A review of three sugarcane simulation models with respect to their prediction of sucrose yield

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Abstract

A review of the agronomic and physiological concepts of three sugarcane simulation models was conducted with the view of highlighting their published strengths and limitations with respect to the simulation of sucrose yield. A brief history and description of each model is presented with an examination of their performance and a suggested way forward to improve their accuracy and utility. The models examined were the Australian APSIM-Sugarcane model, the South African CANEGRO model and another Australian model; QCANE. Despite limited published performance data, all the models have performed reasonably well, but the prediction of sucrose yields were not the same. Mean errors of prediction (root mean square of residuals) for sucrose yield for APSIM-Sugarcane were $4.12 \, \text{Mg ha}^{-1}$, for CANEGRO $6.07 \, \text{Mg ha}^{-1}$ and for QCANE $2.51 \, \text{Mg ha}^{-1}$. Improvements for each of the models lie in better understanding (1) the effects of stress (water, nitrogen and temperature) on the partitioning of photosynthate to stored sucrose, (2) the response of different cultivars to stress, and (3) the differences between plant and ratoon crops in respect of radiation-use efficiency and transpiration efficiency. A new approach employing a source–sink concept is suggested, but includes the volume of stalks as a state variable to define the sink size. A central feature is to include a new state variable; reducing sugars to allow the hydrolysis and re-synthesis of sucrose for the construction of the structural stalk carbon (fibre) and to supply stalk maintenance carbon (CO_2). Such an approach should offer more mechanistic and explanatory investigations into the growth and management of sugarcane with respect to its sucrose yield and purity, particularly in respect of various ripening strategies. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: Sucrose yield; APSIM sugarcane model; QCANE sugarcane model; CANEGRO sugarcane model

1. Introduction

The application of simulation models in agriculture is widespread across various industries for different uses. For the sugar industry globally, simulation models have application to numerous questions of sugarcane production with respect to its biochemistry (Moore et al., 1997), agronomy, physiology and management of pests (Kropff et al., 1997), milling processes (Wood, 1995; Peacock and Starzak, 1996) and

off-site environmental damage (Keating et al., 1997). Of current agronomic and physiological interest is the improvement in the accuracy of simulation output and, in particular, the simulation of sucrose yield as affected by year-to-year and site-to-site variation in management, soils and weather (Muchow et al., 1997; Robertson and Donaldson, 1998). Such advancement in the improvement of the accuracy of the prediction of sucrose yield will greatly help improve the efficiencies of production and milling in the industry.

There are two main sugarcane simulation models currently in use throughout the world, excluding the

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more numerous regression-type models utilised in site-specific studies. The models are an Australian model, APSIM-Sugarcane (Keating et al., 1999) and a South African model CANEGRO (Inman-Bamber, 1995a). The CANEGRO model has been included into the Decision Support System for Agrotechnology Transfer (DSSAT Version 3.1) suite of models as CANEGRO Version 3.10 that has been used throughout the Americas, Africa and Asia (Inman-Bamber and Kiker, 1997; Jintrawet et al., 1997). These two models, whilst developed independently, have similar origins and some have precursor older models that are still in use. For example, AUSCANE (Jones et al., 1989) is a precursor to APSIM-Sugarcane that was adapted from the older EPIC (Williams et al., 1984) soil erosion model. There is, however, another less well-known model that was recently developed in Australia (QCANE, by Liu and Kingston, 1995) that arose from the conceptual framework of Bull and Tovey (1974). That model has some interesting features to explore in conjunction with the two more popular models.

This paper reviews the agronomic and physiological concepts of the three models with the view to highlighting their published strengths and limitations with respect to the simulation of sucrose yield. A brief history and description of each model is presented with an examination of their performance and a suggested way forward to improve their accuracy and utility. Other important aspects, like water use, where CANEGRO has recently been shown to need revision (van Antwerpen, 1998), are not dealt with, rather a selective review is made on the aspects to improve the simulation of partitioning to sucrose. It is through such review that new advances may be more easily targeted and open up the potential for new collaborative programmes amongst other research groups working in the field of sugarcane agronomy and physiology.

2. Model history and concepts

2.1. APSIM-Sugarcane simulation model

The APSIM suite of crop and soil models comprises a collection of models, termed modules, assembled in a way specified by the user (McCown et al., 1996). It represents a philosophy that separates the soil processes from those of the crop or crops that are simulated, except in any special interactive way specified by the designers of the crop modules. To this end, the APSIM system is agronomically soil-centric, linking optional crops with the chosen soil module (Keating and Huth, 1995). APSIM-Sugarcane, therefore, represents a model of sugarcane that follows the structure of other crop modules in APSIM (e.g. maize or wheat), but its crop-specific characteristics are defined in a table of input variables, some of which are considered constants.

The philosophy of the APSIM system arose out of a dissatisfaction of contemporary models (e.g. CERES-Maize (Jones and Kiniry, 1986) and AUSCANE) with each providing their own soil water and nitrogen sub-models. This was a problem, at that time, for analyses of cropping systems containing different crops where the soil to be modelled was the same. Additionally, unstructured computer code was also seen as a hindrance to model building. Therefore, a new standard was applied to APSIM through professional programmers. Thus, a large team of agronomists, physiologists and programmers at the Agricultural Production Systems Research Unit (APSRU) in Queensland, Australia has worked on the APSIM modelling system for close to a decade. Access to APSIM is through individually negotiated legal contracts (Keating and Huth, 1995; McCown et al., 1996).

The first widely distributed sugarcane model was the Australian AUSCANE model (Jones et al., 1989). That model was developed from EPIC (Williams et al., 1984) which was designed to address issues of soil erosion, crop productivity and economics. AUSCANE was considered weak in the biological aspects of sugarcane and comprised unstructured computer code. The opportunity was taken to construct a new module for APSIM, now called APSIM-Sugarcane (Keating et al., 1999) which would take advantage of the soil water and nitrogen modelling underway at APSRU at that time (Robertson et al., 1995; Probert et al., 1998). The model has been classified as a simple, physiological-based model that avoids the complexity of each process typically used in the reductionist approach. It is, however, simpler than the more complex generic SUCROS87 model of Spitters et al., (1989), that is also described as a simple model.

