A SYSTEMS APPROACH TO BENCHMARKING FOR SUGARCANE PRODUCTION IN AUSTRALIA AND SOUTH AFRICA

NG INMAN-BAMBER[1], A SINGELS[2] AND RC MUCHOW[3]

[1]*CSIRO Tropical Agriculture, Davies Laboratory, Townsville, Queensland 4814*
[2]*South African Sugar Association Experiment Station, Private Bag X02, Mount Edgecombe, 4300*
[3]*CSIRO Tropical Agriculture, 306 Carmody Road, St Lucia, Queensland 4067*

Abstract

Growers, breeders and policy makers require benchmarks to measure performance in regard to management of the crop, genetic improvement and prospects for investment and employment. Cropping systems are difficult to benchmark because of the unpredictable nature of the climate. In this paper previous attempts to benchmark sugarcane production systems in Australia and South Africa are reviewed, and benchmark yields produced by two models are compared. Some South African commercial yields are then compared with appropriate benchmarks and possibilities for yield improvements are assessed. Efficiency of various processes in the use of radiation and water by the crop, and where gains are most likely to be made in breeding and in management, are then considered. The most promising avenues for yield gains in both industries are (i) raising the standard of field management to narrow the gap between actual and benchmark yields (ii) introduction of supplementary irrigation in some rainfed areas where attainable yields are well below potential, (iii) increasing irrigation water use efficiency and (iv) increased partitioning of dry matter to sucrose.

Introduction

The overall efficiency of a sugar production system depends on the efficiency of individual processes both in the growing and milling sectors of the industry. As world markets become more open and subject to international competition it is important to improve efficiency in each process involved in transforming CO_2, water and nutrients to sugar. The overall efficiency of sugar recovery in the factory is close to 90% in Australia and not much less in South Africa (Fry, 1996) and it is therefore more likely that efficiency can be improved in the agricultural sector and in the interface between growing and milling sectors (Muchow *et al.*, 1998). Knowledge of the physiology of yield formation in crops has increased sufficiently to estimate, with some confidence, the limits to crop yield based on physiological and environmental contraints (Sinclair, 1997). Despite this, cropping systems remain difficult to benchmark because of the unpredictable nature of the climate and the large number of management and environmental factors impacting on the various processes. Systems research programs at the South African Sugar Association Experiment Station (SASEX) and at CSIRO, Australia, are providing tools to integrate the large amount of information required to benchmark yields. These include process level growth models of sugarcane: APSIM-Sugar in Australia (Keating *et al.*, 1998) and CANEGRO in South Africa (Inman-Bamber, 1991, 1994b). These models integrate current quantitative knowledge of crop growth in response to climate and soil and allow consideration of the contribution of efficiency of various processes to overall resource use efficiency. In this paper previous attempts to benchmark cane production systems in Australia and South Africa are reviewed and benchmark yields produced by the two models are compared. Some South African commercial yields are compared with appropriate benchmarks and possibilities for yield improvement are assessed. The paper then considers the efficiency of various processes in the use of radiation and water by the crop and notes where gains are most likely to be made in breeding and management. Nutrition, and weed, disease and pest control are assumed to be non-limiting to yield.

Review of estimates of climatic yield potential

Rabbinge (1993) provides a useful outline of factors that define yield potential, that limit attainable yield and that further reduce actual yield. Yield potential is defined by the radiation and temperature environment and by rate limits of physiological processes. If water and nutrients are limiting, then attainable yield will be lower than potential and if weeds, diseases and pests are prevalent then actual yields will be lower than those attainable. Early attempts to benchmark potential yields were based on simple derivations of photosynthetic efficiency of sugarcane. These have been reviewed by Inman-Bamber (1995) and Muchow *et al.* (1994). Bull and Glaziou (1975) theorised that 240 to 280 tons cane/ha would be possible for Queensland and a maximum yield of 200 tons cane/ha for Mount Edgecombe was derived from assumptions of Glover (1972). Muchow *et al.* (1991) predicted potential yields for five locations in Australia using a simple framework of efficiencies similar to the one outlined by Sinclair, (1997). In this outline, cane yield (Y) is the product of the ratio of cane mass to total biomass (R) and the daily sum (Σ) of the product of intercepted radiation (I) and radiation use efficiency (RUE) for the duration (d) of the crop.

