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ORIGINAL PAPER

Sugarcane evapotranspiration and irrigation requirements in tropical climates

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Abstract
Irrigation is necessary to help meet the high demand for water by sugarcane in several countries including Brazil and Australia. The crop irrigation requirements are typically estimated using the crop coefficient-reference evapotranspiration (Kc-ETo) procedure. Sugarcane evapotranspiration rates were measured in three different sugarcane-producing regions of the world, and crop coefficients (Kc) were derived for those diverse environments, irrigation methods, and farming systems, therefore representing a robust basis for irrigation management. We also verified the occurrence of the inverse relation between Kc and ETo found in previous studies. Two experiments in Brazil and one in Australia were used for the analysis. Our data showed that Kc for a full canopy cover was lower than 1.0 in the three experimental sites and that sugarcane evapotranspiration (ETc) seems to be limited and exceeds ETo only when this is below 4 mm day^{-1}. In one of the Brazilian experiments, Kc declined at higher rates than in the other two experiments, and for the three sites, average Kc was 0.77 and 0.87, respectively, for initial and full cover phase when ETo > 6 mm day^{-1}. The increase of aerodynamic and other upstream resistances to water transport of plants appears to be one of the reasons for Kc to decrease at high levels of ETo. Based on our data and the literature, the Kc values provided by Allen et al. (1998) could overestimate the irrigation needs of sugarcane under high evaporative demand conditions. Irrigation management based on Kc should use the average ETo from the preceding 3 days before irrigating to save water and energy while maintaining high yield levels.

1 Introduction

Despite the advance in technologies for water supply, irrigation management has not received proper attention and many irrigated areas are often overirrigated, unnecessarily depleting natural water sources and producing undesirable rates of runoff and drainage, as well as a waste of energy.

Irrigation scheduling using evapotranspiration estimated from climatic data is appealing because this approach is relatively simple compared to on-site measurements. This approach makes use of crop coefficients (Kc) to relate crop evapotranspiration (ETc) of a disease-free crop grown in a large field adequately supplied with water, to a reference crop evapotranspiration (ETo) (Jagtap and Jones 1989). This procedure is known as the crop coefficient-reference evapotranspiration (Kc-ETo) procedure and, in the last two decades, it has been the main option for quantifying water requirement for many crop species. Based on such an approach, Allen et al. (1998) systematized the procedure for ETo estimates and compiled a set of Kc values covering 126 crops.

Large amounts of water are commonly used for sugarcane plantations in Australia and Brazil as both countries have sugarcane as one of the most important crops in terms of irrigated area. Wood et al. (1998) reported 3250 mm per annum with values ranging from 1530 to 5380 mm in the northwestern Australia. In the same region, Muchow et al. (2001) found that annualized gross irrigation could be reduced from 2957 to 2176 mm without affecting the crop yield and

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demonstrated that a further reduction to 1723 mm would decrease yields only marginally. In Brazil, Silva et al. (2011) applied 2525 mm during one sugarcane-growing season by following the Kc-ETo procedure but found that the measured crop evapotranspiration was only 1743 mm.

Sugarcane irrigation in Brazil is still a recent technology, accounting for ca. 10% of the crop area. However, sugarcane has expanded to new areas with sandy soils, high temperatures, and insufficient rainfall, increasing the irrigated sugarcane area in such regions (Walter et al. 2014). In addition to the expansion of sugarcane production into the warmer and drier regions, the use of irrigation has also increased in the traditional sugarcane-producing regions adding to the rapid increase of sugarcane irrigation throughout Brazil in the last decade. We conducted several studies in Southern Brazil (ca. latitudes from 20°S to 25°S) (Nassif et al. 2014; Marin et al. 2016; Nassif et al. 2019; Marin et al. 2019) aiming to support the irrigation management, following the approach proposed by Allen et al. (1998). Besides the well-known crop variables influencing Kc (e.g., canopy architecture, crop phenology, fraction of soil covered etc.), those papers showed that antecedent ETo should also be considered for more accurate estimates of subsequent irrigation requirements.

In this paper, we add a whole year of measurements to the dataset described in Marin et al. (2016) (latitude 22°S) and put them together with another two experiments conducted in northern Australia (latitude 15°S) and northern Brazil (latitude 9°S), to gather a robust database with enough diversity of environments and irrigation methods, to (a) provide robust Kc values for sugarcane based on three different environments and (b) verify the occurrence of the inverse relationship between ETo and Kc as being of general occurrence irrespective to the irrigation method, farming systems, and environments.

