PREDICTING YIELD RESPONSES TO IRRIGATION OF SUGARCANE FROM A GROWTH MODEL AND FIELD RECORDS

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Abstract

A process level growth model, CANEGRO, has been developed along the lines of the IBSNAT* models of maize, soyabean and other annual crops. The model consists of detailed balances for carbon and water and a selection of energy balance equations for determining crop water requirement. The Penman-Monteith equation (Monteith, 1965) was selected for this exercise because of its sound physical base. Although predictions by the model were subject to errors resulting from inexact assumptions, it was possible to experiment with coefficients of equations in the water balance, and to arrive at a set of coefficients that accounted for a large number of yield responses to variations in soil and climate, including several levels of irrigation. Three additional irrigation experiments were selected from the literature to test the model's ability to simulate responses to precipitation (water production functions). The systematic error of the model was reduced to 1% and the non-systematic error to about 10%, after rejecting one of the nine crops (25 yields) involved. The model was used to generate water production curves for three soil forms on an irrigated estate in northern Natal. These curves were compared with the apparent response to total precipitation based on field records. Simulated yields were similar to field records when precipitation was low, but mean farm yields were low compared with the potential predicted by the model when precipitation was adequate. A demonstration conducted on the 7th and 8th ratoon of a 1,7 ha block of NCo376 on the estate, supported the prediction that sucrose yields of 20 t/ha/annum could be obtained with about 1 500 mm rainfall plus net irrigation on the best soils.

*IBSNAT = International Benchmark Sites Network for Agro-technology Transfer

Introduction

The recent drought, increasing costs of production and increased competition for water from industry, have focused attention on the principles of irrigation of sugarcane in South Africa. The matter of increased productivity from irrigation water was addressed by several authors at the recent Southern Africa Irrigation Symposium. Bruwer and van Heerden (1991) noted that mining earns 60% more than agriculture with the use of water. Hugo (1991) noted that future irrigation schemes will be supported by the South African Government only if a positive cash flow can be expected. Two recent technical developments in the sugar industry have prompted a new attempt to predict yield responses to irrigation: 1) sufficient data from the industry's Field Record System (FRS) have accumulated to consider yield responses to irrigation in the farm environment rather than in experiments; 2) the sugarcane growth model, CANEGRO, has recently been revised and it may provide a means of predicting yield responses to irrigation for any soil or climate in the industry. If reasonable accuracy in model estimates can be demonstrated, and these correspond with FRS data, we may have an improved procedure for irrigation planning.

The irrigation model published by Thompson and Harding (1986) is the standard for irrigation advice in the sugar industry. This was based on sound theoretical and experimental principles, but excluded considerable detail for the sake of practical advice. Thompson and Boyce (1972) compared a number of aerodynamic and energy balance methods for predicting crop water use. The Penman-Monteith (PM) equation (Monteith, 1965) accounted best for evaporation from their lysimeters, but they recommended the use of the class A pan for practical irrigation advice because of its simplicity. The advent of automatic weather stations and telecommunications in the capture of weather data, now make it possible to use sophisticated evaporation and growth models in irrigation advice and such advice is already being offered to a limited number of farmers in South Africa (Mottram *et al.*, 1991).

This paper discusses prospects and problems with the model and with FRS data with regard to yield response to precipitation.

Methods

Estate data

Irrigation and yield records of 140 fields from 1985 to 1992 were obtained from an irrigated estate in northern Natal, and were scrutinized for errors and bias as far as was possible. The extent of the bias, if any, was not known. During 1991 and 1992 a field (no. 61a) of the variety NCo376 in its 7th and 8th ratoon was irrigated strictly according to a water budget and neutron probe measurements. The 7th ratoon crop received 675 mm and the 8th ratoon received 855 mm net irrigation. The intention was to measure cane and sucrose yields under optimum commercial conditions.

A soil survey of the area conducted by Drennan *et al.* (1975) was supplied by the estate. This report placed soils in five classes according to how suitable they were for irrigation. The present irrigation scheme is located predominantly on the most suitable soil classes (A and B). A few fields are located on class E soils. The soil details supplied in the report were not adequate as input for the model. The physical properties of well documented Shorrocks and Shortlands series soils at Pongola and Mtunzini respectively, were therefore used to represent the Hutton and Shortlands soil forms of classes A and B on the estate. The texture of the soils used in the simulation was similar to that of soils sampled at pits 5 and 44 in the report by Drennan *et al.* (1975). Details obtained from pit 1 were used to generate a file for the Bonheim soil form (Table 1).

