CLIMATE AND WATER AS CONSTRAINTS TO PRODUCTION IN THE SOUTH AFRICAN SUGAR INDUSTRY

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Abstract

Yield potentials for sugarcane in South Africa have in the past been defined in various ways. This paper attempts to draw the various definitions together and establish links between previous estimates based on growth analysis, whole plant carbon exchange and single leaf photosynthesis, with the now popular concepts of radiation use efficiency (RUE) and water use efficiency. Evidence from growth analysis experiments indicates that RUE in sugarcane is greater than that of other C4 plants despite single leaf photosynthesis not being particularly high. Long term daily data from 32 meteorological stations in the SA Sugar Industry were processed using the CANEGRO model. Radiation-limited sucrose yield potentials varied from 22 t/ha per annum in the North to 14 t/ha in the South. Yield potentials were closely related to latitude and altitude through the influence of locality on radiation and temperature. Rain- limited potentials were 10 to 90% lower than radiation-limited potentials, depending on locality and soil type. Variations in age and season of planting and harvesting influence the environment experienced by the plant, and the effects of these management options on yield potentials is discussed.

Introduction

The importance of determining ceiling yields or yield potentials for sugarcane has been noted by many scientists and managers, since these provide breeders and managers with goals to aim for or barriers to be broken. Liebig's law of the minimum suggests that there is always some factor limiting yield, therefore yield potential needs to be defined in terms of the limiting factor. Penning de Vries and van Laar (1982) proposed a hierarchy of production systems based on factors that limit yield. At the highest production level (level 1) growth was limited only by radiation and temperature and these systems could deliver between 150 and 350 kg biomass per hectare per day. At production level 2 growth was limited only by a shortage of water. Other production levels involved shortages of water and nutrients. This paper will deal only with production levels 1 and 2.

Bull (1969) measured in single leaves of sugarcane rates of photosynthesis as high as 5,74 g CH_2O per MJ photosynthetically active radiation (PAR). Bull and Glasziou (1975) theorised that, for the wet tropics of Queensland, a cane yield of 240 to 280 t/ha/an would be possible, and noted that yields of up to 250 tons in 12 months had been recorded on rare occasions. The maximum possible yield allowed by radiation received at Mount Edgecombe was estimated to be 198 t/ha/an if the moisture content was 71% (Glover, 1972). The estimate was based on Glover's own measurements of respiration, and single leaf photosynthesis as high as 66 mg $CO_2/dm^2/h$ measured by Irvine (1967) in some Canal Point varieties. Bull and Tovey (1974) measured single leaf photosynthesis rates exceeding 80 mg $CO_2/dm^2/h$ in conditions of saturating light (<700 $J/m^2/s$ solar radiation). Single leaf photosynthesis of NCo376 at midday in summer was 71 mg $CO_2/dm^2/h$ when solar radiation exceeded 800 $J/m^2/s$ (Inman-Bamber *et al.*, 1993). This rate was used in a single-leaf-to-canopy scale-up procedure (Boote and Loomis, 1991) to predict biomass yield and the results were similar to those obtained with earlier estimates of photosynthetic efficiency of the whole canopy (Inman-Bamber and Thompson, 1989). The earlier estimates were based on the slope of the light response curve determined by Bull (1969) which agreed, to a large extent, with the photosynthetic efficiency used in the CERES-Maize model (Jones and Kiniry, 1986). This efficiency (8,8 %), derived from the energy equivalents of gross photosynthesis and intercepted PAR, ignored respiration. Growth and maintenance respiration were considered in the CANEGRO model (Inman-Bamber, 1991a) and, when biomass was small, the equations in CANEGRO predicted that 1,8 g aerial biomass would result from 1 MJ solar radiation intercepted by the canopy, provided water was not limiting. The amount of aerial biomass accumulated per MJ solar radiation intercepted by leaves is termed radiation use efficiency (RUE), and there is considerable evidence that this is constant within a species, across environments and growth stages (Sinclair, 1991). RUE was 1,75 g/MJ for much of the duration of a plant and ratoon crop of the sugarcane variety Q96, but the average RUE from planting to harvest was 1,37 g/MJ because of reduced biomass accumulation when lodging occurred (Muchow *et al.*, 1994). RUE is not directly comparable with the photosynthetic efficiencies (PE) determined for NCo376 by Thompson (1978) because the proportion of incident radiation intercepted by the canopy was not known. For irrigated crops of NCo376, PE was 0,92 ± 0,03 g per MJ radiation received at the soil and canopy surface. The mean maximum PE determined for irrigated NCo376 after 97 days from planting or ratooning, over periods of 55 to 91 days, was 1,48 g/MJ and the corresponding mean for H32-8560 (Hawaii) was 1,93 g/MJ (Thompson, 1978). These PEs were probably determined when light interception was close to 100% and are therefore reasonable approximations of RUE.

