THE EFFECT OF WATER STRESS ON SUGARCANE BIOMASS ACCUMULATION AND PARTITIONING

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Abstract

Crop models are increasingly used to assist agronomic research and management of sugarcane production. Examples are management of irrigation and yield benchmarking. Good management of frequently water stressed crops requires accurate knowledge and models of crop response to water stress.

Biomass accumulation of the stalk (SK), non-stalk (NSK), sucrose (SUC) and the fibre plus non-sucrose (FNS) components of well watered and water stressed sugarcane were measured on a rainshelter facility at Mount Edgecombe. Soil water content was also measured. Biomass accumulation was reduced when relative soil water content (RSWC) dropped below 35% of available capacity. The partition fraction to SUC increased when RSWC dropped below 55%. Partitioning between SK and NSK components were not affected by water stress. Refinements to both crop water uptake and crop water stress equations in the Canegro model are needed to improve its capability to simulate crop response to water stress.

These results will be used to refine crop model simulation of water stress effects on biomass accumulation and partitioning. Crop models could then be used with historical weather data to support management of sugarcane production in South Africa.

Keywords: water stress, model, biomass, partitioning, sucrose, stalk, soil water content

Introduction

Crop models are increasingly used to assist agronomic research and management of sugarcane production. Examples for sugarcane are management of irrigation (McGlinchey et. al., 1995) and yield benchmarking (Singels et. al. 1999). Both irrigated and rainfed sugarcane in South Africa frequently suffers from dry spells. Depending on the severity of the water stress, biomass partitioning between different components could be changed (with consequent effect on sucrose content and yield) and/or biomass accumulation could be reduced (with consequent drop in cane yield). Good management of these crops therefore requires accurate knowledge and models of crop response to water stress.

Increasing levels of water stress that occur as a soil dries out, affect processes in the sugarcane crop at different stages. Work by Inman-Bamber (1986) suggests that growth processes such as plant extension are more sensitive to water stress than photosynthesis. Plant extension ceased at leaf water potentials of between -0.4 to -0.9 MPa, while stomatal resistance only increased rapidly below water potentials of -1.2 MPa and reached a maximum at between -1.4 and -2.3 MPa. Inman-Bamber also found that water stress promotes ripening when stress was sufficient to reduce plant extension but not sufficient to substantially decrease photosynthesis. It is therefore expected that the partitioning of biomass to the different components will be affected by water stress before biomass accumulation is affected.

At present, sugarcane crop models such as APSIM-Sugarcane (Keating et. al., 1999) use two stress factors to regulate the effect of water stress on biomass accumulation and partitioning. Sugarcane simulation models generally have acceptable accuracy for simulating total biomass and even stalk biomass, but this is not the case for sucrose yield (O'Leary, 1999). One of the reasons for this is that current models cannot adequately simulate the subtle shifts in partitioning during periods of mild stress.

The aim of this work was to quantify the effect of water stress on (1) biomass accumulation and its partitioning to stalk and non-stalk components, and (2) partitioning of stalk to sucrose and fibre plus non-sucrose components. This information could be used to refine existing or develop new models of biomass accumulation and partitioning in sugarcane.

Methods

Experiment details

An experiment was carried out at a rainshelter facility at Mount Edgecombe (29°24'S, 31°54'E, elevation 96m). The soil was an artificial, homogenous mix derived from the A horizon of a Westleigh form, Rietvlei series (Soils Bulletin Working Group, 1999) with a clay fraction of 0.22 , silt fraction of 0.11, and a rooting depth of 950 mm . The drained upper and lower limits of plant available water were 26% and 13% respectively. The plant available water capacity is 126 mm.

Variety NCo376 was planted on 6 November 1998 at a row spacing of 1.2 m. The cane was drip irrigated to prevent any water stress. From 15 February 1999 water was withheld from one half of the trial.

Volumetric soil water content was measured with a neutron moisture meter (Campbell Pacific Nuclear 503), in 3 aluminum tubes per plot. Measurements were taken at 15 cm intervals commencing at 25 cm depth to a depth of 85 cm twice a week during the duration of the trial. The neutron moisture meter was calibrated for each 15 cm layer in the soil.

