Aust. J. Agric. Res., 1994, **45**, 37–49

Radiation Interception and Biomass Accumulation in a Sugarcane Crop Grown under Irrigated Tropical Conditions

R. C. Muchow,[A] *M. F. Spillman,*[B] *A. W. Wood*[C] *and M. R. Thomas*[D]

[A] Division of Tropical Crops and Pastures, CSIRO, Cunningham Laboratory, 306 Carmody Road, St Lucia, Qld 40067.
[B] Division of Tropical Crops and Pastures, CSIRO, Davies Laboratory, Private Bag, P.O. Aitkenvale, Qld 4814.
[C] CSR Technical Field Department, Macknade Mill, Ingham, Qld 4850.
[D] CSIRO IPPP Biometrics Unit, Cunningham Laboratory, 306 Carmody Road, St Lucia, Qld 4067.

Abstract

Little quantitative information relating yield accumulation in sugarcane to climatic factors is available to allow the maximum yield in different seasons and locations to be determined. By comparison of actual yield with the climatically determined maximum yield for a given crop, the extent of yield limitation due to management and soil and pest factors can be assessed. This paper analyses the relationship between radiation interception and biomass accumulation for an autumn-planted sugarcane crop grown under irrigated conditions at Ayr, Qld (lat. 19·5° S.). Crop samplings were conducted from 167 to 445 days after planting (DAP). Less than 60% of the seasonal incident solar radiation was intercepted by the crop. A radiation extinction coefficient of 0·38 was estimated from the relationship between green leaf area index and the fraction of the radiation intercepted (f_i). A maximum crop radiation (SW, 0·35–2·5 μm) use efficiency (RUE) of 1·75 g MJ^{-1} was determined. The maximum crop growth rate over a 140 day period was 41·1 g m^{-2} d^{-1}. However, this value is dependent on f_i and the incident radiation (S), and accordingly would be expected to vary across locations. In contrast, the RUE value of 1·75 g MJ^{-1} is independent of f_i and S, and can be used as a baseline value to assess the extent of yield limitation and the scope for yield improvement at different locations.

The maximum biomass production was 72 t ha^{-1} and the maximum fresh cane yield was 201 t ha^{-1}. However, these maximum yields were attained up to 4 months before the final sampling. Future research should examine the wider applicability of this early yield plateau, and focus on the factors responsible for the early cessation in yield accumulation.

Keywords: climate, yield accumulation, radiation use efficiency, biomass, cane yield, sugarcane.

Introduction

The three main climatic elements affecting crop yield are radiation, temperature and rainfall. Where ample irrigation is available, rainfall rarely limits crop yield, except where excess rainfall causes waterlogging and drainage problems. A quantitative understanding of the influence of temperature and radiation on crop yield is useful in establishing a benchmark yield for a given site and season. By comparing the climatically determined yield with actual measured yield, the extent of limitation due to management, soil and pest and disease factors can be assessed, and the scope for yield improvement (both varietal and management) can be determined.

0004-9409/94/010037$05.00

A number of approaches exist for estimating the climatically determined yield. Statistical approaches have been used successfully in several studies. The increase in stalk elongation in sugarcane with increasing temperature has been analysed using the day-degree concept (Das 1933; Clements 1980). Similarly, sugarcane yield is determined to a large extent by the solar radiation incident on the crop (Clements 1940; Chang *et al.* 1963; Nickell 1977). Thompson (1978) has reported biomass production in sugarcane in South Africa, and Kingston *et al.* (1984) have measured biomass production in sugarcane at Ayr and Bundaberg, Australia. In both these reports, productivity was analysed in terms of the efficiency of conversion of total incident short-wave radiation to dry matter, and these values varied with crop age and growth conditions. In Hawaii, Clements (1980) reported a linear relationship between growth unit (defined as the daily increase in cane volume, obtained by multiplying the daily elongation rate by the green weight of the sheaths) and daily incident solar radiation. Using multiple linear regression analysis on sugarcane crops grown in Florida, Allen (1976) reported that yield is positively related to both solar radiation and degree days.

Difficulties arise with these types of analyses because climatic variables are confounded, and there is no mechanistic basis for studying variation in crop performance. For example, differences in photosynthetic efficiency calculated from incident radiation may be associated with differences in leaf canopy development and the interception of radiation. Also, many of the relationships between growth and temperature in sugarcane may be simply a reflection of the relationship between growth and solar radiation, since temperature and radiation tend to be highly correlated. Furthermore, statistical models are only reliable for interpolation within the data sets based on a mean response. Accordingly, it is not possible to extrapolate to other locations or to weather conditions different from those upon which the regression relationships were developed.

An alternative approach is to quantify the importance of different physiological processes and climatic elements in contributing to yield variation and to incorporate these relationships into mechanistic crop growth models (e.g. maize, Muchow *et al.* 1990,1991; sorghum, Hammer and Muchow 1991; kenaf, Carberry and Muchow 1992). Crop growth simulation models are powerful tools that increase research efficiency by allowing the analysis of crop performance at different locations where climate is variable and relatively unpredictable. However, insufficient data relating the key growth processes of sugarcane to climatic factors are available to enable the climatically determined sugarcane yield at different locations to be assessed, and its variation from year to year for different growth durations to be determined. To make such an assessment for sugarcane, it is necessary to obtain growth analysis data by regularly sampling the crop throughout the growing season. Accordingly, in this paper we present a growth analysis of a sugarcane crop under irrigated tropical conditions.