The CANEGRO crop simulation model

The CANEGRO model is essentially a revision of the CANESIM model (Inman-Bamber, 1991) and differs from its predecessor largely in the energy and carbon balances.

Table 1

Physical properties of soils on an irrigated estate in northern Natal derived from a report by Drennan *et al* (1975) and from laboratory and field tests on soils at Pongola and Mtunzini

Class A soil: Hutton form, Shorrocks series, (Pit 5)

Pit data			Horizon Depth (cm) Clay (%)		A 35 22	B 150+ 33
Model inputs: Run-off curve numbers:			Up to 50% canopy: 70 51 to 75% canopy: 46 Over 75% canopy: 14			
Layer Number	1	2	3-5	6-8	9	10
Depth (cm)	5	10	15	30	60	90
Water content (v/v)						
lower limit	0,101	0,101	0,101	0,151	0,151	0,15
upper limit	0,261	0,261	0,261	0,304	0,304	0,30
Saturation	0,368	0,368	0,368	0,399	0,399	0,39
Relative rooting factor	1,00	0,82	0,47	0,12	0,03	0,01
Bulk density (t/m³)	1,39	1,39	1,39	1,34	1,34	1,34

Class B soil: Shortlands form, Glendale series, (Pit 44)

Pit data			Horizon Depth (cm) Clay (%)		A 40 43	B 70+ -
Model inputs: Run-off curve numbers:			Up to 50% canopy: 82 51 to 75% canopy: 75 Over 75% canopy: 70			
Layer Number	1	2	3	4-6	7	8
Depth (cm)	5	15	15	20	30	30
Water content (v/v)						
lower limit	0,175	0,175	0,193	0,221	0,246	0,241
upper limit	0,320	0,320	0,325	0,341	0,309	0,313
Saturation	0,426	0,426	0,417	0,433	0,417	0,421
Relative rooting factor	1,00	0,80	0,62	0,30	0,11	0,05
Bulk density (t/m³)	1,24	1,24	1,30	1,26	1,25	1,25

Class E soil: Bonheim form, Rasheni series, (Pit 1)

Pit data		Horizon Depth (cm) Clay (%)		A 30 65	B1 60 65	B2 150+ 64
Model inputs: Run-off curve numbers:			Up to 50% canopy: 84 51 to 75% canopy: 80 Over 75% canopy: 75			
Layer Number	1	2-3	4-6	7	8	9
Depth (cm)	5	12,5	20	40	40	20
Water content (v/v)						
lower limit	0,330	0,330	0,330	0,330	0,330	0,330
upper limit	0,500	0,500	0,400	0,350	0,350	0,400
Saturation	0,565	0,565	0,504	0,479	0,479	0,504
Relative rooting factor	1,00	0,80	0,45	0,11	0,05	0,20
Bulk density (t/m³)	0,98	0,98	1,04	1,04	1,04	1,04
Sat. conduct. (mm/h)	model default values				1,0	1,0

The PM equation replaced the class A pan as a means of determining crop water use and the hedgerow model developed by Boote and Loomis (1991) replaced the simple equation adopted from McCree (1970). The hedgerow model accounts for hourly variations in sunlit and shaded fractions of the canopy but can be used with daily radiation data. The hedgerow model was developed for C3 plants for which a quantum efficiency of 0,053 mol/mol was assumed by Boote and Loomis (1991). In this case the value 0,065 mol/mol established by Ehleringer and Pearcy (1983) for NADP-malic enzyme C4 grasses was used. In an unpublished experiment (Anon, 1992) maximum leaf photosynthesis of 45 μmol $CO_2/m^2/s$ was measured at 33°C and this was the value used in the photosynthesis model.

An outline of the CANEGRO model is given in Figure 1 which shows that carbon, energy and water are accounted for in three separate balances or budgets. The important exchanges between these balances occur at the root/soil water interface (A) and the canopy/atmosphere interface (B). Water stress occurs when the amount of water required to balance the energy budget exceeds the amount that the roots can absorb. The canopy is involved in all three balances.