Biomass was sampled destructively every two weeks in both plots starting on 18 February 1999 and ending on 28 April 1999. Three sub samples of 0.5 m line of cane were sampled. The aerial biomass was separated into millable stalk and the rest (called non-stalk). The dry matter content of both components was determined together with the sucrose content of the stalk. Stalk population was also measured regularly in both plots. Total aerial dry mass (TOT) was divided between stalk dry mass (SK) and non-stalk dry mass (NSK) and SK was divided between sucrose (SUC) and the rest of the stalk (fibre plus non-sucrose material - FNS). The mean mass per unit area of the different components was determined by averaging the product of the sample mass per stalk and the average stalk population of the trial as interpolated from measurements.

Weather data were recorded alongside the trial by standard methods. Daily solar radiation, maximum and minimum temperature, humidity at 8:00 and 14:00, wind speed and total rainfall were recorded.

Partitioning analysis

The framework for analysis is illustrated in Fig.1. The instantaneous partitioning from aerial biomass increments (dTOT/dt) to millable stalk (dSK/dt) and non-stalk components (dNSK/dt) is governed by the stalk partition fraction (ρ_{SK}) according to eq. 1:

$$dSK/dt = \rho_{SK}.\ dTOT/dt \qquad \text{Eq.1}$$

Average ρ_{SK} over a sampling interval could be calculated from successive SK and TOT measurements according to eq. 2:

$$\rho_{SK} = (SK_i - SK_{(i-1)})/(TOT_i - TOT_{(i-1)}) \qquad \text{Eq. 2}$$

where SK_i - stalk mass at sampling time i (t/ha)

TOT_i - aerial biomass at sampling time i (t/ha)

However, the sample variability and sampling frequency of this experiment did not allow any meaningful results to come out of this. Rather an approach was followed of analytically solving continuous functions and fitting these to the data.

Integrating eq. 1 over time gives:

$$\int (dSK/dt)\ dt = \int (\rho_{SK}\ dTOT/dt)\ dt \qquad \text{Eq. 3}$$

and therefore

$$SK = \int \rho_{SK}\ dTOT \qquad \text{Eq. 4}$$

The value of ρ_{SK} could therefore be determined by obtaining the first derivative of a function (eq. 5) fitted to SK vs. TOT data. The same applies for the non-stalk partition fraction (ρ_{NSK}).

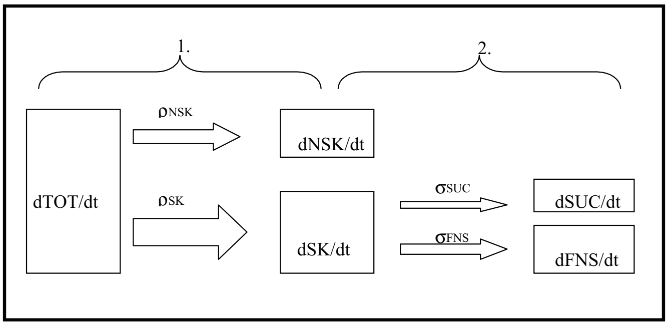

Figure 1. Schematic framework for instantaneous partitioning of (1) aerial biomass increments (TOT) into stalk (SK) and non-stalk components (NSK), and (2) of stalk mass increments into sucrose (SUC) and the fibre plus non-sucrose (FNS) components. For this analysis it was assumed that the stalk and non-stalk partition fractions (ρ) are functions of accumulated aerial biomass and water stress, and the sucrose and fibre plus non-sucrose partition fractions (σ) functions of accumulated stalk mass and water stress.

It was assumed that ρ_{SK} equalled zero (and therefore ρ_{NSK} equalled unity) when TOT was below a given base value (see Robertson et.al., 1995). It was further assumed that these partition fractions were constant when TOT exceeded the base value. The appropriate equation to fit through regression analysis to SK vs. TOT data was therefore:

$$SK = c + \rho_{SK}.TOT \qquad \text{Eq. 5}$$

where c is the y-intercept. The estimated TOT base value is equal to $-c/\rho_{SK}$. The NSK partition fraction (ρ_{NSK}) would just be the compliment of ρ_{SK}.