Crop biomass (g m^{-2}) can be considered as a function of the amount of radiation intercepted (S_i; MJ m^{-2}) and the radiation use efficiency (RUE; g MJ^{-1}). S_i is determined by the crop duration and consequently the cumulative incident solar radiation (S), and by the fraction of the incident radiation that is intercepted (f_i) as determined by leaf area development and the radiation extinction coefficient (k). Leaf area development is strongly influenced by temperature (Muchow and Carberry 1989). The slope of the relationship between biomass accumulation and S_i is the RUE, and this varies with age and specific leaf nitrogen (Muchow and Davis 1988), and also with extremes of temperature. The RUE is a measure of photosynthetic performance. Muchow and Davis (1988) have measured maximum RUE values of 1·6 and 1·25 g MJ^{-1} (SW radiation) for maize and sorghum respectively, and Sinclair and Horie (1989) have predicted a theoretical maximum RUE of 1·7 g MJ^{-1} for C_4 crops. No data are available on maximum RUE values for sugarcane, nor on the variation in RUE over the much longer crop growth cycle of sugarcane, compared with the C_4 annuals maize and sorghum. Accordingly, the primary objective of this paper is to analyse radiation interception and biomass accumulation in a sugarcane crop, and to compare maximum RUE values with other C_4 crops.

Sugarcane yield is traditionally expressed as the fresh weight of millable stalks. Little information is available on the proportion of stalk in the total above-ground biomass, nor on the relationship between fresh cane yield and above-ground biomass. A second objective of this paper is to analyse biomass partitioning in sugarcane, and the change in dry matter content with age. The economic yield of sugarcane is also determined by the partitioning of biomass to sucrose, but this aspect is not considered in this paper.

Materials and Methods

Location and Cultural Details

The field study was conducted on a silty river loam (USDA Soil Taxonomy: Dystropept) in Block 142 of G. and R. Zanetti's farm at Ayr, Qld (lat. 19·5° S. long. 147·3° E.). The meteorological conditions during the study are shown in Fig. 1. Setts of variety Q96 were planted on 20 April 1991 into 1·5 m drills. Fertilizer applied at planting was Crop King 88 (14·8% N, 4·3% P,11·3% K, 13·6% S) at 222 kg ha^{-1}. Ammonium sulfate (20·5% N) was banded into the soil at 314 kg ha^{-1} on 29 July 1991, and urea (46% N) was banded into the soil at 336 kg ha^{-1} on 18 August 1991. The crop was furrow irrigated at 4, 86, 168, 185, 207, 231, 254, 264, 271, 283, 303, 325, 337, 348, 371, and 383 days after planting (DAP). The crop was hilled up at the final cultivation at 164 DAP.

Measurements

Four rows were randomly selected from the 10 ha block as four replicates. In furrow-irrigated sugarcane, it is impractical to measure biomass accumulation until after the final cultivation, when a reference ground level is maintained for the remainder of growth. At 166 DAP (3 October 1991), two pairs of two tube solarimeters (Type TSL, Delta-T Devices, Cambridge, Great Britain) were placed diagonally across the 1·5 m inter-row in each replicate at ground level. The tubes were raised over time to be below the last green leaf, so that radiation interception by green leaf only was measured, and not that additionally intercepted by stalk and trash. A reference tube solarimeter was placed above the crop. The tubes were removed from the crop at 298 DAP (12 February 1992) prior to the crop lodging on 26 February 1992 (311 DAP). Thereafter, only incident radiation was measured with the reference solarimeter.

The tube solarimeters were used to record the transmitted and incident short-wave radiation (0·35–2·5 μm) respectively, at 2 min intervals. Daily totals and individual tube-calibration factors were used to calculate the fraction of the incident radiation intercepted by the crop (f_i). Since the readings from individual solarimeters were found to vary by up to 20% from the nominal calibration, the absolute incident radiation (S) was recorded with a pyranometer (Li 200S, Li-Cor Inc., Lincoln, Nebraska, U.S.A.). The amount of radiation intercepted (S_i) was calculated as the product of the daily f_i and S. The tube solarimeters and pyranometer were connected to a low-power programmable data-logging system described by Muchow and Davis (1988).