2 Materials and methods

2.1 General procedures

We used data from four experiments at three sites around the world as described in Table 1 (and fully described in "General procedures"). All of them were fully irrigated and fertilized to provide non-limiting conditions in terms of water and nutrients for the crop and all were conducted on soils with a high clay content. To avoid the potential confounding factors (i.e., sub-optimal root zone water status and incomplete canopy cover) that can affect the crop evapotranspiration (ETc), we screened all the data to assure that only measurements under high soil water content were used in the analysis, making sure that the variability of Kc and ETc was not due to the lack of soil moisture as evaluated by the common FAO approach, which assumes that soil water is readily available (readily available water, RAW) until some limiting water content between to wilting (WPP, matric potential (ψs) = − 15,000 hPa) and field capacity (FCP, ψs = − 330 hPa) points. We also excluded all data collected before crop emergence to avoid using data collected over bare soil and separated the remaining data into two crop phases, one before canopy closure (initial phase, INI) and the other after full canopy cover (FULL). To define those phases, we assumed that the data belonging to the INI phase were those collected before the fraction of intercepted solar radiation (FIR) reached 0.6; the data for the FULL phase started when FIR > 0.6, as the canopy can be regarded as effectively complete when it intercepts more than 60% of incident solar radiation (Inman-Bamber and McGlinchey 2003). This FIR threshold value of 60% was chosen to match the different crop development rates in each experimental site with the initial phase duration suggested by Allen et al. (1998), ranging from 80 to 140 days.

2.2 Evapotranspiration measurements

Experiments were performed in irrigated sugarcane plantations in three distinct regions across the world, two in Brazil and one in Australia. For all experiments, grass-based reference evapotranspiration (ETo) was calculated following Allen et al. (1998) and crop evapotranspiration was measured by Bowen Ratio Energy Balance (BREB) systems installed in irrigated sugarcane plantations in three distinct regions across the world, two in Brazil and one in Australia. Crop evapotranspiration (ETc) measurements were considered only for those days when more than 70% of the 20-min BREB data from the experiment conducted in Australia passed the acceptance criteria of Ohmura (1982) and 70% of the 15-min BREB data for the experiments conducted in Brazil passed the acceptance criteria of Perez et al. (1999). Gaps in 20 min (Australia) and 15 min data (Brazil) were filled by using a linear trendline connecting anterior and posterior data of each gap. ETc was determined as

$$\beta = \gamma \frac{\Delta \mathrm{T}}{\Delta \mathrm{e}} \tag{1}$$

$$ETc = \frac{Rn - G}{(1+\beta) \bullet \lambda E} \tag{2}$$

where ETc is the crop evapotranspiration (mm day^{-1}); γ is the psychrometric constant (kPa $°\mathrm{C}^{-1}$); β is the Bowen ratio (dimensionless); ΔT and Δe are, respectively, the air temperature (°C) and partial vapor pressure difference (kPa) between two heights; Rn is the surface radiation balance (MJ m^{-2} day^{-1}); G is the soil heat flux (MJ m^{-2} day^{-1}); and λE is the latent heat of vaporization (assumed as 2.45 MJ m^{-2} day^{-1}). Inconsistent physical measurements for the energy balance were ruled out and only data for when the wind direction allowed a fetch of > 100 m over the crop were included.

Table 1 List of experiments and experimental sites, irrigation method and management, soil and climate description

Experiment #	Site	Lat	Lon	Irrigation	Irrigation management	Soil	Clay %	Climate[a]	Tmed[b] (°C)	Rain[c] (mm)
1	Ord River irrigation area (Australia)	− 15.78	128.74	Furrow	Fully irrigated	Kununurra grayish cracking clay	~ 60	BSh	28.0	809
2	Ord River irrigation area (Australia)	− 15.78	128.74	Furrow	Irrigation schedule	Kununurra grayish cracking clay	~ 60	BSh	28.0	809
3	Piracicaba (Brazil)	− 22.71	− 47.42	Sprinkler	Fully irrigated	Hapludox	62	Cwa	22.0	1331
4	Juazeiro (Brazil)	− 9.36	− 40.46	Sub-surface	Fully irrigated	Vertisol	45–53	BSh	27.1	485

[a] Climate acronym based on Koeppen Classification

[b] Mean annual temperature

[c] Mean annual total rainfall

2.3 Experiment description

2.3.1 Ord River, Australia

Sugarcane is currently the major crop in the Ord River Irrigation Area in terms of area. Three BREB experiments (Table 2) are described briefly here and in more detail by Inman-Bamber (2006). Experiments were furrow irrigated and conducted at the Frank Wise Institute (FWI) of the Dept. Agriculture, Western Australia (15.78°S, 128.74°E) on a Northern Ivanhoe Kununurra grayish cracking clay (Vertosol) with a plant available water (PAW) capacity of 129 and 190 mm to depths of 1.0 and 1.9 m, respectively (Plunkett and Muchow 2003). The PAW was calculated based on the difference between FCP and WPP.

2.3.2 Irrigation scheduling experiment at Ord River

A supplementary experiment was conducted in the Ord to evaluate the effect of irrigation scheduling on yield using a range of Kc values. Details about the experiment are described in Inman-Bamber (2006), and here, only the main features are given. An area grown with cultivar Q96 in a 7-ha field was subdivided into 12 plots. Four treatments were randomly allocated to four plots in each of the three replicate plots in order to test Kc values above and below those emerging from the data of the BREB experiments. For all treatments, irrigation was managed to recover the water deficit when soil moisture represented 0.68 of plant available water content.

