AN IRRIGATION SCHEDULING METHOD BASED ON A CROP MODEL AND AN AUTOMATIC WEATHER STATION

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Abstract

Daily crop water use of irrigated sugarcane was estimated using a new version of the Penman-Monteith (PM) evaporation equation which was incorporated into the CANEGRO model. Daily water use of a plant and two ratoon crops of sugarcane growing in three weighing lysimeters (2,4 × 1,5 × 1,2 m) at Pongola were used to test the validity of the PM, estimate. Weekly mean daily PM regressed against three years of lysimeter evaporation, including periods of incomplete canopy, resulted in a regression coefficient of 0,98, with $r^2 = 0,80$ and a root mean square error of 0,69 mm per day. A pilot irrigation scheduling project was established in Northern Zululand on a commercial estate to develop a scheduling technique based on the technology. Meterological variables were recorded by an automatic weather station (AWS) installed on each estate, and the data was transmitted electronically once a week to the Experiment Station at Mount Edgecombe. The soil water content of each of the nine fields in the project was estimated daily using software developed for this purpose. These estimates were checked weekly in four of the fields with a neutron moisture meter. Different soil water deficits and stress criteria were used for scheduling irrigation in four of the fields in order to test the possibility offered by the technology of reducing water application without reducing yields. The other fields were irrigated to replace water used by the crop. A report detailing the current water status of each field, and when next to irrigate, was sent to the irrigator each week. The possibilities offered by this new technology and comparisons with conventional scheduling methods are discussed.

Introduction

In recent years there has been a dramatic increase in the demand for water, especially from the industrial and domestic sectors. This, coupled with the serious droughts experienced over the past four years, has prompted researchers to evaluate current irrigation scheduling techniques in the sugar industry, and to investigate improved methods based on new technology in this field.

In the South African sugar industy, most scheduling systems use class A pan evaporation as an estimate of crop water use (CWU). Thompson (1986) concluded that the ratio between evaporation from a class A pan and potential CWU from a fully canopied sugarcane crop was close to one. To schedule irrigation, growers were advised to use class A pan evaporation and crop factors in a simple water budget. To encourage irrigation scheduling in the industry a simplified system, based on monthly long term mean class A pan evaporation, was developed (George, 1988). This 'pegboard system' and other simple computerised water budgets are currently widely used in the industry as irrigation scheduling tools.

Interest in more accurate methods of scheduling irrigation and the associated savings in water and pumping costs has prompted renewed effort in this area. Recent advances in the modelling of sugarcane and automated data logging techniques have led to the reliable prediction of CWU calculated from meteorological variables measured by an AWS. The first part of this paper deals with the calibration of the CWU estimate using lysimeter evaporation measured at Pongola in Northern Zululand, Natal.

Commercial scheduling services based on crop models and AWSs are available to growers of a number of crops, both in South Africa and abroad (Mottram and de Jager, 1994; CIMIS, 1985). The second part of this paper deals with a pilot project initiated on a commercial estate in Zululand, to develop a remote irrigation scheduling technique for sugarcane using the CANEGRO crop model and an AWS situated on the estate. In addition, a number of scheduling options were investigated and the comparisons between these and conventional scheduling methods are discussed.

CANEGRO CWU estimate - calibration and validation

The CANEGRO crop model

CANEGRO is a process level crop model being developed along the lines of the IBSNAT* models of maize, soyabeans and other annual crops (Inman-Bamber, 1991; Inman-Bamber *et al.,* 1993). The model is comprised of balances for carbon, energy and water, and a detailed canopy routine which calculates leaf area index (LAI) and height of the growing crop. An outline of the model is given in Figure 1. This paper focuses on the water and energy balances (water supply and demand). For the purpose of the model, plant moisture stress is assumed to occur when soil and root water