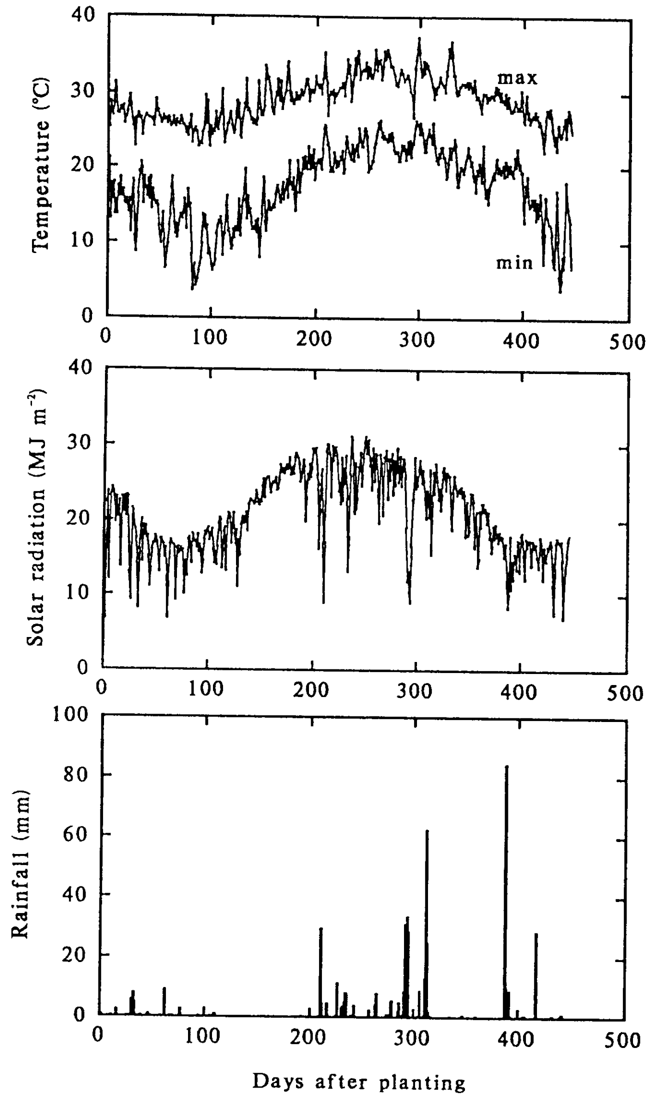

Fig. 1. Daily maximum and minimum screen temperature, incident short-wave radiation and rainfall during the experiment. Date of planting was 20 April 1991.

A 5 m length of row in each of four replicates was cut at ground level on 10 sampling occasions (Table 1). Each successive sampling site down the row was separated by a 3 to 5 m buffer of cane. The total number of stalks was recorded. Ruddweigh load cells were used to determine the total fresh weight ($\pm 0 \cdot 1$ kg) in the field. A 10 stalk subsample, representative on a fresh weight basis, was taken. At the first four samplings (Table 1), these stalks were partitioned into green leaf blades and remaining stalk and sheath material, as no dead leaf was

present. Thereafter, the 10 stalk subsample was partitioned into green leaf blades, dead leaf and dead sheaths, defined as trash, millable stalks, and cabbage, defined as the immature top of the stalk plus green leaf sheaths. The fresh weight of each component was determined. Then the material from each component was fibrated using a cutter-grinder, and two representative subsamples were placed in 850 mL aluminium foil trays for drying at 80°C. After the dry matter content was determined, the green leaf, trash, millable stalk, and cabbage dry matter yield were determined per unit land area from the total fresh weight from the 5 m length of row, the component proportion of the total above ground material on a fresh weight basis, and the component dry matter content. The net above-ground biomass was calculated as the sum of the individual components, and the above-ground biomass per stalk was calculated by further division by stalk number. The fresh cane yield per m^2 was calculated as the product of the total fresh weight from the 5 m length of row and the proportion of millable stalks on a fresh weight basis in the 10 stalk subsample divided by $7 \cdot 5$ (i.e. $5\ m \times 1 \cdot 5$ m row width). The fresh cane weight per stalk was further calculated by division by stalk number.

Table 1. Sampling occasions, and mean daily temperature [(max.+min.)/2] and solar radiation from planting to the first sampling and for the period between samplings for Q96 plant crop at Ayr

The fresh cane yield (±standard error of the mean of four replicates) is also given. Cane yield was not measured (NM) for the first four samplings

Sampling date	Days after planting	Mean temperature (°C)	Mean solar radiation ($MJ\ m^{-2}\ d^{-1}$)	Fresh cane yield ($t\ ha^{-1}$)
4 Oct. 1991	167	20·0	18·5	NM
22 Oct. 1991	185	23·8	27·3	NM
20 Nov. 1991	214	25·9	25·1	NM
4 Dec. 1991	228	25·5	26·8	NM
21 Jan. 1992	276	28·2	26·5	129±8
11 Feb. 1992	297	27·1	22·4	155±3
12 Mar. 1992	327	27·6	24·6	194±4
8 Apr. 1992	354	26·2	23·3	211±11
6 May 1992	382	24·2	19·0	195±11
8 July 1992	445	20·7	15·3	205±8

In addition to the 10 stalk subsample, the green leaves from a further 5 stalk subsample were taken for determination of specific leaf area (SLA). The area of the leaf blades was determined using a leaf area measurement system (Delta-T Devices, Cambridge, Great Britain). Then they were dried at 80°C, and SLA was computed as the leaf area per unit leaf weight. The leaf area index (L) was calculated from the leaf weight per unit land area and SLA.