The APSIM-Sugarcane model simulates the fixation of carbon (C) from the atmosphere using an uncoupled radiation-use and transpiration efficiency (RUE and TE) theory on a daily time step (Tanner and Sinclair, 1983; Monteith, 1988). Different RUEs, but the same extinction and transpiration coefficients, are used for plant and ratoon crops. RUE is reduced under sub-optimal temperatures and nitrogen regimes. Leaf area is cultivar-specific and determined by thermal time and biomass supply and demand, and is used to calculate intercepted total solar radiation. In unstressed conditions, daily biomass production is partitioned into leaf, cabbage, stalk (structural and sucrose fractions) and roots by various constant fractions for particular phenological phases. Daily photosynthate that has been partitioned to stalk is further partitioned into stalk sucrose once the stalk biomass has attained a minimum size (Fig. 1). Stress factors due to water, nitrogen and temperature are applied to the sucrose partitioning fraction with a resultant relative increase in sucrose partitioning (Table 1). APSIM-Sugarcane alters the partitioning fractions to sucrose in the stalk for different cultivars providing an ability to simulate different sucrose concentration for a range of cultivars.

A unique feature of APSIM-Sugarcane is the simulation of stalk water content, through structural stalk

Table 1
Partitioning fractions of daily above-ground photosynthate in APSIM-Sugarcane to various organs for two developmental phases (Keating et al., 1999)[a]

	Emergence–stalk elongation	Stalk elongation–maturity
Leaf	0.630	0.189
Cabbage	0.370	0.111
Stalk biomass	0	0.70
Stalk biomass to sucrose	0	0.55 to 1.0

[a] Partitioning to stalk sucrose is cultivar specific and a function of a stalk stress factor (minimum of water, nitrogen and temperature stress factors on photosynthesis), such that at zero stress the lower partitioning fraction applies. This increases linearly to 1.0 at a predetermined level of stress.

dry matter and thermal time. However, despite an obvious relationship (van Dillewijn, 1952), no direct linkages exist between stalk water content and the soil water content and crop transpiration. The purpose of this state variable is to simulate cane yield and sucrose concentration on a wet mass basis as is done routinely at sugar mills. It, therefore, represents an innovative step in crop modelling.

No formal descriptions of state variables and their rates of change exist in this model, and, therefore, a 'virtual collection' is a better description (after
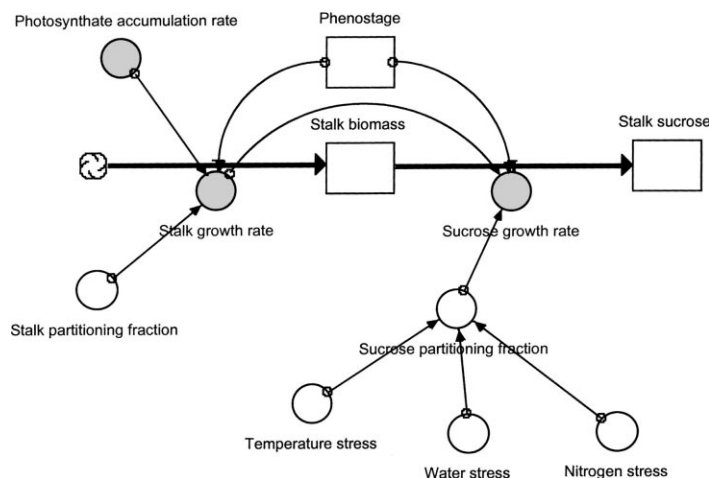

Fig. 1. Sucrose conceptual model translated from APSIM-Sugarcane (Keating et al., 1999) describing the endogenous (○), virtual rate (shaded) and state (□) variables with the flow of biomass and sucrose (➡) and information (→). Phenostage is defined here as a state variable from another sub-model.

Connor and Hall, 1997). However, it is more difficult to compare its structure with other models without Forrester diagrams (Forrester, 1961) that would separate the large mix of states and rates that have collectively been described as processes in APSIM (McCown et al., 1996). Hence, the derived Forrester diagram developed with the STELLA® software system, in Fig. 1, shows the current expression of what virtual state and rate variables determine the accumulation of sucrose.

Water stress effects are simulated in APSIM-Sugarcane by the methods adopted from other crop models such that leaf area expansion is reduced earlier, and more severely, than growth (Ritchie et al., 1986). This is achieved by reducing leaf area expansion and growth in different proportions to soil water supply. With APSIM, the soil water simulation is provided by a cascading or tipping bucket-type water balance adopted from Ritchie (1972) and others, but a water potential-based model is also available (McCown et al., 1996).

The effect of soil nitrogen deficits on sugarcane growth is achieved in APSIM-Sugarcane by an approach similar to that utilised in the CERES crop models (Godwin and Vlek, 1985). That approach uses a crop N demand for growth and supply defined with maximum, critical and minimum tissue N concentrations for the crop. Nitrogen uptake from the soil is simulated through a process of passive flow in the transpiration stream and a more active uptake process. Changes in soil N in the organic (surface residues, fresh organic matter, microbial biomass and humus) and inorganic pools (NO_3^+ and NH_4^-) are simulated with the APSIM SOILN module with respect to the organic C pools corresponding with the organic N pools within module SOILN (Probert et al., 1998).
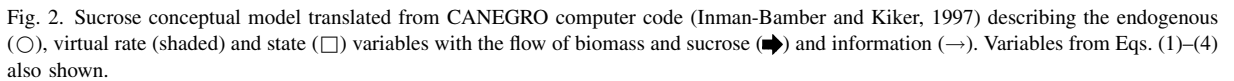
2.2. CANEGRO sugarcane simulation model