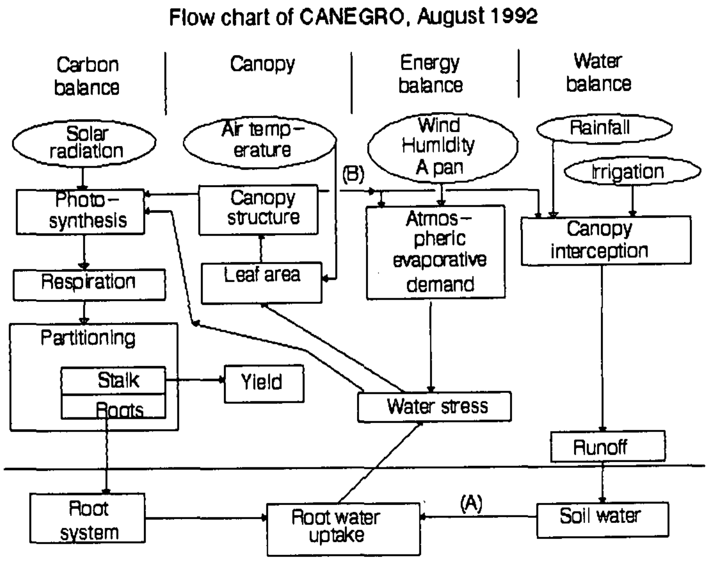

FIGURE 1 Flow chart of CANEGRO, August 1992.

Model calibration

It was necessary to calibrate the model after its revision in 1992. Yields of NCo376 in released variety trials (RVT) on soils of the Hutton, Shortlands and Milkwood forms were used for calibration because these soils were similar to those of the sugar estate for which field records were available. Data in Table 1 were used to compile the necessary files for the Hutton and Shortlands form soils and data in Table 2 were used for the Milkwood form. The calibration procedure concerned mainly the water balance and the coefficients dealing with root length to mass ratio and water uptake per unit root length in particular.

The PM equation was developed in conjunction with Dr Nigel Pickering at the University of Florida, USA, and will be the subject of a more comprehensive publication. The equation differed somewhat from the one used by Thompson and Boyce (1972) for two reasons: 1) it was considered necessary to use the option of varying crop height offered by the equation; 2) it was necessary to estimate the wind, vapour pressure (VP) and temperature profiles above the canopy, because these entities are measured only at 2 m above grass at meteorological stations in the sugar industry. The Thompson and Boyce (1972) equation was derived from measurements made 2 m above the canopy. The profile equations (1, 2 and 3) of Monteith and Unsworth (1990) were used for this purpose and a reference height of 10 m was selected.

$$u_2 = u_1 + \frac{\ln((z_2-d_g)/z_{og})}{\ln((z_1-d_g)/z_{og})} \quad (1)$$

$$e_2 = e_1 + \frac{\gamma LE_1(\ln((z_2-d_g)/(z_1-d_g)))^2}{(c_p(u_1-u_2)k^2} \quad (2)$$

$$t_2 = t_1 + \frac{C(\ln((z_2-d_g)/(z_1-d_g)))^2}{c_p(u_1-u_2)k_2} \quad (3)$$

where,

u_1 and u_2 = wind speed (m/s) at 2 and 10 m
e_1 and e_2 = vapour pressure (kPa) at 2 and 10 m
t_1 and t_2 = temperature at 2 and 10 m
z_1 and z_2 = height 2 and 10 m above ground
LE_1 = latent energy of evaporation from grass
z_{og} = roughness length for grass = 0,013 m
γ = psychometric constant
d_g = zero plane displacement for grass = 0,07 m
c_p = specific heat of air at constant pressure
C = sensible heat flux
k = von Karman's constant = 0,41

The evaporation estimate (E_t) required for the water balance is the evaporation from the cane crop and soil at full canopy when water is not limiting. Partitioning of this amount between soil and crop is done in the water balance where LAI and soil water content are taken into account. The PM equation used was:

$$E_t = \frac{\Delta(R_n-G)+0,0864c_p(VPD_2)/r_a}{\Delta + \gamma(1,0+r_c/r_a)} \quad (4)$$

where

Δ = slope of the saturated VP - temperature curve
G = soil heat flux
VPD_2 = vapour pressure deficit at 10 m
r_a = canopy aerodynamic resistance
= $\ln((z_2-d_c)/z_{oc})^2/(u_2k^2)$
r_c = bulk stomatal resistance
= leaf resistance × leaf area index
z_{oc} = roughness length for sugarcane
d_c = zero plane displacement for sugarcane
R_n = net radiation

A limited amount of calibration was conducted with this equation, using data presented by Thompson (1986) who measured daily evaporation from three weighing lysimeters.