Results

Biomass Accumulation Over Time

During the period from planting to the first sampling at 167 DAP, above-ground biomass production was only 409 $g\ m^{-2}$ (Fig. 2). During this period, maximum temperature was relatively high, but minimum temperature was frequently below 10°C (Fig. 1). The mean temperature during this period was 20°C and the mean S was $18 \cdot 5\ MJ\ m^{-2}\ d^{-1}$ (Table 1). From the third sampling (214 DAP) until the eighth sampling (354 DAP), both temperature and S were high (Fig. 1, Table 1), and above-ground biomass accumulation was approximately linear over time (Fig. 2). Using linear regression, the crop growth rate for the period from 214 to 354 DAP was $41 \cdot 1 \pm 1 \cdot 3\ g\ m^{-2}\ d^{-1}$. During the period from 354 to 445

DAP, there was no further increase in biomass above the mean maximum value for the last three samplings of 7166 g m^{-2} (Fig. 2, Table 2). This cessation in biomass production occurred well before the commencement, in mid-June (*c.* 420 DAP in this study), of the normal harvest season for sugarcane milling at this location.

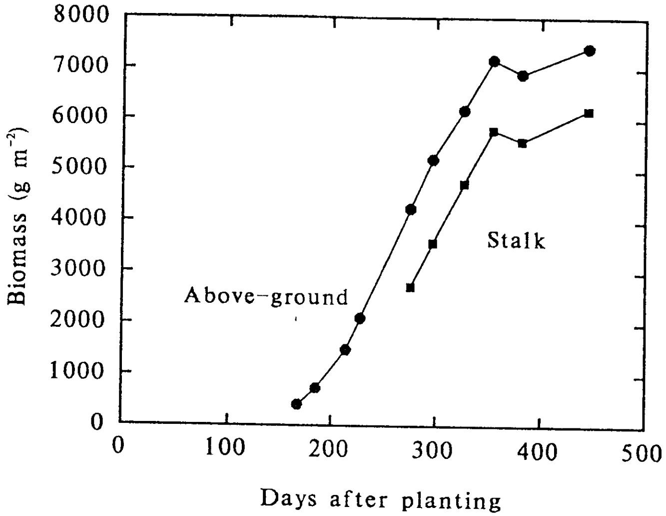

Fig. 2. Total above-ground (●) and millable stalk (■) biomass accumulation over time.

Table 2. Stalk number and biomass per unit land area, and biomass and cane yield per stalk during late growth

The standard error of the mean of four replicates at each sampling is also given

Days after planting	Stalk number (m^{-2})	Biomass ($g\ m^{-2}$)	Biomass per stalk (g)	Cane per stalk (g)
327	9·44±0·25	6191±159	657±8	2067±25
354	9·20±0·61	7178±232	786±31	2298±34
382	8·00±0·37	6902±410	862±27	2435±82
445	7·73±0·43	7420±182	966±42	2656±66

The accumulation of biomass in the millable stalks closely mirrored the accumulation of above-ground biomass, and again there was little increase in stalk biomass from 354 DAP (Fig. 2, Table 3). From 354 DAP, there was a decrease in green leaf biomass and relatively little change in cabbage and trash biomass, but these three components combined, comprised less than 20% of the total above-ground biomass (Table 3). Earlier in growth, these three components comprised a larger proportion of the total above-ground biomass, but the change in biomass in these three components was small relative to the large change in stalk biomass over time (Table 3).

Table 3. Leaf, stalk, cabbage and trash dry matter yield (±standard error of the mean of four replicates) at each sampling

Note that stalk yield given for samplings from 167 to 228 DAP is stalk plus cabbage, as described in text

Days after planting	Leaf ($g\ m^{-2}$)	Stalk ($g\ m^{-2}$)	Cabbage ($g\ m^{-2}$)	Trash ($g\ m^{-2}$)
167	274±14	135±11	NM	0
185	396±17	341±26	NM	0
214	487±17	1009±71	NM	0
228	580±10	1524±37	NM	0
276	723±46	2719±122	444±7	369±49
297	693±54	3587±149	497±32	446±38
327	541±15	4750±121	318±11	582±36
354	591±33	5790±190	322±27	475±100
382	475±31	5587±261	276±15	562±137
445	442±15	6189±127	276±14	513±79

Whilst there was no increase in above-ground biomass per unit land area from 354 DAP (Fig. 2, Table 2), there was a significant increase in above-ground biomass per stalk (Table 2). Stalk number decreases during this period (Table 2), and the linear contrast for stalk number with DAP was significant ($P = 0 \cdot 01$). Consequently, the cessation of biomass accumulation per unit land area was largely due to the loss of stalks, rather than due to a cessation in net photosynthesis per stalk or to a large loss in leaf biomass.