The origins of the CANEGRO model date back to the early 1970s with the development of equations of photosynthesis and respiration that arose out of the Wageningen school of de Wit et al. (McCree, 1970; Inman-Bamber and Thompson, 1989). Its first assembly into a simulation model (CANESIM) occurred in 1991, initiated by the South African Sugar Association Experiment Station (SASEX) (Inman-Bamber, 1991). Improvements were later added to the photosynthesis

calculations to include single leaf photosynthesis, quantum efficiency and growth and maintenance respiration. No direct effects of temperature on photosynthesis were included. The water balance calculations were also improved by the inclusion of Penman–Montieth potential evapotranspiration (Inman-Bamber et al., 1993; McGlinchey and Inman-Bamber, 1996), the CROPGRO water balance model (Hoogenboom et al., 1994) and canopy interception of rainfall. From new experimental data, improved phenological parameters for the development of leaves and tillers were also added together with partitioning factors for biomass allocation to roots. The model comprises a carbon simulation, crop development, energy and water simulation components. It is important to note that, at this point in history, the model was a radiation–water–temperature limited model of sugarcane biomass with no account of nutrient status (Inman-Bamber, 1994, 1995b, 1996a).

One of the major objectives of the development of CANEGRO was to help determine the optimal harvest age in South Africa, because of the widespread infestation of the stalk borer *Eldana saccharina* (Inman-Bamber, 1995a); therefore, the inclusion of sucrose simulation in the model has been a more recent development. Its first report in 1994 shows a reasonable performance in sucrose yield simulation in a graphical comparison of observed data at two locations in South Africa (Inman-Bamber, 1994). In an unpublished review of crop modelling at the South African Sugar Association Experiment Station (SASEX) more mechanistic methods of sucrose simulation were investigated (N.G. Inman-Bamber, unpublished data, 1996). Fig. 2 shows the relationship of the endogenous and virtual state and rate (driving) variables that determine sucrose accumulation (S, Mg ha^{-1}). The fraction (F_s) of accumulated stalk biomass (W, Mg ha^{-1}) (includes sucrose) to total above-ground biomass (W_a, Mg ha^{-1}) is used to determine the daily allocation of photosynthate to stalk:

$$F_s = \text{Maximum}\,[0, \text{Minimum}\,[(-0.03 + 0.02565W_a), (0.72 - e^{(-0.047W_a - 0.4105)})]] \quad (1)$$

Sucrose accumulation is determined from the sucrose fraction ($F = S/W$, dry wt. basis) and stalk biomass. The fraction of sucrose in the stalk is determined from stalk biomass and to provide an annual sinusoidal pattern in the southern hemisphere of the accumulated

Fig. 2. Sucrose conceptual model translated from CANEGRO computer code (Inman-Bamber and Kiker, 1997) describing the endogenous (○), virtual rate (shaded) and state (□) variables with the flow of biomass and sucrose (➡) and information (→). Variables from Eqs. (1)–(4) also shown.

sucrose fraction, an empirical day of year (D, 0–365) and age of cane (A, 0–730 days) function is employed, viz:

$$F_{IRR} = 0.3386 + 0.002308W + 0.04519\left(-\sin\left(\frac{D}{57.3}\right)\right) \quad (2)$$

$$F_{DRY} = 0.288 + 0.00530W - 3.59 \times 10^{-5}W^2 + 0.0533\left(-\sin\left(\frac{(D-10)}{57.3}\right)\right) + 1.153 \times 10^{-4}A \quad (3)$$

$$S = F_n W \quad (4)$$

where the subscript 'n' represents irrigated (IRR) or rainfed (DRY) cane sucrose fraction (F), respectively. These southern-hemisphere functions are applied to the northern hemisphere by a phase shift adjustment to D.

These empirical relationships were always considered a practical alternative to a more mechanistic source–sink approach that was pursued (N.G. Inman-Bamber, unpublished data, 1996), but until now without success. This is because knowledge of partitioning in sugarcane is poor (Muchow et al.,

1996), consequently new studies were initiated to address this in South Africa (Robertson and Donaldson, 1998).

The CANEGRO model now exists in two variations. The first is in a stand-alone SASEX variation that is used exclusively by SASEX as a research tool that has an MS-Windows® front-end for interactive multi-year simulations. The second variation is the DSSAT sugarcane model that has been coupled to a soil-and-plant nitrogen model from the CERES-Maize model (Jones and Kiniry, 1986). That model however, has not been validated with nitrogen deficient soils or crops. Thus, while future provision has been made to study the growth and development response under N deficiency for DSSAT compatibility, it currently is not functional and CANEGRO remains a radiation–water–temperature-limited model.

2.3. QCANE sugarcane simulation model

The QCANE model is the result of a project initiated by the Bureau of Sugar Experiment Stations in Queensland, Australia, to study physiological processes of sugarcane on a daily basis. It originated out of the conceptual framework of Bull and Tovey

(1974). There is a new version of QCANE that includes the effects of water and N deficits (BSES, 1996), but to-date details have not been published. Currently, QCANE is not being developed any further (P. Twine, personal communication, 1999). Nevertheless, there has been good progress made to-date with QCANE. Strong emphasis was applied to photosynthesis (Liu, 1996), respiration and partitioning of the photosynthate. The model considers a more formal arrangement of the states of biomass (cf. APSIM-Sugarcane). These are green leaf blades, stalks, non-millable tops (cabbage in APSIM-Sugarcane) and roots, and in each of these the daily-produced photosynthate is partitioned into growth and sucrose biomass with their resultant respiration making a total of eight states of biomass. A key feature of this model is the central role that sucrose plays as a carbon pool to supply the daily structural-C and maintenance-C requirements.

