Crop coefficient, water requirements, yield and water use efficiency of sugarcane growth in Brazil

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A B S T R A C T

A correct evaluation of water losses as evapotranspiration (ET) by crops is important for allocating irrigation water and improving water use efficiency. Field experiments were conducted throughout 2009/2010 (second ratoon) and 2010/2011 (third ratoon) in a sugarcane field of a commercial distillery located on the coastal area of Paraíba state, Brazil. The main objective of this study was to determine crop coefficient, water requirements and water use efficiency (WUE) of sugarcane grown in a tropical climate. The experimental design was by randomized block design with four irrigation treatments and three replications using two center pivots. Crop evapotranspiration (ET) was determined by field soil water balance and reference evapotranspiration (ET0) was obtained based on Penman–Monteith method (FAO/56), using data of air temperature, relative humidity, wind speed and solar radiation from Data Collection Platform, located next to the experimental site. The experimental area was cultivated with irrigation applied weekly by a center pivot system in addition to rainfall. The irrigation scheduling was based on four irrigation levels (T1 = 25%, T2 = 50%, T3 = 75% and T4 = 100% of ET0). Results showed that ET and WUE are strongly influenced by soil water availability. When averaged across two years, productivity increased according to increases in water level. Sugarcane ET ranged from 2.7 (rain-fed condition) to 4.2 mm day−1 (100% ET0 irrigation treatment)

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1. Introduction

In a tropical area with sub humid climate, evapotranspiration ranges over a large interval depending on water amount. Tropical regions have a large variety of climates. In general, semiarid regions during dry season are characterized by high temperatures, high evaporation rates and low precipitation. It is also important to improve the estimates of crop water use in order to improve the irrigation design parameters and scheduling.

Brazil is one of the major sugarcane producing country in the world, with 8.36 million of hectares in planted area which provides 26.6 million of cubic meters in alcohol and 30 million of tons in sugar. However, only few analyses have been carried out in Brazil for studying sugarcane crop. Due to its application in the food industry and in the production of ethanol, a less polluting renewable biofuel (Menossi et al., 2008), sugarcane has great economic value, especially in Brazil (Pinto et al., 2005). In many regions of Brazil sugarcane is grown in rain-fed areas, especially in humid and subhumid regions in the southern parts of the country. However, full or supplementary irrigation is essential for the production of sugarcane in the northeastern region of Brazil, where the climate is predominantly semiarid with air temperature ranging from 20 to 40 °C and mean annual rainfall being about 800 mm (Silva et al., 2006).

Previous studies have shown the impact of extended reduced water availability on sugarcane production because high biomass crop requires large quantities of water for maximum production (Wiedenfeld, 2008). Much has been reported on different aspects of sugarcane growing, including crop coefficients (Watanabe et al., 2004); transpiration (Chabot et al., 2002); leaf and stalk extension, leaf area development; response to water stress (Inman-Bamber and Smith, 2005); yield and juice quality (Choudhary et al., 2004; Wiedenfeld, 2008); water-use efficiency (Inman-Bamber and McGlinchey, 2003) and evapotranspiration (Omary and Izuno, 1995). Even though Brazil is one of the major sugarcane producing countries in the world, studies on water requirements of sugarcane cultivated under tropical conditions in Brazil are scarce.

Reductions in sugarcane yield in rain-fed area are due to the “verancos” (dry spells of more than 2 weeks during the rainy
season). The water availability is the major cause of inter-annual yield variation and yield differences of sugarcane grown on different soils in Brazil (Van den Berg et al., 2000). Sugarcane is highly productive in tropical and sub-tropical areas of the world, but the water stress decreases plant productivity (Rodrigues et al., 2009). The crop coefficient plays an essential role in various agricultural practices and it has been widely used to estimate the actual ET in irrigation scheduling (Pereira et al., 1999). Empirical crop coefficients have been criticized as regards their meaning and use, because their values vary according to the conditions of both climate and crop stage under which they were derived. Doorenbos and Pruitt (1977) in FAO-24 and Allen et al. (1998) in FAO-56 suggested crop coefficient values for a large number of crops under different climatic conditions which are commonly used in places where the local data is not available. However, there is a need for local calibration of the crop coefficients under given climatic conditions (Kashyap and Panda, 2001).