Table 2

Physical properties of the Milkwood form soil at the irrigation and variety (RVT) trials (Ottawa estate)

Horizon)	A1	A2					
Depth (cm)	30	60					
Clay (%)	44	56					
Model inputs:							
Run-off curve numbers:	Up to 50% canopy: 82 51 to 75% canopy: 75 Over 75% canopy: 70						
Layer Number	1	2	3	4	5	6	7
Depth (cm)	5	10	15	15	15	15	30
Water content (v/v)							
lower limit	,189	,189	,197	,247	,277	,287	,200
upper limit	,319	,319	,392	,427	,377	,387	,240
Saturation	,399	,399	,445	,459	,387	,392	,337
Relative rooting factor	1,00	,82	,64	,47	,35	,26	,05
Bulk density (t/m³)	1,38	1,38	1,33	1,35	1,60	1,60	1,50
Sat. conduct. (mm/h)	model	default	values				1,0

The model was calibrated using the daily mean evaporation of the three lysimeters during the plant crop of Thompson's experiment, when more than 50% of the ground was covered by foliage. The measured and simulated daily values were smoothed as follows:

$E_m = (E_{i-1} + 2E_i + E_{i+1})/4$ where i = value for the ith day and m = weighted mean.

Water production curves (model validation)

Two series of irrigation experiments conducted on sugarcane in South Africa were selected from the literature to test the model's capability of predicting yield responses to irrigation (water production curves).

The irrigation experiments reported by Thompson and de Robillard (1968) and Thompson *et al* (1967) were conducted on two soils near Mount Edgecombe, a Clansthal sand and a Milkwood clay. The site of the Milkwood clay was the site on which the RVT trials at Ottawa were conducted some years later. The physical properties of the Clansthal sand used in the simulation were those reported by Thompson *et al.* (1967) (Table 3). More recent data were used for the Milkwood clay (Table 2) but the soil depth reported by Thompson *et al.* (1967) which was at least 300 mm greater than the current depth, was retained.

The five irrigation treatments that were applied to the four crops were achieved by irrigating when the estimated soil water deficit reached four levels ranging from 25 to 114 mm and by including a zero irrigation treatment. An amount of 25 mm was applied per application.

Hellmann (1978) presented the results of an irrigation experiment at Pongola on a Hutton form sandy clay loam, where three irrigation levels were applied to six varieties during a plant crop and four subsequent ratoons. The different irrigation levels were achieved by varying the frequency of a constant amount of irrigation (61 mm net). The levels which varied for each crop ranged from 122 to 870 mm per crop. Cane dry matter (DM) yields were given only as means for six varieties. It was possible to derive the data for NCo376 from reports in folder 1A of the SA Sugar Industry Agronomist Association's catalogue. The soil in this experiment was similar to that in the RVT trials at Pongola and the appropriate soil criteria presented in Table 1 were used to simulate yields of Hellmann's experiment.

Irrigation simulation

Once the model was validated it was possible to generate water production functions for the three main soil types on the irrigated estate. The soil data required for the simulations were obtained from Table 1 and daily rainfall was obtained from a rain gauge at Mkuze, which is close to the estate. Other weather variables were measured at Pongola, about 50 km from the estate. The mean annual rainfall measured in the rain gauge was 680 mm.

The amount of irrigation was varied from zero to 800 mm per annum by altering the cycle time and keeping the net application rate constant at 45 mm. The net application rate was reduced to 20 mm for amounts of irrigation exceeding 800 mm. A harvest age of 12 months was assumed and crops starting in April, September and December were chosen to represent the milling season. These cycles were repeated each year from 1970 to 1991. Each water production curve was derived from 13 irrigation levels each 'applied' to 60 crop simulations.

Results

Calibration of the model

The calibration of the PM equation was not extensive and required only an adjustment to the leaf resistance value (r_l) and LAI values. Values of 150 and 300 s/m were selected for abaxial (lower) and adaxial (upper) surfaces from the leaf resistance measurements of Inman-Bamber and de Jager (1986). Leaf area indices of 4,0 or more are commonly measured in irrigated sugarcane in South Africa (Inman-Bamber, 1987). With these values the systematic error of the PM estimate was -1% and the standard error was 0,64 mm (Figure 2). Evaporation from a class A pan was measured simultaneously and this exceeded lysimeter evaporation by 6% and produced a standard error of 0,8 mm when processed in the same way as the PM estimate.

The good correlation between yields measured at Pongola, Mtunzini and Ottawa and those predicted by the model (Figures 3, 4 and 5), were obtained by changing one or two coefficients regarding the onset and release of water stress in the three soils. Root length to mass ratio was 1 m/g for the Milkwood and 3 m/g for the Shortlands and Hutton forms. For the Shortlands and Milkwood forms, the stress coefficient (SWDF1) was allowed to decline from its maximum of 1,0 to 0,5 before slow recovery of photosynthesis was invoked, while for the Hutton form SWDF1 had to decline to 0,2 to prevent the immediate recovery of photosynthesis after rain or irrigation. No other coefficients were changed when simulating different soil types. The reasons

Table 3

Physical properties of the Clansthal series soil at the irrigation trial (Cornubia estate)