Millable stalk mass increments (dSK/dt) were partitioned to sucrose (dSUC/dt) and fibre plus non-sucrose (dFNS/dt) using the respective partition fractions (σ_{SUC}, σ_{FNS}, see Fig. 1). These were determined by a method similar to the method described above. It was assumed that these fractions depend on the size of the stalk pool (see e.g. Muchow et.al., 1996 and Robertson et.al, 1996) and the level of water stress. On this basis eq. 6 was used to describe the relationship between σ_{SUC} and SK.

$$\sigma_{SUC} = \alpha.(1 - e^{-\beta.SK}) \qquad \text{Eq. 6}$$

where α and β are constants. Constant α represents the theoretical maximum partitioning from stalk to sucrose at high values of SK. Robertson et.al. (1996) reported a value for σ_{SUC} of .544 for NCo376, 0.527 for N12 and 0.55 for N14 calculated from data reported by Inman-Bamber (1994) and Thompson (1988). On this basis we assumed that α had a value of 0.6. The value of β was determined by fitting the integrated version of eq. 6 (see eq. 7) by eye to SUC vs. SK data.

$$SUC = \alpha.SK + (\alpha/\beta).e^{-\beta.SK} - \alpha/\beta \qquad \text{Eq. 7}$$

The σ_{FNS} fraction was taken to be the compliment of eq. 6. As a test to ensure closure and goodness of fit, the integral of eq. 6 (eq. 8) was compared to FNS vs. SK data.

$$FNS = (1-\alpha).\ SK - (\alpha/\beta).e^{-\beta.SK} + \alpha/\beta \qquad \text{Eq. 8}$$

Quantification of water stress

Water stress was quantified by the SWDEF1 and SWDEF2 stress factors calculated by the Canegro model (Inman-Bamber, 1991) using appropriate soil and weather data. SWDEF1 is used to regulate the rate of photosynthesis and therefore biomass accumulation in crop models. SWDEF2 is used in Canegro to regulate the rate of leaf expansion and is more sensitive to insufficient soil water supply than SWDEF1. SWDEF2 could also possibly be used to regulate the rate at which stress sensitive components grow, thereby regulating shifts in partitioning of biomass to the different components as a result of water stress.

The mean relative plant available soil water content (RSWC) was also used to describe the degree of water stress. This was calculated according to eq. 9.

$$RSWC = (1/n)\ \Sigma\,((SWC_i - LL_i)/(DUL_i - LL_i)) \qquad \text{Eq. 9}$$

where - SWC_i - soil water content at depth interval i (%)

DUL_i - drained upper limit at depth i (%)

LL_i - lower limit of available water at depth i (%)

n - number of depth intervals

RSWC was determined for measured as well as Canegro simulated values.

Results and discussion

Time series of the different mass components and measures of water stress are shown in Fig. 2.

The TOT and SK graphs for stressed and unstressed cane started to deviate at 132 after emergence (DAE) and at SWC = 22%. At DAE = 145 these values for the dry plot were significantly lower than that of the wet plot. Reasons for the lack of growth on the wet plot between DAE 132 and 145 are not clear. SUC of the dry plot is significantly higher than that of the wet plot between DAE 118 and 152. SUC of the dry plot increased at a higher rate than that of the wet plot between DAE 118 and 125. The increase in TOT over this period was not significantly different between the two plots. This suggests that there was an increase in the amount of biomass partitioned to sucrose (and therefore a decrease in partitioning to the other components) during this period. The RSWC measured at the start and end of this period was 55% and 35% respectively. The corresponding values for simulated RSWC were 48% and 20% respectively.

The reduction of SWDEF1 and SWDEF2 below unity occurred at DAE 125 and 121 respectively, which is quite close to the estimated start and end of the period of increased partitioning to sucrose. This however, could be misleading because RSWC was under-estimated by the Canegro model during this period. This implies that the equations used to calculate crop water uptake and to calculate the stress factors may have to be refined simultaneously for more accurate simulation of biomass accumulation and partitioning.