This paper addresses possible errors in supplementary irrigation estimates for sugarcane grown in tropical environment, implying an increase in production cost and low crop yield. Our first objective was to determine the evapotranspiration, crop coefficient and water use efficiency of sugarcane grown in a tropical climate, Brazil. Conversely, our second objective was to analyze the relationship between leaf area index/evapotranspiration and sugarcane crop coefficient. This paper also compares rain-fed and irrigated agricultural production in study area.

2. Materials and methods

2.1. Experimental site

Field experiments were carried out from October 2009 to August 2010 (second ratoon) and from September 2010 to July 2011 (third ratoon) in a sugarcane field of commercial distillery located in the coastal area of Paraiba state, Brazil (latitude 6° 54′ 59″ S; longitude 35° 09′ 17″ W; altitude 121 m). The study crop was sugarcane (Saccharum spp.), cultivar RB 92 579. The mean annual rainfall in study area is about 1500 mm and mean annual air temperature ranges from 23 °C (rainy season) to 27 °C (dry season), while the rainy season generally starts in March and ends in August (Silva, 2004). The local climate is tropical wet with tropical savanna vegetation and the soil type is Lixisols (FAO soil taxonomy) (Silva et al., 2010).

A trench was open in the experimental site for extracting soil samples that were used to determine the textural class, bulk density, porosity, and field capacity and wilting point. The groundwater level at the experimental site dropped down to 3.0 m during the growing season. The experimental area was cultivated with irrigation applied weekly by a center pivot system, in addition to rainfall. Irrigation scheduling was based on four irrigation levels: T1 = 25%, T2 = 50%, T3 = 75% and T4 = 100% of ET0 (reference evapotranspiration), which was obtained by the Penman–Monteith approach (Allen et al., 1998).

2.2. Measurements

Daily measurements of air temperature, wind speed, solar radiation and relative humidity for estimating ET0 as well as rainfall were made on a data collection platform (DCP) located near the experimental site. The soil water content was measured every 2–3 days from October 10 to August 25 in both experimental years using a profile probe PR2 sensor and an HH2 data logger (Delta-T Devices LTA). Once a site specific calibration was identified as necessary for the PR2 probe, we used in situ calibrated equations for estimating soil water content. The voltage outputs were converted to θv using the following equation: \( \frac{\sqrt{v}}{\theta} = a_0 + a_1 \theta \), where \( \sqrt{v} \) is the root square of the permittivity, \( \theta \) is the volumetric water content (cm\(^3\)/cm\(^3\)) and default \( a_0 \) and \( a_1 \) parameters are provided by Delta-T Devices, for mineral (\( a_0 = 1.6, a_1 = 8.4 \)) and organic (\( a_0 = 1.3, 7.7 \)) soils. However, the calibration coefficients for the experimental site were \( a_0 = 1.51, a_1 = 8.73 \). The soil water content was monitored at 0.10 m intervals down 1.0 m starting at 0.10 m. For representative measurements of soil water content by the profile probe, 9 access tubes were inserted into the ground at the experimental plot for each irrigation treatment and rain-fed conditions, and then the mean soil water content was computed as the arithmetic mean of the water content values observed from access tubes.

Crop parameters were measured during different stages of sugarcane growth. The crop data included the planting date, 10% cover date, full cover date, maturity date, harvest date, and leaf area. One plot of 30 m\(^2\) × 30 m\(^2\) size was selected in a sugarcane field for obtaining crop parameters and soil water content. The main experimental area was surrounded by other sugarcane fields of 8000 ha. The leaf area was obtained by gravimetric techniques. The gravimetric method correlates the dry weight of leaves and leaf area using predetermined green-leaf-area-to-dry-weight ratios (leaf mass per area, LMA). LMA is determined from a subsample extracted from the global field sample (Jonckheere et al., 2004). The leaf area index was calculated from the measured mean leaf area dividing the plot area.

2.3. Determination of soil water balance

The soil water balance in the root zone over a given time interval was calculated from the mass conservation equation expressed as:

\[
\Delta S = R + I + CR - RO - D - ET
\]

where \( \Delta S \) is the change of water storage in root zone, \( R \) is the rainfall, \( I \) is the irrigation depth applied, \( RO \) is the runoff from the soil surface, \( CR \) is the capillary rise, \( D \) is the drainage at depth \( z \), below the root zone, and \( ET \) is the actual evapotranspiration. All the water balance components are in mm. Surface runoff was neglected, once the experimental site had flat topography. Similarly, \( CR \) was assumed to be zero because the water table was more than about 1 m below the bottom of the root zone at the experimental site. The change in soil water storage (\( \Delta S \)) was determined as:

