table 6.2).

Stalk elongation phase:

As soon as the TP water stress was relieved in the T treatment, it accelerated its growth rate to similar or higher levels than that of the WW treatment (Figure 6.9a). This resulted in the gradual reduction in the difference in stalk height from 15 cm (21%) at the start of the phase to about 11 cm (5%) at 1st lodging (Figure 6.10 and Table 6.2). It therefore seems that crops can recover from a mild water stress during the TP through enhanced stalk growth rate after the stress event.

The RSER of both the SE and T+SE treatments rapidly declined with declining ASW to levels of between 0.2 and 0.4 when ASW was low (Figure 6.9b and Figure 6.11). When

rainfall increased ASW, RSER of the SE and T+SE treatments increased and often exceeded values of 1.

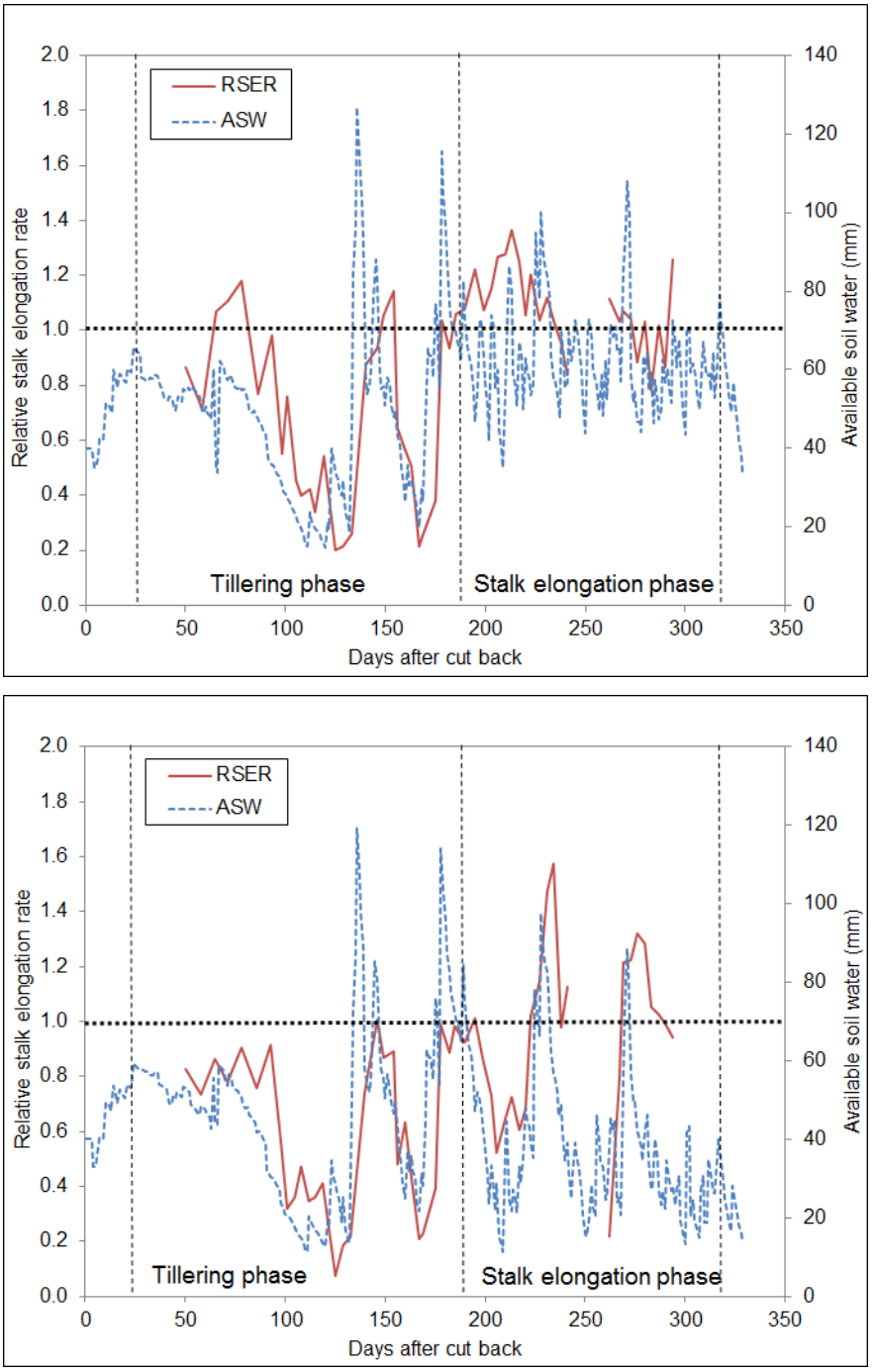

Figure 6.9: Relative stalk elongation rate (RSER) and available soil water (ASW) for the T (a) and T+SE (b) treatments during the tillering and stalks elongation phases of the ratoon crop. The black horizontal dotted line indicates RSER = 1.

Average SER for the SEP of the SE and T+SE treatments were similar and significantly lower (0.15 to 0.25 cm/day) than that of the WW treatment (Table 6.2). This eventually caused a reduction in stalk height in the SE treatment compared to the WW treatment, but

this difference was not statistically significant (Figure 6.10). Stalks in the SE treatment were 13 cm (6%) shorter at 1st lodging, and 20 cm (8%) shorter at final harvest than that of the WW treatment (Table 6.2).

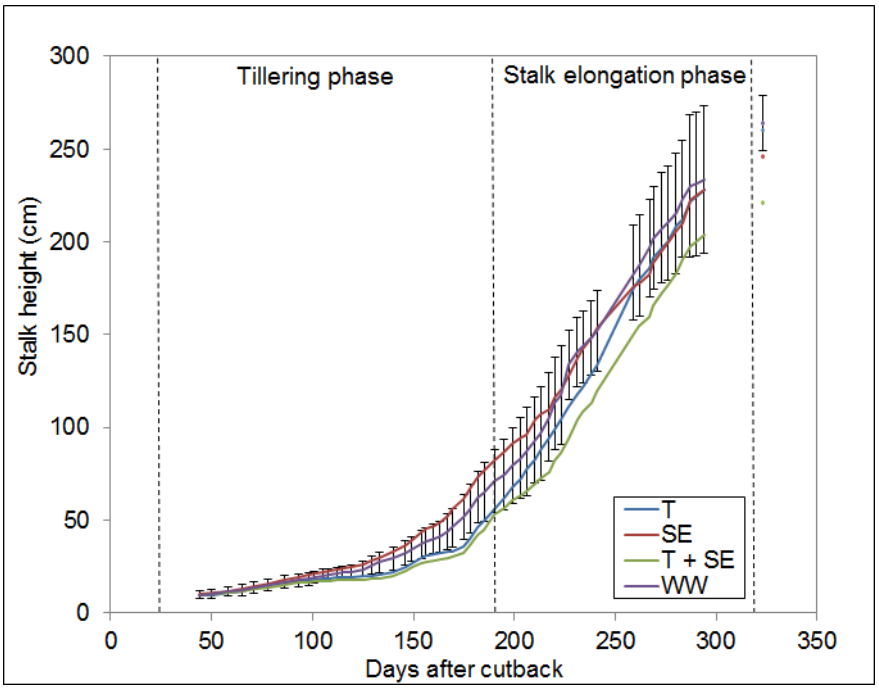

Figure 6.10: Stalk height over time for the different treatments in the ratoon crop. Vertical bars represent the standard deviation of the WW treatment.

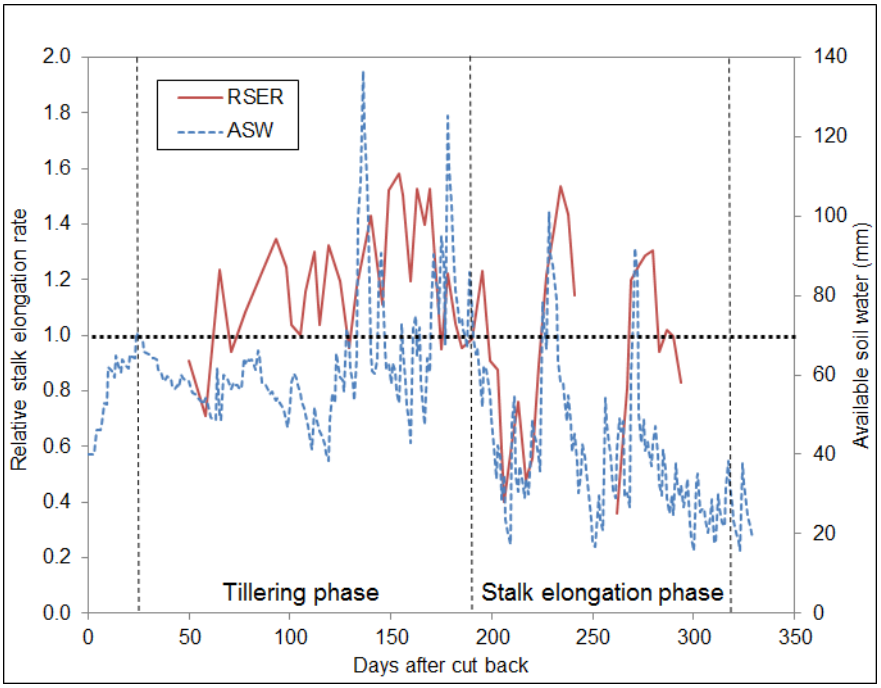

Figure 6.11: Relative stalk elongation rate (RSER) and available soil water (ASW) for the SE treatment during the tillering and stalks elongation phases of the ratoon crop. The black horizontal dotted line indicates RSER = 1.

The slower SER of the T+SE treatment gradually increased the difference in stalk height between this treatment and the WW treatment from 18 cm at the start of the phase, to 32 cm (14%) at the 1st lodging event, and 40 cm (15%) at final harvest (Table 6.2).

6.3 Biomass production and partitioning

Tillering phase:

The unstressed treatments (WW and SE) expectedly had similar stalk dry mass (SDM), green leaf dry mass (GLDM), trash dry mass (TRDM) and total dry mass (TDM) at the end of the phase and partitioned about 30% of TDM to stalks, 65% to green leaves and the remaining 5% to trash (Table 6.4).

The stressed treatments (T and T+SE) had significantly lower SDM (2.31 to 2.38 t/ha reduction), TRDM (0.21 to 0.31 t/ha reduction) and TDM (3.64 to 3.71 t/ha reduction) than the unstressed treatments (Table 6.4). GLDM was also reduced, albeit insignificantly. Significantly less (13.6 to 14.6%) biomass was partitioned towards stalks, and significantly more (14.6 to 14.8%) to leaves, in the stressed treatments, compared to the unstressed treatments. The trash partition fraction did not differ significantly between the stressed and unstressed treatments.

Stalk elongation phase:

At the 1st lodging event the stressed SE and T+SE treatments had lower SDM (1.6 to 4.5 t/ha reduction), GLDM (1.5 to 1.8 t/ha reduction), TRDM (0.68 to 2.88 t/ha reduction) and TDM (4.1 to 8.9 t/ha reduction) than the WW treatment (Table 6.4). Although most of these reductions were not significant, the TDM and TRDM were in proportion to the duration of the water stress in each treatment.

Water stress in the SEP had little effect on biomass partitioning as the only significant difference in partition fractions were between the T+SE and WW treatments, where 4% more biomass was partitioned to trash in the T+SE treatment.

Table 6.4: Dry mass yield of different biomass components (in t/ha and as a percentage of the total; mean ± standard deviation) for each treatment at the end of the tillering phase, after the 1st lodging event and at final harvest, and fresh cane and sucrose yields at harvest.

Crop stage	Component	Treatments				Significance
		T	SE	T+SE	WW	
End of tillering phase (t/ha)						
	Stalk	1.41±0.24[a]	3.85±0.73[b]	1.48±0.19[a]	3.79±0.51[b]	*
	Green leaves	6.80±1.18	8.48±1.17	6.76±0.86	7.84±1.19	NS
	Trash	0.45±0.08[a]	0.61±0.05[b]	0.35±0.09[a]	0.66±0.13[b]	*
	Total	8.66±1.35[a]	12.94±1.87[b]	8.59±0.91[a]	12.30±1.54[b]	*
End of tillering phase (%)						
	Stalk	16.3±1.66[a]	29.6±1.98[b]	17.3±1.93[a]	30.9±3.05[b]	*
	Green leaves	78.3±2.44[b]	65.6±1.88[a]	78.5±2.46[b]	63.7±3.61[a]	*
	Trash	5.34±1.31	4.78±0.77	4.13±1.41	5.41±0.82	NS
1st lodging event (t/ha)						
	Stalk	27.8±2.12	29.8±2.63	26.9±2.84	31.4±4.54	NS
	Green leaves	11.69±2.86	9.29±0.89	9.56±0.91	11.06±2.83	NS
	Trash	7.45±0.74[a]	9.89±1.19[b]	7.67±0.33[a]	10.55±1.26[b]	*
	Total	46.9±5.44	48.9±4.12	44.1±4.13	53.0±7.86	NS
1st lodging event (%)						
	Stalk	59.4±2.68	60.8±1.03	60.9±1.26	59.3±2.07	NS
	Green leaves	24.6±3.31[b]	19.0±0.86[a]	21.7±0.52[a]	20.7±1.64[a]	*
	Trash	15.9±1.09[a]	20.2±1.76[b]	17.4±0.90[a]	20.0±1.15[b]	*
Final harvest (t/ha)						
	Stalk	31.3±4.78	33.9±3.56	32.0±4.89	32.5±4.01	NS
	Green leaves	7.18±1.03	7.43±0.59	8.02±1.60	7.50±1.56	NS
	Trash	9.24±1.30	11.09±1.35	10.41±1.70	9.33±2.97	NS
	Total	47.7±6.53	52.4±4.91	50.5±8.06	49.3±6.81	NS
Final harvest (%)						
	Stalk	65.5±2.16	64.6±1.70	63.5±0.84	66.1±4.64	NS
	Green leaves	15.0±0.86	14.2±0.79	15.8±1.12	15.1±1.46	NS
	Trash	19.5±1.88	21.2±1.66	20.6±0.59	18.8±4.26	NS
Cane yield (t/ha)						
Load cells		144±10.05[bc]	132±4.57[ab]	122±8.00[a]	152±13.66[c]	*
Sampling		140±25.5	136±12.8	130±23.0	148±14.8	NS
Sucrose yield (t/ha)						
Load cells		15.2±1.92	16.4±0.52	14.9±0.58	16.0±1.79	NS
Sampling		14.6±2.18	16.9±1.59	15.9±2.47	15.6±2.19	NS

* indicate significance at $P \leq 0.05$, and NS indicated non-significance of treatment difference.