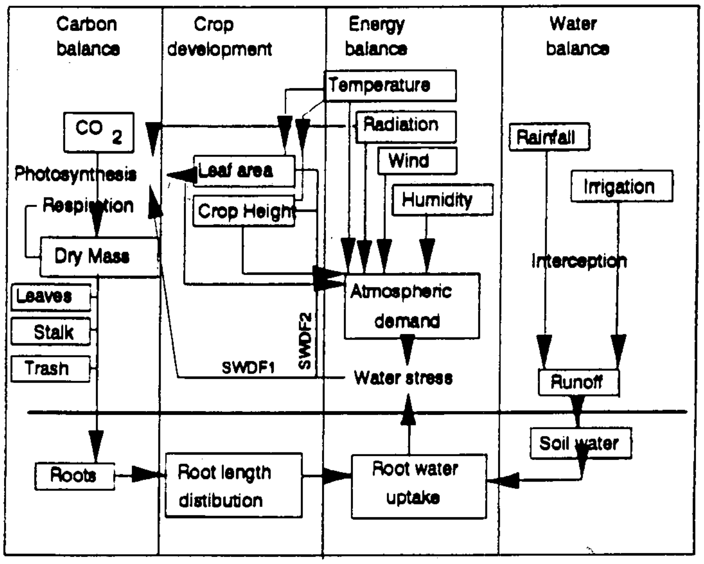

FIGURE 1 Flow chart of CANEGRO

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supply cannot match twice atmospheric demand. The first stage of stress (coded SWDF2 in the model) restricts cell expansion and the production and growth of new leaf and stalk tissue. At a later stage photosynthesis stress (coded SWDF1 in the model) occurs when soil water supply fails to satisfy atmospheric demand. This affects biomass and sucrose accumulation directly.

CWU using CANEGRO

Vapour flux density above a mature sugarcane crop was calculated using the Penman-Monteith (PM) equation (Monteith, 1965) in a modified two step energy balance method developed in conjunction with Dr Nigel Pickering at the University of Florida, USA. Much of the detail of this model has been published (Inman-Bamber *et al.*, 1993) and a summary of only the energy balance and improvements made since 1993 are discussed in this paper.

Reference evaporation is defined as the vapour flux density above an actively growing grass cover, 8 to 15 cm high, completely shading the ground and free from nutrient and water stress (Doorenbos and Pruitt, 1977). This was calculated using standard weather variables recorded two metres above the ground surface. Net radiation was estimated from solar radiation, air temperature and vapour pressure using eq. 1 (Wright, 1982), which was introduced to allow the use of measured global shortwave radiation recorded by an AWS as against daily duration of sunshine.

$$R_n = \left[(1-\alpha)R_s - \sigma\frac{(T^4_{maxk} + T^4_{mink})}{2} \times (a_l - 0.139\sqrt{e_d})\left(a\frac{R_s}{R_{so}} + b\right)\right] \qquad (1)$$

where

α = surface albedo
R_s = measured shortwave radiation (MJ/m^2/d)
σ = Stephan-Boltzman constant
T_{maxk} = maximum daily air temperature (°K)
T_{mink} = minimum daily air temperature (°K)
e_d = vapour pressure of the air (KPa)
R_{so} = clear sky shortwave radiation (0,75R_a)
R_a = extraterrestrial radiation (MJ/m^2/d)
a_l, *a and b* are empirical constants fitted to net radiation data measured by Thompson (1986) at Pongola.

Latent and sensible heat fluxes at two metres above the surface, and profile equations of Monteith and Unsworth (1990), were used to calculate temperature, vapour pressure and wind speed at a new reference height of 10 metres. Potential evapotranspiration (PET) of a sugarcane crop was calculated using the PM equation, meterological variables at the 10 metre reference height, fixed surface resistance and an aerodynamic resistance component adjusted daily using the model's estimate of canopy height. PET was partitioned between soil and canopy in the CANEGRO water balance using a two stage evaporation model governed by simulated LAI and soil water content (Jones and Kiniry, 1986).