\[
\Delta S = S_t - S_{t-1}
\]

where \( S_t \) and \( S_{t-1} \) are the changes in soil water storage at times \( t \) and \( t - 1 \), respectively. The changes in soil water storage (\( S_t \)) were determined by considering the soil layers from the surface \( (z=0) \) down to the bottom of the soil depth measurements \( (z=0.6 \text{ m}) \). For subsequent soil layers, soil water content values from the upper and lower borders of each layer were averaged to find the mean water content of the entire layer. Deep drainage \( (D) \) in the root zone following a heavy rain or irrigation was calculated as a residual from van Genuchten (1980), following Azevedo et al. (2006).

3. Results and discussion

At various times during the growing season, sugarcane leaf area and calculated leaf area index (LAI) were determined. During the entire growth season, LAI ranged from 1.50 to 5.62 m\(^2\) m\(^{-2}\), following a similar course of crop coefficient (Fig. 1). For some intervals of the curve, due to a number of operational problems related to sampling of leaf area, LAI was not available. During the initial and development stages, in both cycles, LAI increased rapidly reaching a maximum value around the day of year (DOY) 170 and ranged between 5.0 and 5.5 m\(^2\) m\(^{-2}\). Thereafter, LAI decreased slowly.
toward to the end of late season. On the other hand, for maximum LAI (completely covered ground surface) $K_c$ decreased from a peak value (~1.4) tending to an asymptotic low value around 1.3. The crop coefficient is dependent upon the stage of canopy height, crop growth, architecture and cover (Allen et al., 1998). Several authors have demonstrated that $K_c$ is highly correlated with leaf area index (Medeiros et al., 2001), leaf area (Williams and Ayars, 2005) and ground cover (López-Urrea et al., 2009). Indeed, these studies showed that the water losses, resulting from evapotranspiration processes, increase when vegetation develops, so that adaptation to local climate promotes canopy development until water shortage prevents further growth.

The present study also shows the relationship between LAI and evapotranspiration, as another means of characterizing the sugarcane canopy. In the combined analysis, interactions between LAI and $K_c$ were observed. Likewise, evapotranspiration (ET) was linearly related to LAI (Fig. 2). The greatest $r^2$ value (0.88) of the relationship with LAI was that for crop coefficient compared to an $r^2$ value of 0.67 for ET. The ET during the growing season increased almost linearly from October 10 (at the beginning of experimental period) until approximately DOY 120.

Furthermore, in spite of the relatively low coefficient of determination, the relationship between LAI and ET was statistically significant by Student’s t-test at the 0.05 significant level. A particularly good fitting between ET and LAI was observed from DOY 343 to DOY 120, when LAI had reached the maximum value. The coefficient of determination of 0.88 confirmed a good agreement between the $K_c$ and LAI data for this period as well as between $K_c$ and LAI for the whole period which is statistically significant at the 0.01 level. This result indicates that reduction in irrigation application in late season had a negative impact on ET reduction compared to a slow decrease in LAI.

The different components of the soil water balance converted to average 2-cycles of sugarcane for treatment 100% ETo under study are given in Fig. 3. Irrigation application was high and rainfall amount was low in almost the entire experimental period in both cycles but resulted in high water supply (P and/or I) which had a positive impact on evapotranspiration. weekly ET was calculated over 7-day periods using the soil water balance method. This method must be used over periods as long as one week to provide an acceptable precision in estimating field evapotranspiration (Trambouze et al., 1998). A similar procedure was used by Azevedo et al. (2003) who determined the soil water balance components for mango orchard grown in a semiarid environment in northeastern region of Brazil. There was a close correspondence between weekly measures of ET and water supplied as rainfall and irrigation, indicating that evapotranspiration ranged over a large interval depending on the water amount. Sugarcane ET by soil water balance presented an average ±standard deviation of 4.3 ± 1.6 mm day$^{-1}$.

