ROBUST ESTIMATES OF EVAPOTRANSPIRATION FOR SUGARCANE

M G MCGLINCHEY[1] and N G INMAN-BAMBER[2]

[1]*Swaziland Sugar Association Technical Services, Simunye, Swaziland*
[2]*CSIRO Sustainable Ecosystems, Townsville, Australia*
E-mail: markm@ssa.co.sz

Introduction

In both Australia and Swaziland large areas of sugarcane rely on irrigation to produce a viable crop or to improve rainfed productivity. Matching water supply to crop demand is essential for productivity and sustainability in any irrigation scheme. Historically Class-A pan evaporation was used as a basis for determining sugarcane water demand or evapotranspiration (ETc). ETc is now frequently obtained using simulation models like CANEGRO (McGlinchey and Inman-Bamber, 1996) and APSIM (Keating *et al.*, 1999). Another approach now endorsed by the United Nations Food and Agriculture Organisation (FAO) is to base ET_C on reference evapotranspiration (ET_0) estimated using the Penman-Monteith equation and crop-specific coefficients (Kc) which are used to convert ET_0 to ET_C for a particular crop at a particular stage of development (FAO 56; Allen *et al.*, 1998). Both the CANEGRO and FAO methods utilize the Penman-Monteith equation to estimate atmospheric demand. In Swaziland a sugarcane reference evapotranspiration estimate (ET_{cane}), derived from CANEGRO, is used extensively to schedule irrigation. In contrast the APSIM-Sugarcane model uses a transpiration use efficiency concept (TUE) to estimate ETc from the increment in above-ground biomass and vapour pressure deficit (VPD).

This paper arises from of a collaborative project between the Swaziland Sugar Association Technical Services and CSIRO, Australia to test these mathematical methods for determining ETc against ETc measured using the Bowen Ratio Energy Balance (BREB) technique in two countries using different cultivars. Revisions to the models and to FAO crop coefficients (ETc/ ET_0) could then be advised if necessary.

Keywords: evapotranspiration, crop coefficient, Penman-Monteith, crop model, energy balance

Methods

Instrumentation

ET was measured above well watered sugarcane crops using two similar BREBs, one at Kalamia near Ayr, Australia (19.57°S, 147.4°E) and the other near Simunye, Swaziland (26.20°S and 31.90°E).

In Swaziland a BREB was installed above a mature 3.5 m high crop for a period of 70 days. In Australia a similar system was erected above a young crop (0.3-0.5 m) for the remaining duration of the crop cycle. A brief description of the BREB installed at Kalamia, Australia follows. Differences between this system and the BREB used in Swaziland are highlighted in *italics.*

The BREB (Campbell Scientific Inc, Logan, UT, USA) consisted of a Q7.1 REBS net radiometer, five HFT3 (REBS, Seattle, WA) soil heat flux plates (*four in Swaziland*) and two identical sensor arms each supporting an air intake through a 50 mm diameter, 1.0 µm pore filter and an aspirated fine wire chromel-constantan thermocouple *(in Swaziland the thermocouples were un-aspirated and exposed, Radiation load on 25µm wire is small and equal for both sensors (Tanner, 1979)*). Air was sampled alternately from each arm every 120 s. This air was passed through a chamber, housing a dew point hygrometer (Dew 10, General Eastern Instruments, Woburn, MA, USA). Dew point and air temperature at the arms was measured and logged every 10 s. The net radiometer was installed about 1.0 m above the canopy on a separate mast. The arms and net radiometer were raised each week as the canopy height increased. The lower arm was about 1.5 x canopy height and the upper arm about 1.5 m above the lower arm.

The soil heat flux (SHF) plates were installed at a depth of 80 mm across the 1.5 m distance between two crop rows. Thermocouples were installed at depths of 20 and 60 mm in two positions either side of the central SHF plates. Two frequency domain reflectometers (model CS615, Campbell Scientific Inc) were inserted horizontally in the soil to monitor water content in the 0 to 80 mm layer every 20 minutes. One sensor was in the interrow and the other in the crop row on the same vertical plane as the SHF plates. Heat flux at the soil surface was derived from SHF plates and heat storage in the soil above the plates from specific heat of water and dry soil (4190 and 840 J kg^{-1} $°C^{-1}$, respectively).