Layer (30 cm each)		1	2	3	5	6	7	8
Clay (%)		7	8	9	8	9	13	16
Model inputs:								
Run-off curve numbers:				Up to 50% canopy: 75 51 to 75% canopy: 59 Over 75% canopy: 35				
Layer Number	1	2	3–4	5	6	7	8	9–10
Depth (cm)	5	25	30	30	30	30	30	120
Water content (v/v)								
lower limit	,040	,040	,040	,040	,030	,050	,050	,050
upper limit	,140	,140	,150	,150	,150	,160	,120	,120
Saturation	,261	,270	,283	,279	,283	,280	,273	,268
Relative rooting factor	1,00	,82	,47	,30	,17	,10	,10	,10
Bulk density (t/m³)	1,64	1,59	1,55	1,57	1,55	1,59	1,52	1,55
Sat. conduct. (mm/h)								

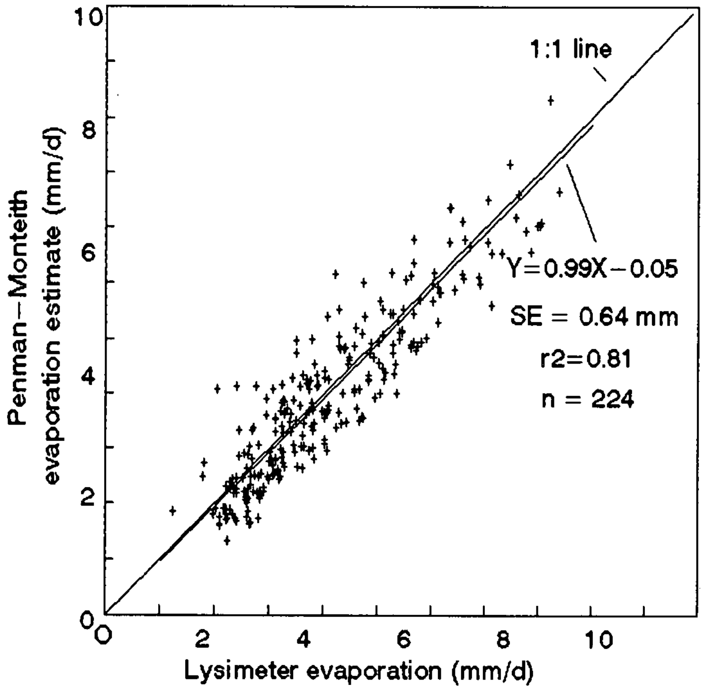

FIGURE 2 Estimated and measured daily evaporation of NCo376 growing in three lysimeters at Pongola, from the 50% canopy stage onwards. Co-ordinates are means of the three lysimeters and weighted (1:2:1) three-day running means.

for the above changes arise from the deficiencies in the present water balance in dealing with unsaturated water flow and from deficiencies in our knowledge of root growth and function of sugarcane. The low root length to mass ratio used in the Milkwood soil probably relates to the low water conductivity in unsaturated conditions. The use of a high critical stress level for recovery in photosynthesis in the clay soils was one way of accounting for the difficulty plants experience in extracting water in dry clay soils. These matters are the subject of current research (van Antwerpen *et al.*, 1993).

The CANEGRO model simulated stalk yields of the 64 crops used in the calibration procedure with a maximum standard error of 6,3 t/ha and a maximum systematic error of 5% (Figures 3, 4 and 5). The successful calibration in-

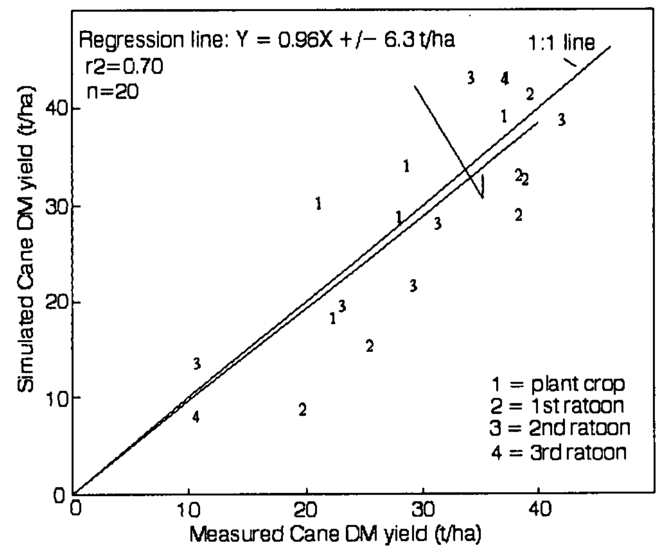

FIGURE 3 Simulated and measured yields of NCo376 in two irrigation experiments on a Hutton form clay loam at Pongola conducted from 1978 to 1985.