The highest water supply of 134.3 mm on DOY 158 was mainly provided by high episodic rainfall events (75 mm) between June 10 and June 18, 2010. The related drainage for this period was 57.5 mm, indicating the high-efficiency of procedure adopted by Azevedo et al. (2006) for detecting deep drainage in the root zone following heavy rain or irrigation. Therefore, this equation can be used for monitoring drainage when sets of mercury manometer

**Fig. 1.** Crop coefficient ($K_c$) and leaf area index (LAI) during sugarcane crop cycle (2-years-average).

**Fig. 2.** Relationship between the leaf area index (LAI) and (A) evapotranspiration (ET) and (B) crop coefficient ($K_c$) of sugarcane growth in a tropical environment. Points represent 7-day averages of daily $K_c$ and ET values. The values represent means across second ratoon (2009/2010) and third ratoon (2010/2011).

**Fig. 3.** Sugarcane evapotranspiration and water supply (irrigation and rainfall) throughout experimental period for treatment 100% ET$_0$. Values represent means across second ratoon (2009/2010) and third ratoon (2010/2011).
tensiometers are not available for determining the soil water negative pressure suction. Although the water supply had the highest influence on the magnitude of sugarcane ET, small influences of the atmospheric demand and leaf area during the development period can greatly affect the daily values of ET. Although soil water content was recorded at regular times at depths of 0.10, 0.20, 0.30, 0.40, 0.50, 0.70, 0.80, 0.90 and 1.0 m, the soil water storage was calculated between the soil surface and a depth of 0.60 m using the trapezoidal rule, allowing for computing the evolution of evapotranspiration with time in the crop root zone. The cumulative change in soil water storage over a depth of 0.60 m and deep drainage as a function of time for the crop season under study also for treatment 100% ET$_{c}$ is presented in Fig. 4. In general, the increase in water supply had a noticeable effect on soil water storage and deep drainage. The highest deep drainage was observed at the end of the mid-season stage followed by a considerable increase in the cumulative soil water storage.

This can be explained by the exceptional high rainfall of 75 mm within 7 days of irrigation in June 2009 resulting in increased subsoil water which caused drainage. At the beginning of the growing season, consecutive rainy days with low rainfall and no irrigation were observed, which reduced the soil water storage and consequently did not provide deep drainage. In second ratoon, below-normal rainfall resulted in lower soil moisture contents than in third ratoon. Timely rainfall has occurred close to the end of third crop cycle season. For comparison purposes, it was used a set drainage rates based on two soil drainage categories: well drained (irrigation based on 100% ET$_{c}$) and poorly drained (rain-fed conditions). The seasonal course of rainfall and drainage for a sugarcane field under rain-fed cropping system during two crop cycles is shown in Fig. 5.

Mean values ± standard deviation of soil drainage during the second ratoon was 0.5 mm ± 0.63 d$^{-1}$, while the soil drainage was higher during the third ratoon (1.8 mm ± 3.08 d$^{-1}$), due to high rainfall and therefore it is not uncommon for the study region. Despite rainfall below normal during the second ratoon upon rain-fed conditions, the timely rainfall around DOY 98, 181 and 255 resulted in a considerable drainage.

The variability in ET throughout experimental period was probably caused mostly by the fact that measured ET from soil water balance responded primarily to the amount of water applied. The drainage started only occurs from DOY 191 for the second ratoon, with a mean value of 3.5 mm and reached a maximum of 43.3 mm in the DOY 253, after rainfall of 40 mm. In the study area, the evaporation is relatively high, at the same time the rainfall was much lower during second ratoon, making the irrigation volume one of the highest. For the drainage and rainfall included in this study, the largest difference was found between second and third ratoons. The maximum drainage and rainfall during the second ratoon represented, respectively, 40.28% and 36.70% of those of the third ratoon. The total drainage during the third ratoon of sugarcane was higher than in the second due to heavy rainfall during that period in the experimental area. Draining during the third ratoon occurs from the DOY 61 ranging from 1.1 mm to 107.5 mm in the DOY 253, after precipitation of 109 mm in 2009.

In order to compare the drainage in a specific condition of high irrigation, Fig. 6 shows the water input and drainage for a sugarcane field under irrigation treatment of 100% ET$_{c}$ during second and third ratoons as function of time. Mean and standard deviation of soil drainage matched measured values very well: 2.7 ± 3.02 mm d$^{-1}$ for second ratoon and 3.0 ± 3.86 mm d$^{-1}$ for third ratoon. The differences among soil drainage are very large between crop cycles. The largest difference was found between growth conditions (optimal/rain-fed); drainage during second ratoon in treatment of 100% ET$_{c}$ was 5 times the drainage of rain-fed system. Differences in water input resulted in differences in attributes of well-drained and poorly drained soils that influenced water balance components at phenological stages of sugarcane.