Canopy development was measured for one replication of each treatment using tube solarimeters as for the BREB experiments. Kc for irrigation scheduling was given the same value for all treatments until the FIR reached 0.6. Until this moment, Kc was assumed to be 1.25 × Kc and at least 0.2. Consequently, Kc reached the value 1.0 when FIR was 0.8. This approach emerged from Inman-Bamber and McGlinchey (2003), who point that Kc reached a maximum when FIR = 0.8. For FIR > 0.6, a 'Low' irrigation treatment was managed by assuming Kc = 0.75. A 'Medium' treatment was irrigated with Kc = 1.00 (for FIR > 0.8). The 'High' treatment was managed by assuming Kc = 1.25. Finally, Kc = 1.00 was used for initial part of the 'Variable' treatment (until the crop produced 30 t ha^{-1} above ground biomass as estimated by APSIM-Sugarcane crop model); after that, it was used Kc = 0.75. The plots were harvested by machine and the yield and quality determined at the mill as for normal harvesting operations.

2.3.3 Piracicaba, Brazil

The experiment was described by Marin et al. (2016), and only a brief description is given here. The BREB measurements were taken on an irrigated sugarcane field with cv RB867515 in Piracicaba, Sao Paulo State, Brazil (Table 3). The experiment was conducted from October 2012 to June 2016 under a center pivot irrigation area of 3 ha with row spacing of 140 cm and nearly 15 planted buds m^{-1} (Table 3). The first 3years of this experiment were used by Marin et al. (2016) and the final year of data is reported here. The field was manually harvested, and the yield and quality determined at the mill as for normal harvesting operations. The BREB system was positioned near the field boundary downwind of the prevailing wind direction to obtain a high chance of achieving a fetch > 100 m within an arc of 180°

Table 2 Details of the experimental data and Bowen-ration energy balance measurements collected in the Ord, Australia

Block	Size	Variety	Ratoon date	Crop class	BREB operational
9a	400 × 580 (m)	Q99	17/9/2003	1st ratoon	10/10/2003
9d	293 × 239 (m)	Q95	2/9/2004	2nd ratoon	16/9/2004
11d	Irregular 15 ha	Q99	5/5/2006	1st ratoon	19/5/2006

Table 3 Details of the experimental data and the time lengths and Bowen ration energy balance measurements collected in Piracicaba, Brazil

Crop system	Crop season	BREB measurements
Plant cane	Oct 12, 2012 to Oct 16, 2013	Feb 13, 2013 to Jul 1, 2013
1st ratoon	Oct 13, 2013 to Jul 15, 2014	Jan 22, 2014 to Jun 6, 2014
2nd ratoon	Jul 15, 2014 to Jun 8, 2015	Aug 1, 2014 to May 4, 2015
3rd ratoon	Jun 8, 2015 to Jul 15, 2016	Sep 28, 2015 to Apr 6, 2016

facing south-east. Solar radiation interception was estimated based from LAI measurements (as described in Marin et al. 2014) and the coefficient of extinction for Beer's law (Monsi et al. 1973) was assumed as 0.5, for consistency with interception measurements in the Ord experiments.

Soil hydraulic properties were obtained from undisturbed core samples taken at five depths at four locations within the experimental area to obtain the soil water retention curves. Three replicates were collected at depths of 5, 15, 30, 60, and 100 cm and taken to a laboratory housing a pressure plate system to obtain volumetric moisture content at various potentials, along with other soil properties shown in Table 4. A 1.8-m soil profile was excavated close to plant rows to expose roots which were found to be exploiting the whole profile, with the bulk of the roots in the top 1.0 m.

Twenty-four frequency domain reflectometer (FDR) access tubes were inserted in the soil to a depth of 1.6 m from the soil surface for soil water monitoring and irrigation management. The FDR (model Diviner 2000, SENTEK) was calibrated using three repetitions of undisturbed soil that were taken at 5, 15, 30, 60, and 100 cm depths and at four random locations in the experiment (total of 60 samples). Monoliths were collected with metal cylinders ($v = 53.8\ cm^3$) immediately sealed in plastic bags, weighed, and taken to the laboratory for deriving soil water retention curves and Mualem-van Genuchten coefficients (van Genuchten 1980) (Fig. 1).

Scaled frequencies (SF) were taken with the FDR probe at same time and depths of the soil sampling. Soil water contents ($cm^3\ cm^{-3}$) derived by gravimetric method and the monoliths weights were paired with the corresponding SF values. Soil sampling occurred after a rain event; hence, the majority of soil samples were at high water content. Thus, we used the Mualem-van Genuchten equation to determine the soil water content at WPP, FCP, and saturation point (STP, $\psi s = -1$ hPa), respectively, and compared these with SF at dry and wet conditions. The lowest SF of the dry season were paired to wilting point, whereas the highest SF just after irrigation events were paired to saturation point. Paired SF and soil moisture were then used to adjust the calibration equation of the FDR equipment using a R-script (Provenzano et al. 2015). The A, B, and C coefficients were, respectively, 0.14, 0.498, and 0.009 ($r^2 = 0.87$; Figs. 2 and 3).