$$Y = R\sum_{0}^{d}(I.RUE) \qquad (1)$$

Potential annual cane yield was greatest at Kununurra (202 and 235 t/ha) and lowest at Mackay (128 and 149 t/ha) depending on whether a low or high radiation use efficiency (see later) was assumed. However, it was clear from this attempt at benchmarking that RUE and I were not known with any degree of certainty. Predictions by Kingston *et al.* (1994) were considerably greater for Kununurra (284 t/ha) even though a similar predictive method was used. Three models of sugarcane growth (APSIM, CANEGRO and QCANE) that expand the simple framework above for predicting yield potential have been developed recently (Keating *et al.*, 1998; Inman-Bamber *et al.*, 1993; Liu and Kingston, 1994). These models have routines to predict R, I and RUE on a daily basis, thus they allow for the effects of temperature, water and nitrogen (in the case of APSIM) on the efficiency of dry matter partitioning, radiation interception and use. In addition, genetic and developmental attributes of the crop are accounted for in ways that would be difficult to achieve with a simple approach like that of Sinclair (1997).

CANEGRO was used to predict potential annual sucrose yields for the South African sugar industry (Inman-Bamber, 1995). Potential yields were negatively correlated with latitude and altitude (R^2=0,96) and were as high as 23 tons sucrose per ha/annum in the most northern part of the industry (25°S) and as low as 12 t/ha/annum in southerly high altitude regions (29°S, 1 000 m). The model predicted that increasing the harvest age from 12 to 18 months would increase annualised sucrose yield by about 38% at high altitude and by about 11% at the coast (30°S, 100 m) (Inman-Bamber, 1995). Simulations with APSIM predicted that as much as 32 tons sucrose/ha/annum could be expected at Kununurra (15,6°S) if planting and harvesting were done in October (Muchow *et al.*, 1997a). There was a general reduction in yield potential with increasing latitude, although some low potential yields were predicted at low latitudes (tropics) because of extended periods of cloud cover. The more southerly Australian locations had similar potential yields to South African locations at similar latitudes. Potential yields for Murwillimbah (28,4°S) and Pongola (27,4°S) were 20,1 and 19,8 tons sucrose/ha/an respectively and for Grafton (29,7°S) and Mount Edgecombe (29,6°S) yield potentials were 17,7 and 17,1 respectively (Muchow *et al.*, 1997a). The predictions of yield potential in South Africa and Australia were shown to be realistic by comparing them with measured yields from experiments or from commercial blocks (Inman-Bamber, 1995; Muchow *et al.*, 1997b). However, only a small percentage (1 to 5%) of fields in the Australian locations considered produced at the potential level. Experimental crops in South Africa yielded as much or more than the potential determined by CANEGRO but the large majority yielded far less (Inman-Bamber, 1995).

Benchmarking tools

Since CANEGRO and APSIM have been developed independently in South Africa and Australia, it would be of considerable importance to benchmarking if these models produced similar potential and attainable yields. Three locations in South Africa were selected to determine the agreement between the models in benchmarking. APSIM-Sugar and CANEGRO were configured to simulate potential and attainable cane yields for variety NCo376 planted and ratooned in spring on a Hutton soil form, Shorrocks series (kraznozem). Replanting was done after the sixth ratoon and this cycle was repeated four times for the 27-year climate record. The agreement between mean benchmark yields of the two models for the three sites was reasonably good (Table 1) considering that these models have been developed independently. The scatter in the data for the individual years was more severe for rainfed than for irrigated simulations (Figure 1) and it is likely that collaboration between the two modelling groups could help to reduce apparent errors in modelling of water stress.