Calibration and validation data sets

Daily meterological variables for a three year period, November 1968 to November 1971, were obtained from a standard weather station situated on the South African Sugar Association Experiment Station (SASEX) farm at Pongola in Northern Zululand, South Africa (27° 23'S and 31°37'E). Daily duration of sunshine and total daily windrun at two metres for the preceding 24 hours were recorded at 08h00 each day. Minimum and maximum temperatures for the same 24 hour period were read daily at 08h00, and wet and dry bulb temperatures were read daily at 08h00 and 14h00. All thermometers were housed in a Stevenson screen two metres above the ground. Net radiation over the sugarcane crop was measured using three Middleton net radiometers.

Daily CWU of a plant and two ratoon crops of the variety NCo376, was measured using three weighing lysimeters (2,44 × 1,52 × 1,22 m), the detail of which has been published by Thompson (1986) and co-workers (Thompson and Boyce, 1971; Moberly, 1974).

Data recorded during the plant crop were used to calibrate both the net radiation and evaporation equations. Data from the two subsequent ratoons were used to validate the calibrated equations.

Model calibration and validation

Daily net radiation calculated using eq. 1 was calibrated against measured values recorded during the plant crop by adjusting the three coefficients *a, b and a1.* The best correlation was obtained by using the following values:

a^1 = 0,35 (an estimation of net atmospheric emissivity)
a = 1,126
b = −0,07 for $R_s/R_{so} > 0,7$
a = 1,017
b = −0,06 for $R_s/R_{so}) \leq 0,7$ (Wright, 1982).

Net radiation measured above the first and second ratoon crops was used to validate the equation. During the first ratoon crop estimated net radiation calculated from measured shortwave global radiation deviated from measured net radiation by 4%. The root mean square error of a single estimate was 1,12 MJ/m^2/day (Figure 2).

Daily lysimeter evaporation recorded during the plant crop was used to calibrate the PM equation. Calibration involved adjustments to the value for surface resistance to vapour transfer of the sugarcane crop. The best correlation was obtained using a value of 32 s/m. Evaporation from the first two ratoon crops was used to validate the PM estimate. Seven day mean lysimeter evaporation measured during the plant crop (calibration data set) and two ratoon crops (validation data set), including periods of incomplete canopy, were compared with simulated evaporation calculated by the CANEGRO model (Figure 3). The slope of the regression was 0,98, the r^2 was 0,8 and the root mean square error was 0,69 mm. Accuracy was improved when periods of incom-

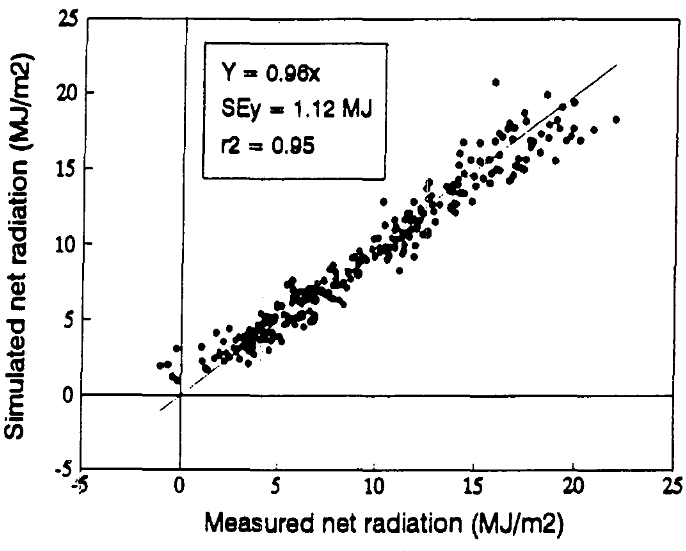

FIGURE 2 Simulated daily net radiation calculated from global shortwave radiation and measured net radiation for a single year at Pongola.

plete canopy were excluded from the regression, the r^2 was increased to 0,84 and the root mean square error was reduced to 0,57 mm (Figure 3).