Radiation Interception and Biomass Accumulation

Green leaf area index (L) increased from 2·5 at 167 DAP to a peak value of 6·8 at 297 DAP, and then declined to 3·9 at 445 DAP (Fig. 3*a*). The SLA was similar over all samplings with a mean value of 95·2±2·0 cm^2 g^{-1}. The measured f_i increased from 0·57 at 167 DAP to a peak value of 0·93 at 297 DAP (Fig. 3*b*). Measurements of f_i ceased at 298 DAP before crop lodging. The relationship: $f_i = 1 - \exp(-kL)$, where k is the radiation extinction coefficient, was fitted to the data from the six samplings from 167 to 297 DAP (Fig. 3*c*). A k value of 0·38±0·01 was estimated. This k value was used to estimate f_i for the samplings from 327 to 445 DAP based on the mean L between samplings (Fig. 3*a*, *b*). These estimates assume no change in k after crop lodging, and this is supported by visual observations that the green leaf canopy rapidly became erect again after the crop lodged on 26 February, and by the relationship between biomass and S_i remaining linear until the 8 April sampling (Fig. 4). The estimated f_i at the final harvest at 445 DAP was 0·79 (Fig. 3*b*).

The relationship between above-ground biomass accumulation and S_i was linear ($r^2 = 0 \cdot 99$) for the first eight samplings (Fig. 4). A sigmoid relationship gave a marginally better ($r^2 = 0 \cdot 997$) empirical description of the relationship between biomass and S_i, but for modelling purposes, the linear fit is more useful as a basis for estimating RUE. The fitted slope of the linear relationship (i.e. the RUE) was 1·75±0·09 g MJ^{-1}. Extrapolation of the fitted linear relationship in Fig. 4 to zero biomass (i.e. at planting), gave an estimated S_i from planting to 167 DAP (i.e. the first sampling occasion) of 71 MJ m^{-2}. Using this estimate, the

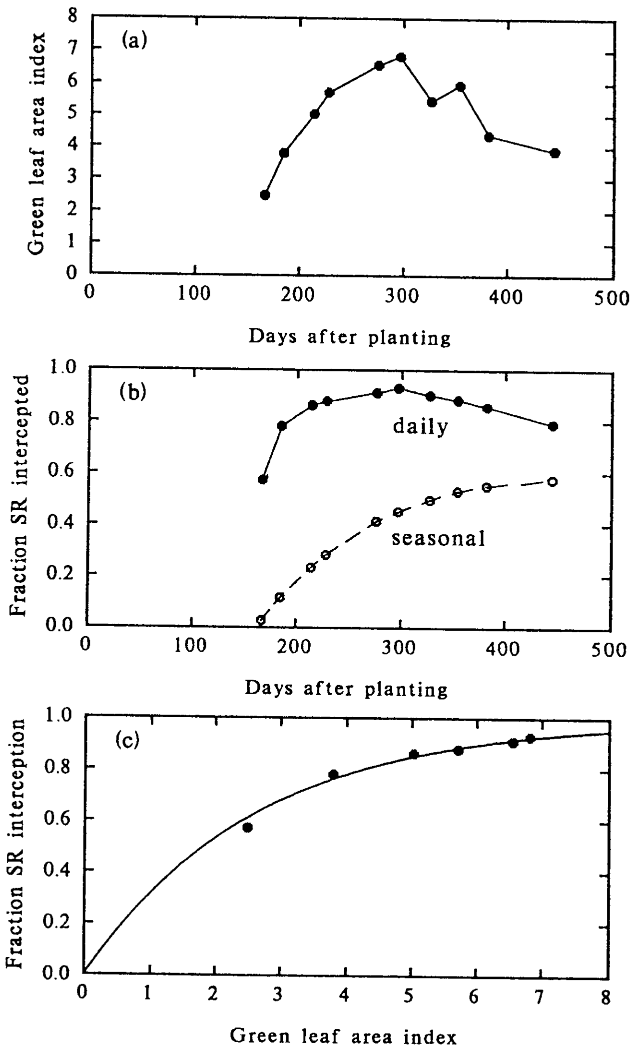

Fig. 3. Trends in (*a*) leaf area index (L), and (*b*) daily (f_i) and seasonal (f_s) fraction of radiation intercepted, over time; and (*c*) the relationship between f_i and L. The relationship $f_i = 1 - \exp(-0\cdot38 \pm 0\cdot01\ L)$ was fitted to the data in (*c*).

seasonal fraction of radiation intercepted (f_s) was calculated on each sampling occasion as the ratio of S_i to S from planting to the sampling (Fig. 3*b*). Only 3% of S was intercepted from planting until the first sampling at 167 DAP; at final harvest (445 DAP), f_s was 0·58 (Fig. 3*b*).