Table 1. Potential and attainable yield determined by CANEGRO and APSIM-Sugar models for three sites in South Africa.

Site	CANEGRO	APSIM
	Potential cane yield (t/ha)	
Pongola	144	140
Mtunzini	143	135
Mount Edgecombe	128	124
	Attainable cane yield (t/ha)	
Pongola	34	36
Mtunzini	98	97
Mount Edgecombe	86	97

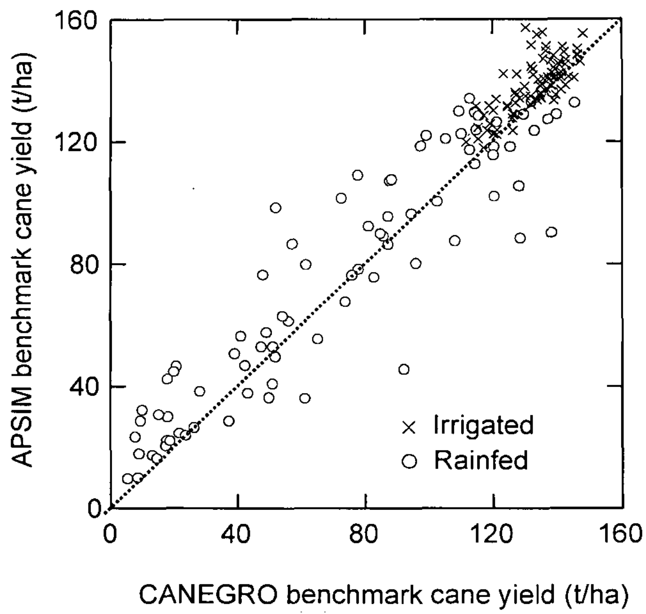

Figure 1. Cane yield estimates by APSIM and CANEGRO for annual spring crops at three sites in South Africa for the period 1966 to 1996.

Attainable and actual cane yields

Actual yields from commercial fields were obtained for one irrigated region (Pongola) and two rainfed regions (Zululand South and Mount Edgecombe) in South Africa from the Field Record System (FRS) of the South African Sugar Association. Mean annualised yields were compared with mean yields of annual spring and autumn crops simulated by APSIM-Sugar. A Cartref soil form, 650 mm deep with 60 mm total available moisture (TAM), was used to represent the poorer soils of each region. A Hutton soil form, 3 220 mm deep with 320 mm TAM, was used to represent the best soils, although these do not occur to any great extent in the Mount Edgecombe or Zululand South regions. For Pongola simulations, irrigation was applied to remove soil water deficit when this exceeded 0,1 TAM.

Actual yields were highly correlated with yields simulated with the Cartref soil form for Zululand (r^2=0,83) and for Mount Edgecombe (r^2=0,70) but not for Pongola. Climatic effects, captured by the model, were therefore largely responsible for year to year variation in commercial yields at the rainfed sites but not at Pongola, where irrigation tended to reduce year to year yield variation for both simulated and actual yields (Figures 2 and 3). Actual cane yields were 15 to 30 t/ha lower than attainable Cartref yields at Mount Edgecombe, except in the dry years of 1992 and 1993, and the mean actual yield was only 70% of the mean attainable yield despite the use of a poor soil for determining attainable yield. In Zululand South, mean actual yield was 86% of the mean attainable Cartref yield and at Pongola, mean actual yield was 73% of the Cartref mean yield and 51% of the Hutton mean yield, which is equivalent to the yield potential for this site. Irrigated crops in the Burdekin (Australia) yielded about 60% of the potential yield (Muchow *et al.,* 1997b) which was slightly better than the performance at Pongola. The difference may be due the reliable supply of irrigation water in the Burdekin compared to a variable supply from the Pongola river. The range of recorded yields for all sites was substantial (Figure 3) and many of the recorded crops in Zululand South, for example, produced more than Cartref benchmark yields (125 out of 398) and some produced more than Hutton benchmark yields (44 out of 398).