2.3.4 Juazeiro, Brazil

Crop evapotranspiration of a second ratoon of the cultivar VAT 90-212 was measured in one plot of 5.0 ha by the BREB method in a commercial field sugarcane area of the São Francisco Valley Agroindustry Company, located in Juazeiro, Bahia, Brazil (9°29′51″ S; 40°21′43″ ; 400 m) (Table 1), between August 2015 and July 2016. Irrigation was supplied through subsurface 1.6 L h^{-1} emitters spaced at 0.5 m and buried 0.20 m below each crop row. Micrometeorological sensors and BREB methods were the same described in the Piracicaba experiment. Soil samples were collected at six depths (5, 10, 20, 30, 50, and 90 cm) to obtain volumetric moisture content at two potentials and some other properties (Table 5). Soil water content was not measured, so irrigation was managed to assure the crop remained in the readily available water range along the cycle based on a soil water balance, in which irrigation was scheduled to reset the soil moisture to the field capacity. Nevertheless, data were screened

Table 4 Soil depth (DP), volumetric moisture content at the wilting point (WPP, $\psi s = -15{,}000$ hPa), field capacity (FCP, $\psi s = -330$ hPa), and saturation (STP, $\psi s = -1$ hPa), saturated hydraulic conductivity (KSAT), sand (Psand), silt (Psilt), clay (Pclay), and organic (Porgm) matter fractions for each soil layer of the experiment

DP (cm)	WPp ($cm^3\ cm^{-3}$)	FCp ($cm^3\ cm^{-3}$)	STp ($cm^3\ cm^{-3}$)	KSAT ($cm\ h^{-1}$)	Psand ($g\ g^{-1}$)	Psilt ($g\ g^{-1}$)	Pclay ($g\ g^{-1}$)	Porgm ($g\ g^{-1}$)
5	0.216	0.285	0.380	1.70	0.185	0.150	0.650	0.015
15	0.240	0.303	0.352	1.01	0.185	0.150	0.650	0.015
30	0.278	0.347	0.390	0.49	0.199	0.170	0.620	0.011
60	0.307	0.394	0.428	0.21	0.199	0.170	0.620	0.011
100	0.253	0.393	0.456	0.21	0.211	0.160	0.620	0.009

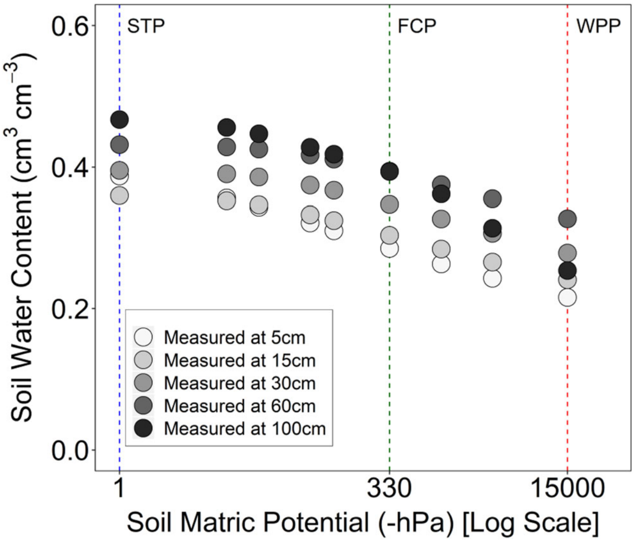

Fig. 1 Soil water content (SWC) in samples from 5, 15, 30, 60, and 100 cm depth as a function of matric potential ($n = 12$), determined for the Piracicaba experiment. STP, FCP, and WPP are the SWC at the saturation (− 1 hPa), field capacity (− 330 hPa), and wilting (− 15,000 hPa) points, respectively

to minimize the chance of soil water limiting ETc by simulating the soil water balance following Thornthwaite and Mather (1955) and Allen et al. (1998). Data were rejected when less than 80% of the soil water holding capacity (conservatively assumed to be 50 mm) was available. Solar radiation interception was estimated from LAI measurements as in the Piracicaba experiment ("Piracicaba, Brazil") to define the crop phenology.

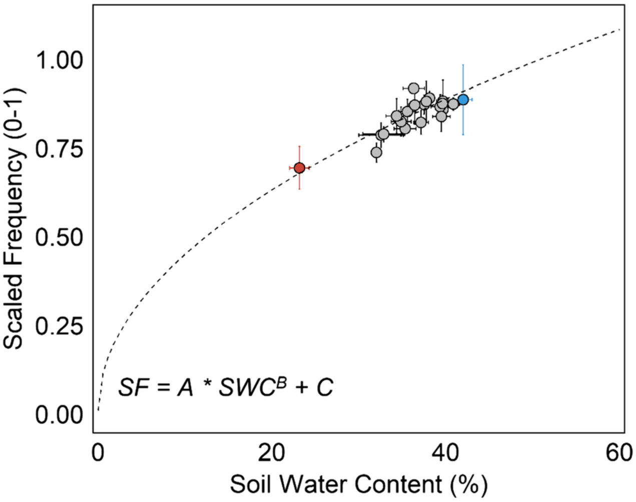

Fig. 2 Calibration relationship between scaled frequencies (SF, 0–1) of the FDR probe and volume-based percentage of soil water content (SWC) measured by gravimetric method (gray circles) and calculated using the Mualem-van Genuchten equation (van Genuchten 1980) at the wilting (red circles, − 15,000 hPa) and saturation (blue circles, − 1 hPa) points

