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Crop coefficients and water-use estimates for sugarcane based on long-term Bowen ratio energy balance measurements

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Abstract

Sugar industries in Australia and Swaziland rely on irrigation to a large extent (60 and 100%, respectively) to produce a viable crop. Some large irrigation schemes are vulnerable to degradation of ground water quality and it is important to have reliable estimates of water use in order to better calculate runoff and drainage losses from sugarcane fields. It is also important to improve estimates of crop water use in order to improve irrigation design parameters and scheduling. Matching water supply and demand on a daily or weekly basis is essential for productivity and sustainability in any irrigation scheme. The United Nations Food and Agriculture Organisation has recently produced clear guidelines ('FAO 56') on determination of water requirements for a number of crops including sugarcane. Two process-level models, APSIM and CANEGRO are being used to support various decisions regarding the use of irrigation in sugarcane. The aims of this research were to confirm or otherwise refine FAO 56 crop coefficients for sugarcane, to refine simulation of water use in the APSIM-Sugarcane model and to assess the reference evapotranspiration (ET) procedure from the CANEGRO model now used in Swaziland for irrigation scheduling and system design. Bowen ratio energy balance (BREB) systems were installed in the Burdekin district, Australia and in Swaziland to determine daily ET from well-irrigated sugarcane crops. Automatic weather stations were installed within 1 km of the BREB systems in order to determine ET_0 according to FAO 56. Radiation interception and biomass accumulation were measured in the Australian experiment. The results from the two countries provided a sound basis for confirmation of the current FAO 56 crop coefficients for sugarcane during 'initial' (0.4) and 'mid' (1.25) growth phases. The FAO 56 crop coefficient for the 'final' stage (0.7) was not supported. Instead a value of 1.25 is suggested for working out the water balance. However, 0.7 may be desirable for irrigation scheduling in order to impose some stress on the crop and so enhance sucrose content. Transpiration use efficiency for APSIM-Sugarcane was increased from 8.0 to 8.7 g kPa kg^{-1} on the basis of the Australian results. The reference ET procedure was supported equally by the new BREB measurements in Swaziland and by the original lysimeter data but the new data indicated that systematic improvements to the reference procedure could be made.

Keywords: Sugarcane; Evapotranspiration; Crop coefficients; Bowen ratio energy balance; APSIM; CANEGRO; Irrigation management

1. Introduction

Sugarcane is grown under full or supplementary irrigation in many countries including Australia and Swaziland. About 40% of the approximately 500 000 ha under sugarcane in Australia is irrigated

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Nomenclature

a	resolution of vapour pressure measurements (kPa)
b	resolution of temperature measurements (°C)
C_p	specific heat of air at constant pressure (J kg^{-1} K^{-1})
d_r	zero plane displacement of reference surface (m)
e	vapour pressure (kPa)
e_z	vapour pressure at height z (kPa)
E	evaporation from the soil surface (mm per day)
ET_{cane}	sugarcane reference evapotranspiration
ET_C	crop evapotranspiration (mm per day)
ET_0	reference evapotranspiration (mm per day)
G	soil heat flux density (W m^{-2}) or (MJ m^{-2} per day)
H	total sensible heat flux density (W m^{-2})
k	von Karmans' constant = 0.41
K_C	crop coefficient
$K_{C\,end}$	crop coefficient at harvest
$K_{C\,ini}$	crop coefficient at start of crop growth
$K_{C\,mid}$	crop coefficient during mid-growth period
Le	latent heat flux
r_a	aerodynamic resistance (s m^{-1})
r_s	canopy surface resistance (s m^{-1})
R_n	net radiation at the crop surface (MJ m^{-2} per day and W m^{-2})
t	transpiration (kg m^{-2} per day or mm)
T_z	temperature at height z (°C)
u_z	wind speed at height z (m s^{-1})
VPD	vapour pressure deficit (kPa)
w	aboveground biomass (g m^{-2})
z	height above the ground (m)
z_{0r}	roughness length of reference surface (m)

Greek symbols

β	Bowen ratio
γ	psychrometric constant (kPa °C^{-1})
Δ	slope of the vapour pressure curve (kPa °C^{-1})
ε	ratio of molecular weights of water vapour and air
λ	latent heat of vaporisation of water (J kg^{-1})
ρ	air pressure (kPa)

either to supplement rainfall or because irrigation is essential for crop growth, as in the Burdekin, Atherton Tableland and Ord (Western Australia) regions. Irrigation is also essential for the production of a viable sugarcane crop in Swaziland where the climate is semiarid with hot wet summers and cool dry winters. Accurate estimates of crop water use are required to determine irrigation allocations and to improve management of both surface and underground water storages. For example, the delta region of the Burdekin Irrigation scheme and the Ord Irrigation scheme (Australia) are both vulnerable to impacts of irrigation on the water table and it is important to have reliable estimates of water use in order to better calculate runoff and drainage losses from sugarcane fields. It is also important to improve estimates of crop water use in order to improve irrigation system design and scheduling and to ensure that water supply and crop water requirement are well matched on a daily or weekly basis. Matching water supply and demand is essential for productivity and sustainability in any irrigation scheme (Meyer, 1997).

Micrometeorological methods for measuring evapotranspiration (ET) have not been applied widely to sugarcane. Grantz and Meinzer (1991) used Bowen ratio energy balance (BREB) to determine stomatal responses in sugarcane to humidity. Crop evapotranspiration (ET_C) determined from BREB was used to derive stomatal conductance from canopy surface conductance in a study extending over a limited number of days. Denmead et al. (1997) used BREB to assess the effect of a trash mulch on evaporative losses from sugarcane crops in the early stages of development. The longest experiment was 18 days and the results were not compared with other estimates of crop water use. Inman-Bamber and Spillman (2000) demonstrated near closure of the water balance in trickle irrigated field of sugarcane over a period of 6 weeks. Cumulative rain plus irrigation was close to cumulative ET_C determined with BREB, at times when change in soil water content was near zero. Drainage was shown to be minimal while rainfall and consequent runoff were low.

Combined energy balance and aerodynamic approaches have been used to estimate potential ET_C from sugarcane in southern Africa. Thompson (1986) developed coefficients for the Penman–Monteith (PM) equation in order to calculate ET_C of cane in weighing lysimeters. McGlinchey and Inman-Bamber (1996) developed a form of PM equation which allowed for the influence of increasing cane height on aerodynamic resistance and hence on ET_C. This modification to the PM equation led to accurate predictions of ET_C of cane crops growing in Thompson's lysimeters. This approach was later simplified to a reference cane ET (ET_{cane}) in which canopy height was set at 3.0 m and LAI at 3.5. To a large extent, this represents the condition of the irrigated cane crop in South Africa and Swaziland during the most important irrigation period. ET_C of crops in other stages of development was derived from a simple table of factors provided to growers. This approach is being used increasingly to schedule irrigation on a large scale in Swaziland and it is important that the accuracy ET_{cane} be tested in conditions different to those pertaining to the lysimeter experiments.

