

# SOME PHYSIOLOGICAL FACTORS AFFECTING THE OPTIMUM AGE AND SEASON FOR HARVESTING SUGARCANE

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## Abstract

During the past decade the age at which sugarcane is harvested has been reduced considerably, largely to control *Eldana saccharina* Walker, a borer which thrives in older cane. It is necessary to consider how other factors may influence harvest age and season, and to consider how to adjust harvest schedules if new technology should lead to a reduction in the threat from *eldana* borer. The factors considered in this paper were rate of canopy development, moderate water stress, photosynthesis, respiration, and dry matter distribution. The effects of these factors on growth have been integrated by means of a computer model which provided an indication of how various harvest options may affect economic returns.

## Introduction

When technology has developed to a stage where sugar production is limited only by climate, soil and the genetics of the sugarcane plant, growers will be able to manipulate planting and harvesting schedules so that maximum profit is obtained from the conversion of solar energy via photosynthesis to sucrose. In some situations the constraints imposed by weeds, pests and diseases and inadequate nutrition have been removed, and growers are interested in using varieties and harvest schedules to optimize production. Maize growers are able to similarly assess the length of the growing season in a particular year or place, and then select a hybrid that will mature in the given time and not tassel when the probability of drought is high (Du Toit and Nordier, 1990). In this paper some physiological factors involved in optimizing the cropping schedule are considered. The 'sigmoid' (S-shaped) growth pattern, characterized by a slow rate of growth at the start and end of the life cycle, and rapid growth between, is important. This pattern, which is common to living organisms, is found also in various organs that constitute the plant (Causton, 1983) and it is important that, when the growth of a plant is discussed, the organ or yield component involved is defined. McMartin (1979) demonstrated the sigmoid nature of development in the height of sugarcane stalks in Malawi. The development of cane yield

could be expected to closely follow that of stalk height, but the development of sucrose yield could be expected to lag considerably behind that of cane yield (Lorber *et al.*, 1984). The main factors responsible for the sigmoid nature of accumulation of dry matter by sugarcane are: 1) the interception of light by the leaves, 2) photosynthesis and 3) respiration. These factors have been included in a computer model of the sugarcane crop (CANESIM) being developed at the Experiment Station (Inman-Bamber, 1991, in preparation). The model, together with recent data obtained from a growth analysis experiment, was used to provide some indication of how these factors may affect yields and the economics of the cutting cycle.

## Methods

In October 1988, 16 plots (25 x 12 m) were planted to each of two varieties, NCo376 and N12, on a sandy clay soil of the Swartland form at the La Mercy experiment farm on the Natal north coast. Fertilizer was applied in the furrow and later as a top dressing, to provide 90 kg N, 48 kg P and 150 kg K per hectare. Two plots of each variety were harvested during the first three days of every alternate month starting in June 1989. Fertilizer, amounting to 140 kg N, 30 kg P and 140 kg K per hectare, was applied along the row of the ratoon crop when tillering began. The amount of photosynthetically active radiation (PAR) intercepted by the green leaf canopy on clear days was determined every two to three weeks, using a 1 m line quantum sensor (LiCor, Nebraska). The sensor was read first above or outside the canopy, then at several points at the base of the green canopy, at an angle to the row with one end in the centre of the row and the other midway between rows. Six to twenty readings were taken per plot, depending on the variation in the canopy. The results reported here concern only the variety NCo376 harvested before October 1990.

Crop simulations were carried out with the CANESIM model using daily meteorological data from the Experiment Station site at Mount Edgecombe. Soil pits at the La Mercy growth experiment, about 12 km to the north, were analyzed to provide soil data for the simulations (Table 1), which were

Table 1  
Attributes of the Swartland soil form required for the CERES-Maize water balance routine of CANESIM (Jones & Kiniry, 1986)

Soil albedo	0,17								
Maximum soil evaporation (U)	12,0 mm								
Runoff curve number (Schmidt and Schulze, 1987)									
Up to 50% cover	82								
50 to 75% cover	75								
Over 75% cover	70								
Layer No	1	2	3	4	5	6	7	8	9
Depth (cm)	5	10	15	15	15	15	15	15	15
Lower limit	,138	,138	,134	,149	,148	,158	,234	,302	,327
Upper limit	,265	,265	,248	,239	,249	,268	,339	,360	,386
Root dist.	1,00	,82	,64	,47	,35	,26	,05	,02	,01
BD (t m <sup>-3</sup> )	1,65	1,60	1,61	1,57	1,34	1,28	1,25	1,25	1,25

done for crops starting on 1 April 1980 and every two months thereafter until the end of the weather record in 1990. Each of the 54 simulations spanned 600 days (20 months). The results of these simulations were averaged to describe an 'average' crop in these conditions.