The objectives of this paper are to provide yield potentials for the variety NCo376 when 1) only radiation and temperature are limiting, 2) when water is limiting and 3) to examine possible effects of harvest age on yield potential.

Methods

The CANEGRO model, which has been validated extensively in KwaZulu-Natal (Inman-Bamber and Thompson, 1989; Inman-Bamber, 1991a; Inman-Bamber *et al.*, 1993), was used. Details of the model have been provided in these publications. The simple approach to photosynthesis introduced by McCree (1970) was used instead of the more elaborate method of Boote and Loomis (1991) since the simpler method provided an easier comparison with other means of determining yield potential from radiation conversion efficiencies. Clear sky radiation (CSR), which is the theoretical radiant flux at the earth's surface in the absence of clouds, was derived as $0,7R_o$, where R_o is extra terrestrial radiation derived from equations by Spitters *et al.* (1986).

Solar radiation (R_t) was derived from daily sunshine duration (d) using a calibrated Angstrom equation (1) (Thompson, 1986).

$$R_t = R_o(0{,}29COS(\theta) + 0{,}57(d/D)) \quad (1)$$

where D = maximum duration of sunlight (hours)
θ = latitude South (radians).

The Penman-Monteith method was used to determine atmospheric evaporative demand (E_p) unless relative humidity (RH) and/or wind speed data were missing, in which case class A-pan evaporation × 0,9 was used. Daily weather data for rainfall, hours of sunshine, maximum and minimum temperature, wind speed, RH and class A-pan evaporation were obtained from 32 manually operated weather stations in the SA sugar industry (Table 1). Monthly mean values were used when daily values for variables other than rainfall were missing. Daily data was available for at least 20 years for most weather stations (Table 1).

Root and soil water supply (E_a) was derived for each day of the simulation by CANEGRO and, when this amount was less than E_p, a stress duration index (stress-days) was increased by the amount, $1\text{-}E_a/E_p$. Simulations of water-limited crops were carried out for two soils. A Cartref form was chosen to represent the shallow loamy sands that occupy about 60% of the cane land in South Africa. A Shorrocks form was selected to represent the deeper and better structured red soils, which comprise about 19% of the area and are found more in the Northern and inland regions than in the Southern coastal region. Two annual crops were simulated for each year of the weather record of each site. One crop started on 1 May and the other on 1 September. Two complete simulations were carried out. In one, 7 mm irrigation was 'applied' as soon as this amount had been used, so that water was never limiting, and in the other the irrigation option was by-passed. These simulations were repeated for two sites using two 18-month crop cycles per year, the one crop starting on 1 May and the other on 1 November.

The database developed for the Released Variety Trial (RVT) programme (Inman-Bamber and Stead, 1990) was used to provide a comparison of predicted and measured yields of NCo376.

Results and discussion

Radiation-limited yield potential

Annual clear sky radiation (CSR) varied from about 9 100 MJ/m² in the North to about 8 700 MJ/m² in the South of the industry. The effect of cloudiness can be gauged by the extent that solar radiation reaching the crop or soil deviated from CSR (Figure 1). Solar radiation, normally referred to simply as 'radiation', varied between 7 300 and 6 100 MJ/m² per annum, or between 80 and 70% of CSR from the North to the South of the industry. The fraction of radiation intercepted by the crop depends on the development rate of the canopy and this depends largely on temperature or heat units for a crop not limited by water, nutrients or weeds. Annual heat units computed with a base temperature of 10°C varied with latitude, and particularly with altitude, as would be expected (Table 1). The estimated amount of radiation intercepted by foliage, expressed as a percentage of the total annual incoming radiation, varied from 76% in the North to 52% in the midlands indicating that, even without water stress, a considerable amount of radiation is wasted (Table 1). In practice, the wastage of radiation in the midlands is reduced by harvesting up to 24 months after planting or ratooning, so reducing the proportion of exposed soil.