The PM equation is now regarded by the United Nations Food and Agriculture Organisation (FAO) as the preferred method for determining reference evapotranspiration worldwide (Smith et al., 1996). FAO have recently produced clear guidelines ('FAO 56') on determination of water requirements for a number of crops including sugarcane (Allen et al., 1998). The guidelines make use of reference evapotranspiration (ET_0) determined with the PM equation and crop coefficients which are used to convert ET_0 to ET_C for a particular crop and stage of development. It is necessary for the sugar industry to consider new developments in micrometeorology not only for possible use in scheduling but also to meet demands by the community at large for increased efficiency of water use.

The aim of this research was to confirm or otherwise refine FAO 56 crop coefficients for sugarcane based on BREB measurements in Australia and Swaziland. A second aim was to verify or refine ET_C simulation in the APSIM-Sugarcane model (Keating et al., 1999) and a third aim was to provide an independent assessment for the PM based ET_{cane} approach now used in Swaziland.

2. Methods

2.1. Bowen ratio energy balance (BREB)—Kalamia, Ayr, Australia

BREB installation was initiated on 28 September 2000, in a 10.3 ha commercial block of sugarcane

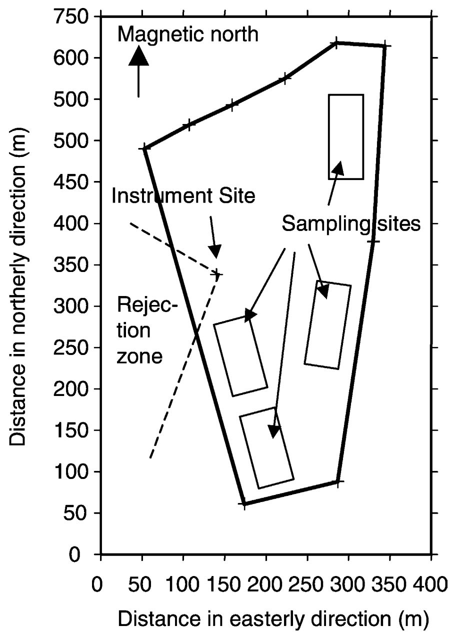

Fig. 1. Scale diagram of the Kalamia experiment, showing fetch rejection zone and destructive sampling sites.

(cv. Q127, first ratoon) at Kalamia estate (19.6°S, 147.4°E), near Ayr in the Burdekin district, northeast Australia. At this stage the crop was 35 days old, 300 mm tall and had about 5% canopy cover. Location of the system was based on wind direction measurements over the previous 12-month period. Wind from an arc of 200–300° occurred only 10.9% of the daytime (0600–1800 h). BREB data were rejected when the wind came from this westerly direction even though the entire region was under irrigated sugarcane at full canopy for most of the duration of the experiment. The minimum fetch was about 75 m at 200° and 300° and the maximum fetch was nearly 350 m in a NE direction (Fig. 1).

The BREB system (Campbell Scientific Inc. (CSI), Logan, UT, USA) consisted of a net radiometer (Q7.1, REBS, Seattle, WA, USA), five soil heat flux plates (HFT3, REBS) 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. A standard arm height was adopted with the lower arm about 1.5 × canopy height and the upper arm about 1.5 m above the lower arm. The maximum canopy height was about 4 m. 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) and dew point was measured at 10 s intervals. The mean dew point temperature for the final 80 s of each sampling period was stored in a 23X data logger (CSI). Air temperature at the arms was also measured and logged every 10 s. The net radiometer was installed about 1 m above the canopy on a separate mast. The arms and net radiometer were raised each week as the canopy height increased. The dew point mirror was cleaned and reset each week.

Substantial changes were made to the factory airflow design for measuring dew point because of leakage and condensation problems encountered during a previous installation of the equipment at this site. All tubing and connectors were replaced and the volume exchangers were replaced and fitted with more robust connections and were mounted outside the logger housing. Tubing to the arms was kept above the canopy to minimise condensation. A heater and thermometer were attached to the Dew 10 mirror block. The logger was programmed to maintain block temperature at 31 °C to reduce condensation. Inspection of data for mirror temperature and temperature inside the logger panel showed that air was saturated sometimes as late as 0900 h and it remained unsaturated and reasonably stable until at least 1600 h unless it rained or a new air mass was encountered. Condensation was sometimes evident before 0900 h but not during the period of high radiation later in the day.

The soil heat flux (SHF) plates were installed at a depth of 80 mm, equidistant across the 1.8 m space between two ridges. Each ridge had two crop rows 0.5 m apart. Thermocouples were installed at depths of 20 and 60 mm in two positions in line with SHF plates 2 and 4. A second new net radiometer (Q7.1) was mounted alongside the first radiometer periodically to check drift in the first instrument. A three-cup anemometer and a wind vane were installed atop the telescopic mast. Readings from all these instruments were averaged or summed at 20 min intervals. Two frequency domain reflectometers (model CS615, CSI) were inserted horizontally in the soil at a depth of 75 mm and were scanned and logged every 20 min.

Crop evapotranspiration (ET_C) was obtained from latent heat flux (Le) as $ET = Le/\lambda$, where λ is the latent heat of vaporisation of water ($\lambda = 2500.9-2.373T_L$ (J kg^{-1})) and T_L is air temperature at the height (z_L) of the lower arm). Le was obtained by solving the surface energy balance equation:

$$R_n - G - H - Le = 0 \quad (1)$$

where R_n is the net radiation at the crop surface, G the soil heat flux density and H is the total sensible heat flux density (W m^{-2}). Bowen ratio (β) is the ratio of sensible heat flux to latent heat flux (H/Le) and was determined as

$$\beta = \gamma \frac{T_L - T_U}{e_L - e_U} \quad (2)$$

where e is the vapour pressure (kPa) obtained from the Dew 10, γ the psychrometric constant ($\gamma = \rho C_p/\lambda\varepsilon$), where ρ is the air pressure (101.23 kPa), C_p the 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) and subscripts L and U refer to lower and upper arms, respectively. Heat flux at the soil surface (G) was derived from SHF plates and change in heat storage in the soil above the plates, using specific heat for water and dry soil (4190 and 840 J kg^{-1} °C^{-1}, respectively). From Eqs. (1) and (2),

$$Le = \frac{R_n - G}{1 + \beta} \quad (3)$$

The acceptance conditions given by Ohmura (1982) were applied to β measurements to screen data for two possible sources of error: (1) around sunset and sunrise, the sensible and latent heat fluxes often become near equal and opposite in direction such that β tends to -1. This results in Le in Eq. (3) approaching infinity. (2) Data were rejected when $T_L - T_R$ and $e_L - e_U$ were less than the resolution of the sensors. Data were rejected if $(T_L - T_U) < [(e_L - e_U)/\gamma] - [2a/\gamma + b]$ or $(T_L - T_U) > [(e_L - e_U)/\gamma] + [2a/\gamma + b]$, where a is the resolution of vapour pressure measurements (0.01 kPa) and b is the resolution of temperature measurements (0.006 °C). Data were also rejected if $-0.01 < (e_L - e_U) < 0.01$.