The SAS statistical package (SAS Institute, Cary, NC, USA) was used to produce regression equations for the prediction of juice purity and brix content from stalk dry mass. These data were obtained for NCo376 from the released variety trial (RVT) data base (Inman-Bamber and Stead, 1990). Irrigated trials and those on weak sands were excluded from the analysis. A simple analysis of cash flow resulting from different cutting cycles was carried out with the following assumptions: 1) sucrose price = R430/ton, 2) sucrose % cane = 12,5%, 3) average cost of planting and ratoon maintenance = R1 020/ha, 4) the number of ratoons is not affected by age at harvest, 5) total cost of harvesting and haulage = R15/ton, and 6) discount rate = 15 or 25%.

### Results and discussion

#### Canopy development

The initial phase of the sigmoid growth curve is associated with the development of a leaf canopy and the increasing amount of PAR that it intercepts ( $L_i$ ). More than 90% of the intercepted PAR is absorbed by pigments in the leaves (Ross, 1975).

The effect of date of harvest on the interception of PAR by the developing leaf canopy for the La Mercy crop is shown in Figure 1. As may be expected, leaves emerged slowly during the winters of 1989 and 1990, and  $L_i$  of crops starting in June was not much greater than that of crops which started in August. Closure of canopy was delayed by a dry spell in February 1990, but the crops that started in June, August, October and December simultaneously reached the point at which 90% of midday PAR was intercepted. The most rapid development in leaf canopy was observed in the crop starting on 1 February 1990. Rate of canopy development for the different crops may be seen by comparing the PAR inter-

ception two months after ratooning (Figure 1). The difference in PAR interception at two months, between crops starting in October to February and those starting between April and August, was considerable.

The model's estimate of light interception during the first 100 days after ratooning is shown in Figure 1. The predicted  $L_i$  was too high for the crop starting in June 1989 and too low for the crop starting in April 1990, but estimates for the intervening crops were reasonably accurate. The PAR intercepted by the crops at La Mercy during the period of incomplete canopy was computed, using an exponential function to fill in the very early stages of development. The comparison made when each crop had received an arbitrary 1 250 MJ/m<sup>2</sup> is shown in Table 2. Simulated crops were then compared in the same way by computing their nine year average  $L_i$  values.

Table 2

Photosynthetically active radiation (PAR) intercepted by the real and simulated green leaf canopy from the date of ratooning to the date when 1 250 MJ/m<sup>2</sup> incident PAR had accumulated. The time interval (age) is given

Date of ratooning	Observed data for 1989/90		Simulated data for 1980 to 1990		Intercepted PAR	
	MJ/m <sup>2</sup>	(%)	Age (days)	MJ/m <sup>2</sup>	(%)	Age (days)
1 June	180	14	161	359	29	162
1 August	366	29	140	418	33	139
1 October	524	42	119	451	36	121
1 December	575	46	119	507	40	121
1 February	788	63	141	512	41	153
1 April	527	42	182	432	34	173