Benchmark yields are thus useful for explaining year to year variation in rainfed yields and can be used as an incentive to improve management standards. Such yields are attainable.

Radiation resource use and partitioning efficiency

The systems approach to benchmarking has led to rapid progress in the analysis and synthesis of the processes of radiation and water use by the cane crop. The efficiency of conversion of incoming radiation to sucrose is the product of a number of other efficiencies which may be considered in turn. Thus:

$$\frac{\text{Sucrose mass}}{\text{Incoming radiation}} = \frac{\text{Radiation intercepted by leaves}}{\text{Incoming radiation}} \times \frac{\text{Dry matter produced}}{\text{Radiation intercepted by leaves}} \times \frac{\text{Dry mass of cane}}{\text{Dry matter produced}} \times \frac{\text{Sucrose mass}}{\text{Dry mass of cane}}$$

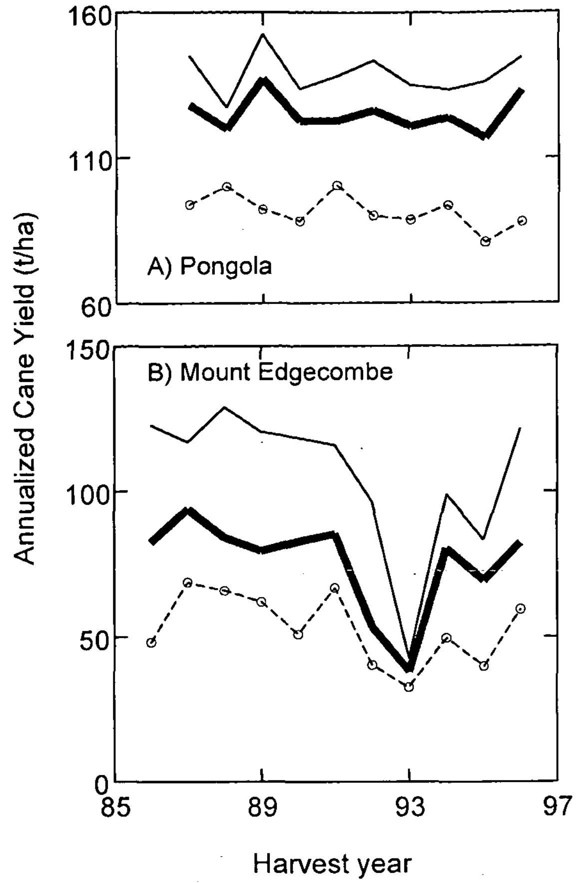

Figure 2. Mean annualised cane yield from FRS records (A) for Pongola and (B) for Mount Edgecombe (broken lines) and benchmark yields for a Cartref soil form (bold solid line) and for a Hutton form (fine solid line) generated with the APSIM-Sugar model using Pongola (A) and Mount Edgecombe (B) weather records.

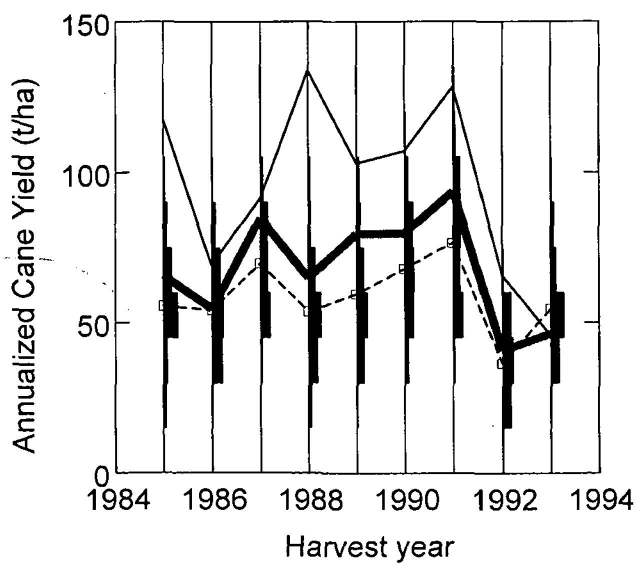

Figure 3. Mean annualised cane yield from FRS records for Zululand South (broken line), annual frequency distribution of cane yields (shaded histogram), benchmark yields for a Cartref soil form (bold solid line) and for a Hutton form (fine solid line) generated with the APSIM-Sugar model using Mtunzini weather records.