The rejection rate for night time readings (1920–0540 h) was 69% compared to 22% for daytime readings. When Le could be measured at night, it was negligible so readings only between 0600 and 1900 inclusive were used to determine ET_C. Missing values were replaced with interpolated values in order to obtain a complete set of 20 min readings during the day (0600–1900 h) provided at least 28 (70%) of the possible 40 readings were valid. If not, daily total ET_C was deemed missing. ET_C was valid for 193 of the 290 days when the BREB was operating at Kalamia. Acceptance rate exceeded 80% for 129 days and it exceeded 90% for 42 days.

2.2. Tube solarimeters—Kalamia

On 22 October 2000, four recently calibrated tube solarimeters (1 m long) were placed on the soil surface in two places near the BREB installation, to span the dual crop row configuration exactly. Two more tube solarimeters were mounted above the canopy so that fraction of intercepted radiation could be determined. Mean voltage from the solarimeters was logged at 20 min intervals.

2.3. Bowen ratio energy balance (BREB)—Simunye, Swaziland

The BREB system (CSI) at Simunye was similar to the system installed at Kalamia, Australia. The main differences were that the airflow system and heating arrangement for the dew point hygrometer were not modified and the fine wire thermocouples were not aspirated. The BREB system was erected over a 3 m high, erect, fully canopied sugarcane crop, variety NCo376, near Simunye, Swaziland (26.2°S and 31.9°E) for a period of 70 days. Two 9 m masts were erected in the middle of an 80 ha commercial field to maximise fetch in any direction. Distance to the nearest field edge was 400 m and there was no need to discard data on the basis of wind direction as was the case at Kalamia. The arms were raised regularly to position the thermocouples and air intakes at 2 and 4 m above the crop canopy. Net radiation was measured using a REBS Q7.1 net radiometer positioned 2 m above the crop surface on the second mast. Soil heat flux was measured using four REBS soil heat flux plates placed 50 mm below the soil surface and spaced evenly across the inter-row. The soil storage energy term above the plates was estimated from average soil temperature in the top 50 mm soil layer and soil water content in this layer measured using a single calibrated CS615 soil water sensor (CSI).

Invalid data were rejected using the criteria suggested by Ohmura (1982) as in the Kalamia experiment. Latent heat flux was calculated at 20 min intervals using valid measurements and summed over the day between 0600 and 1900 h. Where less than three consecutive measurements were rejected, latent heat flux was estimated by interpolation between valid measurements. Generally this was only necessary during the early morning and late afternoon when sensible and latent heat fluxes were either small or changed direction.

2.4. Automatic weather stations and ET calculations

On 17 September 1998, a purpose built (CSI) automatic weather station (AWS) was installed in an open grassed area about 1 km from the BREB system at Kalamia. The AWS consisted of a tipping bucket rain gauge (T.B.3; Hydrological Services, Warwick Farm, Australia) an anemometer (RM Young Co., Traverse City, MI, USA), a pyranometer (Li 200×, Licor Inc., Lincoln, NE, USA) and a combined temperature and humidity sensor (HMP45ac, Vaisala, Helsinki, Finland). The 50 m × 50 m area around the AWS was mown and irrigated frequently. At Simunye a similar model AWS was positioned 800 m from the BREB site over a well-watered grass sward 50 m × 35 m in size. The instruments were identical to those installed at the Kalamia site with the exception of the tipping bucket raingauge which was manufactured by Texas Weather Instruments (Dallas, TX). All data were logged hourly.

AWS data were used to determine daily reference evapotranspiration (ET_0) from Eq. (4) (Allen et al., 1998, 'FAO 56'), where R_n is the net radiation at the crop surface (MJ m^{-2} per day), G the soil heat flux density (MJ m^{-2} per day), T the air temperature (°C) at 2 m height, u_1 the wind speed at 2 m height (m s^{-1}), VPD the vapour pressure deficit (kPa), Δ the slope of the vapour pressure curve (kPa °C^{-1}) at T and γ the psychrometric constant (kPa °C^{-1}).

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma(900/(T+273))u_1\,\mathrm{VPD}}{\Delta + \gamma(1 + 0.34u_1)} \qquad (4)$$

An estimate of ET_{cane} was also obtained from the AWS, using a modified two step approach in which ET could be subject to changing canopy height and leaf area index. This required ET to be referenced well above possible canopy height as described by McGlinchey and Inman-Bamber (1996). A brief description follows. During the first step ET_0 was calculated using Eq. (4). The latent and sensible heat components and appropriate profile equations (Eqs. (5)–(7)) of Monteith and Unsworth (1990) were used to estimate temperature, vapour pressure and wind speed at a new reference height of 10 m:

$$u_2 = u_1 + \frac{\ln((z_2 - d_r)/z_{0r})}{\ln((z_1 - d_r)/z_{0r})} \tag{5}$$

$$e_2 = e_1 + \frac{\gamma \mathrm{ET}_0(\ln((z_2 - d_r)/(z_1 - d_r)))^2}{C_p(u_1 - u_2)k^2} \tag{6}$$

$$T_2 = T_1 + \frac{H(\ln((z_2 - d_r)/(z_1 - d_r)))^2}{C_p(u_1 - u_2)k^2} \tag{7}$$

where u_1 and u_2 is the wind speed at 2 and 10 m (m s^{-1}), e_1 and e_2 the vapour pressure at 2 and 10 m (kPa), T_1 and T_2 the temperature at 2 and 10 m (°C), z_1 and z_2 the heights 2 and 10 m above the ground, d_r the zero plane displacement of reference surface = 0.07 m, z_{0r} the roughness length of reference surface = 0.013 m, and k the von Karmans' constant = 0.41.

ET_{cane} is defined for a crop that is 3.0 m high as was the case for the crop in BREB experiment at Simunye. ET_{cane} was derived using Eq. (8) and the estimated vapour pressure deficit at the new 10 m reference height (VPD_2). To comply with the definition of a sugarcane reference, crop height was fixed at 3.0 m during the calculation of the aerodynamic resistance (r_a) component and surface resistance (r_s) was set at 40 s m^{-1} (McGlinchey and Inman-Bamber, 1996).

$$\mathrm{ET}_{\mathrm{cane}} = \frac{\Delta(R_n - G) + \rho C_p \mathrm{VPD}_2/r_a}{\Delta + \gamma(1 + r_s/r_a)} \tag{8}$$

2.5. Net radiation

The BREB system used at Kalamia was previously installed at a site at Millaroo about 60 km inland from Kalamia (Inman-Bamber and Spillman, 2000). Readings from this net radiometer at Millaroo and later at Kalamia and the net radiometer at Simunye were compared to assess the method in FAO 56 for estimating net radiation from solar radiation, T_1, e_1 and clear sky radiation.

2.6. Irrigation

At the Kalamia site furrow irrigation was scheduled by an experienced grower using the mini-pan method of Shannon and Holden (1996). Inflow and outflow measurements made by Charlesworth (pers. commun.) provided information on infiltration for each irrigation. In the Simunye experiment irrigation was applied on the soil surface using drip irrigation tape laid between each crop row. Irrigation was scheduled on a daily basis using a soil water balance approach in line with current estate practice at Simunye.