The favourable water status experienced during the SEP by the T treatment allowed it to achieve similar SDM (3.6 t/ha lower), GLDM (0.63 t/ha higher) and TDM (6.1 t/ha lower) to that of the WW treatment. TRDM remained significantly lower (3.1 t/ha) than the WW treatments (Table 6.4). In comparison to the WW treatment, a significantly higher fraction (3.9%) of biomass was partitioned to green leaves than in the T treatment, while a significantly lower fraction (4.1%) was partitioned to trash.

Final harvest:

The TDM yields of the SE and T+SE treatments which did not lodge at the 1st lodging event increased by 3.5 and 6.4 t/ha, respectively, from the 1st lodging event until final harvest. On the other hand the TDM yields of the lodged T and WW treatments from the 1st lodging event until final harvest increased by 0.8 t/ha and decreased by 3.7 t/ha, respectively. Therefore, regardless of the imposed water stress, biomass accumulation over the last month of the growing cycle was greater in the treatments which had not lodged, suggesting that lodging affected biomass production. Confounding effects of lodging masked the water stress effects, resulting in no significant differences between treatments in SDM, GLDM, TRDM or TDM (Table 6.4).

Results from both the load cell and destructive sampling techniques suggest that TP water stress reduced cane yield by 8 t/ha (5%), although this was statistically insignificant (Table 6.4). In a study by Pene & Edi (1999) cane yield was reduced by 3.4 (4%), 6.5 (7%), 1.0 (1%) and 2.9 (3%) t/ha (statistically insignificant) for different deficit irrigation treatments. Robertson *et al*. (1999) reported a slightly improved cane yield (7 t/ha or 5%) when irrigation was withheld during the TP of a plant crop, but reported a 24 t/ha (21%) reduction in the first ratoon crop. These large differences reported in literature were due to differences in the severity of the water stress imposed. Therefore results from the current study are similar to what has previously been found, namely that crops can recover from a water stress during the TP, provided the stress is not too severe.

Estimated magnitude of cane yield reduction due to water stress imposed during the SEP depended on measurement techniques. A statistically significant reduction of 20 t/ha (13%) was found when using the load cell technique, while a statistically insignificant reduction of 12 t/ha (8%) was found when using the destructive harvest technique (Table 6.4). These reductions were slightly lower than the 19% and 13% reductions reported by Pene & Edi

(1999) and much lower than the 40% reduction found by Robertson *et al.* (1999). This large difference is due to Robertson *et al.* (1999) imposing a severe water stress as irrigation was withheld for 56 days during the SEP. Results suggest that the smaller reductions in cane yield in the current study and in Pene & Edi (1999) was due to deficit irrigation maintaining growth and development processes closer to an unstressed crop than when irrigation was withheld.

The continuous water stress through both phases reduced cane yield by a significant 30 t/ha (20%) when determined using the load cell technique, while the destructive sampling technique suggests a 18 t/ha (12%) reduction (statistically insignificant) (Table 6.4). Pene & Edi (1999) reported a much larger yield reduction of 35.1 t/ha (38%) but this was in response to withholding irrigation through both development phases.

It is important to note that the differences in SDM and cane yields between treatments would possibly have been larger if the WW treatment had not lodged and continued to grow at the potential rate. Results suggest that the reduction in cane yield is dependent on the duration of the imposed water stress (Table 6.4).

It is also important to note that stalk dry matter content (SDMC) was very low in all treatments, ranging from 22 to 25% (Table 6.5). Typical values range from 30 to 35% (Inman-Bamber, 2004). The low SDMC in the current study was due to a very short drying-off period of 12 days.

The SDMC of the T and WW treatments was significantly lower (1.7 to 1.9%) than that of the SE and T+SE treatments (Table 6.5). This difference was firstly because the ASW during the SEP of the latter treatments was below 60% of capacity from 285 DAC until harvest (Figure 6.1b and c) while the ASW in the T and WW treatment only dropped below 60% of capacity during the drying-off period. Secondly, the dry-off period in the SE and T+SE treatments was more severe with a greater number of stress days, than for the T and WW treatments (Table 6.1).

It has widely been reported (for example Inman-Bamber & de Jager, 1988; Inman-Bamber, 2004) that water stress enhances sucrose accumulation. Therefore at final harvest the significantly lower (about 1.8%) sucrose content of stalks (SSC) in the T and WW treatments

compared to the SE and T+SE treatment is because the latter treatments endured a longer period of water stress (through the SEP and dry-off) while the T and WW treatments only endured a short 1 to 5 days of water stress during the 12 day drying-off period (Table 6.1 and Table 6.5).

Table 6.5: Cane quality measures on a fresh mass basis (mean ± standard deviation) at final harvest.

Measure	Treatments				Significance
	T	SE	T+SE	WW	
Sucrose content (%)	10.57±1.24^{a}	12.42±0.23^{b}	12.26±0.71^{b}	10.53±0.87^{a}	*
Non-sucrose content (%)	1.97±0.22^{b}	2.06±0.20^{b}	2.43±0.22^{c}	1.62±0.12^{a}	*
Fibre content (%)	10.1± 1.68	10.4±0.52	10.0±0.22	9.84±0.73	NS
Stalk dry matter content (%)	22.6±3.06^{ab}	24.9±0.87^{c}	24.7±0.80^{bc}	22.0±1.46^{a}	*

* indicate significance at $P \leq 0.05$, and NS indicated non-significance of treatment difference.

Pene & Edi (1999) also reported that deficit irrigation (25, 50 and 75% of Class A pan evaporation) during the TP or SEP had no effect on SSC at harvest. Findings from Robertson *et al.* (1999) contradict the current study and Pene & Edi (1999) because the SSC of a crop which endured 56 days with no irrigation during the SEP was found to have a significant 6% lower SSC than the unstressed crop. This was despite both crops enduring the same drying-off period. Robertson *et al.* (1999) found that withholding irrigation during the TP had no influence on SSC. Therefore it can be concluded that the deficit irrigation strategy adopted during the TP and/or SEP was not severe enough to affect the crops ability to accumulate sucrose during the drying-off period.

Although the SSC in the T and WW treatments were lower than the SE and T+SE treatments, sucrose yields were similar at harvest (Table 6.4). This result is because the treatments with the higher SSC had lower SDM than the treatments with lower SSC and hence nullifying differences in sucrose yields (Table 6.4 and Table 6.5). Similarly, Pene & Edi (1999) also found that sucrose yield depended more on stress effects on cane yield than on SSC. Robertson *et al,* (1999) however, reported that withholding irrigation during the SEP significantly reduced sucrose yield by 8.4 t/ha (43%) due to the combined stress effect of a decreased SSC and decreased cane yield.

6.4 Summary

6.4.1 Effects of water stress during the tillering phase only:

- During the TP the T treatment received 127 mm (72%) less irrigation and used 50 mm (13%) less water than the WW treatment and endured 50 days of water stress. The imposed water stress had no effect on CWU in the subsequent unstressed SEP.
- SWP (0.25 and 0.40 m soil depths) of the T treatment fluctuated between -10 to -90 kPa during the TP and between -10 and -30 kPa during the unstressed SEP. The corresponding values for the WW treatment were -10 and -40 kPa and -10 and -60 kPa.
- Stalk population through the entire growing season was not affected by the water stress during the TP.
- Water stress during the TP reduced the GLN, GLAI and PAR capture of the T treatment, but during the following unstressed SEP the crop recovered and no differences in these parameters between the T and WW treatments were evident at final harvest.
- SER declined with the decreasing ASW but the plant compensated somewhat for the slower growth through accelerated SER during periods with favourable soil water status. On average, stalks in the T treatment grew 0.14 cm/day (30%) slower than those in the WW treatment and thus at the end of the TP, stalks were 15 cm (21%) shorter. Average SER for the SEP of the T treatment were slightly higher (0.03 cm/day or 2%) than the WW treatment and stalks were only 4 cm (1%) shorter at harvest.
- At the end of the TP SDM yield of the T treatment was reduced by 2.38 t/ha (61%), GLDM by 0.68 t/ha (9%), TRDM by 0.21 t/ha (32%) and TDM by 3.64 t/ha (30%), compared to the WW treatment.
- At the end of the TP about 15% less biomass was partitioned to stalks and about 13% more to leaves in the T treatment than in the WW treatment. These differences were no longer evident at final harvest.
- Water stress during TP reduced cane yield by 8 t/ha (5%), and sucrose yield by 0.8 t/ha (5%) and had no effect on SSC.

6.4.2 Effects of water stress during the stalk elongation phase alone:

- The SE treatment received 307 mm (80%) less irrigation, used 69 mm (10%) less water and endured 55 more days of water stress than the unstressed WW treatment.
- SWP (0.25 and 0.4 m) in the SE treatment fluctuated between -10 and -90 kPa when ASW was in the targeted stress range.

- Water stress during SEP had no effect on stalk population, GLN, GLAI or PAR capture.
- SER was very sensitive to ASW. Stalks had the ability to compensate somewhat for the reduction in SER during stress periods by accelerating SER during periods when soil water status was favourable (after irrigation or rain). The average SER of the SE treatment was 0.25 cm/day (15%) slower than that of the unstressed treatments and stalks were 13 cm (6%) shorter at the 1st lodging and 18 cm (7%) shorter at final harvest.
- Water stress during SEP had no effect on SDM, GLDM, TRDM and TDM or the partitioning fractions of any of these components.
- Cane yield was reduced by 20 t/ha (13%), while SSC and sucrose yield was increased by 1.89 units (18%) and 0.4 t/ha (3%), respectively.

6.4.3 Effects of water stress during the tillering and stalk elongation phases:

- The T+SE treatment received 426 mm (76%) less irrigation and used 163 mm (15%) less water than the WW treatment and endured 123 days of stress.
- SWP of the T+SE treatment fluctuated between -10 and -90 kPa, compared to -10 to -40 kPa (in the TP) and -10 to -60 kPa (in the SEP) for the WW treatment.
- The imposed water stress had no effect on stalk population throughout the crop.
- Although GLN was reduced by TP stress a similar GLN to that of the WW treatment was achieved in the SEP, despite the prolonged intermittent stress that was endured.
- The GLAI of the T+SE treatment was lower than the WW treatment at the end of the TP as well as after the 1st lodging event. However, at final harvest there were no differences.
- PAR capture was reduced for most of the growing period.
- In the T+SE treatment the compensatory ability of stalk growth continued through the and SEP. During the TP stalks grew 0.12 cm/day (26%) slower than the WW treatment and during the SEP they grew 0.15 cm/day (9%) slower. Consequently the slower growth rates resulted in stalks being 18 cm (25%) shorter at the end of the TP, 32 cm (14%) shorter at the 1st lodging event and 43 cm (16%) shorter at final harvest.
- Large differences between the T+SE and WW treatments in SDM (61% reduction), GLDM (14% reduction), TRDM (47% reduction) and TDM (30% reduction) were evident at the end of the TP. These differences were not evident anymore after the 1st lodging event because rainfall allowed the crop to recover somewhat.
- At the end of the TP the T+SE treatment partitioned 13.6% more biomass to stalks and 14% less to leaves than the WW treatment. The trash partitioning faction was similar for

these two treatments. At final harvest no differences in the partitioning fractions were evident.

- The imposed water stress reduced cane yield by 30 t/ha (20%), increased SSC by 1.73 units (16%) and decreased sucrose yield by 1.1 t/ha (7%)

The crop during the TP received 72% less water, consequently lowering CWU during the phase by 13%, stalk heights by 21%, affecting GLN and GLAI (i.e. canopy development) and altering the partitioning fractions of biomass towards stalks and leaves. However, maintaining the ASW above 60% of capacity during the SEP, allowed the crop to re-establish its canopy, restore the partitioning of biomass between components and regain a similar CWU to the unstressed WW treatment. Additionally during the unstressed SEP stalks elongated at a 2% faster rate than stalks in the unstressed treatment and thus at harvest stalks were only 1% shorter. Cane and sucrose yields were both reduced by 5%.

Irrigating the SEP with 80% less water reduced the CWU during this phase by 10% and had no effect on the crop canopy. The slower growth rate of stalks during the SEP resulted in stalks being 7% shorter. Cane yield was reduced by 13%, while sucrose yield was reduced by only 3%.

Deficit irrigation through the TP and SEP, aimed at maintaining ASW between 30 and 60% of capacity, resulted in 71% less water being irrigated, which in turn affected canopy development and PAR capture and reduced the seasonal CWU by 15%. At final harvest, stalk height were reduced by 16%, cane yield by 20% and sucrose yield by 7%.

CHAPTER 7: GENERAL DISCUSSION AND CONCLUSIONS

This chapter will focus on the effects of water stress imposed during different phases on crop water use (CWU, sum of evaporation and transpiration), canopy development, stalk elongation, biomass accumulation and partitioning and propose mechanisms of water stress impacts on yield. Thereafter soil water status thresholds for irrigation management are discussed and implications from the study for management of limited irrigation water are highlighted. Lastly, areas requiring further research are highlighted.

7.1 Crop water use

Findings from this study indicate that CWU is relatively insensitive to deficit irrigation during the tillering (TP) and stalk elongation phases (SEP) (Table 5.1 and Table 6.1) because the lower soil water content (SWC) levels allowed for more efficient use of rainfall (see Figure 5.1 and Figure 6.1). Therefore irrigation can be saved through deficit irrigation, given similar climate and soil conditions.

During the TP of the ratoon crop 127 mm (72%) of water was saved and resulted in the crop enduring a water stress for about 32% (50 days) of the phase (Table 6.1). This resulted in a 13% decline in CWU. However, relieving water stress during the SEP resulted in the crop using a similar amount of water during the SEP as the well-watered control (Table 6.1).

Water stress during the SEP resulted in large irrigation savings of 317 mm (40%) and 307 mm (80%) in the plant and ratoon crops, respectively (Table 5.1 and Table 6.1). Although water stress was endured during this phase in the plant (74 days, 35% of the phase) and ratoon crops (56 days, 44% of the phase), CWU was only reduced by about 7% and 10%, respectively.

Water stress during both phases (only occurred in the ratoon crop) caused 120 days of water stress (41% of both phases) which resulted in a 15% reduction in CWU (Table 6.1).