3 Results

3.1 Evapotranspiration and crop coefficients in the initial phase

The average Kc_{INI} for the three experimental sites and all crop ages was 0.916, varying from 0.885 at 3 months to 1.002 at 4 months after emergence (Fig. 4). Even during the early crop stages, Kc_{INI} tended to consistently decline with increasing ETo, agreeing with Marin et al. (2016). Kc declined at a rate of − 0.0502 [mm day^{-1}]$^{-1}$ with ETo for the average of data from 2 to 4 months after emergence, ranging from − 0.061 [mm day^{-1}]$^{-1}$ at 2 months to − 0.157 [mm day^{-1}]$^{-1}$ at 4 months (Table 6). For practical irrigation scheduling in sugarcane plantations, Kc could be taken as 0.3 before the crop emerges (Inman-Bamber 2006), and as varying from 0.93 to 0.77 as ETo increases from the range of 2–4 mm day^{-1} to values higher than 6 mm day^{-1} (Table 6).

3.2 Evapotranspiration and crop coefficients in the full canopy cover phase

The ETc data varied with ETo for the three locations (Fig. 5), tending to reach a plateau after some level of ETo. Such plateau was reached at lower ETo values in Piracicaba, followed by Ord and Juazeiro, respectively. In Juazeiro, we observed the lower variability of ETc data and the highest ETc average. Still, the linear regression for Juazeiro showed the highest angular coefficient (0.843), while in Piracicaba, we found the lowest angular coefficient (0.422) compared to others.

In average, Kc declined 0.21 for each mm increased in antecedent ETo in Piracicaba, followed by Ord (− 0.11 for each mm increased in ETo) and Juazeiro (− 0.05 for each mm increased in antecedent ETo), with an average value for the three sites of − 0.15 for each mm increased in antecedent ETo based on the Kc equations shown in Table 6. Simple regression analysis of the database from the three sites showed that mean ETo for the preceding 3 days also had a significant ($p < 0.01$) negative effect on Kc suggesting that Kc is reduced not only for the day of high evaporative demand but also for the previous 3 days of high demand (Table 6). This has an interesting practical meaning for irrigation scheduling. Thus, a Kc of 1.67 ± 0.61 could be used for irrigation on a given day when average ETo for the past 3 days was lower than 2 mm day^{-1} (Table 6). Kc could be reduced to 1.07 ± 0.57 when ETo for the preceding 3 days ranged from 2 to 4 mm day^{-1}, and it should be further reduced to 0.91 ± 0.39 for ETo between 4 and 6 mm day^{-1} (Table 6). Finally, for periods with average ETo higher than 6 mm day^{-1}, the Kc values were 0.87 ± 0.37 (Table 6).