Crop evapotranspiration (ET_C) was obtained from latent heat flux (Le) as ET_C= Le/λ, where λ is latent heat of vapourization of water = 2500.9 - $2.373T_1$ (J kg^{-1}) and T_1 is air temperature at height (z_1) of the lower arm. Le was obtained by solving the surface energy balance equation; Rn – G – H – Le = 0 where Rn is net radiation above the crop, G is the soil heat flux density and H is total sensible heat flux density (units are W m^{-2}). Bowen ratio (β) is the ratio of sensible heat flux to latent heat flux (H/Le) and was determined as $\beta = \lambda (T_1-T_2)/(e_1-e_2)$ where e is vapour pressure (kPa) obtained from the Dew 10 and the psychrometric constant (γ) = ρCρ/λε where ρ = air pressure (101.23 kPa), Cρ = specific heat of air at constant pressure (4190 J kg^{-1} K^{-1}) and ε = the ratio of molecular weights of water vapour and air (0.622). Subscripts 1 and 2 refer to lower and upper arms respectively. Soil heat flux (G) was the sum of soil heat flux density at a depth of 80 mm and the heat stored in the 0 to 80 mm soil layer.

Omhura's (1982) criteria for instrument resolution were used to reject arm measurements when necessary and Bowen Ratio (BR) values were interpolated to replace missing 20-minute values. Daily ETc calculations were rejected when more than 30% of the 20-minute intervals between 0600 and 1800 hours readings required interpolation.

At each site an automatic weather station (AWS) was erected 800-1000 m from the BREB system above a well-watered grass surface. Short-wave radiation, temperature, relative humidity, wind speed and rainfall were logged hourly. Daily records required by the models were constructed from these hourly values.

At the Australian site the fraction of intercepted radiation (FIR) was obtained from the ratio of radiation measured above and below the crop canopy with tube solarimeters.

ET estimates

AWS data were used to determine ET_0 from equation 1 (Allen *et. al.*, 1998), where R_n = net radiation at the crop surface (MJ m^{-2} day^{-1}), G = soil heat flux density (MJ m^{-2} day^{-1}), T = air temperature at 2 m height (^oC), u_2 = wind speed at 2 m height ($m.s^{-1}$), VPD = vapour pressure deficit (kPa), Δ = slope vapour pressure curve ($kPa.^oC^{-1}$) and γ = psychrometric constant ($kPa.^oC^{-1}$):

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma \dfrac{900}{T+273} u_2 VPD}{\Delta + \gamma(1 + 0.34u_2)} \qquad (1)$$

An estimate of ET_{cane} was also obtained from the AWS, using a modified two-step approach that was fully described by McGlinchey and Inman-Bamber (1996).

Results and Discussion

Net radiation
Net radiation (Rn) is the most important variable in both the FAO reference ET_0 and in the sugarcane reference ET_{cane}. Rn used to calculate ET_{cane} in Swaziland was estimated using an equation developed by Wright (1982). Empirical constants in the equation were adjusted during initial model development (McGlinchey and Inman-Bamber 1996). This method of estimating Rn and the FAO method were biased in a similar way when compared to measured Rn in Swaziland and Australia. Rn in the ET_{cane} method (Y_1) and measured Rn in Swaziland (X_2) were related as; Y_1=0.70 + 0.80X_1 ± 1.37 MJ d^{-1} m^{-2}, n=36, r^2=0.88. Rn estimated by the FAO method (Y_2) and measured Rn in Swaziland were related as Y_2=3.12 + 0.70X_1 ± 0.98 MJ d^{-1} m^{-2}, n=36, r^2 = 0.92. Rn estimated by the FAO method (Y_2) and measured Rn in Australia (X_3) were related as; Y_2=3.60 + 0.72X_3 ± 1.04 MJ d^{-1} m^{-2} , n=201, r^2 = 0.88. The bias in the FAO estimate of Rn in Swaziland and Australia was nearly identical. It should be emphasized that ET_0 is of interest only for derivation of ETc and errors in estimating Rn be will be incorporated in the crop coefficient (Kc = ETc/ET_0) so that ETc is correct even though ET_0 may be biased. The similarity in the bias in Rn estimate at both sites provides common ground for comparisons between measured ETc and ET_0 in Australia and Swaziland.

FAO crop factor determination
Determination of Kc described in FAO 56 is obtained from measured ETc divided by ET_0. Kc measured in the Australia experiment increased from 0.4 to 1.0 while the FIR increased from about 0.05 to 0.25. Kc varied between 0.5 and 1.5 while FIR increased from 0.5 to 0.8 and then Kc became more stable at about 1.3 (Figure 1). Winds up to 15 m s^{-1} caused some lodging on 19 January but this did not have a major impact on Kc. Mean ET_C for the period when FIR>0.8, was 5.48 ± 0.13 mm and mean ET_0 was 4.44 ± 0.07 mm (n=112). Weighted mean Kc was thus 1.23.