7.2 Canopy development

Water stress imposed through the TP or SEP of both crops had no effect on the emergence or senescence rates of stalks (Figure 5.6a and b, Figure 6.6 and Figure 6.7a). This differs from

the finding by Moreira & Cardoso (1998) and Robertson *et al.* (1999) that withholding irrigation during the TP reduced stalk emergence rate. Smit & Singels (2006) also found that the stalk senescence rate increased when irrigation (and rainfall) was withheld for a long period. This apparent contradiction is ascribed to more severe water stresses imposed in these studies than in the current study. Therefore it can be concluded that deficit irrigation, as applied in this study, had no effect on stalk development processes and hence on the population of stalks carrying the crop canopy.

TP water stress lowered the number of green leaves per stalk (GLN, Figure 6.7b), GLAI (Table 6.2) and canopy cover (CC, Figure 6.8 and Table 6.3) towards the end of the TP phase. However, the crop regained a similar GLN, GLAI and CC as the well-watered control when stress was relieved in the subsequent SEP. It is concluded that deficit irrigation during the TP, as applied in this study, only affects canopy development temporarily, and that the crop quickly re-establishes a canopy when stress is relieved during the SEP, enabling the crop to capture adequate amounts of photosynthetically active radiation (PAR) during this phase.

Water stress during the SEP affected GLN for a short period in the plant crop only (Figure 5.7). It is believed that the two big rainfall events in the ratoon crop brought stress relief that accelerated leaf emergence (Figure 6.1c and Figure 6.6), a phenomenon previously described by Inman-Bamber (1991, 2004) and Inman-Bamber & Smith (2005). There were no treatment differences at final harvest in both crops in GLN (Figure 5.7and Figure 6.7b), GLAI (Table 5.2 and Table 6.2) and CC (Figure 5.8 and Figure 6.8, Table 5.3and Table 6.3). These results therefore indicate that deficit drip irrigation during the SEP, as applied in this study, had no effect on the amount of PAR captured during this phase.

Water stress during both phases had no effect on GLN, but reduced GLAI and CC (Table 6.2). This lowered the PAR captured by the crop in the SEP (Figure 6.8 and Table 6.3). Therefore it is concluded that prolonged water stress through the growing cycle, even if it is mild and intermittent, affected the canopy and the crop's ability to capture PAR negatively.

7.3 Biomass accumulation and partitioning

Fresh biomass is composed primarily of water and water content can vary considerably depending on the plant's past and present water status. In these experiments, stalk moisture

contents of treatments differed markedly for reasons explained elsewhere. Therefore, dry biomass was used to compare treatments to avoid the confounding influence of varying moisture contents. In the ratoon crop, meaningful comparisons of values at final harvest between treatments were not possible due to the confounding effect of variable lodging (the WW and T treatments mostly lodged early, causing reduced growth, while the stressed treatments were largely unaffected). Therefore, water stress effects were investigated using destructive harvest data collected shortly after the 1st lodging event, instead of at the final harvest one month later.

TP water stress in the ratoon crop did not reduce the total dry biomass (TDM) at the 1st lodging event, although a reduction at the end of the TP was evident (Table 6.4). SEP water stress lowered TDM by about 15% and 8%, and stalk dry biomass (SDM) by about 13% and 5% respectively in the plant and ratoon crops (Table 5.4 and Table 6.4). Water stress throughout the TP and SEP reduced TDM and SDM by 17% and 14% respectively (Table 6.4). Therefore as expected, the longer the duration of the water stress imposed, the greater the reduction in biomass produced (Table 6.4).

Biomass partitioning was affected by water stress during the TP, with a lower fraction of biomass partitioned towards leaves and a higher fraction to stalks, in comparison to the WW treatment (Table 6.4). This is in agreement with the findings of Inman-Bamber *et al*. (2002). However stress release during the SEP restored partitioning ratios similar to that of the well-watered control. Water stress during the SEP had no effect on biomass partitioning in both crops, and thus the lower SDM of stressed treatments were largely due to the lower TDM produced (Table 6.4).

Stalk dry matter content (SDMC) and stalk sucrose content (SSC) were strongly related to the water stress experienced during the last part of the growing season leading up to the final harvest. In the plant crop all treatments experienced similar water stress (Table 5.1) during the drying-off period, resulting in similar SDMC and SSC values (Table 5.4). In the ratoon crop, differences in the extent of the water stress experienced during the drying-off period (Table 6.1) caused treatment differences in the SDMC and SSC (Table 6.5). Results suggest that mild, intermittent water stress imposed through deficit drip irrigation has little effect on the crop's ability to accumulate sucrose and that the severity and duration of the drying-off period was more influential.

This result confirms previous research (Gosnell & Lonsdale, 1974; Inman-Bamber & de Jager, 1988; Robertson *et al.*, 1999; Donaldson & Bezuidenhout, 2000; Singels *et al.*, 2000; Inman-Bamber & Smith, 2005) showing that that drying-off or mild water stress enhances sucrose accumulation. This enhancement is due to expansive growth being more sensitive to water stress than photosynthesis (Inman-Bamber & de Jager, 1988), causing photo-assimilates which are usually metabolised for expansive and structural growth, being stored as sucrose in the stalks.

7.4 Suggested mechanisms of sugarcane yield response to water stress

As mentioned previously, dry mass values were considered in this analysis, rather than fresh mass because of the differing SDMC of treatments in the ratoon crop. Also, data collected shortly after the 1st lodging event in the ratoon crop was used as a proxy for final yield to avoid the confounding effect of variable lodging on yields at final harvest, a month later. For the plant crop, dry mass yields at final harvest shortly after lodging were used.

Treatments differences in TDM and SDM, as well as other key yield contributing factors, relative to that of the well-watered control, are shown in Table 7.6. Possible mechanisms of yield response to water stress will now be explored using the following framework for yield formation:

> Yield (SDM in t/ha) is a product of stalk population (stalks/ha) and stalk mass (kg/stalk). Stalk mass is the product of stalk height (cm) and mass per unit length of stalk (kg/cm). The rate of stalk elongation (SER) will determine stalk height, while mass per unit stalk length is determined by the rate of photo-assimilate production. The latter process requires adequate energy (intercepted PAR) and high stomatal conductance during the SEP for rapid gas exchange. In this study, SER (stalk height) and PAR capture (CC) were measured. Photosynthesis and transpiration, the dominant component of CWU, are both dependant on gaseous exchange through leaf stomata, and would be similarly affected by variations in stomatal resistance (Giorio & d'Andria, 1999). Therefore CWU is considered a good proxy of the photo-assimilate production potential of the crop.

Table 7.6: Differences in stalk population, photosynthetically active radiation (PAR) capture, stalk height, crop water use (CWU), cane yield, stalk dry matter content (SDMC), total dry biomass (TDM), and stalk dry biomass (SDM) between a given treatment and the well watered control (WW treatment), expressed as a percentage of the value for the well-watered control. The T treatment in the plant crop was not reported because water stress was not endured by this treatment. In the plant crop, differences are those which occurred at final harvest, while in the ratoon crop they were those that occurred shortly after the 1st lodging event.

	Treatments	Stalk population (%)	PAR capture (%)	Stalk height (%)	Cane yield[1] (%)	SDMC (%)	TDM (%)	SDM (%)
Plant crop	SE	-2.80^{NS}	-10.18^{NS}	-7.08^{NS}	-10.40^{NS}	-0.50^{NS}	-12.12^{NS}	-12.46^{NS}
	T+SE	-8.39^{NS}	-2.44^{NS}	-6.69^{NS}	-17.61^{NS}	+0.08^{NS}	-17.69^{NS}	-17.28^{NS}
Ratoon crop	T	+3.87^{NS}	-0.63^{NS}	-4.93^{NS}	-9.19^{NS}	-0.49^{NS}	-11.51^{NS}	-11.46^{NS}
	SE	+5.16^{NS}	+1.64^{NS}	-5.83*	-9.88^{NS}	-1.17^{NS}	-7.74^{NS}	-5.10^{NS}
	T+SE	+7.74^{NS}	-4.35^{NS}	-14.35*	-17.01*	-0.67^{NS}	-16.79^{NS}	-14.33^{NS}

* Significance at $P \leq 0.05$; NS non-significance of treatment differences
[1] Determined through destructive sampling

Bearing the above framework in mind it is evident that mild and intermittent water stress, as imposed in this study, had no effect on peak stalk population or on final stalk population in any of the crops (Figure 5.5, Figure 6.5 and Table 7.6). Moreira & Cardoso (1998), Robertson *et al.* (1999) and Smit & Singels (2006) found reductions in stalk population but this was in response to prolonged periods of severe water stress. It is concluded that stalk population had no influence on yield variation observed in this study.

SER was very responsive to changing available soil water (ASW), declining as ASW declined and resurging when the soil was wetted (Figure 5.9a and b, Figure 5.10, Figure 6.9 a and b and Figure 6.11). Resurgence in SER during periods when stress was relieved could not however completely negate the reduced growth rate during periods of declining ASW. On average SEP stressed stalks elongated 14% slower than that of the well-watered control (Table 5.2 and Table 6.2). This resulted in an insignificant reduction in stalk height in the SE and T+SE treatments in the plant crop while for the same treatment in the ratoon crop stalk heights were significantly reduced, compared to the well-watered control (Table 7.6). Relieving the TP stress during the SEP allowed the T treatment to produce stalks of a similar height to the well-watered control (Table 7.6). SEP water stress induced reductions in stalk

height were larger than reductions in CWU, confirming that stalk elongation is more sensitive to water stress than CWU and presumably photo-assimilate production. This has previously been reported by Inman-Bamber & de Jager (1986b).

Water stress during the TP affected the crop canopy only during this phase. Due to the rapid re-establishment of the canopy during the unstressed SEP the average amount of PAR captured was similar to that of the well-watered control (Table 6.3 and Table 7.6). CWU was also affected only during the TP, and was similar to that of the well-watered control during the SEP (Table 6.1 and Table 7.7). Therefore the ability of the crop to accumulate biomass during the SEP was not affected by TP stress as the primary resources needed for carbon fixation were not limiting.

Table 7.7: Differences in irrigation applied, the duration of the water stress endured and crop water use (CWU) between a given treatment and the well-watered control (WW treatment), expressed as a percentage of the value of the well-watered control. In the plant crop, differences are those which occurred at final harvest while in the ratoon crop they were those that occurred shortly after the 1st lodging event.

	Treatments	Irrigation applied (%)	Water stress duration (%)	CWU (%)
Plant crop	SE	-29.1	+16.3	-3.06
	T+SE	-44.6	+23.7	-3.98
Ratoon crop	T	-23.4	+15.3	-4.97
	SE	-51.5	+12.6	-4.27
	T+SE	-73.9	+34.2	-13.7

Water stress during the SEP had no effect on the crop's ability to intercept PAR in any of the crops. The reduction in SDM of the SEP stressed treatments are therefore ascribed to reduced photo-assimilate production, as suggested by the observed reduction in CWU (Table 5.1, Table 6.1and Table 7.7). Water stress during the TP and SEP caused a prolonged reduction in PAR intercepted (Figure 6.8) and CWU (Table 7.7). Therefore both primary resources required for biomass production were affected negatively by prolonged water stress, even though the stress was mild and intermittent.

Evidently, SDM yields were reduced in all stressed treatment in both crops, although not significantly, because of a combination of shorter stalks and a lower production of photo-assimilates. The large reductions in SDM yield was found for the crop which endured water

stress for most of the growing cycle (T+SE treatment) (Table 7.6). This result was expected because both stalk elongation and photo-assimilate production were suppressed for the longest time during this treatment in comparison to the others.

The larger reduction in SDM observed in the T treatment of the ratoon crop was not significant but was unexpected and needs some discussion (Table 7.6). Stalks at 1st lodging were about 5% shorter (not significant), similar to that of the SE treatment. The duration of water stress was similar to that of the SE treatment, as was the reduction in CWU (Table 7.7), suggesting that SDM yields should have been similar to that of the SE treatment (Table 7.6). PAR capture and stalk population was not affected by water stress, and could not have contributed to the yield reduction. No logical explanation is therefore apparent for the relatively large reduction in yield. The fact that all treatment differences in SDM yield were not significant, suggest that more precision is required in the biomass sampling techniques.

Finally, in terms of the studies hypotheses, H_1 can be accepted because the T treatment recovered during the SEP and H_2 can also be accepted because SDM yield did decline, although not significantly, as a result of the imposed water stress during the SEP. H_3 was not tested because rainfall during the TP of the plant crop prevented the T treatment from enduring a water stress. H_4 could also not be tested because of differences in the length of individual stress periods and the total number of stress days endured by both crops during the SEP.

7.5 Soil water status thresholds for irrigation scheduling

It is argued that the well-watered treatments in this study experienced little or no water stress and had a favourable soil water status for most of the growing period, excluding the drying-off periods. Simulations by the MyCanesim sugarcane model (Singels, 2007), assuming optimal irrigation, predicted SDM yields of 31.5 t/ha and 27.2 t/ha for the well-watered plant and ratoon crop, respectively, compared to actual yields of 35.3 t/ha and 32.5 t/ha (Table 5.4 and Table 6.4). A further indication that the well-watered controls did not experience significant water stress is that, apart from a few exceptions, ASW remained above 50% of capacity (Table 5.1, Figure 5.1d, Table 6.1and Figure 6.1d). The 50% of ASWC threshold is a well-established rule of thumb for water stress (Singels *et al*., 2010).

The chosen depletion level for the well-watered control treatments was 60% of ASWC, which is equivalent to a SWC of 216 mm/m and corresponds to a SWP of about -40 kPa (see soil water retention curves in Annexure E, Figure 5.2d and Figure 6.2d). It is therefore suggest that the SWP, as monitored in this study, can be allowed to drop to about -40 kPa before irrigation is applied, without sacrificing cane or sucrose yields.

Results also suggest that once the soil profile has been refilled after harvest that SWP can drop as low as -80 kPa during the TP without affecting cane, SDM or sucrose yields, provided that the SWP is maintained above -40 kPa during the subsequent SEP (see Figure 6.2a). Similar results have also been found when more severe water stresses were imposed (Robertson *et al.*, 1999; Pene & Edi, 1999).

The chosen depletion levels of the stressed treatments were 30% of ASWC, which corresponds to a SWC of 184 mm/m and a SWP of less than -90 kPa (see soil water retention curves in Annexure E, Figure 5.2c and Figure 6.2c). Allowing the SWP to decline to -90 kPa during the SEP produced a cane and sucrose yield of about 87% and 96% of potential, respectively. These results therefore suggest that during dry seasons reasonable yields can be achieved with limited water using deficit irrigation as done in this study.