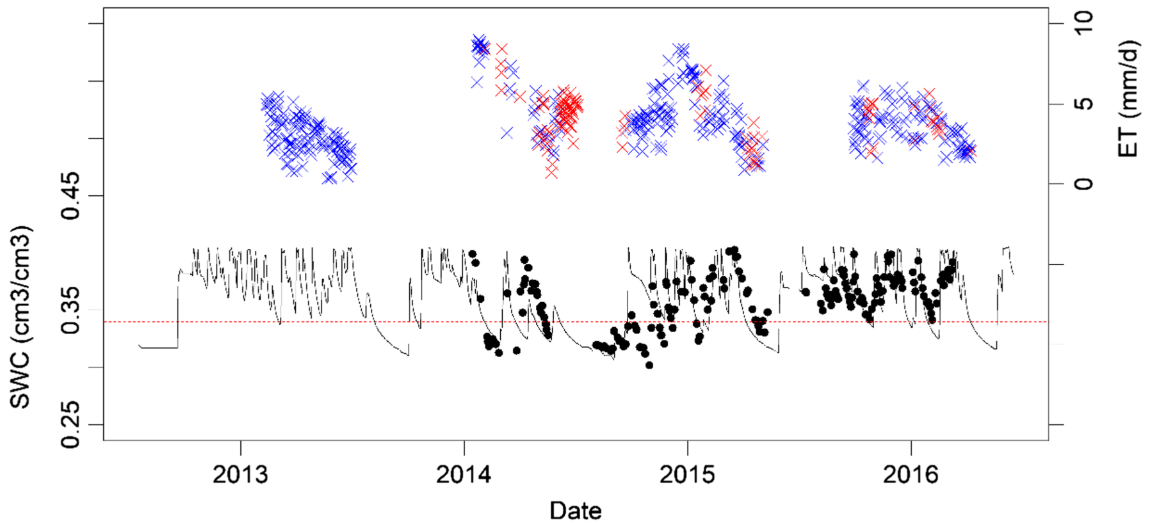

Fig. 3 Average soil water content (SWC, cm^3 cm^{-3}) between 0 and 60 cm depth and crop evapotranspiration (ETc, mm day^{-1}) during the Piracicaba experiment. Filled dots are SWC measured with frequency domain reflectometry (FDR) probe; dashed red line is the 80% of total available water (TAW) given by the difference between the SWC at field capacity (− 330 hPa) and wilting point (− 15,000 hPa); solid black line is the water content simulated with a "tipping-bucket" soil water balance provided by the SAMUCA model (Marin and Jones 2014; Marin et al. 2017; Vianna et al. 2020) in order to permit the time interpolation of soil moisture data. Blue crosses are the crop evapotranspiration when SWC was optimum and the red crosses indicate the evapotranspiration data that was ruled out for being under the threshold of 80% of TAW

3.3 Verification of Kc through the scheduling experiment

Irrigation was simultaneously applied three times in all treatments along the growing season, and 14, 16, 17, and 20 times in total for the low, medium, variable, and high treatments, respectively (Fig. 6). For those treatments with less than 17 irrigations (variable and low treatments) and Kc = 0.75, the stalk fresh yield was reduced significantly (Fig. 6). The reduction by one irrigation gift caused 5 t ha^{-1} yield difference between the medium and variable treatment, and this was due to the larger water deficits in the variable treatment compared to the medium and high treatments (Inman-Bamber 2006). There was no yield benefit from irrigating with Kc_{FULL} at 1.25 rather than 1.00, and therefore, such measurements from Ord confirmed that the Kc values suggested in Table 6 were adequate for irrigation scheduling in the Ord sugarcane plantations. The lack of difference between the medium and high treatments also indicated that the target deficit of 60 mm was appropriate for irrigating the heavy soils in the Ord.

4 Discussion

Evaporation from the soil surface is a non-negligible component of crop evapotranspiration even in large sugarcane crops (Inman-Bamber and McGlinchey 2003; Olivier and Singels 2012), and therefore, it is to be expected that Kc would decline when the soil surface is dry. In the four experimental datasets used here, the surface soil was never allowed to dry providing assurance that root water extraction to a depth of at least 1.0 m (Plunkett and Muchow 2003) was not limiting for crop water use at any stage during the determination of ETc.

In both experiments in the Ord, Kc_{FULL} was higher than 1.1 only on a few days. The Kc_{FULL} values were expressively lower than those recommended for the Burdekin region of Australia and in Swaziland (Inman-Bamber and McGlinchey 2003). On average, our Kc values were about 25% less than those suggested by Allen et al. (1998). In Pongola South Africa, Olivier and Singels (2012) used large weighing lysimeters to determine Kc for sugarcane growing in one of three levels of soil mulching in their sub-tropical environment, and Kc was found to be lower by

Table 5 Volumetric moisture content at − 15,000 hPa (WPP) and − 330 hPa (FCP), soil bulk density (ds), sand (Psand), silt (Psilt), clay (Pclay), and organic (Porgm) matter fractions for each sampling soil depth (DP) of the experiment located in Juazeiro, Bahia, Brazil

DP (cm)	WPp (cm cm^{-3})	FCp (cm cm^{-3})	ds (g cm^{-3})	Psand (g g^{-1})	Psilt (g g^{-1})	Pclay (g g^{-1})	Porgm (g g^{-1})
5	0.350	0.510	1.33	0.209	0.213	0.468	0.109
10	0.360	0.520	1.36	0.228	0.176	0.491	0.105
20	0.330	0.460	1.37	0.231	0.153	0.505	0.111
30	0.340	0.480	1.39	0.232	0.175	0.482	0.111
50	0.320	0.450	1.38	0.215	0.224	0.449	0.112
90	0.330	0.480	1.37	0.186	0.174	0.532	0.108

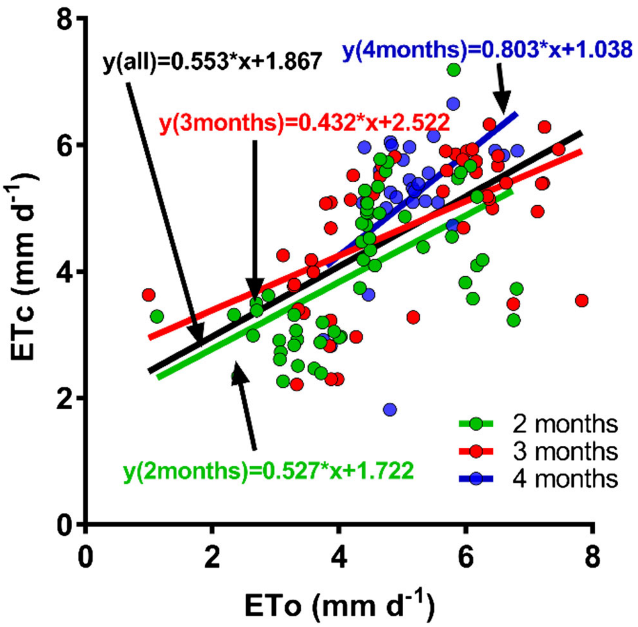

Fig. 4 Relationship between sugarcane evapotranspiration (ETc) and reference evapotranspiration (ETo) for crops for the initial phase, from 2 to 4 months after emergency, in the Ord, Juazeiro, and Piracicaba. All coefficients of linear equations were statistically significant ($p < 0.05$)