The first term is 'fraction radiation interception' and the second is 'radiation use efficiency'; these are components of radiation resource use. The third term is 'fraction millable stalk' and the fourth term is 'sucrose content' (on a dry matter basis), and these are components of dry matter partitioning.

Fractional radiation interception (FRI)

Photosynthetically active radiation (PAR) is absorbed by green leaves more efficiently than short wave radiation (SR) and care needs to be taken when comparing reported values of FRI.

The perennial sugarcane crop intercepts considerably more radiation than annual food crops which often complete their life cycle in less than six months. Sugarbeet in the UK and California intercepted 60 and 79% of the incident PAR received during the cropping cycle compared with 63 and 83% for sugarcane grown in Queensland and Mpumalanga (SA) respectively, but the cropping cycle for sugarbeet was only 200 to 230 days (Austin *et al.*, 1978). Biomass yields were consequently lower in sugarbeet than in sugarcane. Planting and ratoon date can affect FRI considerably. In SA, NCo376 ratooned in February intercepted 82% of annual incident PAR compared with other 12 month crops ratooned in June, which intercepted only 61% (Inman-Bamber, 1994a). Although daily radiation was greater in February than in June, less radiation was wasted by the February crop because it developed a full canopy in 65 days compared with 166 days for the June crop. Interception of SR by varieties Q117 and Q138 growing under high input conditions in Queensland was about 65% in the plant crop and 70% in the ratoon crop (Roberston *et al.*, 1996a). In another set of high input conditions in Queensland, variety Q96 intercepted about 60% of SR received during the 450 day period after planting even though daily interception efficiencies between 200 and 400 days exceeded 80% (Muchow *et al.*, 1994). This illustrates how much radiation is wasted while the canopy is developing and raises the question of extending harvest age to reduce the proportion of time when canopy is incomplete. Model simulations for several sites in South Africa showed that FRI based on PAR could be increased by 16% by harvesting at 22 instead of 12 months (Inman-Bamber, 1996b). There are thus possibilities for enhancing overall efficiency of sucrose production by increasing the efficiency of radiation interception either by reducing row spacing or extending age at harvest.

Results of row spacing experiments in South Africa indicated that sucrose yield gains up to 10% could be achieved with 0,90 m rows compared with 1,37 m rows when growing conditions were favourable (Inman-Bamber, 1996b).

Radiation use efficiency (RUE)

Indirect estimates of RUE from growth analysis in South Africa and Hawaii yielded values of 1,48 and 1,93 g/MJ for the two countries respectively (Inman-Bamber, 1995). In Queensland, the first direct measurements of RUE yielded 1,7 g/MJ for the plant crop and 1,6 g/MJ for the first ratoon crop of varieties Q138 and Q117 grown under high input conditions (Robertson *et al*, 1996a). RUE for Q96 growing under high input conditions, was 1,8 g/MJ during the period when cane yield was less than 200 t/ha (Muchow *et al*,. 1994) and for H73-6110 and H78-7234 in Hawaii, RUE was 1,8 and 1,7 g/MJ up to 12 months after planting (Evenson *et al.*, 1997). Sinclair and Muchow (1998) suggest that, if degradation of trash is taken into account, maximum RUE for sugarcane is close to 2,0 g/MJ, which exceeds RUE for other C_4 species such as maize and sorghum. These experimental values are consistent with RUE derived from a more detailed knowledge of biochemistry and thus there seems to be little opportunity for increasing RUE above the maximum measured (Sinclair and Muchow, 1998) unless new technology can enhance the fundamental process of photosynthesis.