At the beginning of the both growing seasons, consecutive rainy days with low rainfall and no irrigation were observed, which reduced the soil water storage and consequently did not provide deep drainage. In both experimental years, drainage took place only after irrigation. Rainfall 60–70 days prior to irrigation did not affect drainage compared with irrigation immediately. Daily average ET calculated over 7-day periods using soil water balance averaged across second ratoon (2009/2010) and third ratoon (2010/2011) is shown in Fig. 7. Due to normal data scatter, ET values by crop coefficients were reported as 7-days. The values of ET from soil water balance ranged from 1.05 to 7.76 mm day$^{-1}$, with average ± standard deviation of 4.47 ± 1.05 mm day$^{-1}$. 

Fig. 4. Evolution of cumulative soil water storage and deep drainage with time for treatment 100% ET, for the crop season under study. Values represent means across second ratoon (2009/2010) and third ratoon (2010/2011).

Fig. 5. Seasonal course of rainfall and drainage for a sugarcane field under rain-fed cropping system during (A) second ratoon (2009/2010) and (B) third ratoon (2010/2011).
Our results of ET are consistent with other studies. Average measured daily evapotranspiration rates can be as high as 7.4 mm during the summer months for sugarcane growing areas in Australia (Australian Bureau of Meteorology, http://www.bom.gov.au/). When determining crop coefficients and water-use estimates for sugarcane based on the long-term Bowen ratio energy balance measurements in Australia and Swaziland, Inman-Bamber and McGlinchey (2003) found similar results for ET. The data showed that minimum ET rates occurred during August through December (2–4 mm day$^{-1}$) and maximum ET rates (6–9 mm day$^{-1}$) occurred during March through May throughout mid-season stage.

Similar results were obtained by Moroizumi et al. (2009) when estimating the actual evapotranspiration of rice and sugarcane using micrometeorological data and crop coefficients for a semi-humid tropical climate in Northeast Thailand. For the same region, Watanabe et al. (2004) found ET rates for the sugarcane field ranging between 2 and 6 mm per day during the rainy season. The values of $K_c$ and leaf area index (LAI) for each crop growth stage averaged over the two ratoons crop and initial and final growth stage for each ratoon of sugarcane under study are also given in Table 1. On the whole crop season, due to high irrigation load, $K_c$ was higher in mid-season while LAI reached the maximum at late season growth stage.

The $K_c$ values based soil water balance ($K_c$-WB) were very different with those recommended in the FAO bulletin ($K_c$-FAO) for initial growth stage which difference is about 118%. The difference between values of $K_c$-WB and $K_c$-FAO in the whole crop season is about 18%. The $K_c$-FAO – $K_c$ ini are general values under typical irrigation management and soil wetting in subhumid climates (RHmin ≈ 45%, u2 ≈ 2 m/s). For frequent wettings such as with high frequency sprinkle irrigation or daily rainfall, these values may increase substantially and may approach 1.0 to 1.2 (Allen et al., 1998).

The smallest difference between $K_c$-WB and $K_c$-FAO occurred on late season stage, which correspond an underestimate of only 1.2%. In practice, results reported here showed that $K_c$-FAO can lead to significant errors in irrigation scheduling of sugarcane in tropical conditions. The $K_c$ values derived from field soil water balance varied over growing season being 0.18 in the initial growth stage, 1.06 in the mid-season and 0.76 at late stage of sugarcane growth in a tropical region. These values are similar to those recommended by Inman-Bamber and McGlinchey (2003) for sugarcane.

Table 2 shows the mean values of reference evapotranspiration, cumulative values of irrigation levels and rainfall for each growth stages during two sugarcane crop cycles. Interaction was observed between rainfall and ET$_{0}$. Total reference evapotranspiration in second ratoon tended to be 10.9% higher compared with the third ratoon while rainfall in second ratoon was less than half the value obtained in third ratoon.

During second ratoon, mean values of ET$_{0}$ varied from 5.6 mm d$^{-1}$ in mid-season growth stage to 8.00 mm d$^{-1}$, at late season. Similarly, the smallest mean value in ET$_{0}$ during third ratoon was in the mid-season growth stage. As a consequence of high atmospheric demand the largest volume of water applied per irrigation was of 1312.2 mm during second ratoon.