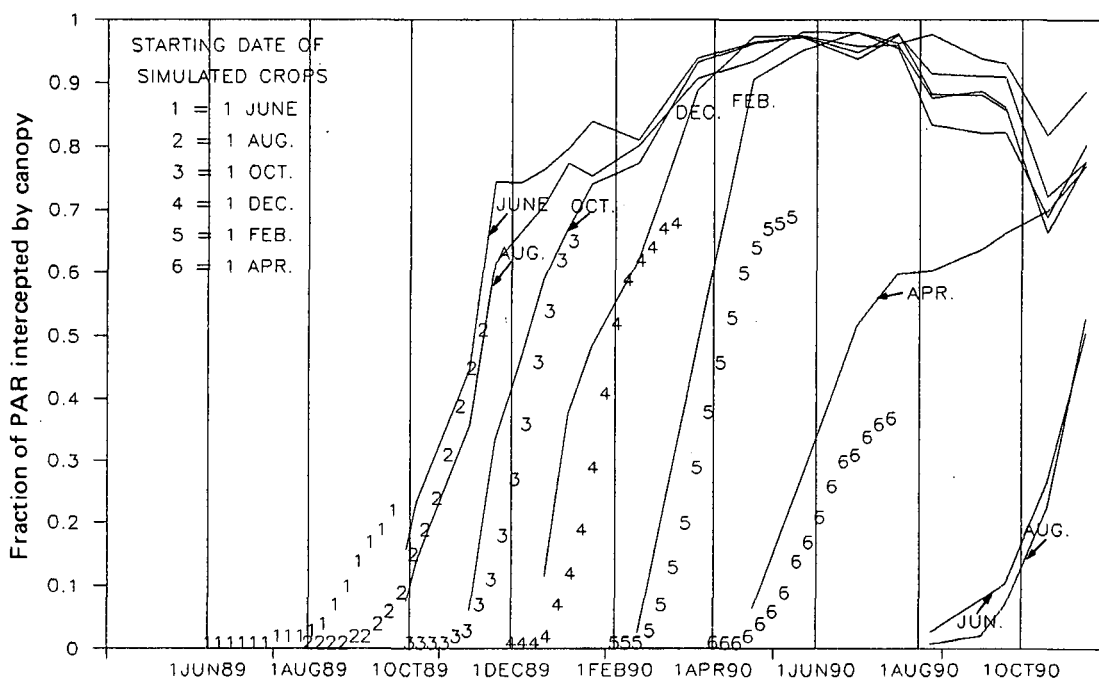


Figure 1 Observed (lines) and simulated (symbols) fractions of PAR intercepted by the green canopy of crops of NCo376 ratooned at the start of alternate months in 1989 and 1990 on a Swartland soil at La Mercy.

The time taken for 1 250 MJ/m<sup>2</sup> PAR to accumulate during the 1989/90 season did not differ markedly from the nine year mean. Although the observed and simulated amounts of intercepted PAR differed substantially, both simulation and field observations indicated that crops starting in December and February were the most efficient absorbers of PAR and, if no other factors were involved, these crops would be expected to accumulate dry matter more rapidly than crops starting at other times. It may be for this reason that cane yields of crops planted in December and February at Pongola were greater than yields of crops planted at other times (Rostron, 1972, unpublished data). However, the ratoon crops of the Pongola experiment responded differently to starting date. Sweet and Patel (1985) reported that cane yields of irrigated crops in Zimbabwe and Swaziland were greatest when harvested in April and May.

### Dry matter accumulation

When maximum PAR interception has been attained, the rate of dry matter accumulation depends entirely on the rates of photosynthesis and respiration. McCree (1970) demonstrated that a certain fraction of the respiratory loss is proportional to the rate of photosynthesis, and the remaining fraction is proportional to the total dry mass of the crop. The terms 'growth' and 'maintenance' respiration ( $R_g$  and  $R_m$  respectively) have been used to distinguish the substrate involved (Thornley, 1976). Since  $R_m$  is proportional to the total dry mass of the crop, the amount of carbon respired increases as the crop develops until it equals the amount gained through photosynthesis, at which point growth in terms of DM accumulation ceases. The CANESIM model, which is based on the work of McCree (1970), Hesketh *et al.*, (1971) and Lorber *et al.*, (1984), accounted satisfactorily for 33 observations of total dry mass of various irrigated crops of the variety NCo376 ( $r^2 = 0,96$ ,  $b = 1,00$ ). The model also accounted adequately for dry matter accumulation by two rainfed crops of NCo376 (Inman-Bamber, 1991). It may therefore be concluded that the coefficients for photosynthesis and respiration are at least broadly correct. These coefficients may be used to establish a potential growth pattern for a crop in any bioclimatic region.