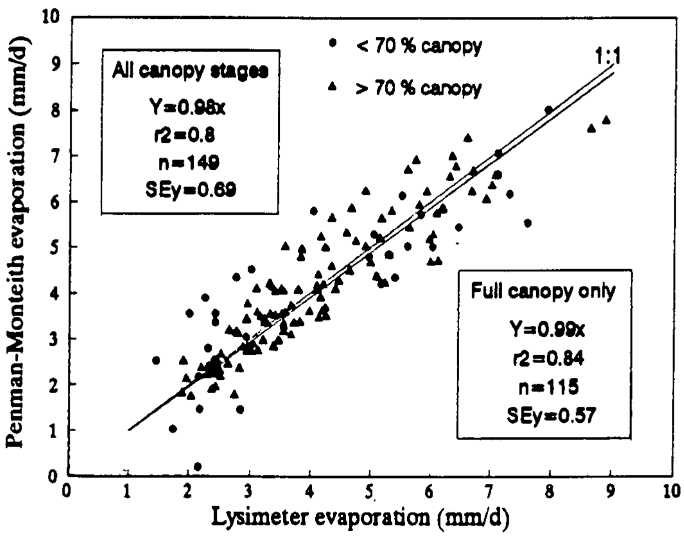

FIGURE 3 Estimated and measured seven day mean evaporation for a plant and two ratoon crops of NCo376 growing in three lysimeters at Pongola.

Methods

Irrigation scheduling pilot project

An unreplicated pilot trial was laid out on nine hectares of land supplied with drip irrigation at Mondi Farm's Northlands Estate, Mkuze. The drip system was flexible enough to allow six different scheduling treatments. Five hectares were planted with varieties N19 and N22 on 13 April 1993 (treatments 1 and 2). Treatments 3, 4, 5 and 6 were planted with N19 on 31 November 1993 on the remaining four hectares. The six treatments were managed as follows:

treatments 1, 2 and 3 – irrigation scheduled with the model and an AWS to replace 45mm of soil moisture when required;

treatment 4 – (control) irrigation scheduled with the pegboard to replace 45 mm of water on a 10 day minimum cycle when a soil water deficit of 45 mm was reached;

treatment 5 – water was applied to replace water used in the past week. CWU estimated using an AWS and the CANEGRO model;

treatment 6 – water scheduled to be applied when the model indicated that cell expansion stress was imminent (SWDF2).

Treatment 4 was chosen as the control. It was felt that this treatment represented the scheduling method most commonly used in the sugar industry at present. Treatments 1, 2 and 3 were selected to evaluate the potential water savings as a result of using the CANEGRO CWU estimate, as op-

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 FIELD    FIELD CAP   TARGET DEF  SW CONT     APPLY     START DATE
            (mm)         (mm)        (mm)      (mm)
---------------------------------------------------------------------
 Trt_1.     539.1       494.1       491.5       45.0        12  1 95
---------------------------------------------------------------------
             DEFICIT (mm) - *               | IRRIG (mm)   - o  RAIN (mm) - +
Yr Mn Dy|  17.  33.  50.  67.  83. 100.|   8.  17.  25.  33.  42.  50.
        |----+----+----+----+----+----+|----+----+----+----+----+----+
94 12 20|      *                        |               o
94 12 21|        *                      |
94 12 22|         *                     |+
94 12 23|         *                     |+
94 12 24|      *                        |        +
94 12 25|        *                      |
94 12 26|  *                            |            +
94 12 27| *                             |   +
94 12 28|  *                            |+
94 12 29|    *                          |
94 12 30|     *                         |
94 12 31|      *                        |+
95  1  1|        *                      |
95  1  2|         *                     |
95  1  3|          *                    |
95  1  4|           *                   |
95  1  5|             *                 |
95  1  6|              *                |
95  1  7|     *                         |                   o
95  1  8|      *                        |
95  1  9|       *                       |
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FIGURE 4 Soil water balance software report.

posed to long term mean pan evaporation values. Treatment 5 was included to represent a conventional drip irrigation system. This treatment also served as a non-stressed control treatment. Treatment 6 was included to test the model's ability to schedule irrigation more efficiently without a loss in yield.