2.7. Crop biomass

Total aboveground biomass was determined on seven occasions during the development of the crop at Kalamia. Four sampling sites were demarcated as in Fig. 1. All plant material was removed from one 18 m^2 quadrat in each sampling site on each occasion. This material was weighed. A subsample of stalks was also weighed and then partitioned into green leaf, sheath plus immature stem, mature stem and dead leaf components. A subsample of each of these components was weighed and then dried to constant mass in a forced draught oven set at 80 °C.

2.8. APSIM simulation of Kalamia experiment

Daily radiation, temperature and rainfall from the AWS at Kalamia provided climatic data for simulation of the crop in the BREB experiment at Kalamia using the APSIM-Sugarcane model (Keating et al., 1999). The soil (clay to 1 m over sand) was similar to that described by Inman-Bamber and Spillman (2000) except that the clay layer was 1.0 m rather than 0.4 m. Soil hydraulic properties for input to the model were adjusted accordingly. Irrigation and rainfall was such that very little stress was simulated thus reducing the impact of errors in soil hydraulic values. Genetic coefficients for cultivar Q96 were used because those for cultivar Q172 in the experiment have not yet been documented. In APSIM-Sugarcane, genetic coefficients affect only canopy development, phenology and dry matter partitioning (Keating et al., 1999).

2.9. APSIM simulation of lysimeter experiments by Thompson (1986)

Thompson (1986) reported lysimeter experiments with sugarcane (cv. NCo376) in sufficient detail to allow simulation of his experiments with APSIM-Sugarcane. The experiment involved a plant and a first ratoon crop growing in three weighing lysimeters, 1.22 m deep and 2.44 m × 1.22 m at the surface. Irrigation was applied to minimise water deficits and ET_C was measured daily. Soil input data for the simulation was modified from Robertson et al. (1997) to cater for the limited depth of the lysimeters. Genetic coefficients for the cultivar NCo376 were supplied with the APSIM software.

3. Results

3.1. Weather and irrigation

Maximum temperatures at Kalamia were less variable than those at Simunye for the same period of the year (Fig. 2a). This was due to some low maximum temperatures at Simunye during the summer months rather than differences in higher values which were about 33 °C in both localities. Minimum temperatures were lower at Simunye than at Kalamia for the comparable period. During autumn and winter at Kalamia, minimum temperature decreased more than maximum temperature and there were several nights when minimum temperature dropped below 10 °C. The range in radiation was similar in the two locations but the range in ET_0 was lower at Simunye (Fig. 2b and c). This was due to greater wind speed at Kalamia (187 km per day) than at Simunye (129 km per day) as well as lower minimum relative humidity at Kalamia (43%) than at Simunye (59%) over the comparable period (31 January–21 March). Daily rainfall was considerably greater at Kalamia than at Simunye, however rainfall at Kalamia after mid-January was infrequent and irrigation had to be applied regularly (Fig. 2d). Irrigation was required at Simunye only towards the end of the experiment.

3.2. Net radiation

Net radiation (R_n) is an important variable in both FAO reference ET_0 and in sugarcane reference ET_{cane}. At Kalamia and Millaroo the R_n estimate in FAO 56 was biased in a similar way but the random (unsystematic) error at Millaroo was small compared to that at Kalamia (Fig. 3). R_n used to calculate ET_{cane} at Simunye 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). R_n estimated with this method was similar to R_n estimated using the FAO 56 approach, however both underestimated measured R_n at Simunye. The bias was similar to that obtained at the Kalamia and Millaroo sites. The reliability of the R_n estimate at a particular site affects ET_0 to a varying extent depending on the relative sizes of the energy and aerodynamic components of the PM. It should be emphasised that ET_0 is a reference for comparison with crop ET (ET_C) and errors in estimating R_n only affect the comparison between ET_C and ET_0 not ET_C itself (Allen et al., 1998). The similarity in the bias in R_n estimate at all sites provides common ground for comparisons between measured ET_C and ET_0 in Australia and Swaziland.

3.3. Canopy radiation interception

Canopy development at Kalamia was reflected in measurements of the fraction of intercepted radiation (FIR). Simulated FIR was lower than measured FIR when this was less than 0.7. Simulated FIR was greater than measured FIR when this was between 0.7 and 0.9 and then measured FIR rose to 1.0 while simulated FIR remained at about 0.9 (Fig. 4). The crossover between measured and simulated FIR occurred when solar radiation (Fig. 2b1) changed from the lowest to highest levels recorded during the experiment. APSIM-Sugarcane does not account for the effect of diffuse light on radiation interception which would have been greater than simulated interception during cloudy weather in November (Fig. 2b1). There was a rapid increase in measured FIR when the crop started to lodge after a storm on 19 January but this was not reflected in the simulation.

The Simunye experiment was designed to measure evapotranspiration during the fully canopied period only.

3.4. Crop coefficient (K_C)

Determination of K_C described in FAO 56 is in relation to crop development and is obtained from