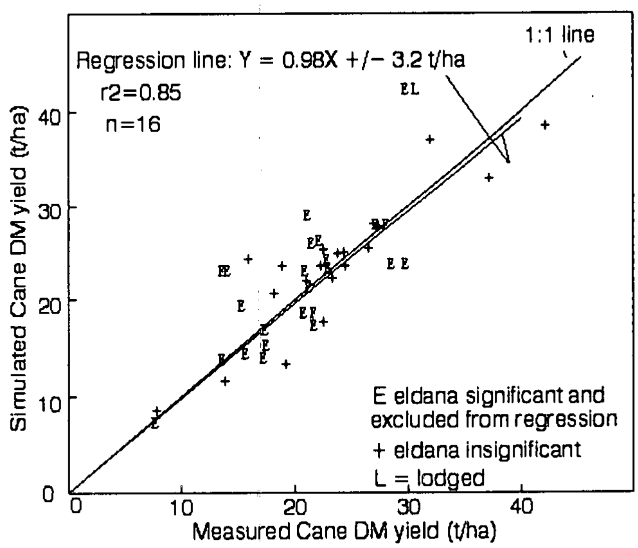

FIGURE 4 Simulated and measured yields of NCo376 in nine variety trials on a Shortlands form soil conducted at Mtunzini from 1978 to 1992.

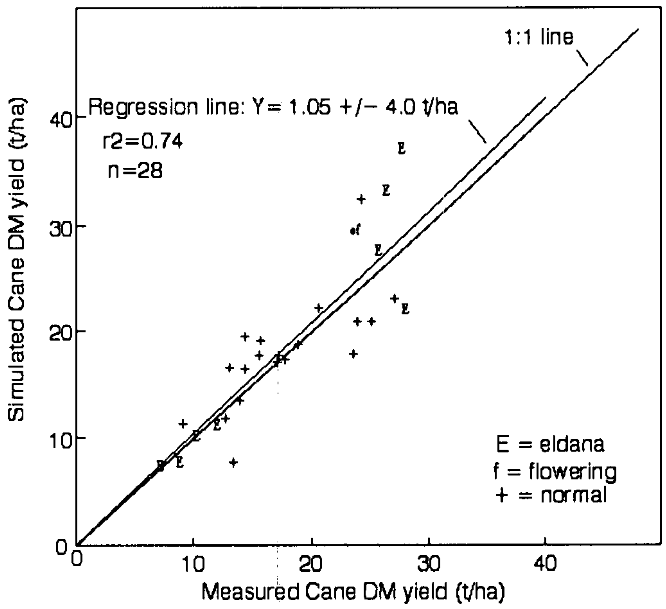

FIGURE 5 Simulated and measured yields of NCo376 in six variety trials on a Milkwood form soil conducted at Ottawa from 1978 to 1992.

volving a wide range of growing conditions was encouraging and good results with an independent set of yield data were anticipated.

Water response curves and model validation

Curves were fitted by least squares to the measured and simulated yields pertaining to the experiments near Mount Edgecombe (Figure 6). The curves serve only to smooth the responses and have no general application, but the standard error of the estimate provides some indication of the reliability of the curves for economic planning. The simulated response to total precipitation was more marked than the measured response for the Clansthal sand but the reverse was true for the Milkwood clay (Figure 6). The simulated yields were reasonably close to the measured yields in most cases, but yields for the ratoon crop at Ottawa were underestimated by 10 t/ha. The second simulation demonstrated the sensitivity of the model to the root length to mass ratio.