Total water applied for each irrigation treatment was significantly lower during third ratoon than during second ratoon. The highest $K_c$ values were recorded during the mid-season growth stage, when LAI was high. On other hand, lowest $K_c$ values during initial growth stage were attributed to small LAI and little plant growth. In second ratoon, rainfall was almost 50% below normal and, in contrast, it was close to normal during the third ratoon. The mean annual rainfall for the study area is 1500 mm (Silva et al., 2006). Minimum and maximum temperatures for the two periods were vastly different, resulting in temporal variability of atmospheric evaporative demand. ET$_{0}$ values during the experiment in 2009/2010 and 2010/2011 averaged 6.8 and 5.8 mm day$^{-1}$, respectively. On the other hand, total ET$_{0}$ in 2010/2011 was approximately 90% of ET$_{0}$ in 2009/2010 period. Differences in ET$_{0}$ values are directly attributed to temperature and wind speed, rather than sunlight, since solar radiation was high during both experimental years (data not shown). In summary, the variation in ET$_{0}$ was mainly related to weather conditions.

Water was applied differentially by a center pivot system at rates of 25%, 50%, 75% and 100% of ET$_{0}$ in second ratoon (2009/2010) and third ratoon (2010/2011). The applied irrigation based on ET$_{0}$ had a significant effect on crop evapotranspiration (Table 3). The change in evapotranspiration from rain-fed to 100% ET$_{0}$ increased as the field received more irrigation. The greatest amount of water in treatment 100% ET$_{0}$ provided an increase in cumulative

![Fig. 6. Seasonal course of rainfall + irrigation and drainage for a sugarcane field under irrigation treatment of 100% ET$_{0}$ during (A) second ratoon (2009/2010) and (B) third ratoon (2010/2011).](image)

![Fig. 7. Time course of evapotranspiration on a sugarcane crop field throughout experimental period for the treatment 100% ET$_{0}$. Values represent means across second ratoon (2009/2010) and third ratoon (2010/2011).](image)
Table 1
Crop coefficients for non stressed and well-managed crops based on soil water balance (Kc-WB) and values recommended in the FAO bulletin (Kc-FAO), leaf area index (LAI) and lengths of crop development stages of sugarcane grown in tropical region. Values represent means across second ratoon (2009/2010) and third ratoon (2010/2011).

<table>
<thead>
<tr>
<th>Growth stage</th>
<th>Period second ratoon</th>
<th>Lengths of crop development stages</th>
<th>Kc-FAO</th>
<th>Kc-WB</th>
<th>LAI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial</td>
<td>October 10 to November 8, 2009</td>
<td>30</td>
<td>0.40</td>
<td>0.18</td>
<td>–</td>
</tr>
<tr>
<td>Development</td>
<td>November 9 to 28 December, 2009</td>
<td>50</td>
<td>0.85</td>
<td>0.74</td>
<td>1.50</td>
</tr>
<tr>
<td>Mid-season</td>
<td>December 29, 2009 to June 26, 2010</td>
<td>180</td>
<td>1.25</td>
<td>1.06</td>
<td>4.86</td>
</tr>
<tr>
<td>Late season</td>
<td>June 27 to August 25, 2010</td>
<td>60</td>
<td>0.75</td>
<td>0.76</td>
<td>5.62</td>
</tr>
<tr>
<td>Mean</td>
<td></td>
<td>0.81</td>
<td>0.69</td>
<td>3.99</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>320</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 2
Mean values of reference evapotranspiration (ETo), cumulative values of irrigation levels and rainfall for each growth stage during second ratoon (2009/2010) and third ratoon (2010/2011).

<table>
<thead>
<tr>
<th>Growth stage</th>
<th>ETo (mm d⁻¹)</th>
<th>Rainfall (mm)</th>
<th>Irrigation (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Daily</td>
<td>Total</td>
<td>25% ETo</td>
</tr>
<tr>
<td>Second ratoon</td>
<td>--------------</td>
<td>---------------</td>
<td>---------</td>
</tr>
<tr>
<td>I Initial</td>
<td>6.9</td>
<td>207.8</td>
<td>0.0</td>
</tr>
<tr>
<td>II Development</td>
<td>6.6</td>
<td>330.1</td>
<td>12.0</td>
</tr>
<tr>
<td>III Mid-season</td>
<td>5.6</td>
<td>1011.6</td>
<td>421.0</td>
</tr>
<tr>
<td>IV Late season</td>
<td>8.0</td>
<td>479.3</td>
<td>188.0</td>
</tr>
<tr>
<td>Mean</td>
<td>6.8</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Total</td>
<td>2029.4</td>
<td>621.0</td>
<td>401.6</td>
</tr>
<tr>
<td>Third ratoon</td>
<td>–</td>
<td>1829.1</td>
<td>1319.2</td>
</tr>
</tbody>
</table>

Table 3
Cumulative evapotranspiration (CET - mm) and mean daily evapotranspiration (DET-mm/d) for each crop growth stage of sugarcane for rain-fed conditions and the irrigation treatments 25%, 50%, 75% and 100% of reference evapotranspiration (ETo). Values represent means across second ratoon (2009/2010) and third ratoon (2010/2011).