Over the 70 days duration of the Swaziland experiment a total of 30 days were considered useable. Mean ET_C for this period was 5.19 ± 0.26 mm and mean ET_0 was 3.98 ± 0.16 mm and weighted mean Kc_{mid} for this period was thus 1.30. Kc_{mid} varied between a low of 0.91 and a high of 1.54 (Figure 1).

Weighted mean Kc for the two experiments was 1.24. Kc for a closed sugarcane canopy during the grand period of growth (Kc_{mid}) in FAO 56 is 1.25 and is therefore authenticated by these results. It is suggested that canopy closure is essentially complete when FIR>0.8 and that Kc = 1.25 for sugarcane crops in this condition. In FAO 56, Kc for the initial stages of crop development $Kc_{initial}$ (0.4) was equal to the lowest Kc in the Australian experiment. This initial value is therefore also supported by these results. Kc for the final stages of crop development Kc_{fin} (0.7) differed considerably with the Australian results (Figure 1). It is possible that data for FAO Kc_{fin} were based on experiments where drying off was applied although Kc is defined in terms of adequate water, nutrients, disease and pest control (Allen *et al.*, 1998). We suggest that Kc should apply to a crop with adequate water supply throughout its development. An additional coefficient could be invoked to force the crop to use water deeper in the soil profile and to impose some stress which may be necessary to enhance sucrose concentration.

The relationship between daily ET_0 and daily ET_C measured when the canopy was closed (FIR>0.8) in Australia was similar to the relationship between daily ET_0 and daily ET_C measured in Swaziland (Figure 2). Differences in intercept and slope coefficients between sites were not statistically significant. This constitutes a good agreement between two sets of data for determining Kc across different countries. The similarity between Kc_{mid} determined in Australia and Swaziland indicates that crop coefficients derived from these experiments are sufficiently robust to be used across contrasting environments and cultivars.

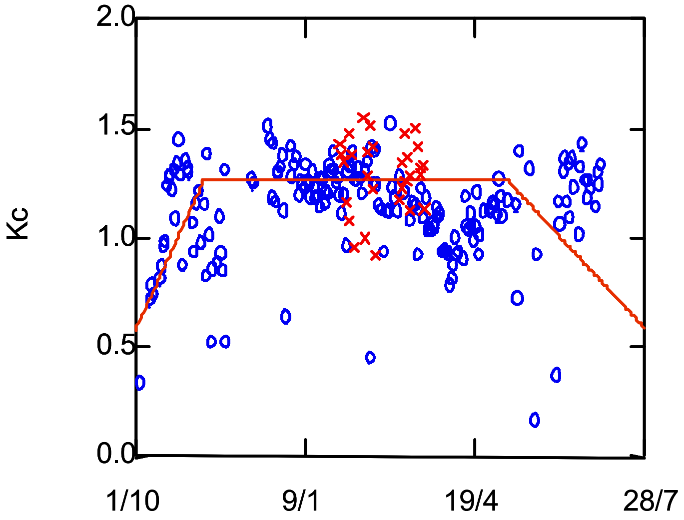

Figure 1. Time course for crop coefficient (Kc) in Australia, 2000/01 (O) and Swaziland, 1999 (X), and Kc from FAO 56 (line).