7.6 Implications

Results from the ratoon crop clearly shows that cane and sucrose yields are relatively insensitive to deficit drip irrigation during the TP, due to crops' ability to rapidly re-establish its canopy, capture adequate PAR and restore rates of photo-assimilation and stalk elongation to support rapid biomass production in the subsequent SEP. Results obtained suggest that using this irrigation strategy will allow growers to save a substantial amount of water, depending on rainfall.

Deficit irrigation allows for more efficient use of rainfall because the ability of the soil to retain rainfall in the root zone is improved. This means that less rainfall is lost through deep drainage and run off. Leaching of nutrients will also be reduced.

Deficit drip irrigation using a SWP threshold of around -40 kPa during the TP and SEP, maintained the water status of the soil at a level which did not affect sugarcane growth and development and hence final cane and sucrose yields.

Deficit drip irrigation using a SWP threshold of about -80 kPa during the SEP of the plant and ratoon crop, resulted in a cane yield of about 87% of the unstressed potential and a sucrose yield of greater than 96% of the potential.

Significant differences in SDM and sucrose yields between treatments which endured the stress in different phases were not evident. Therefore it was not possible to distinguish which development phase was most sensitive to the imposed water stresses.

Drying-off is a good strategy to adopt because it not only encourages sucrose accumulation but also raises the SDMC. This means that less "water" is transported to the mill, thereby raising the economic value of cane and reducing transport costs.

7.7 Recommendations for further research

In this section recommendations for further research which were beyond the scope of this study are listed:

- The applicability of the results in this study need to be tested on different cultivars as cultivars are known to differ in their tolerance to water stress (Olivier & Singels, 2003; Inman-Bamber & Smith, 2005; Smit & Singels, 2006).
- The applicability of ASW and SWP thresholds determined for drip irrigation in this study needs to be tested in different soils because the lateral conductivity of water in sandy soils is less than in clayey soils resulting in different wetting patterns below emitters.
- The placement of soil water monitoring instruments relative to drip emitters and cane rows also requires further investigation. The SWP measured below the emitter will be higher (less negative) than the SWP measured halfway between emitters and scheduling thresholds will have to be adjusted accordingly.
- It was difficult to calibrate the neutron water meter (NWM) for the soil in the current study. The correlation between gravimetrically determined soil water content and

NWM counts was mediocre. A reliable calibration is obviously critical in crop water relation studies like this one, as it is used to estimate crop water use and schedule irrigation. There is therefore a need to investigate alternative more reliable methods to determine soil water content

- Investigate the profitability of adopting a deficit irrigation strategy by exploring the trade-off between reduced electricity, harvesting and transporting costs and reduced income due to slightly lower yields.
- The study highlighted the precision required in research sampling methods when investigating effects of mild water stress. Sampling error should be reduced to allow confident determination of small but significant differences in yield. This can be done by increasing sample size and numbers.

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ANNEXURE A: SOIL TEXTURE ANALYSIS

Table A1: Soil texture was analysed by the Soil Physics laboratory of the South African Sugarcane Research Institute (SASRI). Eight sub-samples were taken from soil mixed from 20 samples collected at different locations in the field at depths of 0.25 and 0.4 m.

Sample Number	Sand (%)		Silt (%)		Clay (%)	
	0.25 m	0.4 m	0.25 m	0.4 m	0.25 m	0.4 m
1	44	52	18	14	38	34
2	44	56	16	12	40	32
3	46	42	14	18	40	40
4	50	58	14	14	36	28
5	44	54	18	14	38	32
6	42	58	20	14	38	28
7	46	54	16	12	38	34
8	40	56	19	12	41	32
Average	44	53	17	14	39	33

ANNEXURE B: SOIL CHEMICAL ANALYSIS.

Table B1: These soil analysis results were used by the South African Sugarcane Research Institutes (SASRI) Fertilizer Advisory Service (FAS) to make fertilizer recommendations.

Analysis	Unit	Sample values		
		Plant Crop Block (Sample taken prior to planting)	Ratoon Crop Block (Sample taken prior to planting)	Ratoon Crop Block) (Sample taken after cut back)
pH (in calcium chloride)		6.55	6.3	6.0
Phosphorus (Ambic)	mg/L	16.7	4.8	288.3
Potassium (K)	mg/L	529	380	261
Calcium (Ca)	mg/L	4268	4018	4108
Magnesium (Mg)	mg/L	555	667	611
Sodium (Na)	mg/L	211	296	312
Exchangeable Acidity (AI+H)	cmol/L	0.04	0.01	0.01
Total Cations	cmol/L	28.22	27.85	27.6
Acid Saturation	%	0.14	0.04	0.04
Exchangeable Sodium % (ESP)	%	3.0	5.0	4.9
Ca/ Mg (Equivalence ratio)		4.7	3.7	4.1
Zinc (Zn)	mg/L	0.9	1.0	1.9
Copper (Cu)	mg/L	11.7	15.1	17.9
Manganese (Mn)	mg/L	10.0	12.0	8.9
Silicon (Si)	mg/L	41.0	41.0	43.6

ANNEXURE C: LEAF ANALYSIS

Table C1: Leaves from the ratoon crop at a crop age of 5½ months were sampled from each treatment and analysed by SASRI's FAS. Fertilizer topdressing advice was based on these results.

Analysis	Unit	Leaf sample values			
		T	SE	T+SE	WW
Nitrogen (N)	%	1.65	1.58	1.68	1.69
Phosphorous (P)	%	0.18	0.17	0.17	0.16
Potassium (K)	%	1.03	0.90	1.00	1.07
Calcium (Ca)	%	0.22	0.24	0.22	0.23
Magnesium (Mg)	%	0.16	0.19	0.16	0.18
Sulphur (S)	%	0.14	0.15	0.15	0.18
Zinc (ZN)	%	1.55	1.60	1.50	1.69
Silicon (Si)	ppm	13.63	14.18	13.32	12.48
Manganese (Mn)	ppm	25.64	31.28	26.12	59.17
Copper (Cu)	ppm	5.26	5.71	6.10	5.68
Iron (Fe)	ppm	106.89	102.35	102.33	114.66

ANNEXURE D: NEUTRON WATER METER CALIBRATION RELATIONSHIP

The calibration equation shown in Figure D1 was used to convert count ratios (CR) obtained using the neutron water meter (NWM) from all soil depths (0.25, 0.5 and 0.62m depths) to volumetric soil water content (SWC in %).

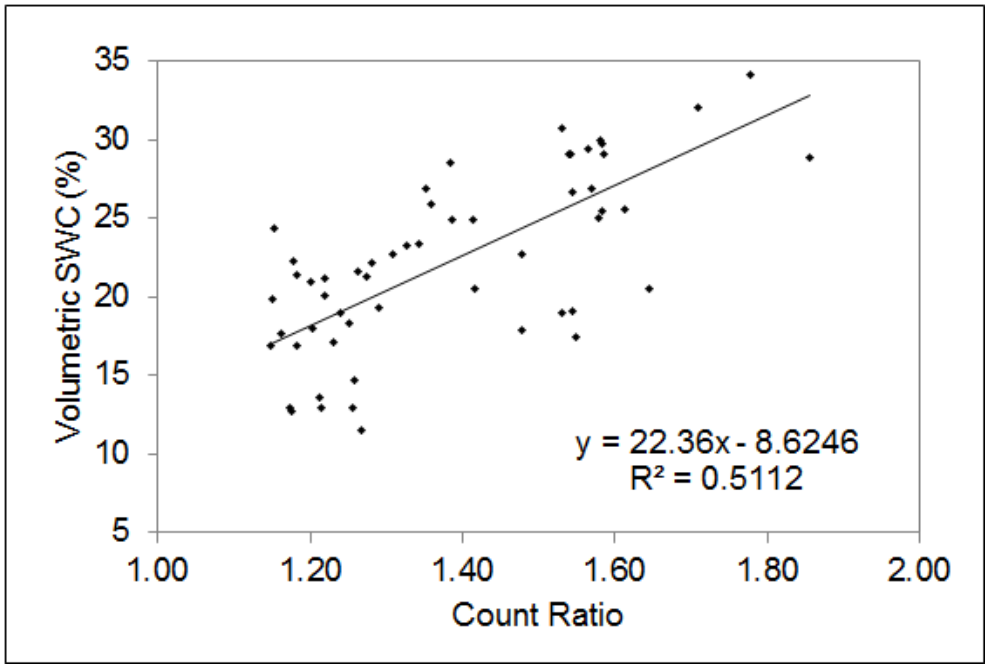

Figure D1: Goodness of fit line determined for the neutron water meter.

The goodness of fit of the NWM calibration was disappointingly poor (Figure D1, R^2 =0.51). A rocky layer occurred at varying depths of between 40 to 70 mm in the experimental area which may have contributed to the poor calibration because soil cores were taken within an infield calibration plot and from the plant and ratoon crop fields. In previous studies poor R^2 values for the same field on the research station were also obtained (Olivier *et al.*, 2006, Olivier *et al.*, 2009).

The reliability of the combined NWM calibration was investigated by comparing it with calibrations for individual soil layers (0.25, 0.40 and 0.55 m). The R^2 values for the 0.25 and 0.55 m layer calibrations were relatively good, while that of the 0.4 m layer was poor (Table D1).

Table D1: Calibration parameters for the combined and individual layer calibrations.

	Combined calibration	Individual layer calibrations		
		0.25 m	0.40 m	0.55 m
Slope (CR)	22.36	21.45	18.83	25.34
Intercept (%)	-8.62	-4.44	-3.57	-16.03
R^2	0.51	0.76	0.48	0.69

Applying individual layer calibrations to estimate profile average soil water content gave almost the same values than applying the combined calibration. An example for three soil water content levels is given in Table D2.

Table D2: Comparisons between the combined and individual layer calibrations and how the volumetric SWC (%) estimates differ.

Count ratio	Volumetric SWC (%)					
	Combined calibration	Individual layer calibrations				Difference between combined and individual layer calibrations
		0.25 m	0.40 m	0.55 m	Average	
1.50	25	27.81	24.74	22.07	24.88	-0.12
1.28	20	23.02	20.53	16.41	19.99	-0.01
1.06	15	18.22	16.32	10.74	15.09	0.09

From this investigation it can be concluded that although the R^2 value of the combined calibration was poor, suggesting a low accuracy, it estimated volumetric SWC similarly to what was estimated using the average of individual layer calibrations, which had higher R^2 values (Table D2). Therefore in this study the combined calibration was selected to estimate volumetric SWC (%).

ANNEXURE E: SOIL WATER RETENTION

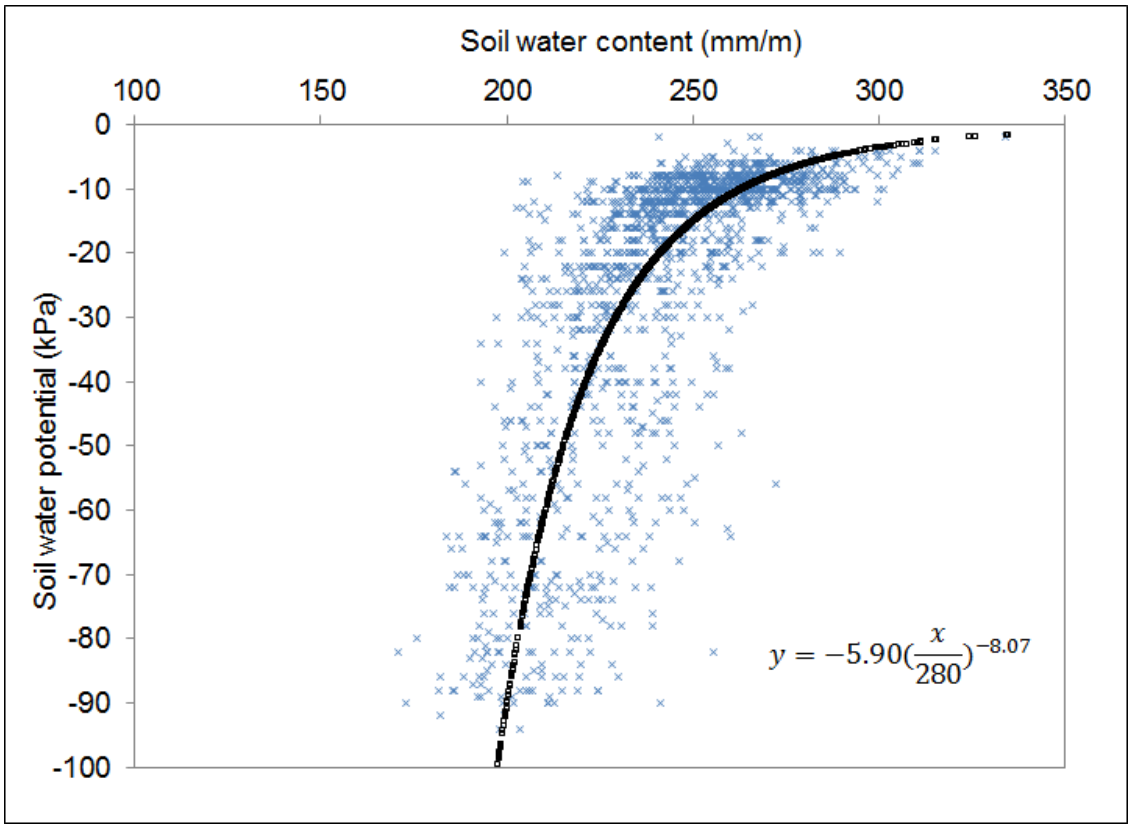

Figure E1: Soil water retention curve created using soil water potential and soil water content data collected in this study. No significant differences between the retention curves at 0.25m and 0.40m soil depths were evident. The relatively large scatter of points around the curve is attributed to spatial variation in the soil across the plant and ratoon crop blocks.