This potential should be attainable when all management requirements have been met, and when severe water stress, flooding, heavy flowering, or pests and diseases do not occur. The average coefficients for water stress and light interception for the duration of such a crop were obtained from the results of the 10 year simulation (Figure 2). These coefficients limit the model's prediction of the amount of CO<sub>2</sub> assimilated each day when water is limiting, or when the canopy is incomplete. The results indicate that the canopy of the 'average' crop grown on a Swartland soil on the north coast, usually intercepts less than 80% of incident PAR. Failure to intercept all PAR after the early stages of development is due to periodic water stress. The direct effect of water stress is evidently minimal during the first 100 days of growth and after 200 days generally reduces growth by about 30%. The two coefficients are multipliable so that the overall effect of water stress is to limit growth to about 50% of the potential determined by the level of solar radiation. These coefficients, together with coefficients for photosynthesis, growth and maintenance respiration, were used to predict average total biomass accumulation (including roots) by crops of NCo376 in this region (curve A, Figure 3). The average biomass obtained in this way differed little from the average biomass of the 54 simulations. A crop in these conditions would evidently grow most rapidly at about 200 days (6 months) and would be capable of considerable growth even after 600 days (20 months, curve G).

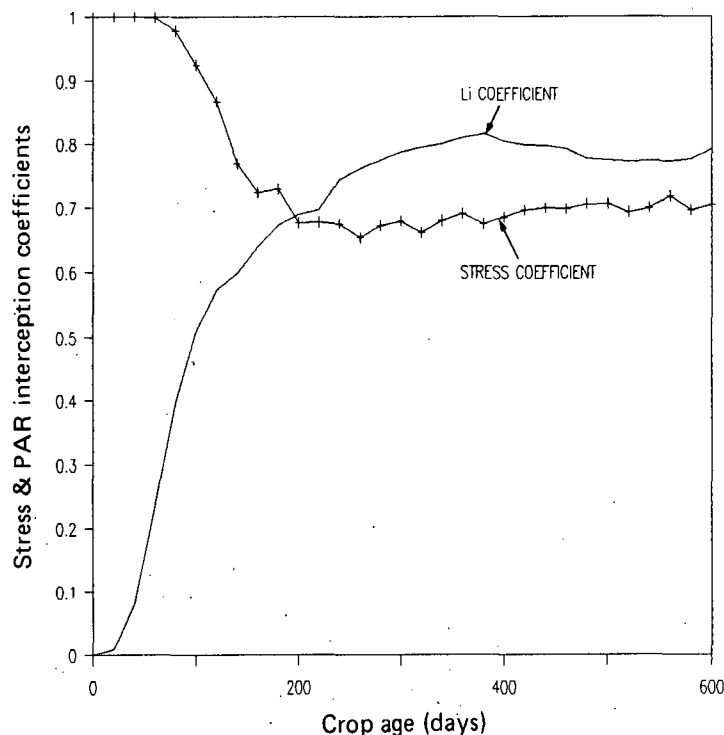


Figure 2 Coefficients for PAR interception and water stress for the duration of an 'average' crop on the north coast in a Swartland soil, determined by computer simulations.