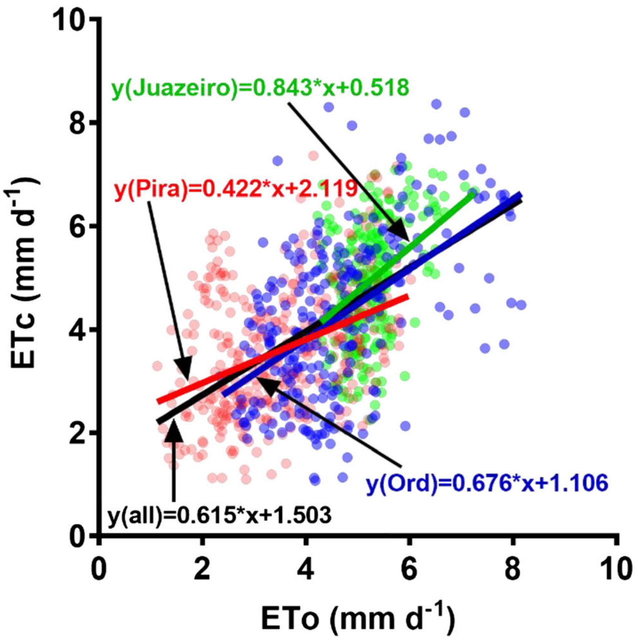

Fig. 5 Relationship between crop evapotranspiration (ETc) and reference evapotranspiration (ETo) for the 3 days prior to Kc measurement for full canopy cover phase. All coefficients of linear equations were statistically significant ($p < 0.001$)

10% than the ones from Allen et al. (1998). Together with our results, these findings suggested that there would be a limit to the amount of water that can be transpired from a full canopy of sugarcane even for very high soil water content. Maximum daily ETc was 8.3 mm day^{-1} in the Ord, 7.4 mm day^{-1} in Piracicaba, and 7.2 mm day^{-1} in Juazeiro. Maximum ETc recorded with BREB in the Burdekin seldom exceeded 8 mm day^{-1} (Inman-Bamber and McGlinchey 2003). In Pongola, Olivier and Singels (2012) found a maximum ETc around 7 mm day^{-1} and Thompson (1986) found that the mean ETc of three weighing lysimeters at Pongola exceeded 8 mm day^{-1} on only 4% of days in the nearly 5-year period of measurements. Yet, such limitation to the amount of water that can be transpired raises doubt on the approach suggesting that soil water is readily available until some limiting water content between FCP and WPP. In fact, our findings suggested that water transport from soil to plant to atmosphere under high atmospheric demand turns from sink-limited to source-limited, possible under any soil water content, corroborating the findings from Denmead and Shaw (1962) and Cowan (1965).

We found that sugarcane Kc decreases as ETo increases even under high soil water content and despite the level of canopy cover. Measurements of leaf diffusive conductance and environmental variables showed that sugarcane leaves restrict their water loss under high atmospheric water demand (Machado et al. 2009; Nassif et al. 2014). Indeed, several papers have noted the dependence of stomatal conductance on air temperature and VPD with stomata tending to close as these variables increase (Grantz and Meinzer 1991). Therefore, our observed inverse relationship between Kc and ETo for sugarcane might be due to an increase of inner resistances to water transport in plants when subjected to conditions of high atmospheric water demand (McNaughton and Jarvis 1983a,b). Data collected by Nassif et al. (2014) for a

Table 6 The Kc values for sugarcane for four ranges of antecedent ETo for initial and full canopy cover phases and the general Kc equations derived from linear regressions that are shown in Figs. 4 and 5 using their respective entire datasets. Values between brackets are respective standard deviations

Crop phase	ETo range (mean for the preceding 3 days)				Kc equation
	< 2 mm day^{-1}	2–4 mm day^{-1}	4–6 mm day^{-1}	> 6 mm day^{-1}	
Initial	–[a]	1.04 [0.34]	0.97 [0.19]	0.78 [0.29]	$\text{Kc} = 0.553 + 1.867 * \text{ETo}^{-1}$[b]
Full cover	1.67 [0.61]	1.03 [0.39]	0.99 [0.30]	0.93 [0.20]	$\text{Kc} = 0.615 + 1.503 * \text{ETo}^{-1}$[c]