The estimate of radiation interception at all coastal sites North of Glendale was influenced more by altitude than latitude. The effect of altitude, which may also include the influence of proximity to the coast, is evident in comparisons

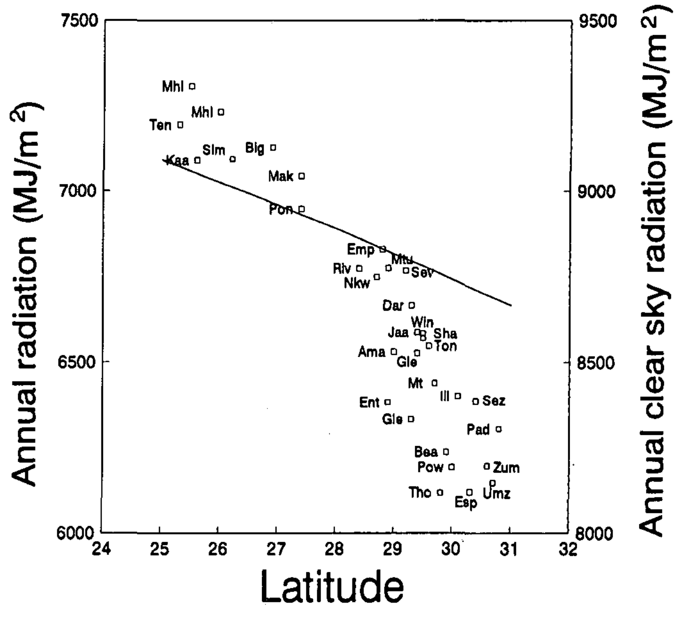

FIGURE 1 Mean annual solar radiation (□) and clear sky radiation (——) for weather stations at various latitudes in the SA sugar industry. Note that the range for the Y-axes differ but not the scale.

Table 1

Mean annual totals for climatic factors and mean simulated annual yields with adequate water at locations in the SA sugar industry represented by a weather station

Site	Lat	No Years	Altit	Radtn	Rain	Evaporation		Heat units	Intercepted Radtn
						A pan	PenMon		
			(m)	(MJ/m2)	(mm)	(mm)	(mm)	(deg, d)	%
Tenbosch	25,3	22	179	7 196	629	1 974	1 777	4 524	75,8
Mhlati	25,5	22	309	7 308	604	2 007	1 806	4 344	74,4
Kaalrug	25,6	19	366	7 091	926	1 838	1 654	4 394	76,1
Mhlume	26,0	22	280	7 233	798	1 993	1 794	4 348	74,8
Simunye	26,2	12	233	7 094	711	1 986	1 788	4 414	75,6
Big Bend	26,9	22	100	7 129	632	2 049	1 844	4 391	74,2
Pongola	27,4	22	308	6 947	683	1 855	1 669	4 071	72,2
Makatini	27,4	21	69	7 045	696	2 034	1 831	4 493	75,8
Riverview	28,4	22	46	6 773	983	1 832	1 649	4 379	76,1
Nkwaleni	28,7	12	136	6 749	803	1 741	1 567	4 192	74,2
Empangeni	28,8	12	74	6 829	1 188	1 971	1 774	4 164	74,8
Mtunzini	28,9	21	36	6 774	1 351	2 019	1 817	4 265	75,0
Entumeni	28,9	21	587	6 382	1 184	1 568	1 411	3 184	63,3
Amatikulu	29,0	22	45	6 530	1 073	1 845	1 660	4 295	74,8
Sevenoaks	29,2	22	1 067	6 767	959	1 774	1 596	2 516	52,1
Darnall	29,3	22	85	6 664	1 124	1 740	1 566	4 082	74,1
Glendale	29,3	22	129	6 332	932	1 792	1 613	3 991	71,8
Gledhow	29,4	22	33	6 526	1 063	1 863	1 677	3 952	72,4
Jaagbaan	29,4	14	1 018	6 587	802	1 767	1 590	2 565	52,0
Windy Hill	29,5	22	988	6 570	989	1 661	1 495	2 687	54,5
Shakaskraal	29,5	22	50	6 583	1 032	1 595	1 436	3 803	69,7
Tongaat	29,6	22	72	6 548	1 066	1 602	1 442	3 692	67,9
Mt Edgecombe	29,7	22	96	6 438	1 045	1 530	1 377	3 793	70,8
Thornville	29,8	8	860	6 117	847	1 661	1 495	2 882	58,0
Beaumont	29,9	9	732	6 235	848	1 596	1 437	3 016	62,0
Powerscourt	30,0	22	631	6 191	1 051	1 584	1 426	2 946	59,4
Illovo	30,1	22	15	6 400	1 053	1 744	1 569	3 805	69,9
Esperanza	30,3	21	195	6 119	970	1 554	1 398	3 572	66,8
Sezela	30,4	15	90	6 386	960	1 834	1 651	3 747	70,6
Umzumbe	30,6	10	95	6 194	1 168	1 715	1 543	3 760	71,5
Umzimkulu	30,7	19	19	6 145	1 150	1 517	1 365	3 814	71,0
Paddock	30,8	8	503	6 303	1 073	1 593	1 433	3 217	64,0