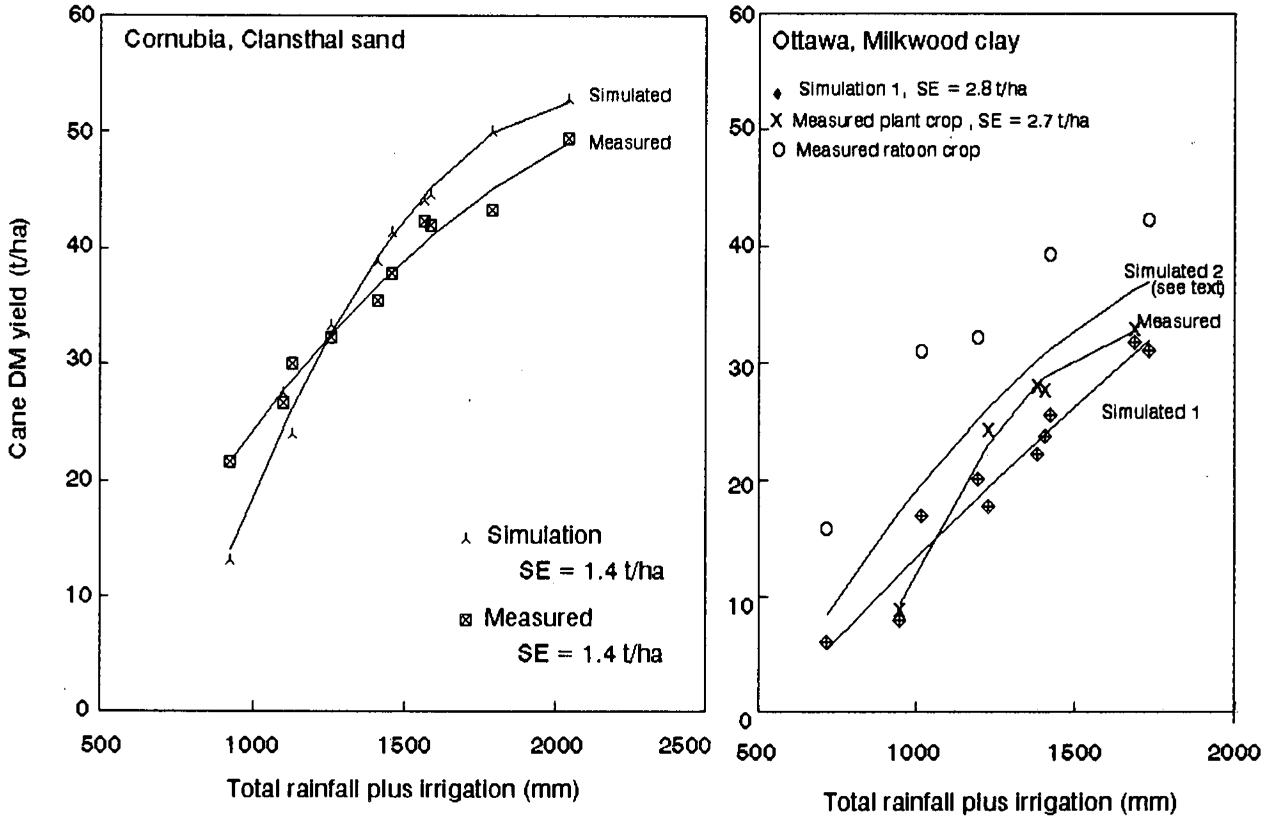

FIGURE 6 Simulated and measured yields in relation to rainfall plus different levels of net irrigation applied to two crops of NCo376 in two experiments near Mount Edgecombe from 1964 to 1967.

For simulation 2 this ratio was changed from 1 to 3 m per g of root. The greater value was used for all other soils. The uncertainty of the simulation was matched by the unexpectedly different yield responses between plant and ratoon crops.

Measured and simulated yield responses in the Pongola experiment differed less than the standard errors arising from the smoothing process (Figure 7). The water production curve derived from the model was as reliable as the curve derived from the experiment in this case.

It may be noted from Figures 6 and 7 that responses to precipitation up to 1 500 mm were generally linear and responses above this amount were curvilinear.

When the results of the ratoon crop at Ottawa were excluded, the validity of the model was highly satisfactory, with a systematic error of less than 1% and a standard error for a single estimate less than 5 t/ha. Willmott (1982) provided a statistical analysis for the evaluation of models, and in his terms, the D index for the validation exercise was 0,93 (maximum = 1,0) and the systematic error was 0,56 t/ha. The non-systematic error, which depends on both simulated and measured variances, was 4,8 t/ha.

Irrigation simulation and analysis of field records

For class A soils (Hutton form) the model predicted that a mean sucrose yield of 20 t/ha was attainable with approximately 1 500 mm total precipitation and that the response to irrigation amounts greater than 820 mm (1 500-680 mm) was small (Figure 8). Yields for class B and E soils fell rapidly when the annual precipitation was less than 1 500 mm. The records from block A were considered to be