Partitioning efficiency

While increases in FRI and RUE may be difficult to achieve, yield increases may be possible through improved partitioning efficiency. Past genetic increases in wheat yields, for example, have largely been due to improved partitioning of dry matter to grain (Loss and Siddique, 1994). Management options may also be considered for improving partitioning efficiency.

Fraction millable stalk

From three irrigated experiments on NCo376, it was clear that the proportion of above ground dry matter in the cane stalk increased until a maximum of about 0,7 was reached at a total biomass of 80 t/ha (Inman-Bamber and Thompson, 1989). For two Hawaiian varieties, the stalk fraction was 0,66 after biomass exceeded 50 t/ha (Evenson *et al.*, 1997) and for two Australian varieties, the fraction was about 0,8 at a biomass yield of about 60 t/ha (Robertson *et al.*, 1996a). The high stalk fraction reported for the Australian varieties may have been due to degradation of trash, which accounted for less than 10% of total biomass compared with about 30% for the Hawaiian varieties. [1]Unpublished data on NCo376, N12, N16, N17, N19, Q117 and Q137 indicate that, if trash is ignored, about 82% of the biomass eventually ends up in the stalk. This maximum is reached at a low green biomass of ±30 t/ha in conditions of severe water stress and at about 60 t/ha in well watered crops. These data indicate that there may be little opportunity for improving the stalk component of green biomass, but more attention needs to be given to the trash component in order to establish the true variation in fraction millable stalk among varieties and between environments.

Sucrose content of cane stalks

Bull and Glaziou (1963) predicted from a study of a large number of *Saccharum* species and clones that the limit of total sugar concentration in fresh cane stalks is about 27%. Sucrose content of dry mass in two South African and two Australian varieties tended to a maximum of 0,48 g/g regardless of N and water regimes (Robertson *et al.*, 1996b). Sucrose content of dry mass of 18 Australian sugarcane clones fell into the 0,57 to 0,59 g/g class in yield observation trials of 347 clones at Meringa and Tully (Berding, 1997).

[1]Inman-Bamber, Muchow and Robertson, CSIRO, Townsville, Australia and Singels, SASA Experiment Station, Mount Edgecombe, South Africa

Sucrose content of basal internodes of rainfed NCo376 contained as much as 0,56 g/g sucrose when sampled in August and not much less when sampled in December (Inman-Bamber, 1996a). Of the 4 110 analyses of whole stalk samples recorded in the Released Variety Trials database of the SA Sugar Association (Inman-Bamber and Stead, 1990), 42 samples contained more than 0,56 g/g sucrose and half of these were CP66/1043. However, none of the Australian and South African stalk samples contained more than 0,6 g/g sucrose and it appears that this value may be approaching the upper limit for sucrose content of dry matter. Since commercial cane usually contains less than 0,5 g/g, there appears to be considerable room for improvement in this term of the efficiency equation.

Water resource use

The fraction of rainfall stored in the soil and later evaporated from the soil and crop can be termed either 'effective rainfall' or 'evapotranspiration' (ET) and is one component of water resource use efficiency. The other component is yield gain in relation to effective rainfall. In sugarcane literature, water use efficiency (WUE) usually refers to fresh cane yield produced per 100 mm effective rainfall or ET.

Rainfall efficiency (RE)

RE is difficult to measure, and only recently has it been possible to improve on simple estimates such as that of Thompson (1976b) where rainfall was assumed to be 70% efficient. Variation in RE in the Australian sugar industry was assessed with the aid of the APSIM-Sugar model (Robertson and Muchow, 1997) and was found to vary between 87% at Maryborough, where mean annual rainfall is 1 099 mm, to 28% at Babinda where annual rainfall is 3 198 mm. Simulated irrigation reduced RE by more than 20% in some cases. RE can be improved considerably by altering soil surface properties to improve infiltration. During an artificial storm generated by a mechanical rainfall simulator, RE was only 8% for a bare soil compared with 78% for the same soil covered with trash (Dewey and Meyer, 1989). Yield responses to trash mulching in excess of 10 t/ha/annum were found (Thompson, 1965). The systems approach can extend the understanding of the benefits of trash mulching by establishing probabilities of RE and yield increases in various soils and climates. This has yet to be done.