between Pongola and Makatini and between Esperanza and Sezela in respect of both heat units and radiation interception (Table 1). Radiation-limited sucrose yield potentials (Y_{pr}) varied from 22 t/ha/an in the North to 12 t/ha/an at the high altitude sites. The yields at high altitude may be misleading because it is doubtful that crops would be harvested at 12 months even if water was not limiting.

Latitude (θ) and altitude (A) of the 32 weather stations accounted for 96% of the variation in Y_{pr} determined by CANEGRO using daily weather variables recorded at these stations (Figure 2). The close association between Y_{pr} and θ and A will be useful for developing a yield potential map of the SA sugar industry.

$$Y_{pr} = 0{,}18 + 2{,}9\theta - 0{,}0776\theta^2 - 0{,}0058A \text{ t/ha/an} \quad (1)$$
$$SE_y = 0{,}72 \text{ t/ha/an}$$
$$n = 32$$
$$r^2 = 0{,}96$$

Comparison of the yields derived from (1) for 100 m altitude and the annualised sucrose yields obtained for NCo376 from RVTs since 1966 (Inman-Bamber and Stead, 1990) indicated that the predicted yield potentials were realistic (Figure 3). Most of the RVTs in the North were irrigated and most trials in the South were rainfed and, in both cases, there were some years of good rainfall in which the measured yields were near the maximum for NCo376 in conditions limited only by radiation and temperature. Some low yields were obtained in experiments in the North because irrigation at the Pongola farm was designed to supplement rainfall and not to satisfy crop water demand completely. The high experimental yields at latitude 29,6° near Mount Edgecombe, where a large number of RVTs were located, probably occurred when harvest age exceeded 12 months.