Soil water holding characteristics were determined *in situ* to a depth of two metres. Lower limits of available water were determined during July 1992 following two years of severe drought. The profiles were then wetted to saturation, allowed to drain for 48 hours, and samples taken to determine upper limits. These limits were used as inputs for the soil files required to run the model. At planting, neutron probe access tubes were inserted in each field to monitor the simulated soil water balance. Samples were taken to determine the current water status of each treatment. This water content was used as the starting point for the soil water budget of each treatment.

Wet and dry bulb temperatures, global shortwave radiation, average windspeed and rainfall were recorded hourly using an AWS (MC Systems, Cape Town) situated adjacent to the trial site. On a prescribed day each week these hourly data were transmitted by computer modem to SASEX at Mount Edgecombe. Daily meterological records were calculated from the hourly data and used as inputs for the model.

Computer software capable of dealing with a number of fields was developed to interpret model outputs. A soil water balance was updated daily using calculated CWU, rainfall measured by the AWS and irrigation recorded by the irrigator. A simple report, depicting the current water deficit within each field and the date for the next irrigation, was sent to the irrigator (Figure 4).

Treatments were sampled at harvest to determine cane and sucrose yield. Four 10 m row lengths of sugarcane in each treatment were cut, topped and stacked by estate cane cutters to simulate a commercial operation. Each stack was weighed and the yield/hectare was calculated using the mean of the four rows. A sample of 12 stalks/10 m row length was analysed for sucrose content and quality at SASEX at Mount Edgecombe. In addition, cane consignments harvested from each treatment were loaded separately, weighed at the Umfolozi mill weigh-bridge and their sucrose contents determined at the mill's laboratory.

Pilot project results and discussion

Once initial problems with the water balance software had been solved and the data transfer process perfected, the system operated smoothly. The entire process of data capture, processing and notification of results was accomplished during a five minute telephone call.

Treatments 1 and 2 were harvested on 26 May 1994. Yield results are presented in Table 1. Both treatments yielded approximately 20 tons sucrose/ha/an. However, almost 1 600 mm water (rainfall + irrigation) was received by the crop. This was somewhat higher than was anticipated. Using crop model simulations, Inman-Bamber *et al.*, (1993) reported that, on average, a yield of 20 tons sucrose/ha/an could be achieved at Mkuze with approximately 1 500 mm total precipitation. Excess water was applied during autumn in an attempt to fill the soil profile in anticipation of a water shortage in winter (which did not occur). This decision was made at the end of autumn, taking cognisance of critical water supply levels and the unlikelihood of rainfall during winter.

Treatments 3, 4, 5 and 6 were harvested on 23 November 1994. Yields from treatments 3 to 6 were lower than those from treatments 1 and 2 (Table 2). In late June 1994, at an age of seven months, the crop lodged severely during a storm accompanied by high winds. This probably affected subsequent growth.

Table 1

Yield results for treatments 1 and 2 at Mkuze.

Treatment	Variety	Age at harvest (mth)	Cane yield (t/ha/an)		Sucrose yield (t/ha/an)		Total precip rain + irrig (mm/an)
			SASEX	Mill	SASEX	Mill	
1	N19	13,4	142	160	18,7	21,2	1 590
2	N22	13,4	135	146	18,5	19,6	1 590

Table 2

Yield results for treatments 3, 4, 5 and 6 at Mkuze.