Water use efficiency (WUE)

Thompson (1976a) reviewed a number of studies, mainly South African, in which cane yield was related to effective rainfall or ET measured in lysimeters in many cases. Cane yield at harvest, increased 9,7 t/ha for each additional 100 mm ET. More recently, Kingston (1994) reviewed published relationships between yield and ET and concluded that most of the published functions fitted within the 95% confidence limits of a function based on experiments at Bundaberg and Burdekin, where cane yield at harvest increased 12,2 t/ha per 100 mm ET. Robertson *et al.* (1997) used APSIM-Sugar to show that WUE differed between sites in South Africa and Australia and between irrigated and rainfed crops. Simulated WUE at Mackay and Pongola was 15,4 and 10,1 t/ha per 100 mm ET respectively for full irrigation and 12,8 and 5,3 t/ha per 100 mm ET for rainfed conditions. In the above cases WUE was derived from effective rainfall measured over the full duration of the crop and it was noted by Inman-Bamber and de Jager (1988) that WUE measured in this way would be less than WUE derived for the stalk elongation phase alone. Mean WUE for a 110 day period in summer, during rapid stalk growth, was 22 t/ha/100 mm while WUE for the full growth period of 326 days was 10 t/ha/100 mm, as expected (Inman-Bamber and de Jager, 1988).

WUE from irrigation can be much greater than from rainfall if irrigation is applied to match soil water deficit when soil water evaporation is low, when stalk elongation has commenced and when relative humidity is high. APSIM-Sugar predictions for irrigation responses were as high as 22 t/100 mm at Mackay and were generally lower (8 to 10 t/100 mm) at Pongola (Robertson *et al.*, 1997). Recent experiments with limited irrigation at Mackay and Ingham have confirmed that large irrigation responses of 20 t/100 mm are possible with well timed applications of water ([2]unpublished data). Field trials at a site near Mount Edgecombe yielded irrigation responses varying from 3 to 48 t/ha/100 mm depending on the scheduling strategy and rainfall ([3]unpublished data). Irrigation options in the past have been evaluated in terms of WUE for the full duration of the crop (Schmidt, 1996) and while this is applicable to fully irrigated crops it may not be appropriate for rainfed crops where supplementary irrigation is an option. There is good reason to reconsider responses to supplementary irrigation in some areas in the South African and Australian sugar industries. The value of supplementary irrigation to these industries can be judged in the light of the large difference between potential and attainable yields for Mtunzini and Mount Edgecombe (Table 1) and for a number of other rainfed sites in South Africa and Australia (Inman-Bamber, 1995; Muchow *et al.*, 1997b).

Conclusions

Growth models for benchmarking sugarcane yields are reasonably well developed in Australia and South Africa and there was reasonable agreement between benchmark yields derived from APSIM-Sugar (Australia) and CANEGRO (SA). Both industries stand to gain much by reducing the 15 to 50% difference between benchmark and mean actual yields. Benchmark yields have been achieved in several commercial crops and this should encourage better benchmarking and better management to achieve these yields.

The systems approach has led to rapid progress in the analysis and synthesis of the processes of radiation and water use by the cane crop. Increases in resource use efficiency appear to be most promising through increased sucrose content and water use efficiency. New insights on irrigation water use efficiency were particularly encouraging and should stimulate research on the use of supplementary irrigation in traditionally rainfed areas.

[2]Inman-Bamber, Robertson and Muchow, CSIRO, Townsville, Australia
[3]Singels, SASA Experiment Station, Mount Edgecombe, South Africa

Increased radiation interception through improved harvest scheduling and increased rainfall efficiency through better infiltration are other processes worthy of consideration.

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