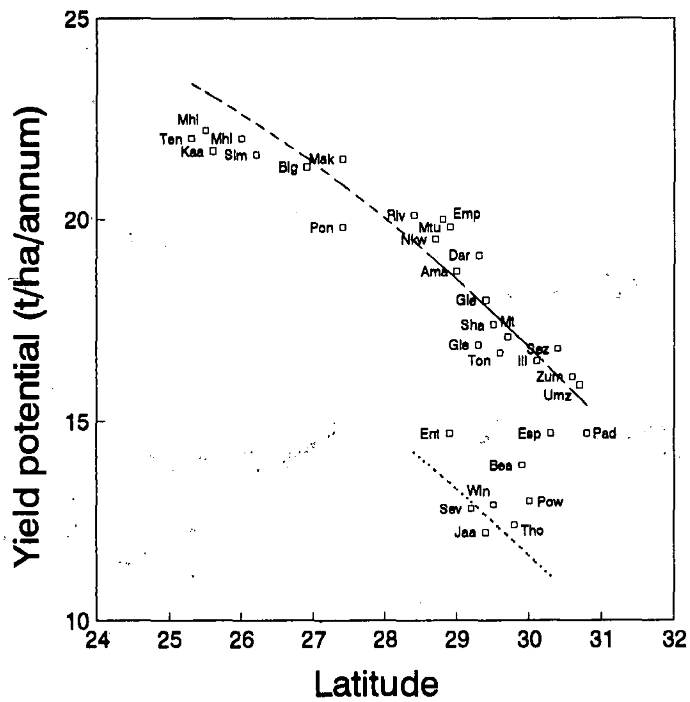

FIGURE 2 Mean annual sucrose yield (□) limited only by radiation and temperature, obtained by simulation for weather stations at various latitudes and curves fitted by least squares for altitudes of 100 m (---) and 1 000 m (·····).

Water-limited yield potential (Y_{pw})

The extent to which rainfall limits cane growth in southern Africa is obvious when annual rainfall and potential evaporation are compared (Table 2). Potential crop evaporation exceeded rainfall by 250% at sites North of Riverview (Mtubatuba) except for Kaalrug. Irrigation is essential at these localities. Irrigation is also practiced at Nkwaleni and Glendale, where cumulative stress duration was substantial. Annual stress duration generally exceeded 150 days for sites North of Riverview and was between 100 and 150 days at other sites for the Cartref form and less than 100 days for the Shorrocks form. At southern locations, soil form was generally more influential than site. Large differences in this regard were noted for Illovo and Paddock, although these differences may reduce when older crops are considered.

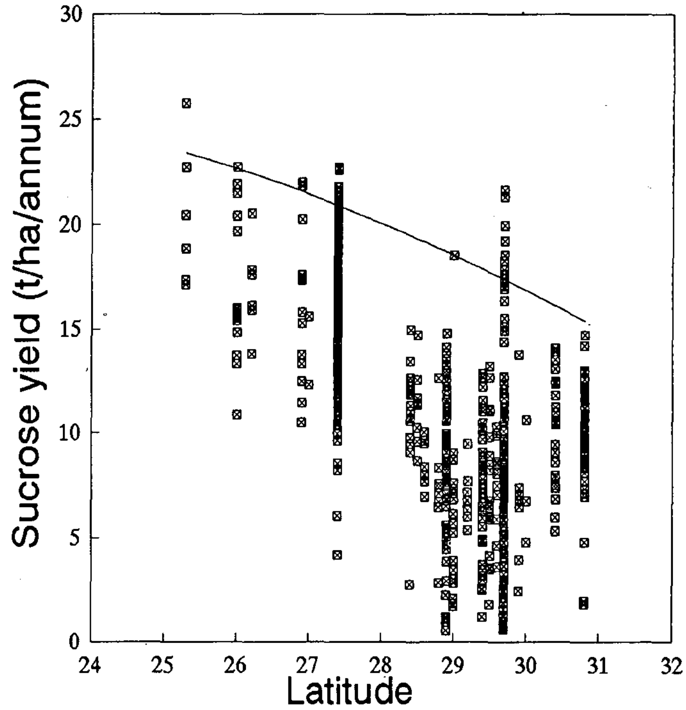

FIGURE 3 Annualised sucrose yields of NCo376 from all released variety trials conducted at different latitudes and radiation-limited sucrose yield potential obtained by simulation and from equation (1) in text for 100 m altitude.

South of Riverview, water stress reduced sucrose yields to between 28 and 52% of Y_{pr} in the more common Cartref form and, in the Shorrocks form, water stress reduced yield to between 44 and 90% of Y_{pr} (Table 2). The large range in the amount by which water stress reduced yield, indicates that care should be taken when planning to use irrigation in the South since benefits could vary substantially depending on climate and soil type.