ANNEXURE F: TRIAL DESIGN

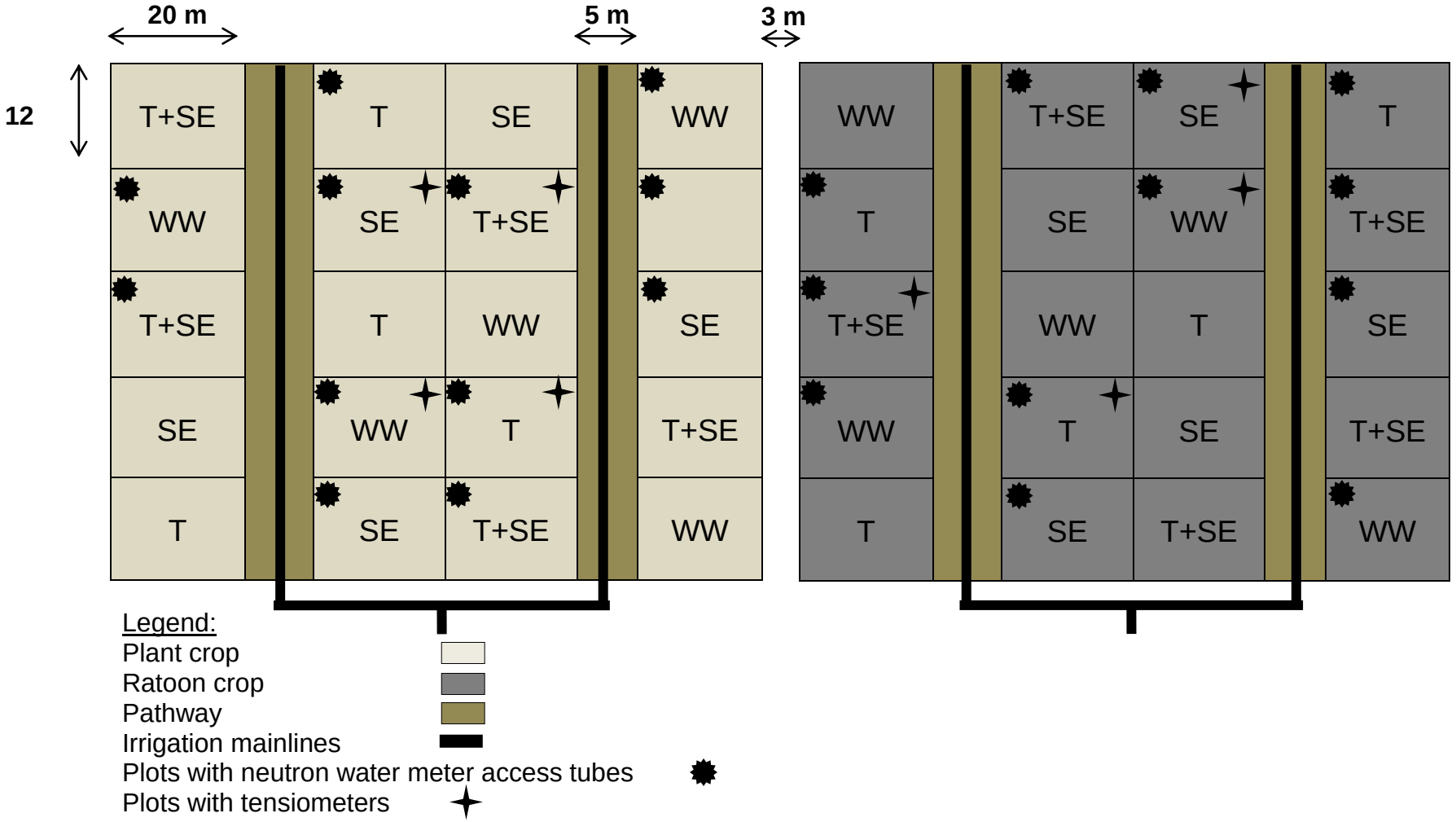

Figure F1: Diagram showing the treatments (T= tillering phase, SE= stalk elongation phase, T+SE= tillering and stalk elongation phase, WW= well watered) and soil water status monitoring locations.

ANNEXURE G: LAYOUT OF DATA COLLECTION POINTS IN A PLOT

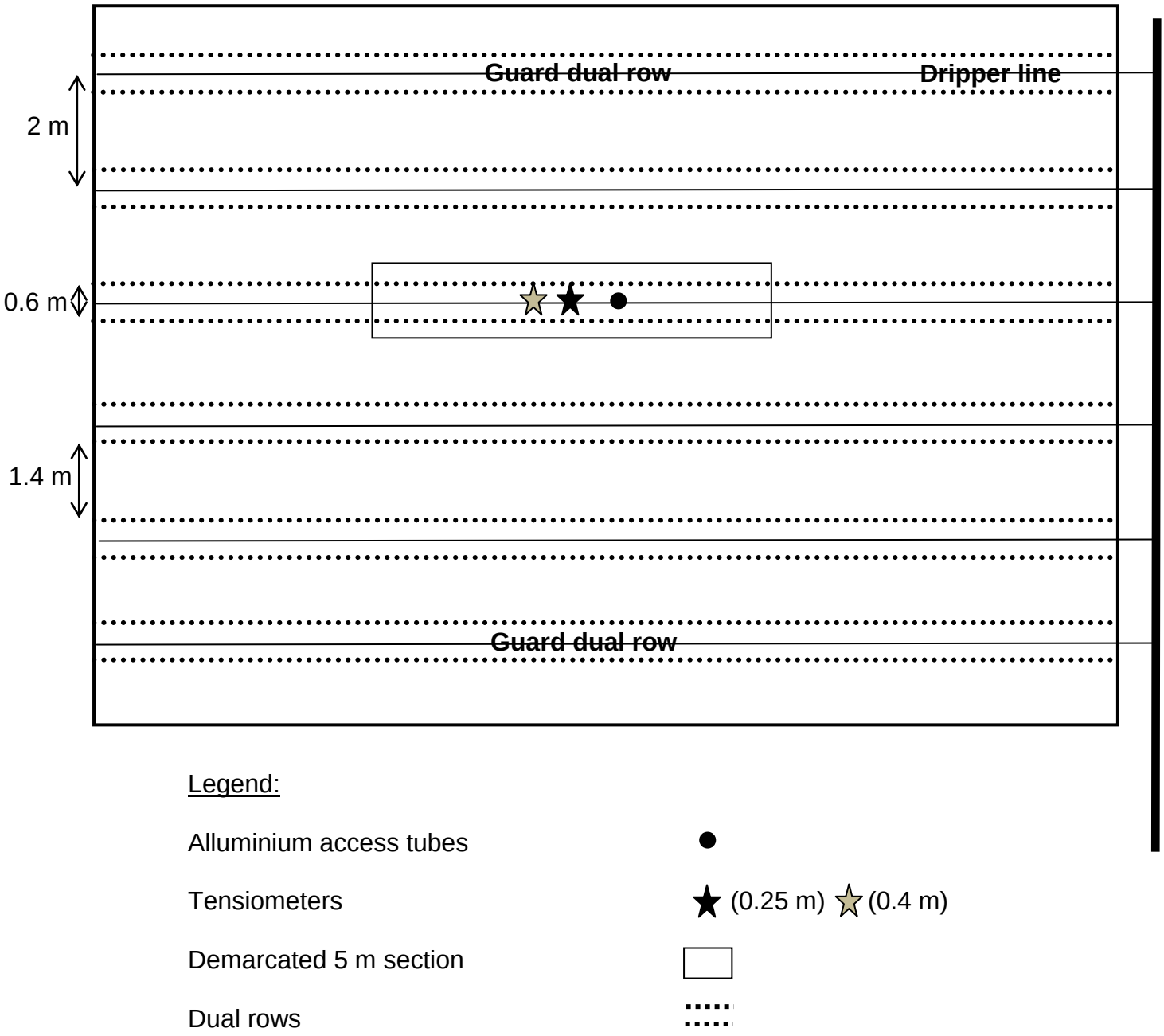

Figure G1: Diagram of a plot (12 x 20 m) showing the location of the aluminium access tubes, tensiometer and the demarcated 5 m sections were all non-destructive measurements were done.

ANNEXURE H: LODGING SKETCH MAP

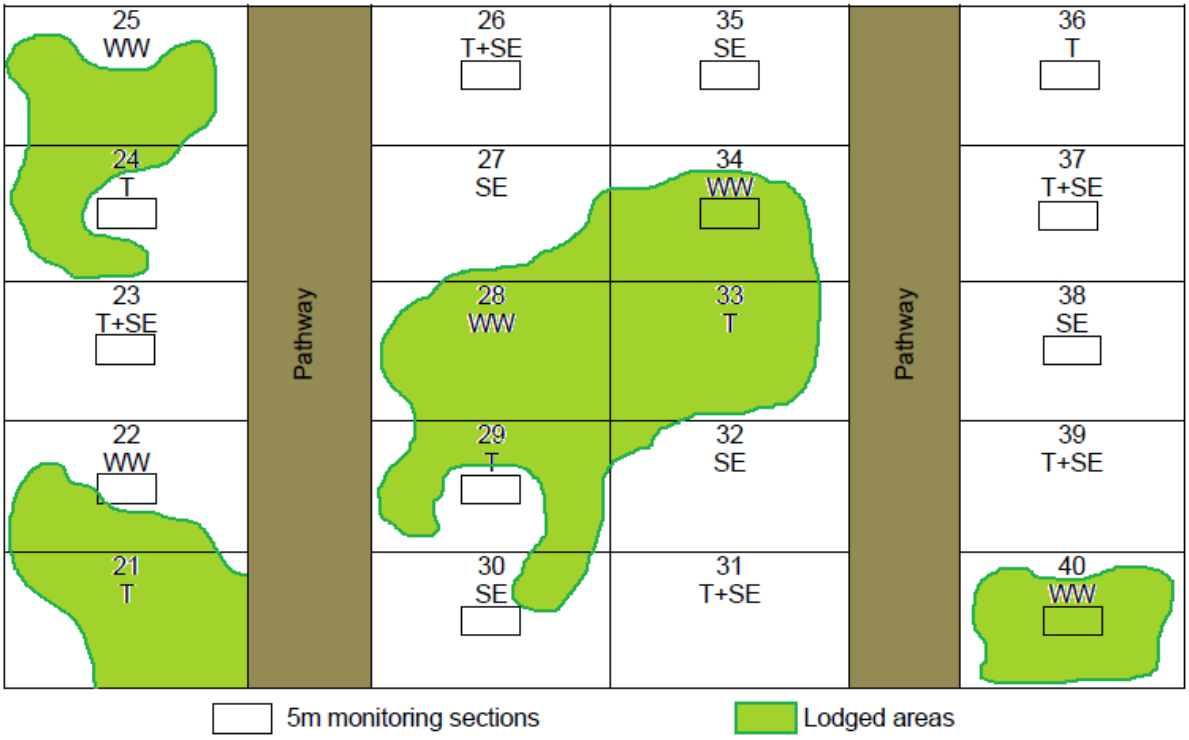

Figure H1: Sketch map showing the areas which lodged in the ratoon crop after 1st lodging (286 days after the cut back, DAC). Numbers in each plot are plot numbers which correspond to the lodge rating of each plot in Annexure I.

ANNEXURE I: LODGE RATINGS

Table I1: Lodge rating at the 1st and 2nd lodging events in the ratoon crop

Plot number	Lodge rating (%)	
	1st lodging event (286 DAC)	2nd lodging event (317 DAC)
21	100	100
22	70	80
23	0	25
24	100	100
25	100	100
26	0	10
27	0	10
28	100	100
29	90	100
30	70	100
31	0	50
32	0	50
33	70	90
34	100	100
35	0	50
36	0	100
37	0	0
38	0	0
39	0	0
40	100	100

ANNEXURE J: PICTURES OF THE 1st LODGING EVENT (286 DAC)

ANNEXURE K: SUGARCANE PRODUCTION AREAS IN THE LOWVELD

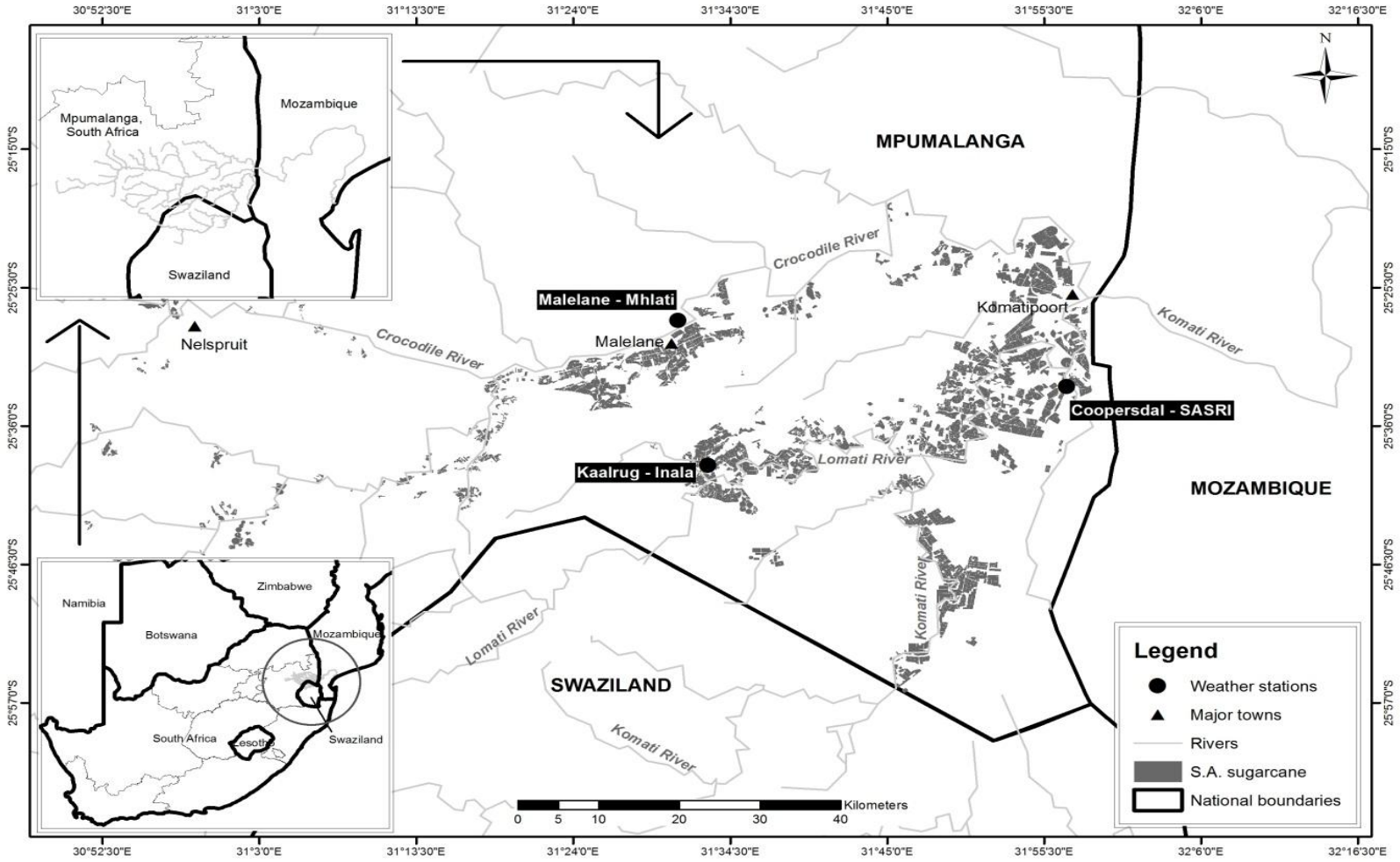

Figure K1: Map depicting the Komati, Lomati and Crocodile rivers and the location of the 3 weather stations used in determining each locations irrigation water demand (Chapter 2.2).