[a] There were no data for ETo < 2 mm day^{-1} during the initial phase in the three experimental sites

[b] $r^2 = 0.268$; $p < 0.0001$

[c] $r^2 = 0.192$; $p < 0.0001$

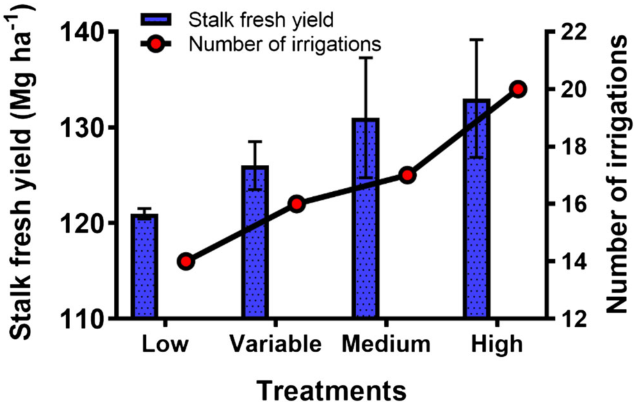

Fig. 6 Mean stalk fresh yield and number of irrigations for each treatment of the scheduling irrigation experiment. Error bars represent the standard deviations of treatment replications

complete canopy cover sugarcane and non-limiting soil water status shows the response of leaf conductance to vapor diffusion (g_s) to weather variables having a quadratic relationship in which g_s decreases when the atmosphere demands high transpiration rates. The *gs* increased when vapor pressure deficit, solar radiation, and air temperature favored increasing demand up to an equivalent ETo of 5 mm day^{-1} and then g_s decreased with further increases in demand (Nassif et al. 2014). Such relations between g_s and weather variables corroborate the hypothesis that sugarcane plants control the transpiration as the ETo increases supporting the use of different Kc values for discrete ETo ranges.

Results in Table 6 represent a novel way to improve sugarcane irrigation management in order to save water and energy without any yield loss. Therefore, in conditions of high available radiant energy, wind speed, and VPD, which are normally found when ETo surpasses 4.0 mm day^{-1}, it may be expected that tall crops such as sugarcane with high inner resistances to water flow do not respond directly to the atmospheric water demand.

This study is in line with others performed for sugarcane (Nassif et al. 2014; Marin et al. 2016; Nassif et al. 2019) and several other crops (Marin et al. 2005; Marin and Angelocci 2011). In these papers, we hypothesized that one possible explanation for the decline in Kc with increasing demand is the high level of plant-atmosphere coupling that was found in well-irrigated sugarcane (Nassif et al. 2014; Marin et al. 2016). Under such conditions, there would be a feed-back between plants and their immediate aerial environment which may diminish the dependence of transpiration on stomatal conductance (Jarvis and McNaughton 1986; Steduto and Hsiao 1998). However, experiments conducted with crops with different levels of plant-atmosphere coupling (Sobenko et al. 2018; Silva et al. 2019; Marin et al. 2019) showed that the inverse ETo-Kc relationship occurred regardless of coupling level, casting doubt on this hypothesis.

Allen et al. (1998) claimed that the Kc values must be used under standard climatic conditions (sub-humid climate, minimum relative humidity of 45%, and wind speeds averaging 2 m s^{-1}) and that variations in wind speed may alter aerodynamic resistance and, hence, crop coefficients mainly for tall crops. They also inferred that under conditions of high wind speeds and low relative humidity, Kc tends to increase, which is different to the observations made from the datasets of the four experiments analyzed here. Firstly, we noted that average Kc decreased as ETo increased and average Kc varied little between experiments when ETo exceeded 4 mm day^{-1}. Secondly, high wind speed and low air relative humidity affected crop evapotranspiration and decreased Kc, contrary to the Allen et al. (1998) recommendation. In this way, it seems that well-irrigated sugarcane production systems around the world might be wasting water since most of them are under high evaporative demanding conditions, during periods of the year when irrigation is needed. Indeed, the irrigation experiment in the Ord confirmed that irrigation applied with Kc > 1.0 did not improve yield, thus reinforcing the hypothesis raised here that the current irrigation management suggested for high evaporative demand conditions, which prevail in most of the sugarcane-producing areas of the world, could lead to overirrigation of sugarcane.

5 Conclusions

Our data showed that Kc was lower than 1.0 in Ord and Juazeiro (sites with high evaporative demand) and ETc seems to be limited and exceeds ETo only when this is below 4 mm day^{-1}. The increase of inner resistances to water transport of plants is probably part of the explanation as to why the crop coefficient (Kc) seldom exceeds 1.0 and tends to decline as ETo increases. For those days when ETo > 6 mm day^{-1}, average Kc was 0.82 in the three sites.

Based on our data and data reported on the literature, the time-based Kc curves in Allen et al. (1998) could overestimate the irrigation needs of sugarcane in high evaporative demand conditions in poorly drained soils. The irrigation management based on Kc should consider the average ETo of the three preceding days before irrigating to save water and energy while maintaining high yield levels.

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