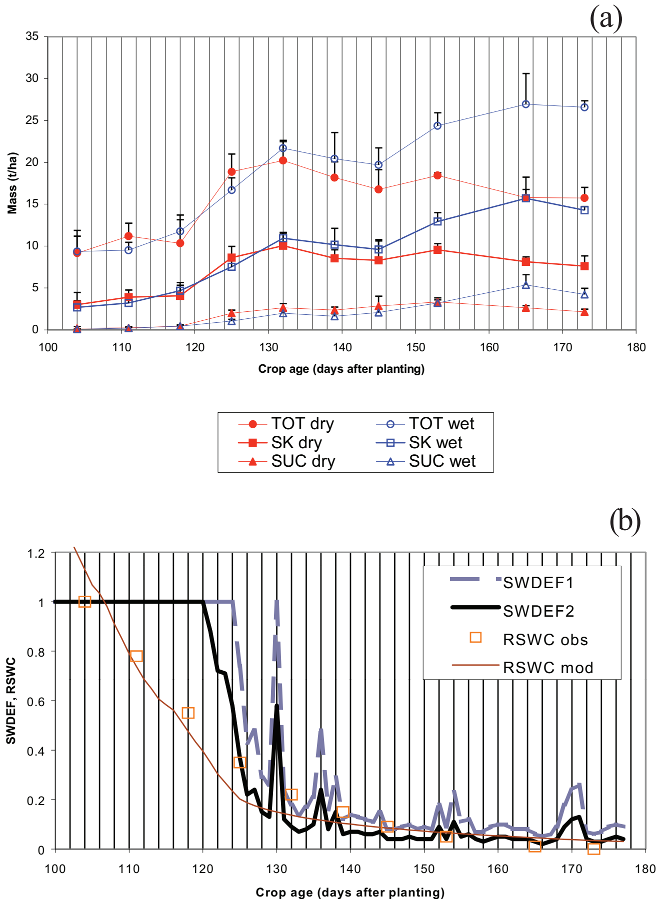

Figure 2. The progression over time of aerial biomass (TOT), stalk mass (SK), and sucrose mass (SUC) of the dry and wet plots (a, bars indicate one standard error), and the observed and modelled relative soil water content (RSWC obs and RSWC mod) and the water stress factors (SWDEF1 and SWDEF2) for the dry plot (b).

Determination of partition fractions

Linear regression analysis (a fit of eq. 5) on SK vs. TOT data yielded no significant differences between the wet and dry plot (Fig. 3). The ρ_{SK} value calculated for the wet plot and dry plot data combined was 0.67, which is lower than values reported in the literature. The APSIM model partitions 0.7 of aerial biomass increments to stalk. Data from Thompson (1988) yields a stalk partition fraction of 0.73 and 0.81 for plant and first ratoon N14.

The combined regression also indicated that the base TOT value below which partitioning to SK were zero, equaled 4.83 t/ha. This compares well with the value of 5 t/ha used by Robertson et. al.(1995) and with the value of 4.4 t/ha derived from the data presented by Thompson (1988) for a N14 plant crop.

It is also interesting to note that the ratio of SK:TOT (this is not the instantaneous partition fraction but the ratio of the accumulated mass of each component) measured in this experiment was considerably higher than that reported by Robertson et.al. (1996), especially at low TOT values (young cane). It also exceeded values found by Inman-Bamber & Thompson (1989) when TOT was below 16 t/ha. For TOT values exceeding 16 t/ha the SK:TOT ratios measured in this experiment was in close agreement with that found by Inman-Bamber & Thompson.

Stalk partitioning results are illustrated in Fig. 4. The best fit of eq. 7 to the data was obtained when the constant b had a value of 0.09 for the wet plot and 0.15 for the dry plot. It is clear from Fig. 4 that eq. 8 fits the data reasonably well. This implies that eq. 6 is appropriate to estimate σ_{SUC} and σ_{FNS}.

The value of σ_{SUC} for the wet plot ranged from approximately 0.14 at SK = 3 t/ha to 0.33 at SK = 9 t/ha. The corresponding values for the dry plot were 0.22 and 0.44. There was a 33% increase in σ_{SUC} (at SK = 9 t/ha) as a result of water stress. The value of σ_{FNS} for the wet plot varied from 0.86 at SK = 3 t/ha to