<table>
<thead>
<tr>
<th>Crop growth stage</th>
<th>Rain-fed</th>
<th>25% ETo</th>
<th>50% ETo</th>
<th>75% ETo</th>
<th>100% ETo</th>
</tr>
</thead>
<tbody>
<tr>
<td>DET</td>
<td>CET</td>
<td>DET</td>
<td>CET</td>
<td>DET</td>
<td>CET</td>
</tr>
<tr>
<td>Initial</td>
<td>0.7</td>
<td>21.0</td>
<td>0.7</td>
<td>21</td>
<td>1.1</td>
</tr>
<tr>
<td>Development</td>
<td>1.6</td>
<td>80.6</td>
<td>1.7</td>
<td>185</td>
<td>3.9</td>
</tr>
<tr>
<td>Mid-season</td>
<td>3.7</td>
<td>666</td>
<td>4.4</td>
<td>792</td>
<td>4.9</td>
</tr>
<tr>
<td>Late season</td>
<td>10.0</td>
<td>1598</td>
<td>10.0</td>
<td>1214</td>
<td>10.0</td>
</tr>
<tr>
<td>Average</td>
<td>2.7</td>
<td>–</td>
<td>2.9</td>
<td>–</td>
<td>3.3</td>
</tr>
</tbody>
</table>

evapotranspiration of 54.8% when compared with cropping systems in rain-fed agriculture. Similar increase is observed in mean daily evapotranspiration from rain-fed to 100%ETo. When averaged across two experimental years, cumulative evapotranspiration (CET) increased 14.6% from rain-fed to 25%ETo, 14% from 25 to 50%ETo, 4.4% from 50 to 75%ETo and 13.3% from 75 to 100%ETo. Comparing the conditions extremes in soil moisture content on ET, both CET and mean daily evapotranspiration (DET) increased approximately 55% from rain-fed to 100%ETo. Similar to earlier findings (Azevedo et al., 2006; Silva et al., 2010), we found that Kc, DET and CET increase from initial to mid-season crop growth stage and then decreases toward to late season.

As expected, the smallest annual and seasonal amount of evapotranspiration was in rain-fed system. In absence of sufficient rainfall and/or irrigation there is always low flux response to evapotranspiration. For rain-fed and all irrigation treatments, the mean daily evapotranspiration was undulating, reaching low during initial and late season crop growth stage; and pick during mid-season. As shown in Table 3, cumulative evapotranspiration was highest during mid-season as consequence of lengths of crop development stages and due to leaf area expansion. In spite of high LAI, high evaporative demand and good water supply were determinants to achieve high evapotranspiration rates during the late season. The ET calculations based on 75–100% ETo indicated that the sugarcane at the experimental site was not under moisture stress. This is mostly due to the high amount and frequency of irrigation application. This type of water management is typical for sugarcane production in Brazil.

Sugarcane yield and water use efficiency based on evapotranspiration for rain-fed conditions and four irrigation levels are show in Table 4. There were significant difference (P<0.05) between sugarcane yields for most treatments. The irrigation treatments of 75 and 100% were the most productive per unit time (110.2–136.1 t/ha·yr⁻¹) while the rain-fed and 25%ETo were least productive (almost 50% below other irrigation treatments).