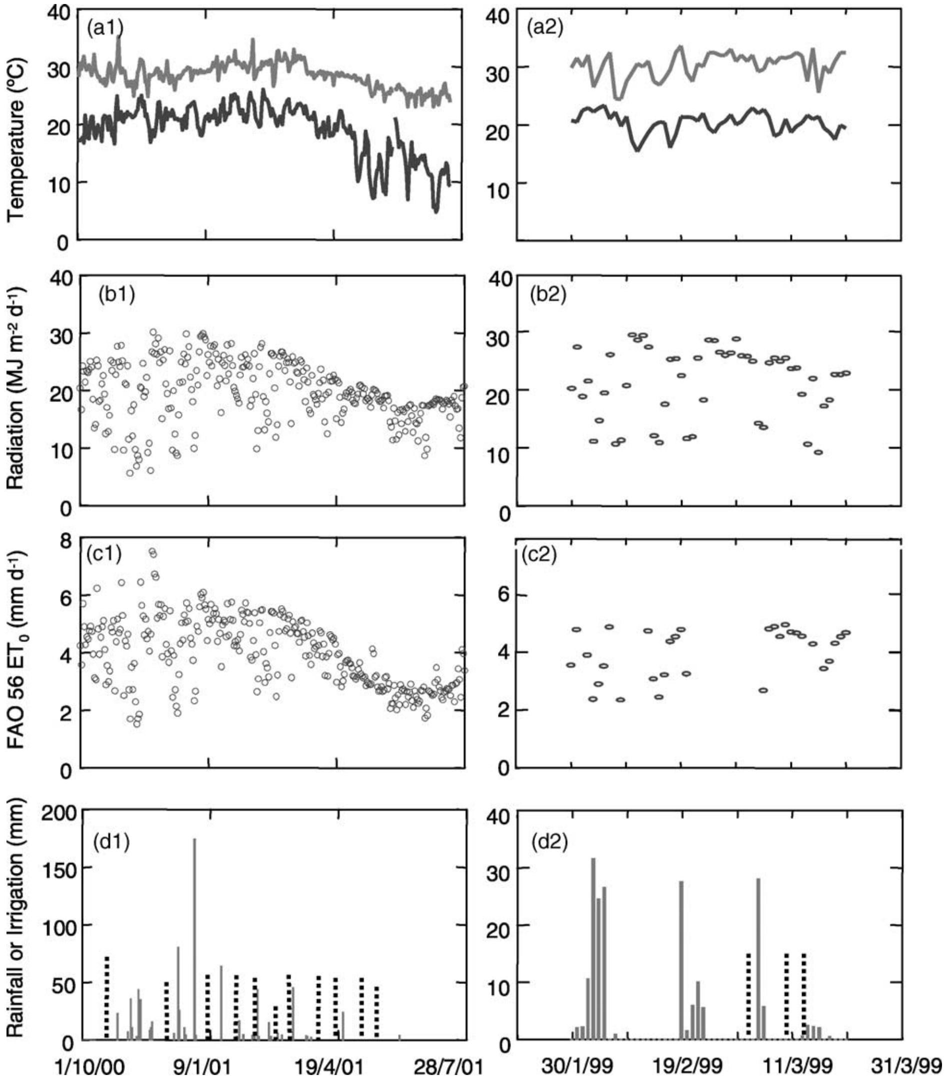

Fig. 2. Daily climate and irrigation at Kalamia (1) and Swaziland (2). Maximum and minimum temperature (a1, a2), radiation (b1, b2), FAO reference evapotranspiration, ET_0 (c1, c2), rainfall (solid bars) and irrigation (broken bars) (d1, d2). Note different scales in d1 and d2.

$K_C = ET_C/ET_0$. K_C measured in the Kalamia experiment increased from 0.4 to 1.0 (Fig. 5) while the fraction of intercepted radiation (FIR) increased from about 0.05–0.25. Then K_C rose sharply to 1.4 after rain on 30 October 2000 and remained at about this value for 8 of the following 12 days while FIR was <0.5 (Fig. 4). K_C varied between 0.5 and 1.5 while FIR increased from 0.5 to 0.8 and then K_C became more stable at about 1.3 declining slowly to about 1.1 prior to irrigation on 19 April which may have relieved a period of mild water deficit stress (Fig. 2d1). Winds up to 15 m s^{-1} caused some lodging on 19 January but this did not have a major impact on K_C. 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 ($n = 112$). Mean K_C was thus 1.23.

Over the 70 days duration of the Simunye experiment a total of 30 days were considered useable in the light of rejection criteria discussed previously. Mean ET_C for this period was 5.19 ± 0.26 mm and mean ET_0 was 3.98 ± 0.16 mm and mean $K_{C\,mid}$ for this period was thus 1.30. $K_{C\,mid}$ varied between a low of

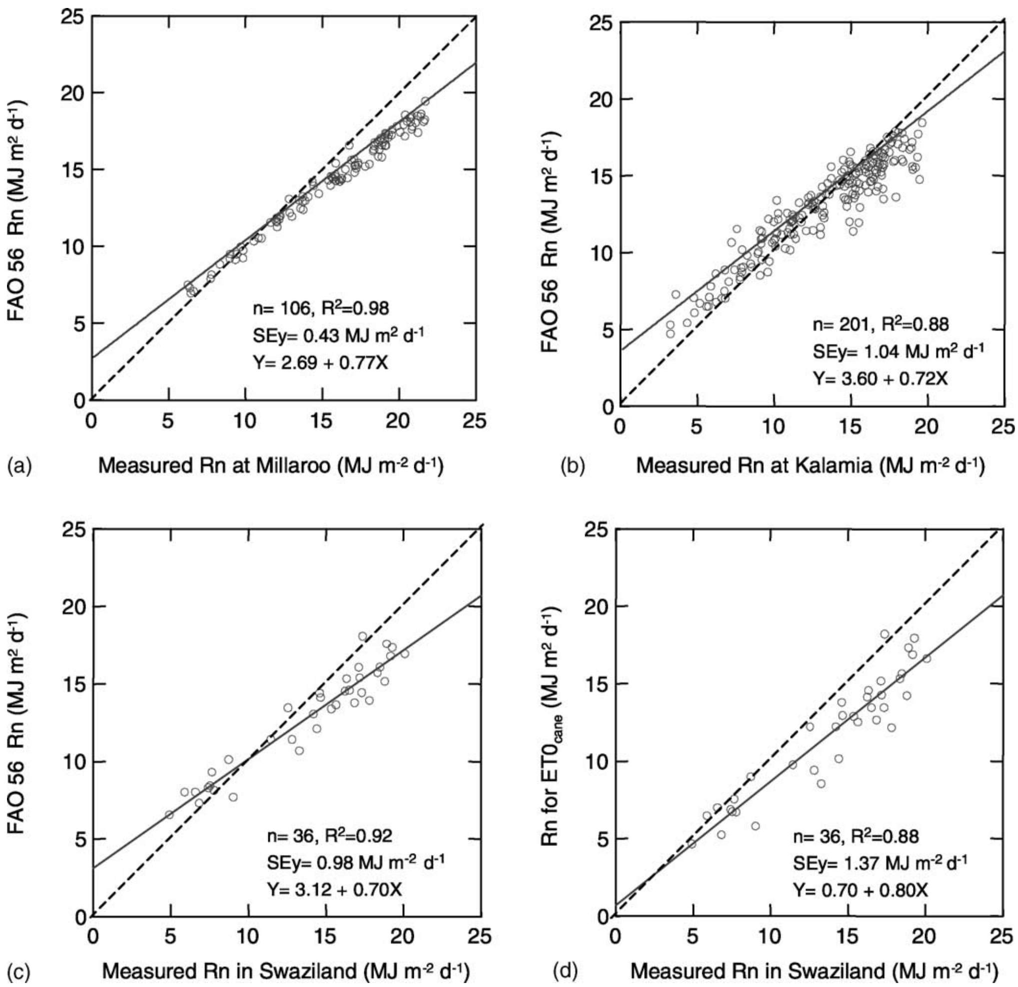

Fig. 3. Net radiation (R_n) estimated from FAO 56 daily time step equations and measured net radiation at Millaroo (a), Kalamia (b) and Swaziland (c). R_n used for calculating ET_{cane} (McGlinchey and Inman-Bamber, 1996) and R_n measured in Swaziland (d). Values are for 24 h periods each day.

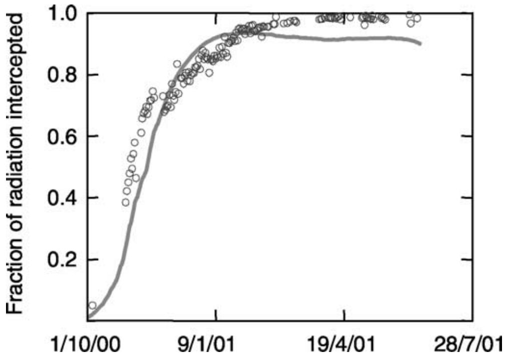

Fig. 4. Time course at Kalamia of measured (○) and simulated (—) fraction intercepted radiation (FIR).