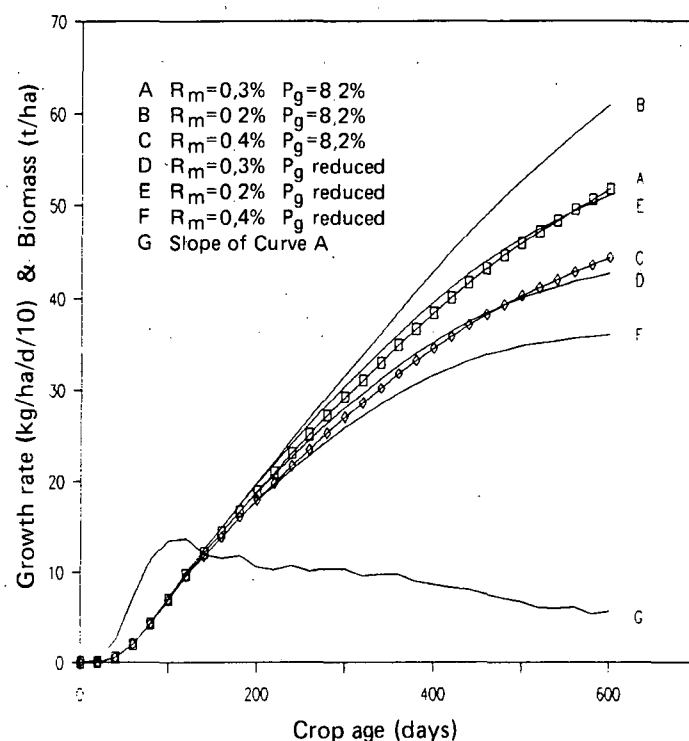


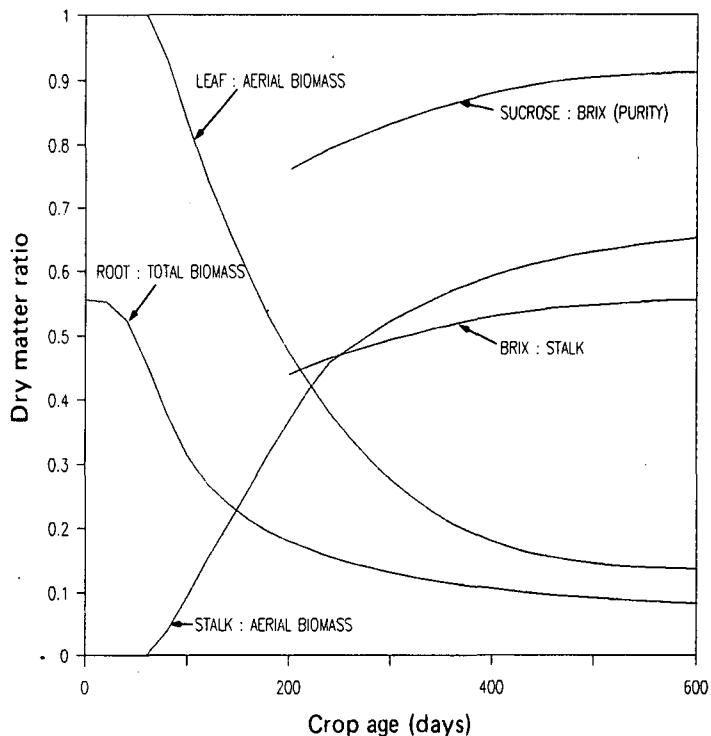
Figure 3 Computer generated total biomass (including roots) of a crop representing moderate soils on the north coast, using different  $P_g$  and  $R_m$  values.

The coefficients for photosynthesis and respiration were then varied to determine sensitivity of the simulation to errors of assumption or genetic variance in these processes (curves B to F). Kortschak and Forbes (1969) showed that photosynthesis of single sugarcane leaves declined by about 30% between six and 15 months after planting. Although

gross photosynthesis of the whole canopy may not respond in the same way, a 30% reduction in  $P_g$  between 150 and 600 days was compared with a constant  $P_g$  (= 0,082 PAR as in CANESIM) and the coefficient for maintenance respiration ( $R_m$ ) was changed 0,1% points above and below the 0,3% value used in CANESIM (Figure 3). Dry matter accumulation would practically cease after 600 days if  $P_g$  declined in this way and  $R_m$  was as high as 0,4%. This is unlikely to happen since rainfed crops are capable of significant growth beyond this stage even after a considerable degree of water stress (Gosnell, 1967, unpublished data). Simultaneous reductions in both coefficients made no difference to the simulation of growth (cf curves A,E and C,D). This raises the possibility of making correct predictions for the wrong reasons (Whistler *et al.*, 1986). After careful experimentation, Hesketh *et al.*, (1971) reported  $R_m = 0,32\% \text{ g g}^{-1} \text{ d}^{-1}$  for cotton, and McCree (1970) reported  $R_m = 1,5\%$  for white clover. This large discrepancy between crops indicates that similar experimentation is necessary for sugarcane if compensatory errors are to be avoided. It can be inferred from the measurements of night respiration of large potted plants of sugarcane (Glover, 1972) that  $R_m$  is not likely to exceed 0,4% of the total crop mass.