Table 4

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Yield (t/ha·yr)</th>
<th>VUE (kg/ha·mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rain-fed</td>
<td>62.6 a</td>
<td>0.056 a</td>
</tr>
<tr>
<td>25% ETo</td>
<td>67.8 a</td>
<td>0.073 a</td>
</tr>
<tr>
<td>50% ETo</td>
<td>100.6 b</td>
<td>0.076 ab</td>
</tr>
<tr>
<td>75% ETo</td>
<td>110.2 b</td>
<td>0.083 bc</td>
</tr>
<tr>
<td>100% ETo</td>
<td>136.1 c</td>
<td></td>
</tr>
</tbody>
</table>

¹ Values followed by the same letter within a column are not significantly different (P<0.05) according to Tukey's test.
Complementary irrigation had a significant effect on sugarcane yield so that increases in yield are directly and linearly correlated with increases in the consumption of water. Since sugarcane yield in treatment 25% ET\(_m\) was higher than in rain-fed conditions, the increased sugarcane yield could not be attributed to increased ET\(_m\). Except to rain-fed system, both yield and WUE seems to higher as the irrigation increased. Similar results were obtained by Silva et al. (2009) who analyzed WUE and ET of mango orchard grown in northeastern region of Brazil. Moisture stress during the growing season in rain-fed conditions affected sugarcane yield when it occurs during development crop growth stage. The greatest effects with regard to WUE and sugarcane yield were seen in treatments 75–100% ET\(_m\) due to high water level. The low yield in rain-fed conditions and 25% ET\(_m\) could be attributed to inadequate rainfall that might have occurred during cropping seasons and low irrigation level. On the other hand, On the other hand, the low performance of rain-fed agriculture could not only be attributed to erratic nature of rainfall but also soil fertility and lack of appropriate technologies. As depicted in Table 4, it is now well documented that yield under water-limited conditions are generally associated with reduced WUE. Conversely, Azevedo et al. (2006) pointed out that the application of a high irrigation water volume does not necessarily result in high yield.

In general, WUE increased with increase in amount of water applied to the field. The mean highest WUE (0.083 kg/ha/mm) was achieved with 100% ET\(_m\), whereas the lowest with 25% ET\(_m\). Results indicated that evapotranspiration, yield and WUE were strongly affected by irrigation level. Higher sugarcane WUE with 100% ET\(_m\) is also attributed to favorable effect of water supply at shorter interval and thereby improvement in contributing to leaf production and stem elongation and their internodes.

Sugarcane yield based on 25% ET\(_m\) was not significantly influenced by irrigation since there is no significant difference by Tukey’s test at significant level of p < 0.05 between rain-fed conditions and 25% ET\(_m\) treatment. Similarly, there is no significant difference between 50–75% ET\(_m\) treatments with both yield and WUE values almost equal. Sugarcane yield had statistically significant difference between 100% ET\(_m\) and other treatments; however, the difference between WUE values for treatments 75% ET\(_m\) and 100% ET\(_m\) was not statistically significant. This could be due to enhancement of moisture availability in the soil layer with frequent irrigations provided by these irrigation levels. The effect of water on yield is regulated, to a certain extent, by crop photosynthetic capacity and nitrogen application (Hu & Mo, 2011). High irrigation application water volume resulted in both high yield and WUE of sugarcane growth in Brazil. Inversely, Azevedo et al. (2006) found that the application of a high irrigation water volume does not necessarily result in high coconut fruits yield and WUE values decreased with increasing irrigation water level for all productivity parameters.

4. Conclusions

1. Complementary irrigation had a significant effect on sugarcane yield so that increases in yield are directly and linearly correlated with increases in the consumption of water. Various irrigations conditions can affect the evapotranspiration and yield of sugarcane growth grown in tropical environment;

2. There is a close association between crop coefficient/evapotranspiration and leaf area index with coefficient of determination up to 0.88;

3. The K\(_s\)-FAO can lead to significant errors in irrigation scheduling of sugarcane in tropical conditions. The K\(_s\) values derived from field soil water balance varied over growing season being 0.18 in the initial growth stage, 1.06 in the mid-season and 0.76 at late stage of sugarcane growth in a tropical region;

4. Both WUE and productivity increased according to increases in water level, and sugarcane ET ranged from 2.7 to 4.2 mm day\(^{-1}\). The yield for irrigated sugarcane ranges from 67.8 to 136.1 t/ha, which is significantly larger than that of rain-fed, 62.6 t/ha.

5. The greatest positive result in yield and WUE was seen in 100% ET\(_m\) treatment. On the other hand, 25% ET\(_m\) treatment did not affect yields significantly compared with other treatments, but did result in a significantly increased yield when compared to rain-fed conditions.

References


Williams, L.E., Ayars, J.E., 2005. Grapevine water use and the crop coefficient are linear functions of the shaded area measured beneath the canopy. Agriculture, Ecosystems & Environment 132, 201–211.