Effects of harvest age

The concept of a crop specific RUE has not been tested rigorously in plantation crops such as sugarcane and there is some doubt as to whether the growth rates measured in young crops can be sustained in older crops. Gosnell (1968) attributed a reduction in growth rate in ageing crops to reduced leaf emergence rate, tissue water content and chlorophyll content. Increased respiration may contribute to reduced growth rate (Thompson, 1988; Inman-Bamber and Thompson, 1989) and stalk senscence has been found to affect yield increments in large crops (Inman-Bamber, 1994; Muchow *et al.*, 1994). In CANEGRO the ageing process is attributed to respiration and the physical processes of water extraction and atmospheric demand which become more critical as the crop ages. Some of these effects may be noted in the comparison of 12 and 18 month crop simulations

Table 2

Mean annual stress-days and mean simulated annual yields limited by rainfall at locations in the SA sugar industry represented by a weather station

Site	Latit	Altit	Stress-days		Predicted water-limited yield potential (Ypw)/				Rain/ Evap	Water-limited yield/ radiation-limited yield (Ypw/Ypr)	
					Stalk dry matter		Sucrose				
			Cartref	Shorrocks	Cartref	Shorrocks	Cartref	Shorrocks		Cartref	Shorrocks
		(m)	(d)	(d)	(t/ha/an)				(%)	(%)	(%)
Tenbosch	25,3	179	213	181	6,3	11,0	2,4	4,5	35,4	10,9	20,5
Mhlati	25,5	309	220	181	6,6	11,2	2,5	4,7	33,5	11,3	21,2
Kaalrug	25,6	366	180	115	12,6	23,5	5,0	10,4	56,0	23,0	47,9
Mhlume	26,0	280	182	137	10,9	17,5	4,3	7,6	44,5	19,5	34,5
Simunye	26,2	233	194	156	7,8	13,8	2,9	5,7	39,8	13,4	26,4
Big Bend	26,9	100	203	166	6,7	11,4	2,5	4,7	34,3	11,7	22,1
Pongola	27,4	308	187	159	7,9	11,6	3,0	4,7	40,9	15,2	23,7
Makatini	27,4	69	210	172	6,4	11,8	2,4	4,8	38,0	11,2	22,3
Riverview	28,4	46	148	91	12,9	23,1	5,3	10,3	59,6	26,4	51,2
Nkwaleni	28,7	136	139	82	10,5	19,8	4,1	8,5	51,2	21,0	43,6
Empangeni	28,8	74	115	64	18,2	27,9	7,6	12,7	67,0	38,0	63,5
Mtunzini	28,9	36	96	51	21,0	31,2	9,1	14,5	74,4	46,0	73,2
Entumeni	28,9	587	84	26	17,7	29,3	7,3	13,3	83,9	49,7	90,5
Amatikulu	29,0	45	131	85	14,2	23,0	5,8	10,2	64,6	31,0	54,5
Sevenoaks	29,2	1 067	94	56	11,2	18,8	4,4	8,1	60,1	34,4	63,3
Darnall	29,3	85	117	71	16,5	26,4	6,8	11,8	71,8	35,6	61,8
Glendale	29,3	129	149	105	10,6	17,7	4,1	7,5	57,8	24,3	44,4
Gledhow	29,4	33	129	84	13,2	22,0	5,3	9,7	63,4	29,4	53,9
Jaagbaan	29,4	1 018	99	56	9,1	17,4	3,5	7,4	50,4	28,7	60,7
Windy Hill	29,5	988	90	43	12,1	21,5	4,8	9,4	66,2	37,2	72,9
Shakaskraal	29,5	50	112	61	15,7	25,7	6,4	11,6	71,9	36,8	66,7
Tongaat	29,6	72	102	46	16,4	27,4	6,8	12,4	73,9	40,7	74,3
Mt Edgecombe	29,7	96	114	58	16,3	27,0	6,7	12,2	75,9	39,2	71,3
Thornville	29,8	860	111	69	9,0	17,2	3,4	7,1	56,6	27,4	57,3
Beaumont	29,9	732	132	92	8,8	16,1	3,3	6,7	59,0	23,7	48,3
Powerscourt	30,0	631	85	34	14,3	24,1	5,7	10,6	73,7	43,8	81,5
Illovo	30,1	15	116	61	14,9	25,4	5,9	11,0	67,1	35,8	66,7
Esperanza	30,3	195	114	62	12,8	22,3	5,1	9,7	69,4	34,7	66,0
Sezela	30,4	90	144	102	11,0	18,4	4,4	7,8	58,2	26,2	46,4
Umzumbe	30,6	95	119	56	14,6	26,5	5,9	11,7	75,7	36,6	72,7
Umzimkulu	30,7	19	89	33	19,7	30,3	8,2	13,8	84,3	51,6	86,8
Paddock	30,8	503	115	42	11,2	25,7	4,3	11,3	74,9	29,3	76,9