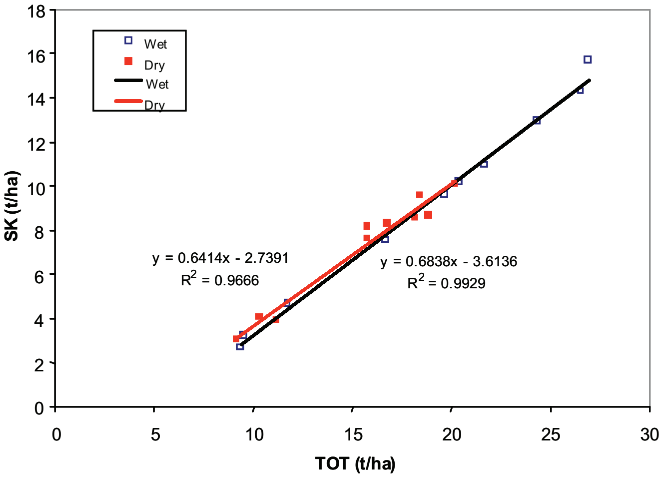

Figure 3. Stalk mass (SK) as a function of aerial biomass (TOT) for the wet and dry plots. Fits of eq. 5 to the wet and dry plot data are also shown.

0.67 at SK = 9 t/ha. The corresponding values for the dry plot were 0.78 and 0.56 respectively. There was a 26 % reduction in σ_{FNS} (at SK = 9 t/ha) as a result of water stress.

Conclusions

The key findings in this study were:

- Biomass accumulation was only affected by water stress after the relative soil water content dropped below 35%.
- Partitioning to the different components was affected by water stress when soil water content was between 55% and 35%. During this period more biomass was partitioned to sucrose and less to the rest of the stalk. Partitioning between stalk and non-stalk components was not affected significantly by water stress.
- The stalk partition fraction was constant at 0.67 after 4.83 t/ha of aerial biomass has accumulated.
- Non-linear equations were developed to estimate sucrose partition fractions for stressed and unstressed sugarcane. Mild water stress increased the instantaneous sucrose partition fraction by 33%.
- Although the timing of the Canegro stress factors was close to that required to accurately regulate biomass accumulation and partitioning, the under-estimation by the model of available soil water content may necessitate refinement of crop water uptake and stress equations.

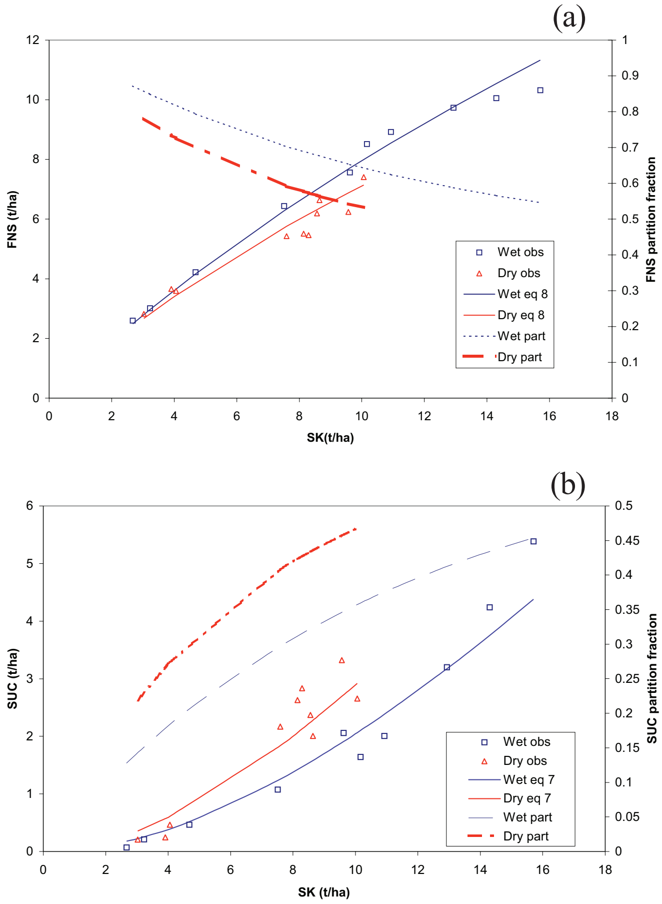

Figure 4. Fibre plus non-sucrose (FNS) (a) and sucrose mass (SUC) (b) as a function of stalk mass (SK). Fits of eq. 7 and 8 to the data are shown (solid lines) as well as the calculated partition fractions (dashed lines).

These findings will be used in conjunction with plant extension measurements from this experiment to develop refined stress equations for models to regulate biomass accumulation and partitioning in sugarcane.

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