Daily gross photosynthesis is determined from photosynthetically active radiation interception and temperature as calibrated on local experimental data (Hartt and Burr, 1967). Respiration is divided into portions for maintenance and growth. The rate constant for growth respiration is set constant with maintenance respiration determined as a function of accumulated biomass and temperature. Considerable

early work has been conducted by numerous workers to determine the respiration rates of sugarcane (e.g. Glover, 1973; Glasziou et al., 1965). Thus, both QCANE and CANEGRO adopted comparable concepts (Inman-Bamber and Thompson, 1989). The QCANE model allocates photosynthate as a function of daily growth, growth stage and temperature to the various state variables (Fig. 3). The requirement for respiration and growth is first met with the balance allocated to sucrose storage. It is designed to provide greater partitioning to sucrose when the temperature is low and radiation is high (Yates, 1986). The daily partitioning fraction of photosynthate (f_s) to stalk biomass (includes stalk sucrose-C and stalk structural-C) is as follows (De Li Liu, unpublished data, 1999):

$$f_s = \frac{\rho_s}{1 + \rho_t + \rho_s + \rho_r} \tag{5}$$

where ρ_t, ρ_s and ρ_r are the ratios of non-millable top (t), stalk (s) and root (r) daily partitioning rate to daily leaf partitioning rate that are different functions for the tillering and maturing phenological phases. These ratios are defined by empirical functions of temperature in the range 10–25°C after Glasziou et al. (1965). They can be considered inverse-temperature-type functions that decrease the partitioning as the temperature increases.
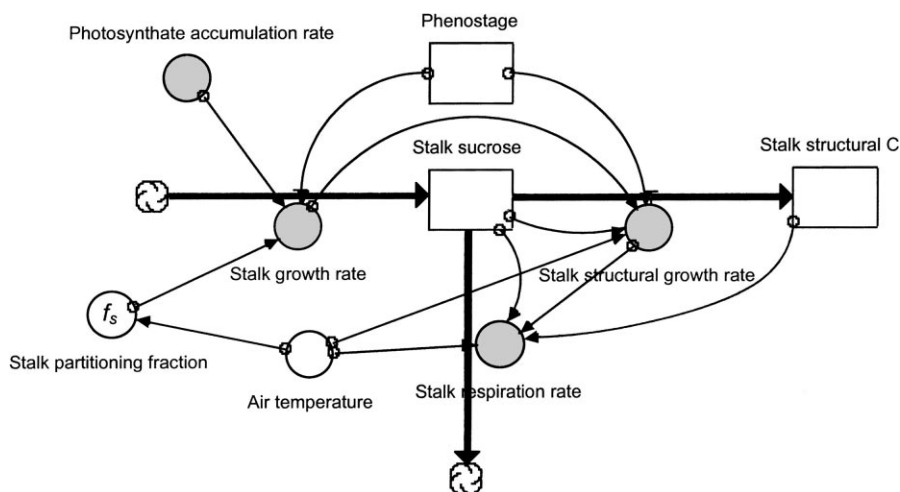

Fig. 3. Sucrose conceptual model translated from QCANE (Liu and Kingston, 1995) describing the endogenous (○), rate (shaded) and state (□) variables with the flow of biomass and sucrose (➡) and information (→). Phenostage is defined here as a state variable from another sub-model. Variable from Eq. (5) also shown.

An interesting concept in this model is that leaf area is determined from partitioned photosynthate and specific leaf area departing from the now common leaf number–thermal time approach of Carberry et al. (1993). The model simulates two Australian cultivars, Q138 and Q141.

3. Model performance

3.1. APSIM-Sugarcane

The performance of APSIM-Sugarcane has been evaluated across a diverse range of environments from Australia, South Africa, Swaziland and USA with considerable success (Keating et al., 1999) (Table 2). Here, though some of the validation data were used to fit the model to the data, it is recognised by Keating et al. (1999) that the validation is not entirely independent. Nevertheless, the wide range of data that was used to develop the model makes it relatively robust and likely to be useful over such environments with considerable confidence. Those environments were mostly irrigated. More recently, the model simulated entirely irrigated sucrose yields in Mauritius with better accuracy (Cheeroo-Nayamuth et al., 2000).

In an earlier independent unstressed test of all three models by Keating et al. (1995) the performance of APSIM-Sugarcane was the least accurate. In that test, the root mean squared deviation (RMSD) was 1.97 Mg ha^{-1} for the simulation of millable stalk

Table 2
Coefficient of determination (R^2), root mean squared error (RMSE) and range of simulated data for selected aboveground state and endogenous variables from APSIM-Sugarcane (Keating et al., 1999)

Variable	R^2	RMSE[a]	Range of data
Green biomass (Mg ha^{-1})	0.93	6.07	0–85
Cane fresh weight (Mg ha^{-1})	0.72	28.7	0–250
Stalk sucrose (Mg ha^{-1})	0.83	4.93	0–45

[a] Erroneous RMSD in Keating et al. (1999) recalculated as RMSE using correct formula (B.A. Keating, personal communication, 1999), as $RMSE = \sqrt{\left\{ \sum_{n=1}^{m} (Y_p - Y_o)^2 / m \right\}}$ where, Y_p and Y_o are the predicted and observed values, respectively, of m observations.

biomass over the range 0–80 Mg ha^{-1}. Since the 1994 comparison, APSIM-Sugarcane and CANEGRO have been used for benchmarking analyses in Australia and South Africa (Muchow et al., 1997; Inman-Bamber et al., 1998). In the Australian study, potential sucrose yields were simulated for two different localities and the means compared to the typical maximum observed yields (Table 4). Here, the model provides accurate simulations of mean annual sucrose yield.