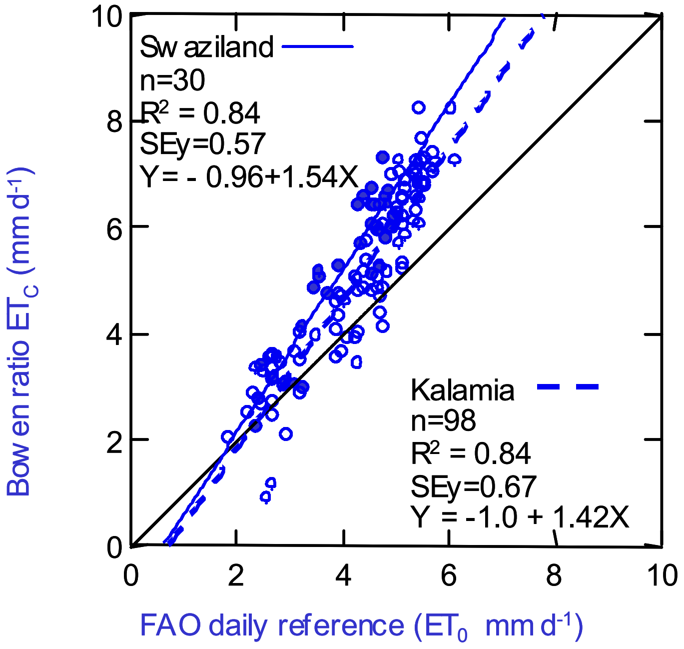

Figure 2. Daily ET_C measured with Bowen ratio in Australia (○) and in Swaziland (●) versus FAO daily reference ET (ET_0). Australian ET_C was with FIR>0.8.

APSIM estimate of ET

The BREB work in Australia was used to calibrate the TUE estimate in the model. The default value of 8.0 g kPa kg^{-1} was increased to 8.7 g kPa kg^{-1} to adequately explain the ETc values measured with the BREB. As an independent validation APSIM was used to estimate cumulative ETc for three weighing lysimeters at Pongola, South Africa (Thompson, 1986). To assess model performance seven-day mean lysimeter evaporation was compared with means estimated by the model. The root mean square error (RMSE) calculated from squared deviations from observed values over the duration of two crops was 1.407 mm.d^{-1} (n = 108). The acceptable simulation of the lysimeter experiment provided independent proof of the validity of TUE = 8.7 g kg^{-1} kPa^{-1} and indirectly of Kc=1.25 for mid and late phases of crop development.

CANEGRO estimate of ET

The ET_{cane} model underestimated ETc measured in Swaziland particularly on days of high evaporative demand. The bias in the comparison was similar to that obtained for the Rn estimate which could account to some extent for the poor performance of the ET_{cane} model during peak demand periods. RMSE (0.72 mm.d)) was of the same order as the validation of ET_{cane} against the Pongola lysimeter data (RMSE = 0.68 mm d^{-1}) reported by McGlinchey and Inman-Bamber (1996) .ET_{cane} totalled 145 mm for the 30 valid days compared with 155 mm measured with BREB during the same period. This 6% error was reduced to 4% (155mm vs 149 mm) when measured Rn was substituted for simulated Rn in the calculation of ET_{cane} (eqs. 1 and 5). This suggests that the remaining bias was inherent elsewhere in the ET_{cane} model.

Conclusions

APSIM-Sugarcane and CANEGRO simulation models were able to simulate ETc with an acceptable degree of accuracy. The results from this collaborative project support the $Kc_{initial}$ (0.4) and the Kc_{mid} values for sugarcane (1.25) published in FAO 56. However there was no evidence to support a reduction in Kc during the final stage of development. The similarity between Kc_{mid} determined in Australia and Swaziland indicates that crop coefficients derived from these experiments are sufficiently robust to be used across contrasting environments and cultivars.

REFERENCES

Allen, RG, Pereira, LS, Raes, D and Smith, M (1998). Crop evapotranspiration - Guidelines for computing crop water requirements. FAO Irrigation and drainage paper 56. FAO, Rome.

Keating, BA, Roberston, MJ, Muchow, RC and Huth, NI (1999). Modelling sugarcane production systems I: Description and validation of the APSIM Sugarcane module. *Field Crops Research* 61: 253-271.

McGlinchey, MG and Inman-Bamber, NG (1996). Predicting sugarcane water use with the Penman-Monteith equation. In: *Evapotranspiration and irrigation scheduling.* Proceedings of the International Conference, November 3-6, 1996, San Antonio. CR Camp, EJ Sadler and RE Yoder (Eds). ASAE, St Joseph Michigan. pp 592-598.

Ohmura, A (1982). Objective criteria for rejecting data for Bowen ratio flux calculations. *J Applied Meteorol* 21: 595-598.

Tanner, CB (1979). Temperature: Critique l. In: *Controlled environment guidelines for plant research*. Proceedings of the Controlled Environments Working Conference held at Madison, Wisconsin, March 12-14, 1979. (Eds) TW Tibbitts and TT Kozlowski. Academic Press 117-130.

Thompson, GD (1986). Agrometeorological and crop measurements in a field of irrigated sugarcane. Mount Edgecombe Research Report No. 5. SASA Experiment Station, Mount Edgecombe, 4300, South Africa. ISBN 0-620-10103-2, pp 244.

Wright, JL (1982). New evaporation crop coefficients. *J Irrig Drain Div, Am Soc Civ Eng* 108(2): 57-74.