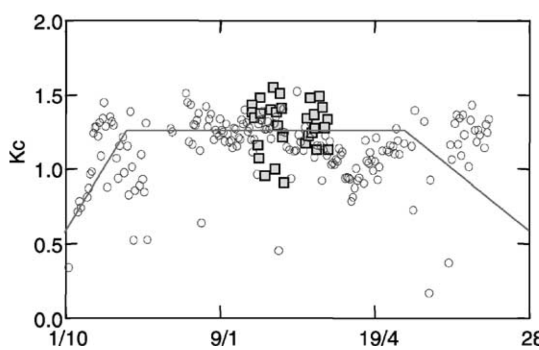

Fig. 5. Time course for crop coefficient (K_C) at Kalamia, 2000/2001 (○) and Swaziland, 1999 (□), and K_C from FAO 56 (—).

0.91 and a high of 1.54 (Fig. 5). These lower values occurred during the first half of the measurement period when evapotranspiration was low due to overcast conditions on some days (Fig. 2b2 and c2).

Mean K_C for the two experiments weighted for number of valid readings during the closed canopy period, was 1.24. K_C for a closed sugarcane canopy ($K_{C\,mid}$) in FAO 56 is 1.25 and is therefore validated by these results. It is suggested that canopy closure is essentially complete when FIR > 0.8 and that $K_C = 1.25$ for sugarcane crops in this condition. In FAO 56, K_C for the initial stages of crop development $K_{C\,ini}$ (0.4) was equal to the lowest K_C in the Kalamia experiment. This initial value is therefore also supported by these results. K_C for the final stages of crop development $K_{C\,end}$ (0.7) differed considerably with the Kalamia results (Fig. 5). It is possible that data for FAO $K_{C\,end}$ were based on experiments where drying off was more severe than in the Kalamia experiment. There is no reference to supporting data in FAO 56. We suggest that K_C should apply to a crop with adequate water supply throughout its development. This would ensure consistency in FAO 56 which defines K_C in terms of adequate water, nutrients, disease and pest control (Allen et al., 1998). An additional coefficient (0.7) could be invoked when scheduling irrigation in the later stages of crop development to force the crop to use water deeper in the soil profile and to impose some degree of water stress which may be necessary to enhance sucrose concentration (Robertson et al., 1999).

The relationship between daily ET_0 and daily ET_C measured when canopy was closed (FIR > 0.8 at Kalamia) was similar to the relationship between daily ET_0 and daily ET_C measured at Simunye (Fig. 6). Differences between intercept and slope coefficients were not statistically significant. This constitutes good agreement between two sets of data for determining K_C across different countries. The similarity between $K_{C\,mid}$ determined in Australia and Swaziland indicates that crop coefficients derived from these experiments are sufficiently robust to be used across contrasting environments and cultivars.

3.5. ET_C, APSIM and transpiration use efficiency (TUE)

APSIM-Sugarcane partitions ET_C between evaporation from the soil surface (E) and transpiration

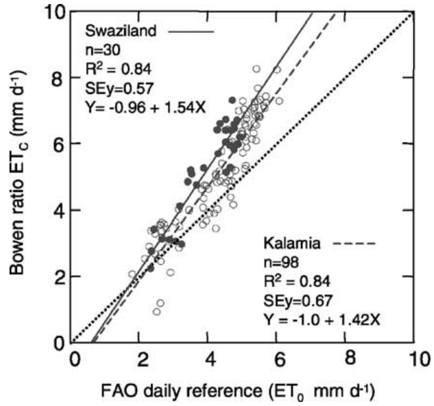

Fig. 6. Daily ET_C measured with Bowen ratio at Kalamia (○) and in Swaziland (●) vs. FAO daily reference ET (ET_0). Kalamia ET_C was with FIR > 0.8.

(t) on the basis of FIR and thus inaccuracies in simulating FIR simulation will lead to inaccuracies in this partitioning. ET_0 was of course much reduced during periods of low radiation (Fig. 2c) and errors in partitioning E and t would have reduced impact on cumulative E and t during these periods.

In APSIM-Sugarcane, t is proportional to the increment in aboveground biomass (w) when soil water is not limiting (Eq. (9)).

$$\Delta t = \frac{\Delta w \, \mathrm{VPD}}{\mathrm{TUE}} \tag{9}$$

where TUE is the transpiration use efficiency and VPD is the vapour pressure deficit derived from the difference in saturation vapour pressure at maximum and minimum temperature. The model simulated Δw accurately between samplings 1 and 4 and between samplings 5 and 6 (Fig. 7). Low Δw between samplings 4 and 5 corresponded with the period of reduced K_C (Fig. 5).

The default value of TUE in APSIM is 8.0 g kPa kg^{-1} obtained by calibration to datasets exhibiting water deficits (Keating et al., 1999). The satisfactory simulation of Δw and FIR between samplings 1 and 4 provided an opportunity to determine TUE directly provided the estimated partitioning between E and t during this period was accurate. While it is not possible to prove the accuracy of this estimate it is reasonable to assume that the error would be similar to the error in predicting FIR which was 10% at most (Fig. 4). Thus, t could be derived from the

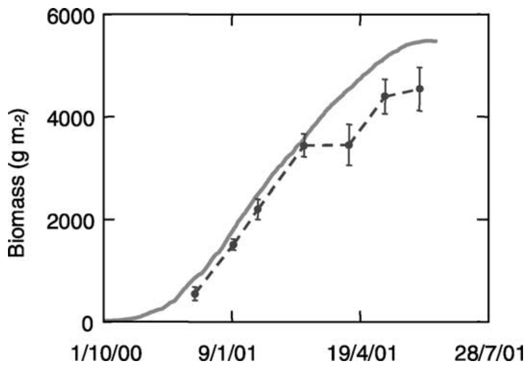

Fig. 7. Time course at Kalamia of aboveground total biomass measured (– – –) and simulated with transpiration use efficiency (TUE) = 8.0 g kPa kg^{-1} (—). Bars are standard errors of the mean.

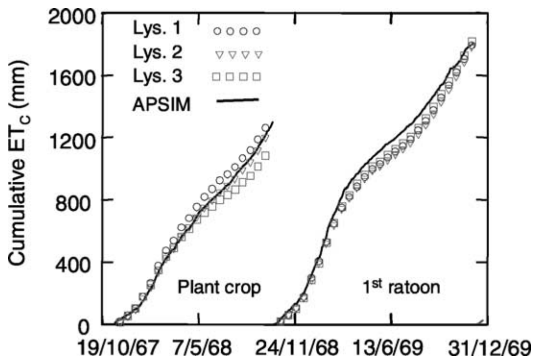

Fig. 8. Cumulative evapotranspiration (ET) from three weighing lysimeters (Thompson, 1986) and simulated ET using the APSIM-Sugarcane model with revised transpiration use efficiency (TUE = 8.7 g kPa kg^{-1}).

product of measured ET_C and simulated partitioning fraction (t/ET). Regression of cumulative t over the period of samplings 1–4 yielded a slope coefficient of 4.88 ± 0.023 mm per day (or kg m^{-2} per day). Regression of measured biomass (w) on time (days) yielded a slope coefficient of 34.1 ± 2.15 g m^{-2} per day. Mean VPD for this period, calculated by APSIM as 0.75 times the difference in saturation vapour pressure between maximum and minimum temperature, was 1.24 ± 0.028 kPa. From Eq. (9), TUE then becomes 8.7 g kPa kg^{-1}. Difficulties in predicting and averaging VPD obviously affected calculation of TUE. For the period between samplings 1 and 4, mean VPD derived from APSIM was similar to mean VPD measured by the BREB system between 0600 and 1900 h (1.22 ± 0.032 kPa). These difficulties were fully discussed by Tanner and Sinclair (1983).