One of the weak points of APSIM-Sugarcane is its inability to accurately simulate sucrose yield under significant water stress. Thus, the overall test of APSIM-Sugarcane was biased towards non-stressed crops. Indeed, five of the 19 data sets were water-stressed with two of these highlighted by Keating et al. (1999) as a problem for an adequate simulation. Where sugarcane is routinely stressed an improved model for sucrose prediction is needed. This will also be important if the effects of chemical ripeners and drying-off are to be incorporated. It is likely that the effects of stress on sucrose partitioning are actually much more complex than allowed for by the stress factors in APSIM-Sugarcane that affect stalk partitioning, biomass accumulation and leaf area differently. The effects of stress on stalk extension or stalk volume may, indeed, be more important since this is the dominant sink for sucrose. Whilst the performance of the current model is encouraging, further experimentation is needed to understand the seasonal response of sucrose yield to changes in weather, planting date, nutrients and cultivars, all of which have been acknowledged to influence markedly the sucrose yield (Inman-Bamber, 1996b; Robertson and Donaldson, 1998; Robertson et al., 1999).

3.2. CANEGRO

The CANEGRO model has been extensively tested in its performance in simulating total above-ground biomass and resultant soil water status for one popular South African cultivar (NCo376). These tests have been over a wide range of latitude (25°S to 31°S), altitude (15–1067 m) and soils in the South African sugar region (Inman-Bamber, 1994, 1995b, 1996a). In the comparative performance test of Keating et al. (1995) without water or N stress, the model is also shown to be generally robust in its performance. The

Table 3
Comparison of root mean squared deviation of selected simulated variables from the observed values for each model (Keating et al., 1995)

	APSIM-Sugarcane	CANEGRO	QCANE
Millable stalk biomass (Mg ha^{-1})	1.97	0.95	0.85
Total above-ground biomass (less trash) (Mg ha^{-1})	2.22	3.07	1.10

Table 4
Comparison of simulated and observed annual sucrose production (Mg ha^{-1}) at two localities in Australia using the APSIM-Sugarcane model (Muchow et al., 1997)

Ingham		Ayr	
Simulated	Observed	Simulated	Observed
24.2	24.5	27.3	26.7

accuracy of the simulation of millable stalk biomass was reasonable (RMSD = 0.95 Mg ha^{-1}, range 0–80 Mg ha^{-1}, Table 3) with no obvious bias at either low or high biomass. In another comparative test CANEGRO explained between 70 and 83% of the variance in observed cane yield (biomass) at two different locations (Inman-Bamber et al., 1998).

There are no reports that quote the accuracy of CANEGRO in simulating sucrose yield or concentration, despite one graphical comparison (Inman-Bamber, 1994) and numerous sucrose benchmarking exercises (Inman-Bamber, 1995b; Inman-Bamber et al., 1993, 1998). A more recent South African validation quoted an RMSE of 6.07 Mg ha^{-1} for sucrose yield and an RMSE of 11.11 Mg ha^{-1} for stalk biomass (G. Kiker, unpublished data, 2000) (Table 5).

3.3. QCANE

There are two published reports of the performance of QCANE (Liu and Kingston, 1995 and Keating et al., 1995). In these reports an accurate performance of QCANE can be seen. In the comparison with APSIM-Sugarcane and CANEGRO (Keating et al., 1995), it consistently had the lowest error in simulating biomass (Table 3). Indeed, the error of QCANE was less than half of that from APSIM-Sugarcane in millable stalk biomass (0.85 Mg ha^{-1} as compared with 1.97 Mg ha^{-1}). The seasonal changes in biomass also followed closely the observed data in other validation studies with Australian and Hawaiian data.

The performance of the model in simulating sucrose yield was also impressive for four crops across such a diverse range of environments (sub-tropical to tropical, data not shown) (see Liu and Kingston, 1995). Root mean squared errors (RMSE) quoted ranged from 2.46 to 2.55 Mg ha^{-1} (mean 2.51 Mg ha^{-1}) and coefficients of determination (R^2) ranged from 0.97 to 0.99 (Table 5) (De Li Liu, unpublished data, 1999). Thus, whilst these validations of QCANE are encouraging with respect to the accuracy of sucrose yield, more tests are warranted to confirm the utility of the partitioning functions employed. This is particularly important under stressed conditions.

Table 5
Comparison of root mean squared error (RMSE) and coefficient of determination (R^2) and source of data for each model in the prediction of stalk biomass and stalk sucrose yield

	Stalk biomass		Stalk sucrose		Source
	RMSE (Mg ha^{-1})	R^2	RMSE (Mg ha^{-1})	R^2	
APSIM-Sugarcane	6.07	0.93	4.93	0.83	Keating et al. (1999)
	6.00	0.73	3.30	0.78	Cheeroo-Nayamuth et al. (2000)
CANEGRO	11.11	0.73	6.07	0.66	G. Kiker, unpublished data (2000)
QCANE	6.11	0.98	2.55	0.99	De li Liu, unpublished data (1999)
	6.37	0.97	2.46	0.97	De li Liu, unpublished data (1999)

4. Discussion

The comparison of models based upon published literature is a difficult task. This is because the models are often not described well or in the same terminology. The scarcity of documentation makes the task even more difficult. Additionally, one runs the risk of comparing *apples* with *oranges*. This was a problem in this review, to some extent, as all the models differed in some important way and extensive testing of their sucrose performance was not available. But, all the models did have one common objective: to simulate sucrose yield; moreover, clear improvements for all of them could be identified even without another side-by-side comparison (shoot-out). Fortunately, there was one useful published comparison (Keating et al., 1995), but this was only for potential (radiation- and temperature-limited) yield and does not consider performance under water or nutrient stresses. As such, these comparisons are limited and more validation and experimentation is needed in all of these models under more typically stressed field conditions. Nevertheless, there is sufficient available data to compare these models. Of course, that comparison is now out of date for APSIM-Sugarcane as the most recent published work show significant improvements since the original 3-way comparison. It does, however, provide a valid comparison of the models at that time, highlighting the important steps forward. That comparison has served to spur on the development of APSIM-Sugarcane, gaining from much of the advances of CANEGRO and QCANE.