**Dry matter distribution**

The mechanisms of dry matter partitioning in plants are highly complex and have yet to be considered for inclusion in the model. In the interim it has been possible to develop empirical associations between total dry mass and some dry matter ratios along the lines of an earlier approach to this physiological problem (Causton, 1983). The fraction of dry matter in stalks or leaves of NCo376, published by Inman-Bamber and Thompson (1989), were clearly related to total above ground dry mass regardless of whether the observations were made on rainfed or irrigated crops (Gosnell, 1967, Rostron, 1972 (unpublished data) and Thompson, 1986). The functions fitted by least squares to these data were applied to the biomass values of curve A in Figure 4 to predict the partitioning of dry matter between leaves and stalks during the growth of an 'average' crop on the north coast (Figure 4).



**Figure 4** Dry matter ratios expected for an average crop growing on moderate soils on the north coast, with  $P_g = 0.082\text{PAR}$  and  $R_m = 0.03 \times \text{biomass}$ .

Regression analysis of the RVT data showed that dry matter partitioning within the stalk was not well correlated with stalk dry mass (Table 3), possibly because of the extent to which this dynamic process is affected by temporal variations in water stress and temperature (Bull and Glaziou, 1975). The limited variation in the purity and brix data also contributed to a low correlation. Stalk dry mass ( $Y$ ) was the most significant of the independent variables included in the multiple regression analysis (Table 3). The square of stalk dry mass ( $Y^2$ ), latitude and then a sine function of the date of harvest, progressively reduced the residual variation in

**Table 3**  
Results of multiple regression analysis of 144 observations made at the harvesting of NCo376 grown in rainfed variety trials (RVT)

	Independent variables				Independent variables			
	Stalk, dry mass (Y, t/ha)		Latitude °S	Harvest		Altitude (m)	Brix: DM ratio	Purity (%)
	Y	Y <sup>2</sup>		DOY (sine)*	age (days)			
Mean	26,8	764	29,4	0,28	482	308	0,54	89,9
Minimum	11,5	132	28,3	-1,0	219	15	0,43	62,0
Maximum	40,2	1 614	30,5	1,0	851	1 018	0,64	98,0
CV%	24,9	46,7	2,5	98,2	28,5	106,2	7,0	4,9
R <sup>2</sup>								
Brix	0,14	0,12	0,00	0,01	0,04	0,02		
Purity	0,18	0,14	0,09	0,01	0,28	0,01		

**Multiple regression statistics**

Regression coefficients					(Intercept)	
Brix	0,00918	-0,00013		1,016	(0,388)	R <sup>2</sup> = 0,25
Purity	1,275	-0,01879	1,276	1,258	(28,3)	R <sup>2</sup> = 0,34
Standard errors						
Brix	0,0028	0,00005		0,005	(0,036)	
Purity	0,3039	0,00568	0,389	0,571	(11,6)	

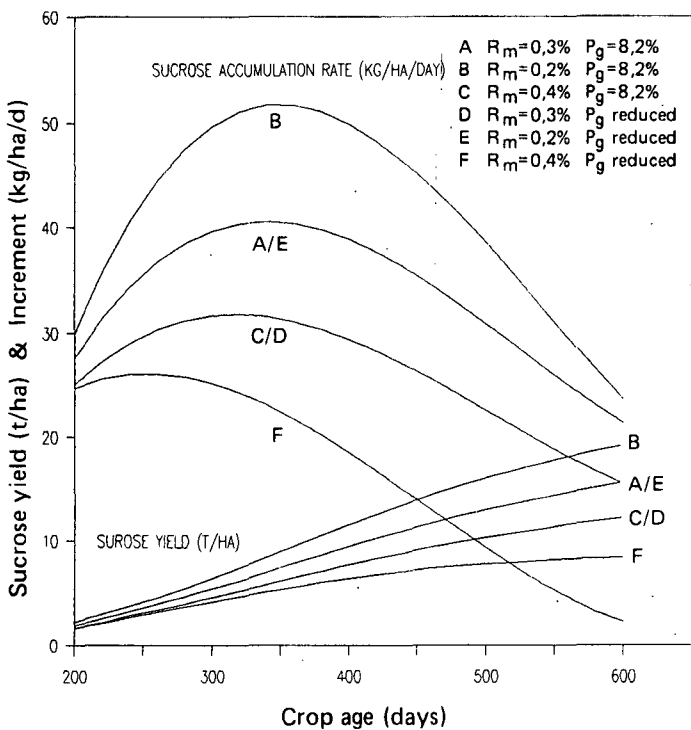
\* negative sine transformation of day of year (DOY)