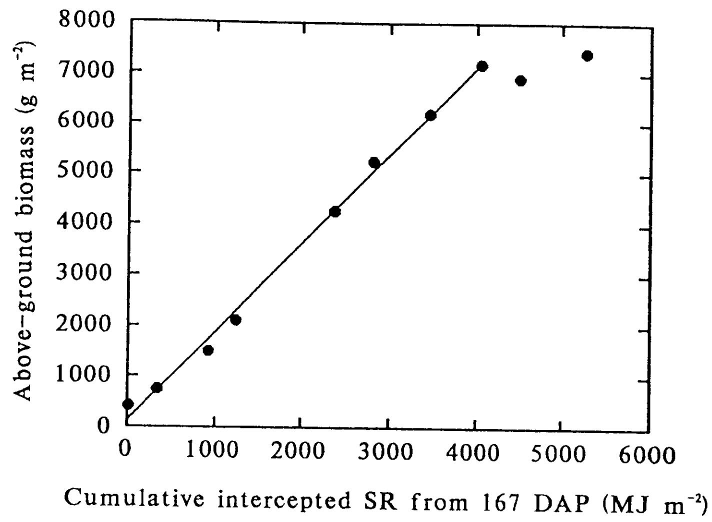

Fig. 4. Relationship between net above-ground biomass and the amount of radiation intercepted from 167 DAP. For the first eight samplings, the relationship $y = 125 \pm 109 + 1\cdot75 \pm 0\cdot05\ x$ ($r^2 = 0\cdot995$) was fitted by linear regression.

Relationship between Fresh Cane Yield and Above-ground Biomass

There was no further increase in fresh cane yield after the sampling on 11 March 1992 (327 DAP), and the mean cane yield of the last four samplings was 201 t ha^{-1} (Table 1). Similarly to biomass accumulation, cane yield per stalk increased from 327 to 445 DAP, and again the early cessation in cane yield accumulation was largely due to loss of stalks (Table 2). The ratio of fresh cane yield to above-ground biomass varied from 3·15 to 2·76, but this variation was not significant and the slope of the fitted relationship between fresh cane yield and above-ground biomass was 2·92±0·06 (Fig. 5). The maximum individual fresh millable stalk weight attained in this study was 2656 g (Table 2). Whilst the relationship between the fresh and dry weights of millable stalks was linear (Fig. 6), the intercept was also significant. Consequently, the dry matter content of millable stalks increased from 0·21 at 276 DAP to 0·30 at 445 DAP.

Discussion

The key findings from this study on an autumn-planted sugarcane crop grown in an irrigated tropical environment are that (i) less than 60% of the seasonal incident solar radiation was intercepted when harvested at 15·5 months after planting; (ii) a radiation extinction coefficient of 0·38 and a radiation use efficiency of 1·75 g MJ^{-1} were measured; and (iii) biomass and cane yield accumulation ceased well before the normal harvest period.

The sensitivity of leaf growth to low temperature, the wide row spacing (1·5 m), and the low radiation extinction coefficient (0·38) contribute to extremely low radiation interception by the crop in the first 6 months ($f_s < 0\cdot05$) when planted in April in this north Queensland environment. For irrigated C_4 annual crops of

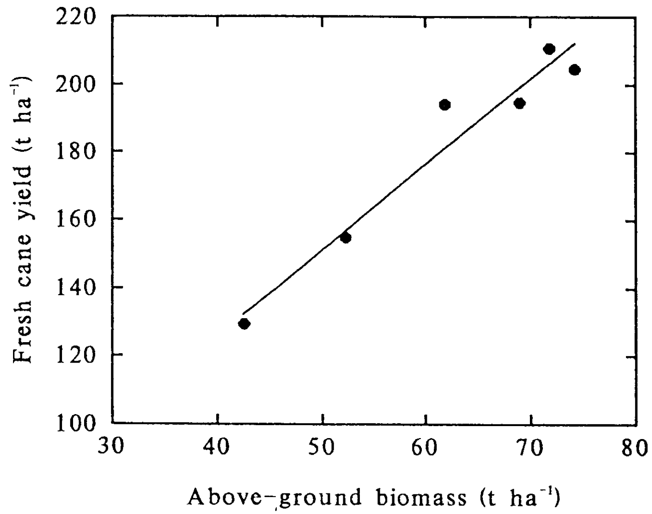

Fig. 5. Relationship between fresh cane yield and above-ground biomass for samplings from 276 to 445 DAP. The relationship $y = 2 \cdot 92 \pm 0 \cdot 06 \times (r^2 = 0 \cdot 998)$ was fitted by linear regression.

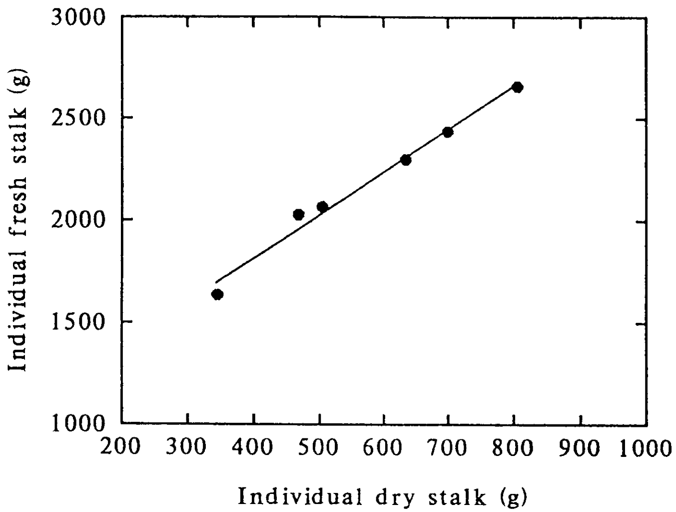

Fig. 6. Relationship between the fresh and dry weights of millable stalks for samplings from 276 to 445 DAP. The relationship $y = 973 \pm 81 + 2 \cdot 11 \pm 0 \cdot 14 \times (r^2 = 0 \cdot 979)$ was fitted by linear regression.