4.1. Model structure

All three models were structured differently in concept, in terms of defining their state and rate variables. This is particularly the case for CANEGRO. In CANEGRO, no clear distinction has been made between the rate-of-change to stalk and sucrose accumulation (differential form) and the integrated form (Eqs. (1)–(4)) in determining stalk and sucrose fractions and accumulated mass (Fig. 2). Whilst this seems no problem, mathematically — either approach can give the same answer, it is more difficult, conceptually, to introduce new factors that affect rate-of-change processes in a model comprising mainly
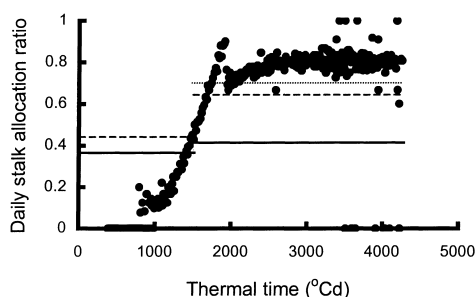

Fig. 4. Example of unstressed daily allocation ratio to stalk biomass relative to the above-ground daily increment for APSIM-Sugarcane (····) and CANEGRO (●) and relative to the total daily increment for QCANE at a mean daily temperature of $10°C$ (- - -) and $25°C$ (—). For simplicity, stalk elongation was assumed to occur at $1500°C$ (base $9°C$), where both APSIM-Sugarcane and QCANE commence stalk partitioning.

integrated processes. This is illustrated in Fig. 4 by comparing the unstressed stalk partitioning functions of each model. In APSIM-Sugarcane, the daily above-ground photosynthate fraction allocated to stalk is constant (0.7 after stalk elongation) and with QCANE (for above-ground and roots) varies according to mean daily temperature. However, in CANEGRO the daily above-ground allocation fraction is determined by the daily growth and mean accumulated fractions, causing significant discontinuities and differences between the other models (Fig. 4). Consideration, therefore, should be given to re-engineer CANEGRO to integrate the component differential processes at each time step, rather than doing it in a non-differential way. Special simulation languages were designed for such tasks (e.g. CSMP, MODELMAKER or STELLA).

APSIM-Sugarcane, despite relying more (than CANEGRO) on daily rate of change functions, also appears to lack some descriptive discipline with respect to its pools of crop biomass and endogenous variables. For example, frosting seems to reduce LAI, but not senesced biomass. For improved clarity a re-description of both CANEGRO and APSIM-Sugarcane's concepts would be useful with Forrester diagrams used to clarify what are state and rate variables and what are the information pathways. The detailed control processes embedded in the models can then be dealt with apart from the conservative quantities being modelled.

4.2. Validation process

Before a model can be considered useful for a designated task, it has to satisfy all the intermediate steps involved in model building and testing. These include (1) verification that the model functions as it ought to (i.e. programming errors are eliminated), and (2) validation, which assures that comparison of performance to the real world is favourable. That is, the model performs as expected and as against measured data. All the models examined here seem to be well tested against some single variables and over time, but no tests of two variables together have been made. Such multiple-variable validation can show how internally consistent the model is in terms of more complex relationships, as for example transpiration efficiency (e.g. O'Leary and Connor, 1996).

An important difference between the models, particularly between APSIM-Sugarcane and CANEGRO, is the way C is fixed into biomass. In CANEGRO, no reductions in C fixation due to sub-optimal temperatures occur; and, in APSIM-Sugarcane, above-ground RUE is assumed different between plant and ratoon crops, but the same root:shoot ratio and transpiration coefficient (TC) for both plant and ratoon crops. There appears to be some inconsistency here as there is no physiological reason why RUE should be different between plant and ratoon crops. The measured above-ground RUE possibly reflects differing root:shoot ratios and points to a more conservative RUE for the whole crop that is consistent with a constant TC. It is likely that many compensating factors contribute to a conservative RUE and TC. Nevertheless, an informative validation of these components would be worthwhile to pursue. Future thought should be given to a more rigorous multi-variable validation of these variables in both models.

4.3. Performance

Emphasis in this review is placed on sucrose yield rather than on sucrose concentration as the preferred measure of the model's performance. This is because sucrose concentration is confounded by stalk biomass and thus requires the simultaneous demonstration of accurate stalk biomass simulation. All three models performed reasonably well with respect to biomass accumulation (cane stalk yield). In the first comparative test, APSIM-Sugarcane had the greatest error— around twice that of QCANE, but more recently across different data sets, the accuracy in simulating sucrose yield were similar for APSIM-Sugarcane and CANE-GRO, but QCANE again had the lower error (Table 5). More importantly, however, both APSIM-Sugarcane and CANEGRO showed loss in accuracy in simulating sucrose yield from a more accurate stalk biomass yield. Table 5 shows the loss in accuracy with the lower R^2 for sucrose yield than for stalk biomass yield. It is suggested that this additional source of error is attributable to partitioning errors due to water and N stress, thus highlighting where more work is needed. Whilst CANEGRO relies on an empirical South African sucrose sub-model, its application elsewhere requires careful validation. The effort with CANE-GRO has been to first achieve realistic simulations of biomass before considering a more complex mechanistic approach to sucrose simulation. It is interesting to note the different philosophies of the modelling groups in this respect. In 1994, only QCANE (and incidentally the older AUSCANE) was able to simulate sucrose accumulation, despite being a limited test. Further, in QCANE no large loss in accuracy is seen in simulating sucrose from partitioned stalk biomass. This may reflect a more robust model, but further testing on a larger data set is needed.