Table 3

Effect of harvest age on mean annual radiation interception, stress-days and simulated sucrose yield, with and without adequate water

Site	Latit	Altit	Crop age	Water regime	Inter-cepted Radtn	Stress days		Sucrose yield	
						Cart	Shorr	Cart	Shorr
		(m)	(mth)		%	(d)	(d)	(t/ha/an)	
Windy Hill	29,5	988	12	Irrig.	54,5	0	0	12,9	12,9
			18	Irrig.	68,4	0	0	17,8	17,8
Mt Edgecombe	29,7	96	12	Irrig.	70,8	0	0	17,1	17,1
			18	Irrig.	80,3	0	0	19,0	19,0
Windy Hill	29,5	988	12	Rain	-	90	43	4,8	9,4
			18	Rain	-	127	89	6,1	9,4
Mt Edgecombe	29,7	96	12	Rain	-	114	58	6,7	12,2
			18	Rain	-	128	66	8,5	13,6

(Table 3). An increase in harvest age from 12 to 18 months resulted in substantial increases in annual radiation interception at the coast and midlands. This led to an increase of 2 t and 5 t in Y_{pr} at the coast and midlands respectively. The effect of harvest age on Y_{pw} was not as great because increased demand for water goes with increased radiation interception. Increased harvest age made no difference to the sucrose yield for the Shorrocks form at Windy Hill, but this does not mean that harvesting should be done at 12 months. A case for delayed harvesting can easily be made on economic grounds (Inman-Bamber, 1991b). These effects of harvest age illustrate the difficulty of deriving an absolute yield potential for a given location. Other factors such as harvest season and variety also weaken the concept of an absolute yield potential but it should be possible, with present model development and with the large body of RVT data to produce tables or maps, to cater for most of these variables.

Comparison with earlier yield potential estimates

The theoretical yield of approximately 200 t cane per hectare for radiation limits at Mount Edgecombe (Glover, 1972) would mean that about 58 t stalk dry matter and least 24 t sucrose could be obtained per annum. This far exceeds the potentials derived from CANEGRO (Table 3). The single leaf photosynthesis used in the calculations (Glover, 1972) was high when compared with more recent measurements, and the possibility of raising maximum photosynthesis levels by breeding or enhanced fertiliser applications is being tested with some interesting results. Stevenson *et al.*, (1992) concluded that dry matter production could be increased appreciably by extending the supply of N to the crop. This practice increased annualised sucrose yield from 21,2 to 25,8 t/ha in variety N14 at Pongola, thus exceeding the theoretical Y_{pr} by some margin. Ludlow *et al.* (1991) measured responses in single leaf photosynthesis up to 63 mg $CO^2/dm^2/h$ by applying up to 320 kg N/ha. However, this rate of photosynthesis is lower than those measured in NCo376 at normal N rates (Inman-Bamber *et al.*, 1993) and lower than the values used in CANEGRO.

Conclusions

Attention has been drawn to efficiencies of photosynthesis and radiation use in determining yield potential for sugarcane. The rate of photosynthesis and RUE used in CANEGRO are in line with measured rates and efficiencies, and the yield predictions of the model are in line with maximum yields obtained with NCo376 in field trials. The radiation-limited yield potentials have some degree of validity for NCo376 grown under present nutritional standards. Harvest age may affect yield potential to a large extent mainly through the processes of radiation interception and respiration. A basis for producing a yield potential map has been developed.

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