ANNEXURE L: PUBLISHED PAPER FROM THIS STUDY

REFEREED PAPER

GROWTH AND YIELD OF A SUGARCANE PLANT CROP UNDER WATER STRESS IMPOSED THROUGH DEFICIT DRIP IRRIGATION

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Abstract

Little is known about the way sugarcane yield is affected by water stress during different phases of crop development. This information is necessary to optimise the allocation of limited water for irrigation. A drip irrigated field experiment of cultivar N49 (a plant crop) was conducted in Komatipoort. Treatments included maintaining available soil water (ASW) between 30 and 60% of capacity during the tillering phase (T), stalk elongation phase (SE) and through both (T+SE), while the ASW was maintained above 60% of capacity in the well-watered control (WW). The WW and T treatments received 1142 and 985 mm of irrigation, respectively, and experienced few days with stress (ASW <50%), while the soil water potential (SWP) fluctuated between -5 and -40 kPa. The SE (809 mm) and T+SE (633 mm) treatments received much less irrigation and went through 62 and 86 days of stress, respectively, while SWP fluctuated between -10 and -90 kPa. Average cane yield at the final harvest (11 months) of the unstressed treatments was 124 t/ha. Water stress during the stalk elongation phase reduced cane yield by 6 t ha^{-1} and 11 t ha^{-1} in the SE and T+SE treatments, respectively. Results showed that the small reduction was due to resurgence in stalk elongation rates after a wetting event. The compensatory stalk growth allowed plants in the stressed treatments to maintain an average stalk growth rate similar to the WW treatment. The findings of this study indicate that reasonable economic yields (>90% of potential) are achievable provided the stress periods are short (<5 days) and mild (SWP >-80 kPa and ASW >30% of capacity). Further research is required to test the applicability of the results on a ratoon crop, on different cultivars and soils, and in areas with different climates.

Keywords: cane yield, stalk growth, deficit irrigation, stalk elongation rate, water stress, soil water potential

Introduction

Irrigation water supply is often less than crops require in fully irrigated areas of South Africa. For example, for the past six and three out of six seasons, irrigation water supply from the Komati and Lomati Rivers (Mpumalanga Province, South Africa) ([1]personal communication) was below sugarcane irrigation water demand as calculated by the MyCanesim sugarcane model (Singels, 2007). In this situation, sugarcane growers have to make tactical decisions regarding the allocation of limited water to the different fields on their farms. These fields often have a sugarcane crop at different development phases, and possibly with different soils

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and water status. The impacts of applying less water than the crop requires will therefore differ. These decisions are extremely complex and require knowledge of how water stress at different phases of crop development affects yields.

Sugarcane develops through the four phases of germination, tillering, stalk elongation and maturation. During the germination phase, primary shoots emerge from vegetative buds found at the nodes of planted setts, or from nodes of the remaining stalk after harvest. Vegetative buds at the nodes of the primary shoot give rise to 6-8 secondary shoots (i.e. tillers), which may in turn produce tertiary shoots (van Dillewijn, 1952). This process continues until peak tiller population is reached. The tillering phase therefore can be defined as the period between the emergence of primary shoots to the occurrence of peak tiller population. From this point, some tillers senesce due to competition for solar radiation (Inman-Bamber, 1994; Bakker, 1999), while the remaining tillers elongate into harvestable stalks. Visible elongation of stalks above the ground surface commences after about eight leaves have appeared. For primary tillers this occurs before the time of peak tiller population, but for many of the lower order tillers this will occur at, or after, peak population occurs. Stalk elongation continues until the crop is harvested. In this study, the time of peak population was taken as the end of the tillering phase and start of the stalk elongation phase. Towards the end the stalk elongation phase the elongation rate of stalks slows and sucrose accumulates in stalks (i.e. maturation phase).

According to Doorenbos and Kassam (1979) yield is most sensitive to the occurrence of a water stress during the germination and tillering phases, followed by the stalk elongation phase, and least sensitive to water stress is the maturation phase. Pene and Edi (1999) reported results that showed that yield is most sensitive to a water stress during the stalk elongation phase, as crops can recover from a water stress during the tillering phase. Robertson *et al*. (1999) also found that crops were able to recover from a water stress during the tillering phase through increased tiller and leaf emergence rates (i.e. re-establishing the canopy), provided the stress was not too severe and did not continue for too long. In a study by Wiedenfeld (2000), yield was not affected by a water stress which was imposed by withholding irrigation for six weeks during the stalk elongation phase. Robertson *et al.* (1999) also withheld irrigation during the stalk elongation phase but for a longer duration (two to three months) and reported significant yield reductions. Reports of widely different crop responses are likely due to the wide range of water stress severity and durations imposed in each study. Many studies (Robertson and Donaldson, 1998; Inman-Bamber, 2004) have shown that water stress during the maturation phase (i.e. the practice of drying-off) increases sucrose yields provided the water stress is not too severe.

It is clear that considerable uncertainty exists regarding crop response to water stress in different developmental phases and that more research is required, especially on how yield is affected by mild water stress under deficit irrigation during different phases. The aim of this study was to investigate the response of sugarcane cultivar N49 to a mild water stress during the tillering and stalk elongation phases. Although data from both phases will be reported, it was not possible to effect a stress in the tillering phase, and the paper will therefore focus on the stalk elongation phase. Crop development, growth and yield were related to crop and soil water status. This information is needed to develop tools for optimising limited irrigation water.

Methods

Site and soils

A drip irrigated field trial was conducted on the South African Sugarcane Research Institute (SASRI) Mpumalanga Research Station near Komatipoort (25°37'S, 31°52'E, 187 masl). Cultivar N49 was planted in dual rows (centres spaced at 2 m, individual rows at 0.6 and 1.4 m) on 8 November 2011 and harvested on 10 October 2012 (11 month growing cycle). Cultivar N49 was chosen because it is not prone to flowering or lodging and there is growing interest from growers to plant this variety. Each dual row had a surface dripper line with emitters spaced at 0.6 m. Standard cultivation, fertiliser application and weed control practices were followed.

The sandy clay loam (37% clay, 16% silt, 47% sand) had a field capacity (FC) and permanent wilting point (PWP) of 165 and 94 mm, respectively, in the assumed root zone of 0.625 m, giving this soil the capacity to hold 71 mm of plant available water (ASWC). These values are similar to those found for the same field by Olivier *et al*. (2006). FC was determined by measuring the volumetric soil water content in the root zone (SWC, in mm) with a neutron water meter (NWM; Model 503DR CPN Hydroprobe, Campbell Pacific Nuclear, CA, USA) two days after an infield calibration plot was saturated and covered with plastic. PWP was determined by measuring SWC with a NWM after all plant available water was extracted by a fully canopied crop (negligible change in SWC over time).

Treatments

Four irrigation treatments were applied with the aim of maintaining plant available soil water (ASW) between 30 and 60% of ASWC through (1) the tillering phase (T), (2) the stalk elongation phase (SE) and (3) through both tillering and stalk elongation phases (T+SE), while the ASW was maintained above 60% of ASWC in the well-watered control (WW) and during development phases where water stress was not imposed. Treatments were replicated five times in a completely randomised block design. Plots were 12x20 m in size and had six dual rows each.

Three weeks prior to harvest all treatments were irrigated to fill the soil profile, and thereafter irrigation was withheld (i.e. drying-off period) for three weeks, following Donaldson and Bezuidenhout (2000).

Measurements

SWC was measured with a NWM three times a week underneath the dripper line halfway between emitters, at 0.15 m depth intervals, commencing at a depth of 0.25 m to a maximum depth of 0.55 m. ASW was calculated as the difference between measured SWC and PWP. Soil water potential (SWP) was measured between emitters in close proximity to NWM access tubes at depths of 0.25 and 0.44 m using tensiometers (CFM Industries). It should be noted that the soil water regime underneath drip emitters is likely to be wetter, and in the interrow drier, than that monitored.

Daily crop water use (CWU) and number of stress days (defined as a day when simulated ASW was below 50% of capacity) was estimated using the MyCanesim sugarcane model (Singels, 2007). Actual irrigation and local weather data were used as inputs, and simulated ASW was corrected with measured values of ASW. This method of determining CWU was preferred over a water balance approach using measured ASW values, because frequent

drainage events due to rainfall made it impossible to calculate reliable values of CWU through the water balance approach.

Stalk height (distance from the ground to the top visible dewlap) was measured twice a week on eight tagged stalks in three plots per treatment. Average stalk elongation rate (SER in cm/d) was calculated as the change in average stalk height between two consecutive measurements divided by the number of days between these measurements. Relative SER (RSER) was calculated as the average SER of stalks in the stress treatments relative to the average SER of stalks in the control treatment. The number of dead leaves (more than 90% of leaf area necrotic) and the number of fully expanded green leaves were counted fortnightly on each of these tagged stalks.

Stalk population was determined in a demarcated 5 m section in three plots per treatment. Fractional interception of photosynthetic active radiation (PAR) was measured fortnightly in three plots per treatment, using a ceptometer (AccuPAR LP-80, Decagon Devices, Pullman, WA, USA).

At the end of the tillering phase and at final harvest, all stalks within 1.5 m of a dual row were harvested and partitioned into millable stalks, leaves (defined as tops, green laminae and sheaths) and trash (defined as dead leaves and stalks) and the mass of each component determined. The dry mass of each component was determined after subsamples were dried in an oven until a constant mass was reached. Stalk subsamples (16 stalks per plot) were analysed for sucrose, fibre and dry matter content using the method described by Singels *et al*. (2005). The green leaf area of a fresh leaf subsample of about 1 kg was measured using an area meter (Li-Cor 3100, LI-COR, Nebraska, USA) to determine specific leaf density. This was used to estimate green leaf area index (GLAI in m^2/m^2) from fresh leaf mass data. At the final harvest, millable stalk fresh biomass (cane yield) was determined by weighing the cane harvested from the total net area (186 m^2) of the four inner dual rows of each plot.

Results

Water relations

Available soil water and soil water potential trends

During the tiller phase the T and T+SE treatments received little irrigation (Table 1), but several large rainfall events prevented ASW from declining into the targeted range (40-60% of ASWC) and the SWP at 400 mm from declining below -30 kPa (Figure 1a,b and Figure 2a,b). Therefore treatments used similar amounts of water and experienced no water stress during this phase (Table 1).

During the stalk elongation phase the stressed treatments received about 320 mm (40%) less irrigation than the WW treatment, resulting in the desired ASW regime for these treatments (Figures 1b,c,d). SWP of the stressed treatments fluctuated between -10 and -90 kPa compared to a range of -5 to -40 kPa for the WW treatments (Figures 2b,c,d). As a result, the SE and T+SE treatments endured more stress than the WW treatment, as reflected by the number of stress days in Table 1. CWU was less affected by water stress, with a reduction of 40 to 58 mm (5 to 8%) in the stressed treatments compared to the unstressed treatments (Table 1).

Table 1. Phase duration, rainfall, irrigation, number of stress days and estimated crop water use for each treatment during the tillering phase, the stalk elongation phase, the three week drying-off period and the total for the growing season.

	Treatment	Development phases		Drying-off	Total
		Tillering	Stalk elongation		
Duration of each phase (days)		65	214	24	337
Rainfall (mm)		373	267	3	694
Irrigation (mm)	T	45	834	–	985
	SE	212	491	–	809
	T+SE	27	501	–	633
	WW	224	813	–	1142
Stress days	T	0	10	15	25
	SE	0	62	15	77
	T+SE	0	86	16	102
	WW	0	7	15	22
Crop water use (mm)	T	336	741	101	1288
	SE	328	702	101	1241
	T+SE	337	684	96	1227
	WW	335	742	94	1280

It is clear from Figure 1b,c that ASW at times was above 50% of ASWC during stress periods because of irrigations applied to maintain ASW above the lower threshold of 30% of ASWC. Therefore, the duration of individual stress periods (consecutive days of water stress) varied from one to 25 days. The frequency distribution of stress period is summarised in Figure 3. The T+SE treatment endured the longest individual stress period (25 consecutive days), followed by the SE treatment (24 consecutive days) while the longest period of stress endured by the T and WW treatments was only 6 and 7 consecutive days respectively.

From 301 to 311 days after planting (DAP), 169 mm of rainfall resulted in the sugarcane lodging in all plots. Stress treatments were terminated at this point to minimise the confounding effect of lodging.