Since all the models have achieved realistic simulation of biomass (cane yield), the effort should now be focused on those factors that affect sucrose accumulation. For APSIM-Sugarcane, attention to water and N stressed conditions is needed; and, for CANEGRO, both water and N stressed and non-stressed conditions need addressing. All the models determined total stalk biomass by different partitioning rules. APSIM-Sugarcane used a constant daily partitioning ratio (Table 1), while CANEGRO used an accumulated biomass function (Eq. (1)) and QCANE employed inverse-type temperature functions. Given the encouraging performance of QCANE, the general utility of this type of partitioning function needs further investigation. This is because it offers potential greater applicability into regions with different temperature regimes than is likely with APSIM-Sugarcane and CANEGRO models. The inverse nature of the temperature effect on partitioning to roots has long been recognised in other grass species (Friend, 1966).

One curious feature of QCANE, however, is the low threshold temperatures for partitioning. As such, the maximum mean temperature of 25°C would frequently be exceeded and the minimum (10°C) rarely achieved in many tropical countries. This may be an artifact of the regression methodology or a narrow range of data employed. Other factors such as photoperiod, cultivar, age of crop, water and nutrient stress and the use of ripeners must also be examined (Inman-Bamber, 1994, 1996b; Robertson and Donaldson, 1998; Robertson et al., 1996a, b, 1999).

All the models examined have their strengths and limitations. APSIM-Sugarcane's strength is that it is backed by a larger modelling effort in the other ancillary modules that may be of interest (e.g. soil water or nitrogen modules). One important factor claimed in favour of APSIM-Sugarcane is its versatility in that other crops (and surface trash and soils) can be included in analyses of crop rotations or sequences, but in some countries there are very few legal crops that economically compete with sugarcane. QCANE's strength is its comprehensive treatment of photosynthesis and sucrose simulation, whereas CANEGRO's strength is its more basic photosynthesis-based C fixation and wider availability in DSSAT.

The ability to simulate different cultivars is a feature of each model. For CANEGRO, however, much of the work has been on one South African cultivar. To simulate other undefined cultivars users are required, without directions, to supply the necessary coefficients which can be time-consuming in establishing new field experiments. Additionally, the required cultivar-specific (genetic) parameters have not been clearly specified in any of the model's documentation. This should be a priority for each of the model developers.

It is important now not to start a lengthy data collection exercise for another 'shoot-out'. Whilst they are useful, it is better to improve the models first. New experiments should, therefore, be designed to first help advance our understanding of sucrose partitioning and update the models when that is understood better. The maintenance of comprehensive data sets like SUGARBAG (Prestwidge et al., 1994) is also important for validation purposes, but this should be secondary to the task of advancing the models.

4.4. New directions

All the models examined here simulate stalk sucrose yield from a dry mass perspective, despite utilising a length dimension parameter (LAI) for leaf growth and development. This is intriguing because stalk elongation, like LAI, is known to be more sensitive to stress than its mass accumulation (Inman-Bamber and de Jager, 1986, 1988). Thus, one could envisage a model of sugarcane that applies a source–sink approach to the stalk on both a mass and volumetric (or length dimension) basis. Like the source–sink approach in many grain models (e.g. Fischer, 1979) such an approach in sugarcane offers increased explanatory behaviour of the crop that would otherwise not be possible.

The modelling effort with APSIM-Sugarcane has taken the harvest-index approach to modelling sucrose yield. That is, some portion of the daily growth increment is partitioned into the sucrose pool with little feedback with respect to its current size. It is essentially a source-dominated process. The alternative approach taken with QCANE was to define a potential sink size (stalk fibre mass) and draw on the stalk sucrose (mass) for that construction. The sucrose that remained in the stalk becomes the allocated quantity of stored stalk sucrose. The approach with QCANE is akin to the source–sink approach in grain models that utilise grain number as a key state variable that control the grain filling process. On the other hand, the empirical approach used in CANEGRO to simulate sucrose yield is pragmatic, but does not allow any explanatory analyses, particularly in respect to ripening issues.

The approach most likely to lead to a more explanatory model is one that utilises the source–sink concept (Connor and Fereres, 1999). Experience in grain crops, however, show that as more explanatory components are added the model tends to be become less accurate because of increasing uncertainty with increasing complexity (O'Leary and Connor, 1996). There is an obvious trade-off between accuracy and explanation that can be expected to vary with application. Fig. 5 shows diagrammatically how such a new model could be constructed.

The effect of stress on growth and partitioning is another area requiring urgent attention. The models to date have been tested on rather few data sets where
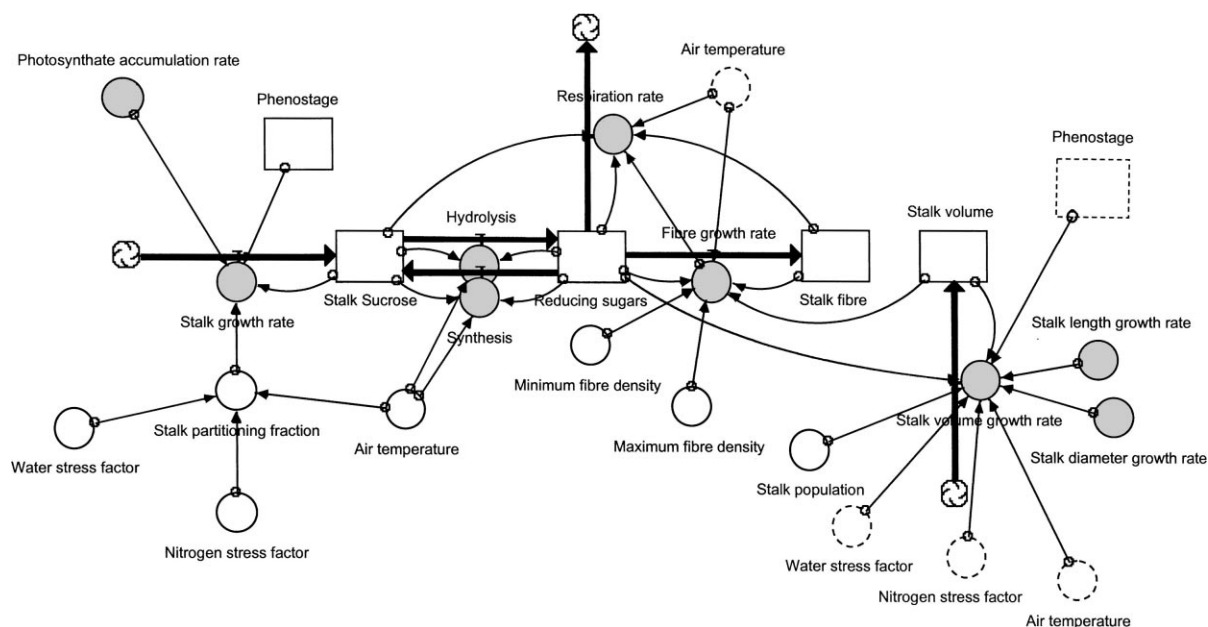
Fig. 5. Proposed new conceptual model of sucrose determination in sugarcane describing the relationship between a stalk mass and volume sub-models showing the endogenous (○), rate (shaded) and state (□) variables with the flow of sucrose-C (➡) to reducing sugars-C and fibre-C states and information (→). Phenostage is defined here as a state variable from another sub-model that determines the timing of partitioning. Dashed symbols are duplicate variables.