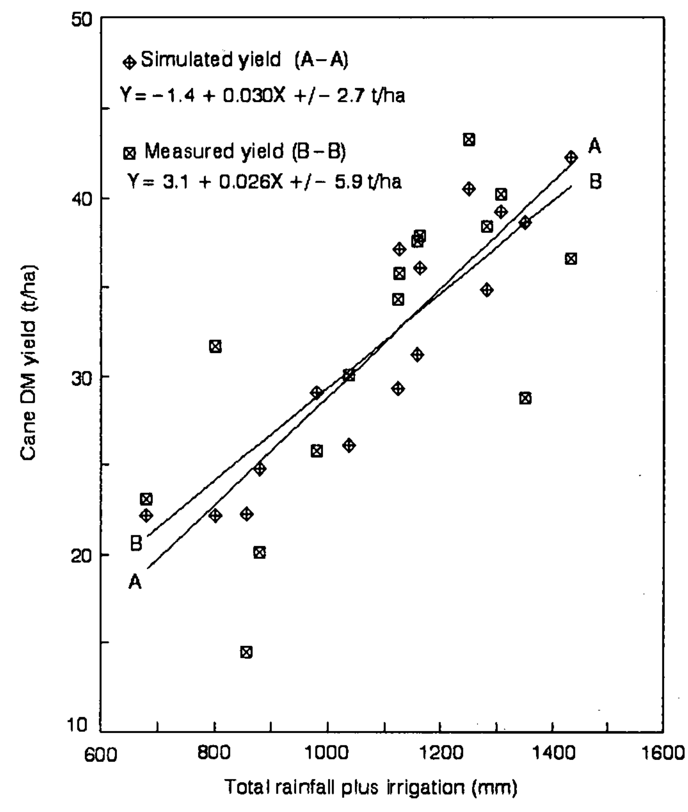

FIGURE 7 Simulated and measured yields in relation to rainfall plus different levels of net irrigation applied to five crops of NCo376 in an experiment at Pongola conducted from 1970 to 1976.

more reliable than those from blocks B and C. Most of the co-ordinates representing yields of fields in block A were bounded by the simulated response curves for class A and E soils (Figure 8). The yields from B and C blocks were more variable and were often considerably lower than the response curve for class A soils.

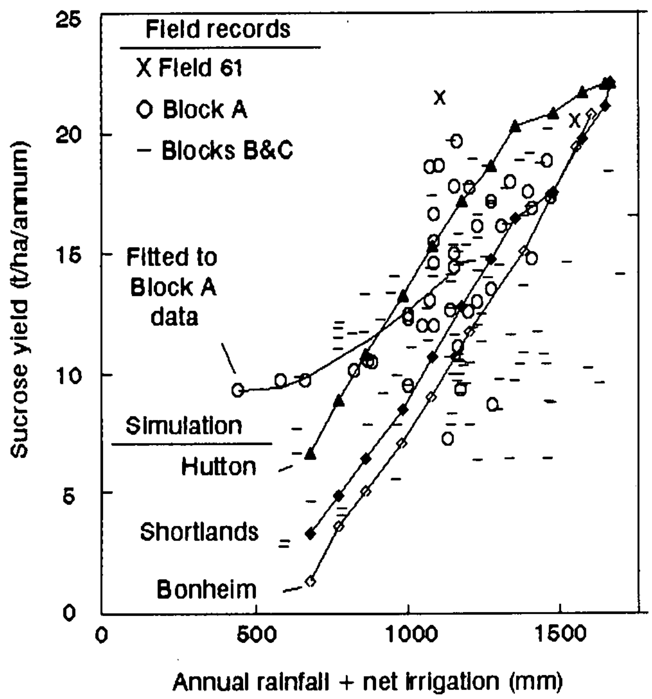

FIGURE 8 Simulated sucrose yield response to rain plus net irrigation for three soils on an estate in northern Natal and the association between recorded yield and net irrigation plus rainfall for fields with Hutton form soils.

It appeared that the estate's crops did not respond to precipitation as well as could be expected from the model's predictions. However some of the estate's yields approached the maximum predicted by the model. The yields of the two ratoon crops of NCo376 in field 61a were 20,5 and 21,5 t/ha/annum respectively and they confirmed that the predictions made by the model were not unrealistic. To obtain these yields on a large commercial scale would be difficult and it is common to reduce the climatic potential by 30% when drawing up economic standards.

Conclusions

During the calibration exercise, the model proved to be capable of accounting reasonably well for the yields of a number of crops of NCo376 growing in a variety of conditions. Confidence in the model was enhanced when it responded to increased precipitation like real crops of NCo376 which had no connection with the building or calibration of the model. Sensitive components of the model were identified and have prompted new research. The water production curves that were generated for the sugar estate demonstrated the influence of soil type on the response to irrigation. Although the FRS data did not provide a clear indication of how crops had responded to increased precipitation, they supported the results of the simulation. The joint use of FRS data and the model was considered to be successful and these tools could be used together to solve other problems in irrigation or various aspects of crop management.

Acknowledgements

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