Treatment	Variety	Age at harvest (mth)	Cane yield (t/ha/an)		Sucrose yield (t/ha/an)		Total precip rain + irrig (mm/an)
			SASEX	Mill	SASEX	Mill	
3	N19	11,7	113	110	15,3	14,9	1 394
4	N19	11,4	102	72	13,8	9,6	1 474
5	N19	11,7	114	122	15,6	16,8	1 456
6	N19	11,7	128	121	16,9	16,0	1 323

Treatment 4 (pegboard control) yielded the least cane of the six treatments. The block was made up of cane of different ages which was not separated during harvest. This could account for the large discrepancy between the yield determined from sample weights and that reported by the mill weigh-bridge. Furthermore, the pegboard system was not strictly adhered to and, although this treatment received the highest total application, more water should have been applied.

The yields from treatments 3, 5 and 6 were similar. Treatment 3, which would be used as a scheduling option should this system be implemented on a commercial basis, achieved a yield of 113 tons cane/ha/an with 1 394 mm total precipitation/ha/an. With no loss in cane yield, saving of 71 mm of irrigation water was achieved using the model's estimate of cell expansion stress (SWDF2) as a signal for water application. More water was applied than scheduled, suggesting that larger savings in irrigation water are possible using simulated stress criteria. Using the model's estimate for the onset of photosynthesis stress (SWDF1) as a trigger for water application could offer the option of controlled deficit irrigation. Cane yield would be sacrificed, but sucrose yield would probably not be reduced greatly. Treatment 5, where CWU in one week was replaced during the following week, remained unstressed throughout the crop.

Simulated water content was compared with measured values determined using a neutron moisture meter (CPN, California) for the three treatments scheduled using the model. In all cases the simulated water balance agreed well with measured water content up to the time of lodging. Thereafter the model tended to over-estimate CWU (Figure 5). At present the CANEGRO model does not provide for lodging, and this factor will require attention should this method of scheduling become more widely adopted in the future.

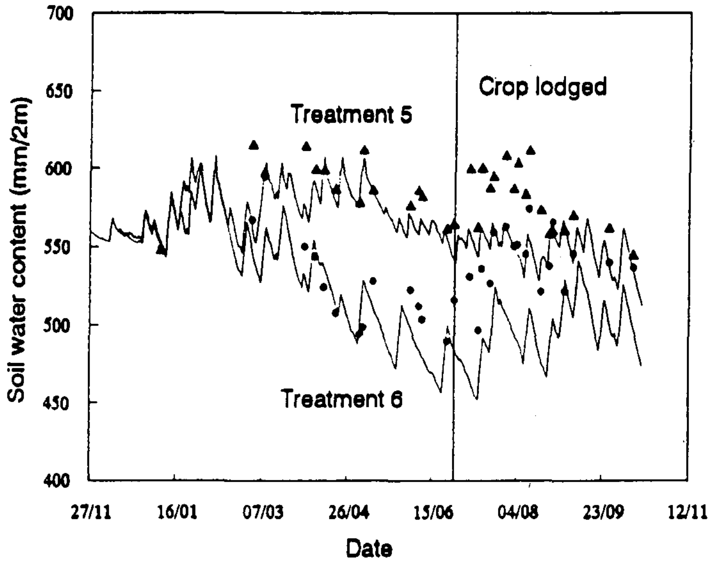

FIGURE 5 Estimated (solid line) and measured (co-ordinates) soil water content of treatments 5 and 6 at Mkuze.

Conclusions

Evaporation from a sugarcane crop was simulated with an acceptable degree of accuracy using the modified Penman-Monteith equation and standard meterological data. The pilot project initiated at Mkuze was used to develop and refine a remote scheduling technique which proved to be both quick and effective. This technique offers growers the opportunity of using advanced scheduling concepts without the need to understand the technicalities of detailed crop evaporation models. Early indications are that significant savings in water and associated pumping costs are possible using this technique. In addition to reducing direct costs of an irrigated enterprise, this scheduling method offers the added benefit of minimising damage to soils as a result of irrigating with poor quality water. There is a need for more conclusive evidence of the benefits of this technology over conventional scheduling methods. To this end, a replicated trial has been initiated at La Mercy on the KwaZulu-Natal North Coast. All the above treatments, including the aforementioned concepts of deficit and near-deficit irrigation, have been included in this trial.

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