As far as is known this is the first time that TUE has been derived independently for sugarcane from simultaneous measurements of ET_C and Δw. The fact that the measured value is close to the original approximation lends credence to the work of Keating et al. (1999) who found good agreement between simulated biomass, LAI and sucrose yield for a large number of experimental crops across several countries.

3.6. APSIM ET_C and lysimeter evapotranspiration

With the new TUE coefficient in APSIM, the simulation of cumulative ET_C of lysimeter 2 for the plant crop was almost exact (Fig. 8). Cumulative ET_C of the other two lysimeters was slightly above and below that of lysimeter 2. In the ratoon crop the agreement between lysimeters was good. Simulated cumulative ET_C was similar to measured cumulative ET_C until the summer of 1968/1969 when the simulated values increased more rapidly than measured. Simulated and measured mean cumulative ET_C differed by 108 mm at most in mid 1969. At the end of the first ratoon crop the difference between simulated and measured cumulative ET_C was negligible (Fig. 8).

The acceptable simulation of the lysimeter experiment provided independent proof of the validity of TUE = 8.7 g kPa kg^{-1} and indirectly of $K_C = 1.25$ for mid and late phases of crop development.

3.7. Sugarcane reference ET (ET_{cane}) and measured ET_C

The ET_{cane} model overestimated ET_C when $ET_C < 4.0$ mm per day and it underestimated ET_C when $ET_C > 6.0$ mm per day (Fig. 9). The intercept was significantly different from zero ($P < 0.01$) and the 95% confidence intervals for the slope excluded 1.0 thus the bias was real. The low regression coefficient was partly due to similar bias in the estimation of R_n (Fig. 3d). ET_C measured with BREB totalled 155 mm for the 30 days when readings were valid compared with a total of 145 mm for ET_{cane} for the same days. This 6% error was only reduced by 2% (155 versus 149 mm) when measured R_n was substituted for simulated R_n in the calculation of ET_{cane} (Eqs. (4) and (8)).

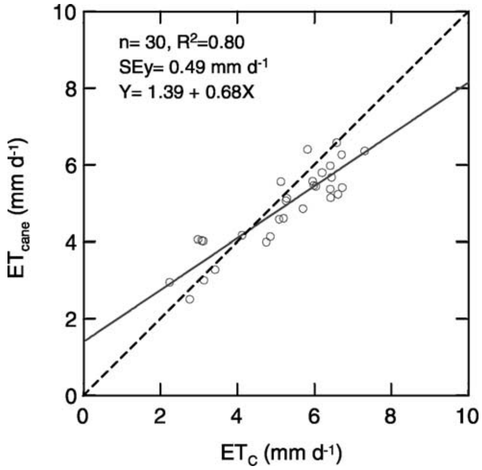

Fig. 9. Sugarcane reference ET (ET_{cane}) and measured ET_C in Swaziland.

The root mean square error (RMSE) calculated from squared deviations from observed values (0.72 mm per day), was of the same order as the validation of ET_{cane} against the Pongola lysimeter data (RMSE = 0.68 mm per day) reported by McGlinchey and Inman-Bamber (1996). However, the systematic error (0.36 mm per day) was twice the systematic error for the lysimeter data (0.18 mm per day). ET_{cane} is therefore supported equally by the new BREB ET_C measurements at Simunye and by the Pongola lysimeter data but the BREB ET_C data indicate that systematic improvements to the ET_{cane} model are possible. A change in reference components of bulk canopy resistance or canopy height could be considered.

4. Discussion

BREB measurements in two countries have provided a sound basis for determining the crop coefficient for sugarcane during the middle period of development ($K_{C\,mid}$) as presented in FAO 56 (Allen et al., 1998). Canopy development of sugarcane in these two countries and many others is relatively short-lived hence the emphasis on the mid and final stages in this research. ET_C measurements at Kalamia started during the 'development' phase when as little as 5% of incident solar radiation was intercepted by canopy. There was good agreement between measured K_C and K_C determined from FAO 56 while FAO 56 K_C was less than 0.8 (Fig. 5). This was calculated following the rules in FAO 56 with $K_{C\,ini} = 0.4$ and $K_{C\,mid} = 1.25$. Thus, $K_{C\,ini} = 0.4$ is appropriate. Measured K_C varied substantially when FAO $K_C > 0.8$ until the canopy was essentially complete and intercepting >80% of radiation. This variation was consistent with the variation in $K_{C\,ini}$ in FAO 56 in relation to varying soil wetness and reference evapotranspiration (Allen et al., 1998).

The support for $K_{C\,mid}$ of 1.25 is substantial. We have pointed out difficulties in estimating net radiation for ET_0 calculations that will affect $K_{C\,mid}$ which can also be altered by wind and humidity even though these are taken into account in the ET_0 calculation (Eq. (4)). Allen et al. (1998) provided equations to account for humidity and wind and when this was done for the Kalamia experiment $K_{C\,mid}$ was reduced to 1.1 at times when humidity was high and wind speed low (data not presented).

It is suggested that for irrigation of sugarcane in the east coast of Australia and in Swaziland that the use of $K_{C\,mid} = 1.25$ for irrigation scheduling will result in adequate water supply to the crop with little wastage and there is little need to consider fine adjustments to K_C to account for the foregoing concerns. It is arguable that lower values could be tried at least in some soils where large soil water deficits may not result in yield reductions. Deficits up to 120 mm had no impact on cane yield or sucrose content in irrigation experiments in the Ord irrigation scheme in Western Australia (Muchow et al., 2001).

An important finding in this research is that there is no justification for reducing K_C during the final stages of crop development even if lodging occurs as was the case in the Kalamia experiment. It is possible that K_C would change if flowering occurred however. Growers need to reduce or cease irrigation during this phase (drying off) in order to improve sucrose content (Robertson et al., 1999) but there is no evidence that the demand for water is in fact reduced. Guidelines for drying off could be developed in terms of an additional factor to ensure that the crop experiences enough stress to enhance sucrose content but not so much stress that sucrose yield is reduced. More work is required to determine if this factor is in the order of 0.7 or some other value.