stress is a frequent occurrence. This lack of capacity in respect of stressed conditions probably reflects the philosophy of building models: first, to obtain the climatic potential, then, when that is achieved, the next most limiting factor, water, is accommodated. After that is achieved, nitrogen is typically the next key explanatory variable added. In the models reviewed here, only APSIM-Sugarcane has reached this level of evolution, though QCANE has been constructed with an N component it has not been validated. The addition of an N sub-model to CANE-GRO is still under construction.

The area now to which attention should be directed is the differential effect of stress on the mass and volumetric variables of the stalks. This is important, because the stalks are a comparatively large sink (volume) for sucrose storage that are highly affected by even mild stresses (Inman-Bamber and de Jager, 1986, 1988). The next priority should be the effects of water and N deficiency on the growth rates and partitioning of the leaf, stalk and root. The partitioning to the root has particularly been neglected in the APSIM-Sugarcane and CANEGRO models. This is

largely because it is a difficult task and model building has also been subject to an economy of effort balanced with reasonable performance without it. Nevertheless, if a source-sink approach is the preferred approach more work in this area will be necessary. It may, indeed, help resolve the inexplicable need for the different RUE used in APSIM-Sugarcane to simulate plant and ratoon crops.

Another feature to consider is the dynamics between sucrose and reducing sugars (Fig. 5). Robertson et al. (1996a, b) evaluated the effects of crop age, N supply and cultivar in fully irrigated crops and concluded that there was little scope for the agronomic management of reducing sugars with current 10–15 month commercial harvest cycles. However, the effect of water stress and ripeners is also known to make substantial changes in harvestable sucrose and reducing sugars (Donaldson and van Staden, 1995). Its inclusion here would allow for hydrolysis and re-synthesis of sucrose in response to growth and maintenance requirements that can be expected to vary between tropical and subtropical environments. It would also provide a basis for collaborative efforts

between biotechnologists, plant breeders and agronomists striving to boost sucrose yield at the farm level. QCANE does simulate reducing sugars, but not in any dynamic way. In the new proposed model (Fig. 5) three key state variables of mass are described, namely stalk sucrose, reducing sugars and fibre. Such a model would open up applications that specifically involve sucrose and reducing sugars (e.g. management of ripening and purity). This concept, therefore, could then be extended specifically to fructose and glucose simulation as ways to better simulate the full economic value of the harvested product. In such a model, the three mass state variables would interact with the volumetric state variable, stalk volume. Environmental effects of water, nitrogen and temperature govern the initial partitioning of photosynthate to the stalk and partitioning within the stalk can be essentially governed by these effects through changes in stalk volume.

Finally, consideration should be given to the development and improvement of the simulation of stalk water content. The stalk water component is an important new concept recently introduced into APSIM-Sugarcane. It is important, because the sugar industries in many countries report cane yield and sucrose content on a wet mass basis, largely for transport needs. The APSIM-Sugarcane stalk water sub-model is unique for sugarcane, but other crops have utilised such concepts in more complex relationships with soil water and transpiration (e.g. sunflower, Connor and Fereres, 1999). The inclusion of a stalk volume state variable may also make the simulation of stalk water content more realistic and the model overall more widely applicable to the industry, in general being able to simulate volume and mass output.

5. Conclusions

Despite limited published performance data, all the models performed reasonably well, but the prediction of sucrose yields were not the same. More amendments to sucrose partitioning under water and N-stressed conditions are needed. All three models have been described in ways that make their translation into state and rate variable models difficult. This is particularly the case for CANEGRO. The challenge ahead is to document better and test more fully the perfor-

mance of these models in their accuracy in simulating sucrose yield and concentration with particular attention to multiple variable validations. This is especially important for CANEGRO given its wide distribution with DSSAT. Improvements for each of the models lie in better understanding: (1) the effects of stress (water, nitrogen and temperature) on the partitioning of photosynthate to stored sucrose; (2) the response of different cultivars to stress; and (3) and differences between plant and ratoon crops in respect to RUE and TE.

A new approach employing a source–sink concept is suggested, but includes the volume of stalks as a state variable to define the sink size. A central feature is to include a new state variable; reducing sugars to allow the hydrolysis and re-synthesis of sucrose for the construction of the structural stalk carbon (fibre) and to supply stalk maintenance carbon (CO_2). Such an approach should offer more mechanistic and explanatory investigations into the growth and management of sugarcane with respect to its sucrose yield and purity, particularly in respect to various ripening strategies.

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