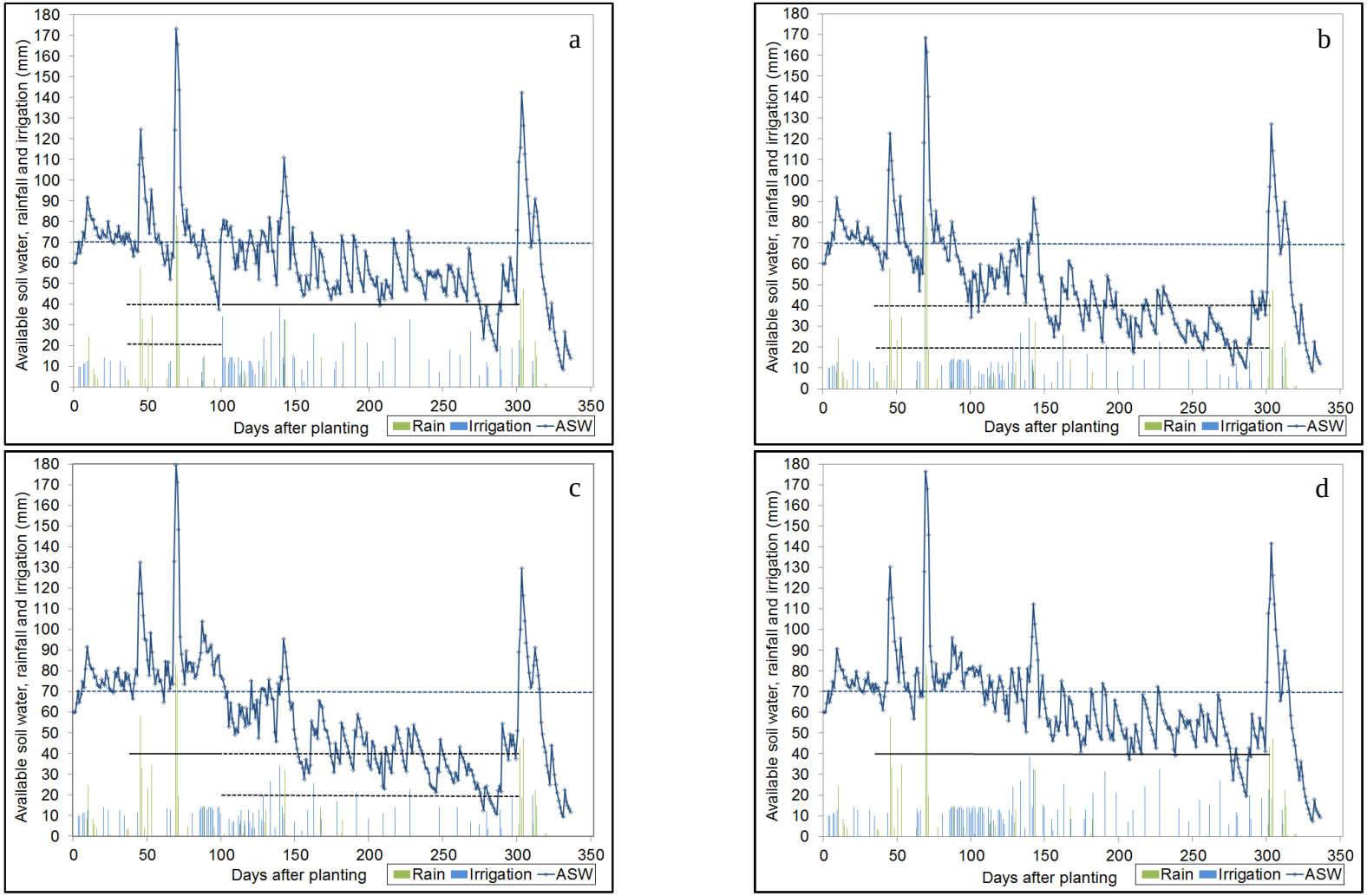

Figure 1. Available soil water (ASW) in the T (a), T+SE (b), SE (c) and WW (d) treatments. The blue dotted horizontal line represents field capacity (70 mm). The black horizontal lines represent 30 and 60% of the available soil water capacity. Where the line is solid no water stress was imposed, while the dotted line represents imposed water stress periods. The green and blue bars represent rainfall and irrigation, respectively.

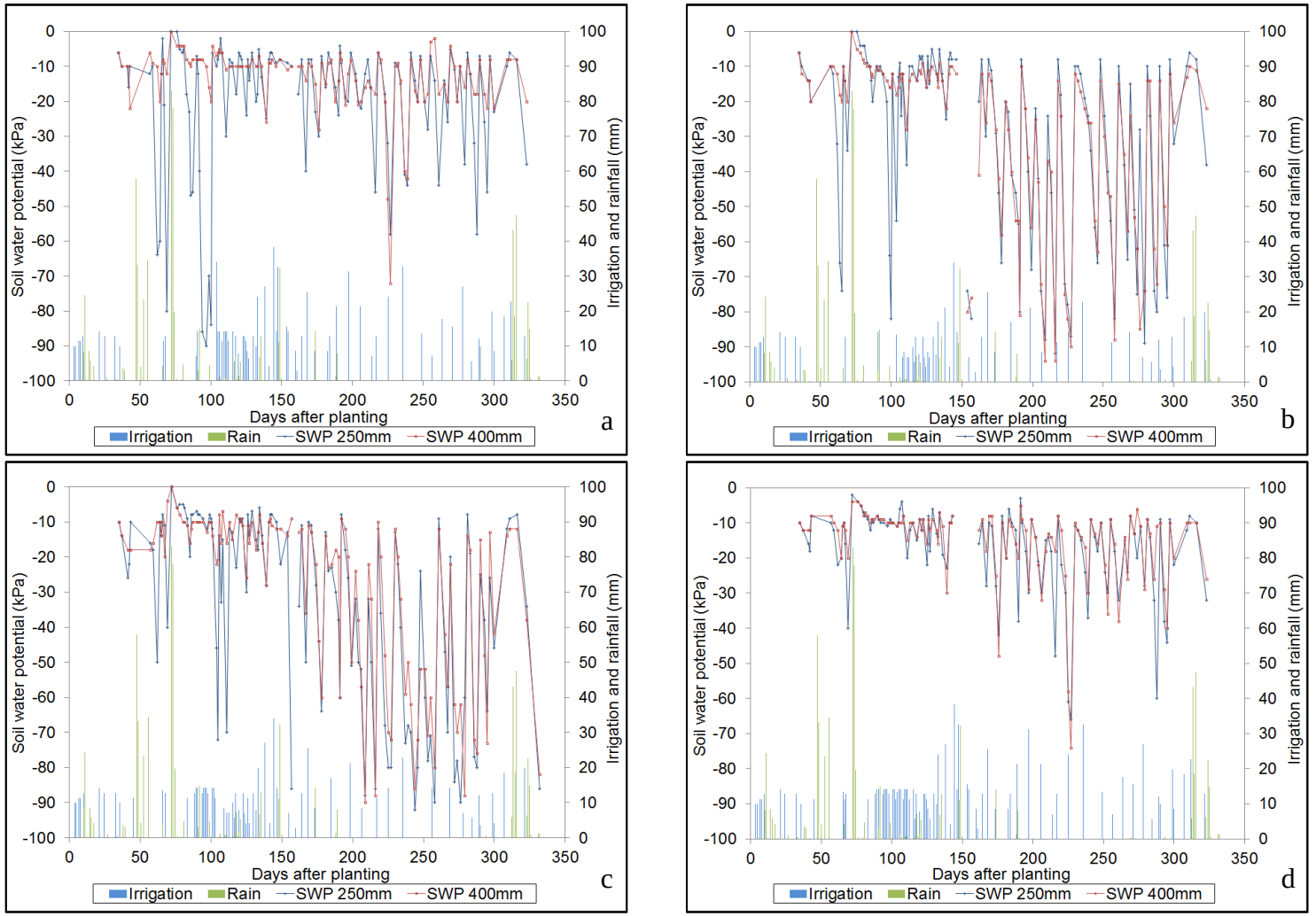

Figure 2. Soil water potential measured at a soil depth of 250 mm (blue line) and 400 mm (red line) in the T (a), T+SE (b), SE (c) and WW (d) treatments. The green and blue bars represent rainfall and irrigation, respectively.

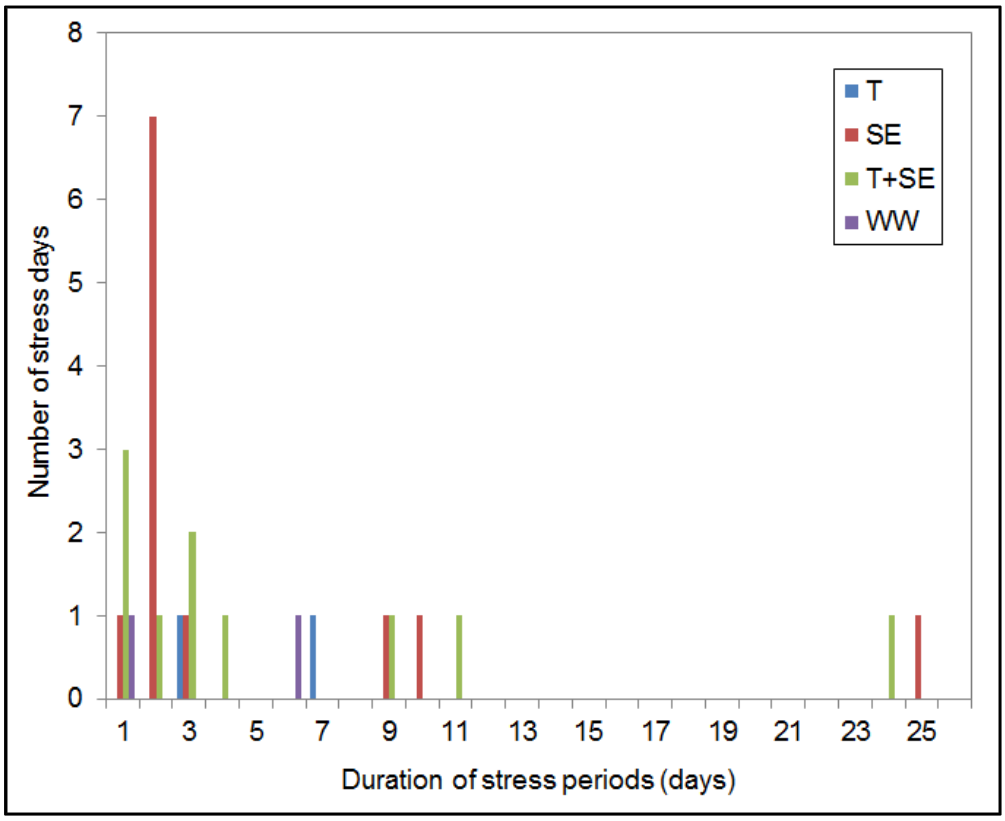

Figure 3. The number of stress events of a given duration during the stalk elongation phase (excluding the drying off period for each treatment.

Growth and development

The imposed water stress had no significant effect on stalk population, total leaf number or on the LAI (Table 2.).

Green leaf number

The number of green leaves per stalk at the end of the tillering phase did not differ between treatments because there was no water stress during this phase (Table 2).

Water stress during the stalk elongation phase slowed the rate of leaf emergence slightly and raised the rate of leaf senescence (data not shown). This resulted in a slightly lower number of green leaves in the SE and T+SE treatments (6.4 and 6.8 leaves, respectively) compared to the WW treatment (8.5 leaves) towards the end of this phase (Figure 5). However, at the end of the stalk elongation phase (before commencing the drying-off) differences between treatments were not significant. Inman-Bamber (1991) reported that leaves tend to accumulate within the leaf whorl during stress periods, and then rapidly emerge once the stress is relieved. This could have been the case here, because stress periods were regularly interspersed with short periods of no stress during which plants could resume leaf development processes at accelerated rates.

Table 2. Crop growth parameters (mean±SD) for the different treatments at the end of the tillering and stalk elongation phases.

Growth indicators	Treatments				Significance
	T	SE	T+SE	WW	
Stalk population (m^2)					
Tillering phase	22.8 ± 1.3	22.1 ± 2.0	23.1 ± 1.1	24.3 ± 1.8	NS
Stalk elongation phase	13.4 ± 0.8	12.5 ± 0.7	13.6 ± 0.3	13.5 ± 0.8	NS
Total number of leaves emerged					
Tillering phase	16.8 ± 3.6	17.9 ± 1.0	17.0 ± 1.4	17.5 ± 1.5	NS
Stalk elongation phase	31.6 ± 7.8	29.7 ± 1.6	30.1 ± 1.6	31.8 ± 1.8	NS
Total number of dead leaves					
Tillering phase	6.8 ± 1.9	6.3 ± 1.5	7.0 ± 1.3	5.9 ± 1.8	NS
Stalk elongation phase	23.8 ± 2.5	22.7 ± 1.6	23.2 ± 1.8	24.0 ± 1.7	NS
Green leaves per stalk					
Tillering phase	10.0 ± 3.0[b]	11.5 ± 1.7[a]	10.0 ± 1.4[b]	11.5 ± 1.1[a]	*
Stalk elongation phase	8.4 ± 2.3	6.9 ± 1.2	6.9 ± 0.7	8.0 ± 1.4	NS
Radiation interception (%)					
Tillering phase	85.9 ± 4.6	90.1 ± 2.9	86.1 ± 2.2	90.7 ± 3.5	NS
Stalk elongation phase	98.7 ± 0.5[a]	97.9 ± 0.9[a]	96.4 ± 1.2[b]	98.2 ± 0.4[a]	*
Green leaf area index (m^2/m^2)					
Tillering phase	3.96 ± 0.70	3.75 ± 0.78	3.10 ± 0.66	4.04 ± 0.28	NS
Stalk elongation phase	3.38 ± 0.51	2.72 ± 0.49	2.78 ± 0.39	3.42 ± 0.46	NS
SER per development phase (cm/day)					
Tillering phase	1.41 ± 0.25	1.60 ± 0.20	1.41 ± 0.26	1.68 ± 0.13	NS
Stalk elongation phase	0.70±0.07[a]	0.52±0.08[c]	0.58±0.06[c]	0.63±0.07[b]	*
Stalk height (cm)					
End of tillering phase	103 ± 14.9	116 ± 12.7	105 ± 14.6	120 ± 8.30	NS
At harvest	258 ± 26.2	236 ± 18.7	237 ± 14.7	254 ± 15.2	NS

*indicate significance at P≤0.05 and NS indicated non-significance between treatments.

As expected, the insignificant impact of stress on stalk population, leaf numbers and LAI also resulted in little impact on canopy cover and radiation interception. The only significant difference found was a slightly lower radiation capture for the T+SE treatment compared to the other treatments (Table 2).

Stalk elongation

The RSER of all treatments declined with declining ASW, while increases in ASW due to rainfall and/or irrigation resulted in a resurgence in RSER (Figure 6). Such fluctuations occurred irrespective of the ASW level, presumably because roots at the top part of the root zone were able to extract enough water for the plant to support high rates of plant processes.

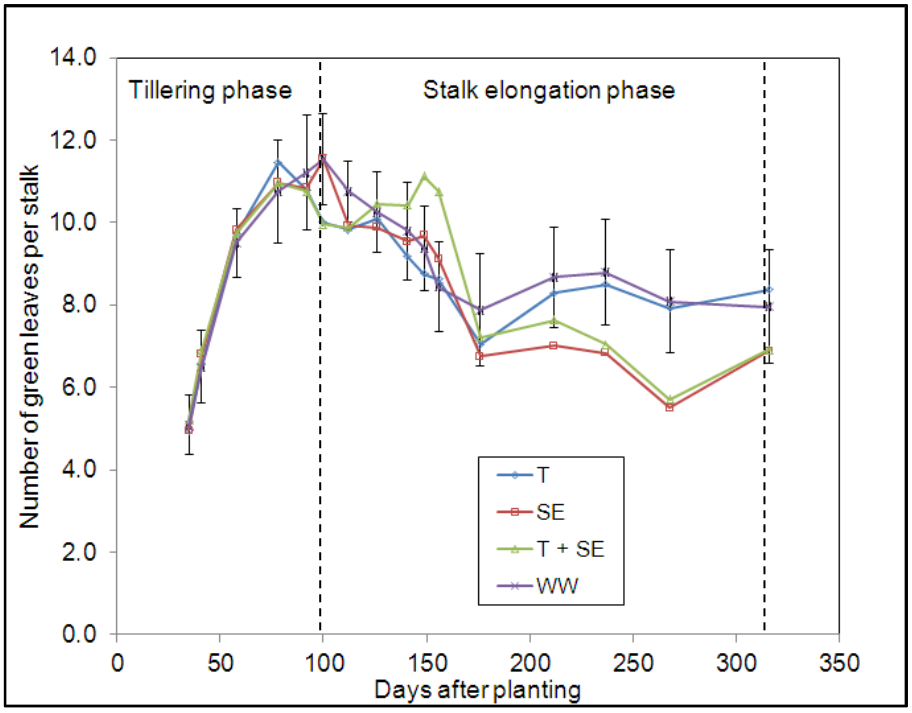

Figure 5. Number of green leaves per stalk for the different treatments (T, SE, T+SE and WW) during the tillering and stalk elongation phases. Error bars represent the standard deviation of the WW treatment.