The research discussed thus far is of value to irrigation schemes with access to FAO 56 technology supported by a good weather station network. Cropping system models for sugarcane are now available (O'Leary, 2000) and these account for leaf area development and soil wetness during the complex partial canopy period. In many situations it would be better to use these models which not only deal with complex surface conditions but with rainfall and the water balance in general. The approach to ET estimation in the APSIM model is taken from one of the simpler approaches involving a transpiration use efficiency (TUE) concept proposed by Tanner and Sinclair (1983). Only daily radiation, maximum and minimum temperatures are required for this. The Kalamia experiment provided data to determine TUE of sugarcane for the first time. TUE $= 8.0$ g kPa kg^{-1}, originally assumed for sugarcane in APSIM (Keating et al., 1999) was not greatly different from TUE $=$ 8.7 g kPa kg^{-1} found in the Kalamia experiment. The range in TUE for maize was 8.2–12.0 g kPa kg^{-1} with mean $= 9.5$ g kPa kg^{-1} (Tanner and Sinclair, 1983), thus sugarcane may be inherently less efficient than maize in the use of water. The new value for TUE gave close agreement between simulated cumulative ET_C and measured cumulative ET_C in lysimeter experiments in South Africa (Thompson, 1986). There is therefore a sound basis for using APSIM with the new TUE to estimate crop water use on a seasonal basis. The ET algorithms in the APSIM model are probably too simplistic for a reliable daily estimate of ET_C. The RMSE (deviations from observed values) of the APSIM estimate of daily ET_C measured in the Kalamia experiment, was 1.3 mm or 34% of mean ET_C which is unacceptable. RMSE of weekly mean ET_C was 0.64 mm which is probably acceptable for weekly irrigation schedules. It is evident from Eqs. (4) and (9) that APSIMs ET_C estimate could be excessive in more arid conditions where VPD may be several times greater than VPDs measured at Kalamia. We recommend that FAO ET_C and APSIM ET_C be compared when using the ASPSIM model in arid climates. Care should also be taken to check that APSIM's estimate of VPD is accurate as was the case in the Kalamia experiment.

The Swaziland ET_{cane} approach is based on the combined energy and aerodynamic approach of the PM procedure and is therefore free of the foregoing potential problems with APSIM but it requires additional climate data (wind speed and humidity). Overall errors in the use of ET_{cane} to predict ET_C in Swaziland were similar to errors in its prediction of ET_C from the Pongola lysimeters. However, the new data have revealed some systematic errors which could be rectified probably by changing the reference leaf area index or stomatal resistance in ET_{cane} (McGlinchey and Inman-Bamber, 1996).

Given the difficulties in estimating net radiation, the predominant factor in ET_C, it is perhaps fortuitous that bias was similar at the three locations. It is possible that bias would be different at another site with different atmospheric properties. This is a problem for methods using ET_0 or ET_{cane} which estimate R_n but not for APSIM which uses measured solar radiation and vapour pressure deficit for climatic effects on ET_C. It would not be difficult to measure net radiation at new locations to make appropriate adjustments to K_C for a new site.

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References

Allen, R.G., Pereira, L.S., Raes, D., Smith, M., 1998. Crop evapotranspiration—guidelines for computing crop water requirements. FAO Irrigation and Drainage Paper 56. FAO, Rome.

Denmead, O.T., Mayocchi, C.L., Dunin, F.X., 1997. Does green cane harvesting conserve soil water? Proc. Aust. Sugar Cane Technol. 19, 139–146.

Grantz, D.A., Meinzer, F.C., 1991. Regulation of transpiration in field-grown sugarcane. Evaluation of the stomatal response to humidity with the Bowen ratio technique. Agric. For. Meteorol. 53, 169–183.

Inman-Bamber, N.G., Spillman, M.F., 2000. Measuring actual and potential water use by sugarcane. In: Proceedings of the 2000 National Conference and Exhibition, Irrigation Association Australia, Melbourne, 23–25 May 2000, pp. 311–318.

Keating, B.A., Roberston, M.J., Muchow, R.C., Huth, N.I., 1999. Modelling sugarcane production systems. I. Description and validation of the APSIM Sugarcane module. Field Crops Res. 61, 253–271.

McGlinchey, M.G., Inman-Bamber, N.G., 1996. Predicting sugarcane water use with the Penman–Monteith equation. In: Camp, C.R., Sadler, E.J., Yoder, R.E. (Eds.), Proceedings of the International Conference on Evapotranspiration and Irrigation Scheduling, San Antonio. ASAE, St. Joseph, MI, 3–6 November 1996, pp. 592–598.

Meyer, W., 1997. The irrigation experience in Australia—lessons for the sugar industry. In: Keating, B.A., Wilson, J.R. (Eds.), Intensive Sugarcane Production: Meeting the Challenges Beyond 2000. CAB International, Wallingford, pp. 437–454.

Monteith, J.L., Unsworth, M.H., 1990. Principles of Environmental Physics. Edward Arnold, London, p. 240.

Muchow, R.C., Triglone, T., Plunkett, G.M., Sherrard, J.H., Wood, A.W., Engelke, J.H., 2001. Field responses to irrigation in the Ord sugar industry. Proc. Aust. Sugar Cane Technol. 23, 109–115.

Ohmura, A., 1982. Objective criteria for rejecting data for Bowen ratio flux calculations. J. Appl. Meteorol. 21, 595–598.

O'Leary, G.J., 2000. A review of three sugarcane simulation models with respect to their prediction of sucrose yield. Field Crops Res. 68, 97–111.

Robertson, M.J., Inman-Bamber, N.G., Muchow, R.C., 1997. Opportunities for improving the use of limited water by the sugarcane crop. In: Keating, B.A., Wilson, J.R. (Eds.), Intensive Sugarcane Production: Meeting the Challenges Beyond 2000. CAB International, Wallingford, pp. 287–304.

Robertson, M.J., Muchow, R.C., Inman-Bamber, N.G., Wood, A.W., 1999. Developing guidelines for the length of drying-off of irrigated sugarcane before harvest in the Burdekin. Proc. Aust. Soc. Sugar Cane Technol. 21, 196–202.

Shannon, E.L., Holden, J.R., 1996. The evaporation minipan: a simple irrigation scheduling tool for the canegrower. In: Wilson, J.R., Hogarth, D.M., Campbell, J.A., Garside, A.L. (Eds.), Sugarcane: Towards Efficient and Sustainable Production. CSIRO Division of Tropical Crops and Pastures, Brisbane, pp. 213–214.

Smith, M., Allen, R.G., Pereira, L., 1996. Revised FAO methodology for crop water requirements. In: Camp, C.R., Sadler, E.J., Yoder, R.E. (Eds.), Proceedings of the International Conference on Evaporation and Irrigation Scheduling, San Antonio. ASAE, St. Joseph, MI, 3–6 November 1996, pp. 116–123.

Tanner, C.B., Sinclair, T.R., 1983. Efficient water use in crop production: research or research? In: Taylor, H.M., Jordan, W.R., Sinclair, T.R. (Eds.), Limitations to Efficient Water Use in Crop Production. ASA, Madison, WI, pp. 1–27.

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

Wright, J.L., 1982. New evaporation crop coefficients. J. Irrig. Drain. Div., Am. Soc. Civil Eng. 108 (2), 57–74.