maize and sorghum growing in comparable tropical environments (lat. 14·5° S.), Muchow (1989) observed f_s values ranging from 0·51 to 0·65 for crop durations ranging from 85 to 110 days. These f_s values are comparable for those reported here for sugarcane, but for a much longer crop duration (445 days). This poses the question whether there would be any yield advantage in improving f_i during early growth and consequently f_s. Given that maximum biomass and cane yield were attained well before final harvest in this study, it is unlikely that yield would be improved by enhancing f_s in autumn-planted crops at this high-radiation location. Nevertheless, further research is warranted on the importance of f_s in spring-planted and ratoon crops at this location, and for all crop classes at other locations.

For growth up until maximum biomass accumulation (354 DAP), the relationship between above-ground biomass accumulation and S_i was linear (Fig. 4), whilst the relationship between biomass accumulation and time was non-linear (Fig. 2) due to variation in f_i and S. The RUE was constant for a 287 day period at 1·75 g MJ^{-1}. Based on theoretical calculations, Sinclair and Horie (1989) suggested that this is the maximum value expected for a C$_4$ crop. This sugarcane value is slightly higher than the 1·6 g MJ^{-1} measured for maize using similar methodology (Muchow and Davis 1988). Clearly, further substantial improvement in the maximum photosynthetic capacity of sugarcane appears unlikely. Of more importance, however, is understanding the factors contributing to the cessation of biomass accumulation well before final harvest. When biomass per unit land area plateaued, above-ground biomass production per stalk continued to increase. The loss in stalk number appeared to be the major contributor to the cessation in biomass accumulation per unit land area in this study, and this may be due to crop smothering and stalk rotting associated with lodging. In another study on high-yielding crops at Ingham, lodging occurred earlier in the crop life cycle, and we did not observe the marked decrease in stalk number during late growth (Muchow *et al.* 1993). Clearly, further research is warranted on the pattern of biomass accumulation during late growth with particular emphasis on stalk dynamics under high-yielding, lodged sugarcane crops.

Biomass production and crop growth rate are not routinely determined in sugarcane trials because leaf, trash and cabbage material are not desirable in sugarcane processing (Irvine 1983). Using linear regression, we calculated a maximum crop growth rate of 41 g m^{-2} d^{-1} over a 140 day period. Thompson (1978) cites maximum crop growth rates of 48 g m^{-2} d^{-1} in Hawaii and 41 g m^{-2} d^{-1} in South Africa, but these were calculated over much shorter growth durations. Our value is less than the record crop growth of 54 g m^{-2} d^{-1} recorded by Begg (1965) for the C$_4$ species *Pennisetum typhoides* over a 2 week period. Given a peak f_i of 0·93 (Fig. 3b) and a RUE of 1·75 g MJ^{-1} (Fig. 4), the daily S would have to be 33 MJ m^{-2} d^{-1} to attain a crop growth rate of 54 g m^{-2} d^{-1} in sugarcane. Such high S values are not observed at this location (Fig. 1). This illustrates the point that crop growth rate is dependent on f_i and S, and accordingly would be expected to vary across locations. In contrast, the RUE value of 1·75 g MJ^{-1} is independent of f_i and S, and can be used as a baseline value to assess the extent of yield limitation and the scope for yield improvement at different locations. More importantly, however, the crop growth rate of 41 g m^{-2} d^{-1} for sugarcane is frequently extrapolated for a 12 month period to estimate biomass production of 150 t ha^{-1} year^{-1} (Bull and Glasziou 1975). In the current study, maximum biomass production was 72 t ha^{-1} at 12–15 months, well below the 150 t ha^{-1} value, due to variation in S and f_i throughout the year, and also due to no further increase in biomass production per unit area during late growth. Our biomass value of 72 t ha^{-1} is close to the maximum values summarized by Irvine (1983). The cessation in biomass accumulation late in the season also resulted in the average RUE for the period from planting to 445 DAP being 1·37 g MJ^{-1}, which was substantially less than the maximum value.

This study has outlined a framework for quantifying the climatic constraints to biomass production in sugarcane, and has established a k value of 0·38 and a maximum RUE value of 1·75 g MJ^{-1} for variety Q96. The wider applicability of these key parameters across varieties and crop classes (plant and ratoon crops) needs to be assessed. Research is required to establish the quantitative relationship between leaf growth and temperature (e.g. sorghum, Muchow and Carberry 1990), so that f_i can be estimated for different seasons and locations. Emphasis then needs to be placed on research into the factors contributing to the cessation of cane and biomass accumulation during late growth, with particular attention being given to stalk dynamics. The relationship between biomass and sucrose accumulation during this period is critical to economic return, and factors affecting this relationship need to be quantified. Fresh cane yield is the economic measure of productivity in the sugar industry, and this study has established a multiplier of 2·92 to convert standing biomass to fresh cane yield. The robustness of this value for different environmental conditions, yield levels and varieties needs to be assessed.