purity. The same was true of the residual variation in brix, with the exception that latitude was not significant. The physical significance of latitude is not clear, but may be related to temperature.

Regression functions resulting from the analysis were applied to the stalk dry mass derived from the model's prediction of total biomass (Curve A, Figure 3) to predict changes in purity and brix content for the 'average' crop (Figure 4). The mean harvest date (August) and the appropriate latitude (29°S) were used in the equations. The steady increase in stalk:biomass, brix:stalk and sucrose:brix ratios between 200 and 400 days resulted in a considerable diversion of photosynthate to the economic portion of the crop. The ratios increased only slightly after 400 days.

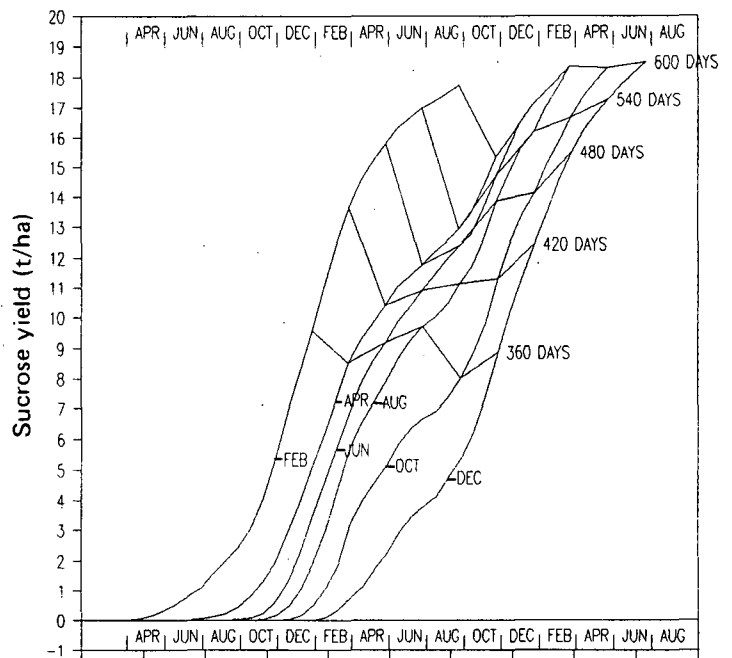
**Sucrose yield**

Having described how an average north coast crop on a Swartland soil develops dry mass, and how this may be partitioned into the various components of the plant, it is now possible to consider how sucrose might accumulate when photosynthesis and respiration coefficients are changed. Since the reduction in  $P_g$  was almost fully compensated for by a 0,1% reduction in  $R_m$ , it was necessary to distinguish between only four of the scenarios represented in Figure 3. If the coefficients currently used in CANESIM are correct, then sucrose would accumulate most rapidly at about 350 days (11 to 12 months) and the crop would still be reasonably productive after 600 days (curve A/E, Figure 5). Sucrose accumulation would decrease rapidly after a maximum rate at about 250 days if respiration losses were higher and photosynthesis progressively lower than expected (Curve F, Figure 5). Other changes in photosynthesis and respiration would affect the rate of sucrose accumulation, but not to any great extent the timing of the peak rate. It seems likely therefore that the rate of sucrose accumulation would generally decline after 400 days but that the accumulation rate would still be significant at 600 days.



**Figure 5** Computer generated sucrose yield and sucrose accumulation rate a crop representing moderate soils on the north coast, using different  $P_g$  and  $R_m$  values.