During the tillering phase the SER of the different treatments was similar, except towards the end of the phase when ASW declined to a value of 43 mm and the RSER of the stressed treatments declined rapidly to 0.5 in response (Figure 6). Although the average SER of the stressed treatments during the tillering phase was lower than that of the unstressed treatments, this difference was not significant, nor were differences in stalk height (Table 2).

During the stalk elongation phase RSER declined rapidly to about 0.5 whenever ASW declined below the 60% capacity. When ASW increased due to rainfall and/or irrigation, RSER quickly recovered to and sometimes exceeded a value of 1, suggesting that stalks were able to compensate for the slow growth during the stress period (Figure 6). Inman-Bamber and de Jager (1986) reported similar results in a potted sugarcane trial, where a stressed crop's SER exceeded that of an unstressed crop soon after stress was relieved. The result of this compensatory growth was ascribed to cells regaining turgor pressure quickly (Inman-Bamber, 1995). RSER did not recover after wetting events after about 250 DAP for the SE treatment, and after about 200 DAP for the T+SE treatment. This suggests that a prolonged period of intermittent stress may eventually damage the plant's ability to compensate.
Average RSER for the stalk elongation phase of the stressed treatments was about 0.1 cm/day (9-17%) lower than that of the unstressed treatments (Table 2). This lower growth rate resulted in stalks being 7% shorter than those in the unstressed treatments at final harvest, although this difference was not significant.

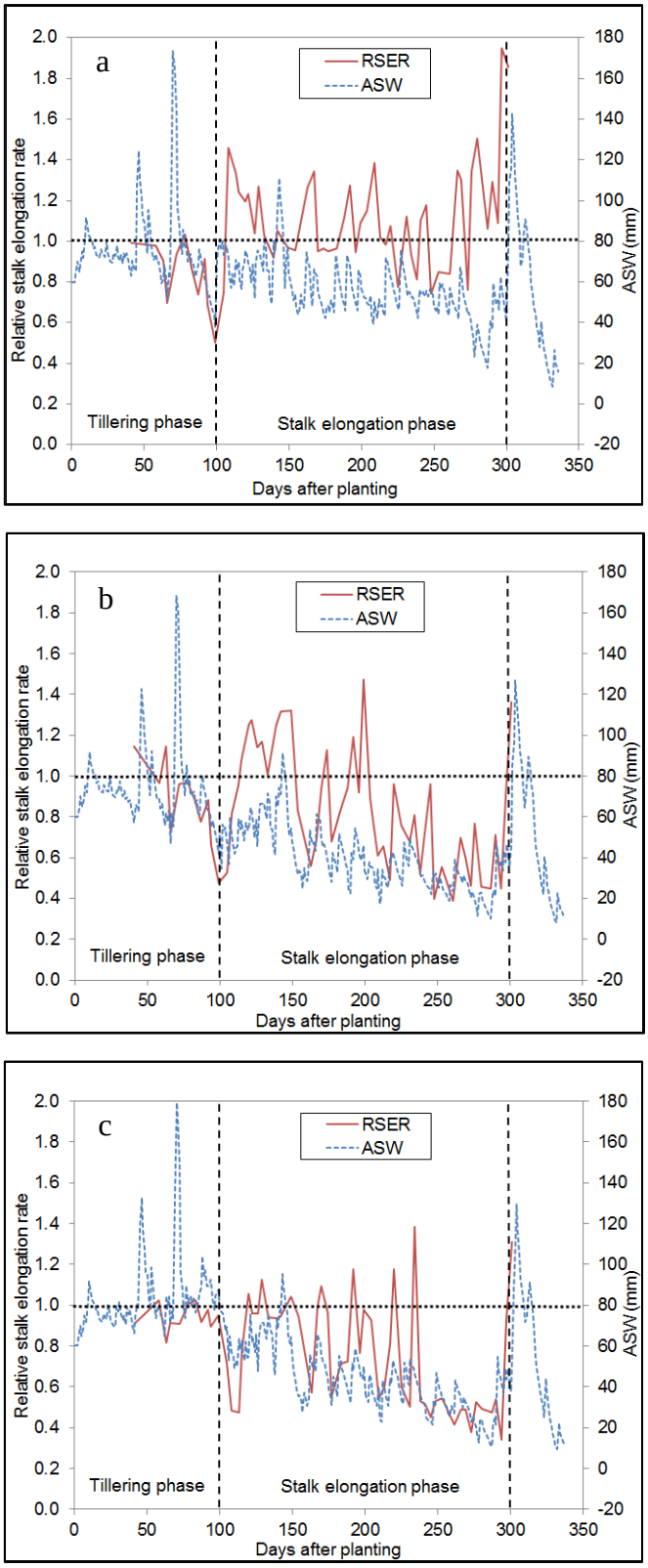

Figure 6. Relative stalk elongation rate and available soil water for T (a), T+SE (b) and SE (c) treatments during the tillering and stalks elongation phases. The black horizontal dotted lines indicate RSER = 1.

Biomass partitioning

At the end of the tillering phase the T+SE treatment had significantly lower leaf dry biomass and higher trash biomass than the other treatments (Table 3). It is unclear why this treatment was different from the others, as no stress occurred during the tillering phase.

Water stress during the stalk elongation phase significantly reduced the dry mass of leaves in the SE and T+SE treatments by 1.4 to 1.5 t/ha, but had no significant effect on millable stalk dry mass (4.4 to 6.1 t/ha reduction) or trash dry mass (0.6 to 1.7 t/ha reduction) (Table 3). Partitioning of biomass was not affected by water stress.

The imposed water stress during the stalk elongation phase reduced cane yield by a statistically significant 6 t/ha and 11 t/ha in the SE and T+SE treatments, respectively. Sucrose yields dropped by 0.4 to 1 t ha^{-1} but these reductions were not significant (Table 3).

Table 3 Dry mass (in t/ha and as percentage of the total) of biomass components for each treatment at the end of the tillering phase and at final harvest, and fresh cane and sucrose yields at harvest.

Crop stage	Component	Treatments				Significance
		T	SE	T+SE	WW	
End of tillering phase (t/ha)						
	Stalk	3.84 ± 0.70	3.56 ± 0.65	3.09 ± 0.55	4.00 ± 0.64	NS
	Leaves	6.07 ± 0.86^{b}	5.77±0.84^{ab}	4.73 ± 0.76^{a}	6.64 ± 0.88^{b}	*
	Trash	0.19±0.06^{ab}	0.12 ± 0.03^{a}	0.25 ± 0.09^{b}	0.14 ± 0.03^{a}	*
	Total	10.09±1.54	9.49 ± 1.42	8.07 ± 1.25	10.77±1.40	NS
End of tillering phase (%)						
	Stalk	37.8 ± 2.01	37.6 ± 2.62	38.2 ± 3.67	37.0 ± 3.25	NS
	Leaves	60.2 ± 1.70	61.1 ± 2.38	58.7 ± 3.58	61.7 ± 3.25	NS
	Trash	1.92 ± 0.59^{a}	1.31 ± 0.28^{a}	3.1 ± 0.86^{b}	1.28 ± 0.15^{a}	*
Final harvest (t/ha)						
	Stalk	34.5 ± 3.10	30.9 ± 5.63	29.2 ± 4.05	35.3 ± 3.32	NS
	Leaves	6.77 ± 1.24^{b}	5.08 ± 1.36^{a}	5.13 ± 0.75^{a}	6.57 ± 0.60^{b}	*
	Trash	10.54±1.73	9.63 ± 1.83	8.44 ± 1.87	10.18±2.14	NS
	Total	51.8 ± 4.85	45.7 ± 8.23	42.8 ± 5.29	52.0 ± 5.54	NS
Final harvest (%)						
	Stalk	66.7 ± 2.99	67.8 ± 1.99	68.2 ± 2.42	67.9 ± 2.33	NS
	Leaves	13.0 ± 1.55	11.1 ± 2.04	12.1 ± 1.80	12.6 ± 0.48	NS
	Trash	20.3 ± 2.62	21.1 ± 1.09	19.7 ± 3.81	19.5 ± 2.45	NS
Cane yield (t/ha)		124 ± 5.3^{b}	117 ± 7.2^{a}	112 ± 6.1^{a}	123 ± 1.7^{b}	*
Sucrose yield (t/ha)		18.4 ± 1.7	17.4 ± 1.7	18.0 ± 0.7	18.4 ± 1.7	NS

*indicates significance at P≤0.05, and NS indicated non-significance between treatments

Concluding discussion

In this study water stress during the stalk elongation phase imposed through deficit irrigation (60% of requirement) had no significant long lasting effects on sugarcane growth and development processes. The stress had no effect on leaf emergence and senescence rates or on the number of green leaves per stalk. Stalk population, GLAI and radiation interception were also not affected.

Stalk elongation rate was found to be highly sensitive to changes in ASW, declining rapidly with declining ASW. However, plants appear to have the ability to compensate to some extent for growth lost during short periods of stress, through accelerated growth when stress is relieved. On average, however, stalk elongation rate was reduced by about 0.1 cm/day, which resulted in water stressed stalks being 7% shorter than unstressed treatments.

Crop water use was not affected much by the deficit irrigation, with a reduction of about 4%.

Water stress during the stalk elongation phase reduced cane yield by 6 to 11 t ha^{-1} (5 to 9 %) and sucrose yield by 0.4 to 1 t ha^{-1} (3 to 5 %). The small size of the yield losses are partially attributed to the compensatory growth of stalks during frequent periods when stress was relieved. In other studies (Robertson *et al.*, 1999; Pene and Edi, 1999) much larger reductions in yield were observed when drought stress was more severe. The reductions in cane and sucrose yields found in the current study are similar to the yield reduction of 4 t/ha found by Pene and Edi (1999) when irrigation was scheduled according to 75% of Class A-pan evaporation.

Results suggest that sugarcane can achieve reasonable economic yields (>90% of potential) with deficit drip irrigation, provided the stress periods are short (<5 days) and mild (SWP >-80 kPa). It is necessary to schedule irrigation accurately to successfully maintain the soil water status in the desired regime and ensure continued water use and stalk growth. However, further research is required to test the applicability of the results on a ratoon crop, with different cultivars and soils, and in areas with different climates. Placement of monitoring instruments relative to drip emitters and cane rows also requires further investigation.

Acknowledgements

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ANNEXURE M: DATA FILE LOCATIONS AND CONTENTS

Data from this study is stored on the H drive on the SASRI network at: PERC/Agronomy/Ryan_Rossler

Simulated data is available at http://portal.sasa.org.za, User name: 700013a

Table M1: Directory to the location off all collected data

Folder title	Primary folder	Secondary folder	Excel spread sheet	Contents
Data collection	Non-destructive		Irrigation_Plant	Notes on trial, daily rainfall and irrigation, Canesim simulated ET (i.e. crop water use) of each treatment
			Irrigation_Ratoon	
			Irrigation Rate	Calculated water application rate (plant and ratoon)
			Project TT	Daily thermal time for the plant and ratoon crops, base temperature 10 and 16 ^{o}C
			Soil Texture	Soil physics determined sand, silt and clay
			FAS soil results	Soil and leaf sample results
			Lodge rating	Two lodging events in the ratoon crop
		Neutron probe	Neutron probe_FC PWP	Determined infield permanent wilting point

			Neutron probe_Plant crop	Measured available soil water (ASW), Canesim simulated ASW corrected with measured ASW, number of stress days per phase
			Neutron probe_Ratoon crop	
			NWM calibration comparisons	Neutron probe calibration
		EcHo Sensor	Calibration	Infield calibration, calibration using neutron water meter (NWM) determined ASW in the plant and ratoon crops
			Echo Sensors_plant	Readings through both crops, readings done on the same day as NWM
			Echo Sensors_ratoon	
		Tensiometers	Tensiometer_Plant	Soil water potential (SWP) measured during plant crop
			Tensiometer_Ratoon	SWP measured during ratoon crop
		Plant crop	Fractional interception	PAR capture through the season
			Leaf water potential	Midday LWP vs RASW
			Retention curves	Retention curves for each treatment, combined plant and ratoon retention curves
			Stalk population	Stalk population per $10m^2$ and

				per m^2
			Leaf number	Leaf emergence, senescence and green leaf number
			Stalk extension	Stalk daily growth rate, growth rate per phase, stalk height
		Ratoon crop	Fractional interception (R)	PAR capture through the season
			Leaf water potential (R)	Midday LWP vs RASW
			Retention curves (R)	Retention curves for each treatment, combined plant and ratoon retention curves
			Stalk population (R)	Stalk population per $10m^2$ and per m^2
			Leaf number (R)	Leaf emergence, senescence and green leaf number
			Stalk extension (R)	Stalk daily growth rate, growth rate per phase, stalk height
	Destructive	Plant crop	Biomass	Destructive harvests at end of tillering and final harvest, wet and dry biomass, biomass partitioning, cane yield determined using load cell and samples
			Leaf area index	GLAI

				determined at each destructive harvest
			Sucrose and fibre	Mill room results, stalk matter content, sucrose %, fibre %, non-sucrose %, sucrose yield, RV%
		Ratoon crop	Biomass (R)	Destructive harvests at end of tillering and final harvest, wet and dry biomass, biomass partitioning, cane yield determined using load cell and samples
			Leaf area index (R)	GLAI determined at each destructive harvest
			Sucrose and fibre (R)	Mill room results, stalk matter content, sucrose %, fibre %, non-sucrose %, sucrose yield, RV%