Acknowledgments

We are appreciative of Gus and Robert Zanetti for providing us with a sugarcane crop that was grown under non-limiting conditions, and for allowing us to destructively sample their crop. We also thank Geoff Routley, Bob Stewart and Damien Ryan for their technical assistance in sampling this large lodged crop, and Roger Davis for design and maintenance of the datalogging system for radiation measurement. This study was funded, in part, by the Australian Sugar Research and Development Corporation.

References

Allen Jr, R. J. (1976). A five-year comparison of solar radiation and sugarcane production in the Everglades Agricultural Area. *Proc. Soil Crop Sci. Soc. Florida* **36**, 197–200.

Begg, J. E. (1965). High photosynthetic efficiency in a low-latitude environment. *Nature* **205**, 1025–6.

Bull, T. A., and Glasziou, K. T. (1975). Sugar cane. In 'Crop Physiology: Some Case Histories'. (Ed. L. T. Evans.) pp. 51–72. (Cambridge University Press: Cambridge, U.K.)

Carberry, P. S., and Muchow, R. C. (1992). A simulation model of kenaf for assisting fibre industry planning in northern Australia. 3. Model description and validation. *Aust. J. Agric. Res.* **43**, 1527–45.

Chang, J. H., Campbell, R. B., and Robinson, R. E. (1963). On the relationship between water and sugar cane yield in Hawaii. *Agron. J.* **55**, 450–3.

Clements, H. F. (1940). Integration of climatic and physiologic factors with reference to the production of sugarcane. *Hawaiian Planters Rec.* **44**, 201–33.

Clements, H. F. (1980). 'Sugarcane Crop Logging and Crop Control: Principles and Practices'. (The University Press of Hawaii: Honolulu, U.S.A.) p. 166.

Das, U. K. (1933). Measuring production in terms of temperature. *Hawaiian Planters Rec.* **37**, 32–52.

Hammer, G. L., and Muchow, R. C. (1991). Quantifying climatic risk to sorghum in Australia's semi-arid tropics and subtropics: Model development and simulation. In 'Climatic Risk in Crop Production: Models and Management for the Semi-arid Tropics and Subtropics'. (Eds R. C. Muchow and J. A. Bellamy.) pp. 205–32. (CAB International: Wallingford.)

Irvine, J. E. (1983). Sugarcane. In 'Potential Productivity of Field Crops under Different Environments'. (Int. Rice Res. Institute: Manila.) pp. 361–81.

Kingston, G., Ham, G. J., Ridge, D. R., and Leverington, K. C. (1984). Biomass accumulation in sugar cane. Report NERD&C Project 79/9028.

Muchow, R. C. (1989). Comparative productivity of maize, sorghum and pearl millet in a semi-arid tropical environment. I. Yield potential. *Field Crops Res.* **20**, 191–205.

Muchow, R. C., and Carberry, P. S. (1989). Environmental control of phenology and leaf growth in a tropically adapted maize. *Field Crops Res.* **20**, 221–36.

Muchow, R. C., and Carberry, P. S. (1990). Phenology and leaf area development in a tropical grain sorghum. *Field Crops Res.* **23**, 221–37.

Muchow, R. C., and Davis, R. (1988). Effect of nitrogen supply on the comparative productivity of maize and sorghum in a semi-arid tropical environment. II. Radiation interception and biomass accumulation. *Field Crops Res.* **18**, 17–30.

Muchow, R. C., Sinclair, T. R., and Bennett, J. M. (1990). Temperature and solar radiation effects on potential maize yield across locations. *Agron. J.* **82**, 338–43.

Muchow, R. C., Hammer, G. L., and Carberry, P. S. (1991). Optimising crop and cultivar selection in response to climatic risk. In 'Climatic Risk in Crop Production: Models and Management for the Semi-arid Tropics and Subtropics'.(Eds R. C. Muchow and J. A. Bellamy.) pp. 235–62. (CAB International: Wallingford.)

Muchow, R. C., Wood, A. W., Spillman, M. F., Robertson, M. J., and Thomas, M. R. (1993). Field techniques to quantify the yield-determining processes in sugarcane. I. Methodology. Proc. 15th Conf. Aust. Soc. Sugarcane Technologists, pp. 336–43.

Nickell, L. G. (1977). Sugarcane. In 'Ecophysiology of Tropical Crops'. (Eds P. Alvim and T. Kozlowski.) pp. 89–110. (Academic Press: New York.)

Sinclair, T. R., and Horie, T. (1989). Leaf nitrogen, photosynthesis, and crop radiation use efficiency: A review. *Crop Sci.* **29**, 90–98.

Thompson, G. D. (1978). The production of biomass by sugarcane. *Proc. S. Afr. Sug. Technol. Ass.* **52**, 180–87.

Manuscript received 4 November 1992, accepted 17 August 1993