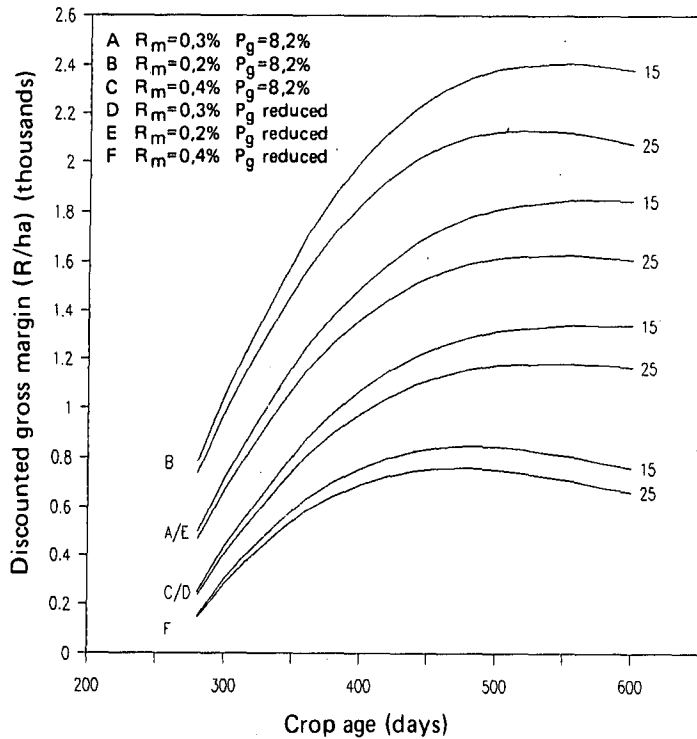
The mean sucrose yield for crops starting on different dates was obtained from the results of the simulations using CANESIM, in which  $R_m = 0,3\%$  and  $P_g = 8,2\%$ . The seasonal changes in brix % DM and juice purity were significant for the comparison of starting and harvest dates shown in Figure 6. According to the model, April was the least favourable time to start ratooning if harvesting was done at 420 days or later (Figure 6). Harvesting at 360 days resulted in low yields for crops ratooning in April and October. Ratooning in December or February gave the greatest sucrose yields regardless of the age at harvest, provided it was more than 360 days. Errors in the prediction of light interception (evident in Figure 1), and difficulties in predicting temporal changes in dry matter partitioning in the stalk, are more serious when comparing starting and harvesting dates than when comparing ages at harvest. When irrigated crops of NCo376 were ratooned on different dates, April was the least favourable date at every harvest age (32 to 72 weeks) and February was the most favourable time when harvesting was done after 56 weeks (Rostron, 1972, unpublished data).



**Figure 6** Sucrose yield expected for crops ratooning at two monthly intervals on moderate soils on the north coast, with  $P_g = 0.082\text{PAR}$  and  $R_m = 0.03 \times \text{biomass}$ .

**Discounted gross margin**

The optimum age at harvest moved well beyond the 400 day mark when the average cost of replanting and maintaining ratoons was considered (Figure 7). The discounted gross margin increased rapidly between 300 and 400 days, and reached maximum values after about 450 days regardless of photosynthesis, respiration or discount rates. A comparison of gross margins resulting from different rates of photosynthesis and respiration provided some indication of what plant breeding could do for farm profits if more variation in the efficiency of these processes could be found or perhaps generated through biotechnology.



**Figure 7** Discounted gross margin in relation to age at harvest for a crop representing moderate soils on the north coast, using different  $P_g$  and  $R_m$  values. The effects of two rates of interest are shown.

### Conclusions

The fate of atmospheric carbon in the sugarcane crop could be one of the most predictable of the many factors that determine when the crop should be harvested, and an initial attempt has been made to quantify the processes involved. Although further research is now required to confirm and refine many of the assumptions made in the model, indications are that the optimum harvest cycle for crops of NCo376 grown on moderate soils on the north coast, is a relatively long one. Eldana borer presently precludes the attainment of this physiological optimum age, and other factors such as flowering and lodging may in practise restrict the harvest age. Severe drought, waterlogging and frost are factors that damage the crop permanently, and force growers to harvest prematurely. These have yet to be included in the model.

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