Water use in a sugarcane plantation

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Abstract
The evapotranspiration (E) from a sugarcane plantation in the southeast Brazil was measured by the eddy-covariance method during two consecutive cycles. These represented the second (393 days) and third year (374 days) re-growth (ratoon). The total E in the first cycle was 829 mm, accounting for 69% of rainfall, whereas in the second cycle, it was 690 mm, despite the total rainfall (1353 mm) being 13% greater. The ratio of E to available energy, the evaporative fraction, exhibited a smaller variation between the first and second cycles: 0.58 and 0.51, respectively. The estimated interception losses were 88 and 90 mm, respectively, accounting for approximately 7% of the total rainfall. The sugarcane yield in the second cycle (61.5 t ha⁻¹) was 26% lower than in the first cycle, as well as lower than the regional average for the third ratoon (76 t ha⁻¹). The below average yield was associated with less available soil water at the beginning of the cycle, with the amount of rainfall recorded during the first 120 days of re-growth in the second cycle being 16% of that recorded in the first (203 mm).

Keywords: eddy covariance, evapotranspiration, rainfall interception, soil water deficit, sugarcane, yield

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Introduction
During the last decade, global biofuel production has increased. This has occurred mainly in the United States and Brazil (Qin et al., 2011); most of the industrial ethanol produced in the world is made either from corn in the United States or from sugarcane in Brazil (Waclawovsky et al., 2010).

The increasing demand for production of biofuels as an alternative to fossil fuel burning is promoting the conversion of existing agricultural areas (Loarie et al., 2011). This trend may intensify with the introduction of second-generation biofuels (lignocellulosic), unless they are based on waste biomass or the land-use changes occur in abandoned agricultural lands (Fargione et al., 2008).

However, high growth rates are likely to be associated with high evapotranspiration rates (e.g. Hall et al., 1998), and the impacts on water resources of widespread bioenergy-crop planting of should be addressed. These impacts should be included in any energy or economic cost-benefit analysis of biofuel production (Das et al., 2011).

Currently, the area of the world under sugarcane is approximately 20 million hectares. This area is spread over 70 countries (Galdos et al., 2009), but the leading country is Brazil with 9.5 million hectares in 2009. Nearly 60% of this area is found in São Paulo state (Pinheiro et al., 2010). The average sugarcane yield in the southeast of Brazil attained after the first year of establishment in rain-fed conditions is 104 t ha⁻¹, the productivity of the re-growth from the stubble, known as the ratoon crop (Cuadra et al., 2012), decreases at a rate of approximately 10% per year between the four successive harvests (ratoons). This reduction is mainly due to the cumulative stalk damage during harvest (Bull, 2000). When it falls beyond about 70 t ha⁻¹, the plantation is re-established (Macedo et al., 2008).

To meet the growing demand for biofuel, future sugarcane expansion in Brazil will probably occur in some low rainfall areas, where the crop may be expected to exhibit some water stress (Manzatto et al., 2009; Waclawowsky et al., 2010; Marín et al., 2011). This is already the case in the western region of São Paulo state where the replacement of pasture has been going on for the last 15 years (Martinelli & Filoso, 2008).

The eddy-covariance method offers the capability of directly measuring the evapotranspiration, including the evaporation of intercepted rainfall and from soil during the time when the canopy cover is not complete, and at the characteristic field-scale of crops (Suyker & Verma, 2009; Denmead et al., 2010). In this study, we present 2 years of eddy-covariance data, covering two complete annual cycles of a representative sugarcane plantation. The objectives are to establish the controls of climate (rainfall, soil water content, and saturation deficits) on the crop development, to assess its water use, and to clarify its likely effect on the regional water...
budget – an important issue (Loarie et al., 2011), as the water availability is considered the major cause of inter-annual yield variation (van den Berg et al., 2000).

Materials and methods

Site

The sugarcane plantation, which belongs to the company Usina Santa Rita, was situated in Luiz Antonio municipality in São Paulo State, Brazil (21°38’S, 47°47’W at 552 m altitude). The distance between planting rows was 1.4 m. The continuous area (>400 ha) exhibited a small slope of less than 2% and was surrounded by pasture, citrus fruit orchards, and the native savanna forest (Cerrado).

The soil (Typic Haplustox) texture fractions are 22% clay, 74% sand, and 3% silt, and the mean dry bulk density (d_b) down to 2.6 m depth is 1500 kg m⁻³. Compaction resulting from previous mechanical harvesting has created a denser layer between 10 and 25 cm (d_b = 1636 kg m⁻³). The available soil water between the potentials of −0.01 and −1500 kPa was 136 mm in the first meter.

The mean annual precipitation (from the years 1971 to 2007) and standard deviation is 1517 ± 274 mm with the maximum in December (274 ± 97 mm) and the minimum in July and August (27 ± 34 mm). The mean annual temperature is 22 °C, varying from 24 °C in January to 19 °C in July.

The sugarcane was planted in 2003, and there had been two previous harvests with stubble burning in the years 2004 and 2005. The data reported here covered the first cycle of second previous harvests with stubble burning in the years 2004 and 2005. The mean annual temperature is 22 °C, varying from 24 °C in January to 19 °C in July.

The soil heat flux (F_H) on a horizontal mast 2.5 m away from the tower at 7 m height. The soil heat flux (G) was measured using four plates (REBS, Seattle, WA, USA) installed in different rows and inter-rows.

The soil water content (SWC) was measured by 10 reflectometers (CS615, Campbell SI) installed in a vertical profile, with each sensor representing layers of 30 cm, down to 3 m depth.

Data processing

The covariances between vertical wind speed (w), and the sonic temperature and the water vapor were obtained from the fluctuations relative to 30 min block averages. Coordinate rotation (Kaimal & Finnigan, 1994) was applied to force the mean w = 0. The water vapor time of travel down the sampling tube was assessed by continuously computing the absolute maximum correlation coefficients between w and a range of delayed signals (Moncrieff et al., 1997). The frequency response corrections were empirically derived based on the low-pass filter technique (see Massman & Lee, 2002; Sakai et al., 2004). The cospectral transfer function (H_{wq}) was calculated as the ratio of the measured normalized cospectrum of water vapor flux to the normalized cospectrum of heat flux (H_{wq} = [Cov(w,q)]/[Cov(T,TS)]) [1/(2πτ_w)]. The characteristic time constant response (τ_w) was obtained following Mammarella et al. (2009) supposing the water vapor was measured by a first-order response sensor (τ_w = 1/(1 + 2π τ_w f)^2, where f is the natural frequency). Because the time lag was applied before the calculation of covariances, the sensor separation and phase-shift were already corrected (see Ibrom et al., 2007).

The water vapor fluxes obtained from the open-path system were corrected for density fluctuations (Webb et al., 1980) and the self-heating effect (Burba et al., 2008).

The heat storage (S) in the air was approximated by the background variation of air temperature and humidity (see the profiles in maize by Santos et al., 2011), and the biomass heat storage was calculated assuming that the aboveground biomass was in equilibrium with the air (see Meyers & Hollinger, 2004). At intervals of approximately 20 days all the aboveground biomass (stalks, green, and dead leaves) was sampled in 10 random plots of 1 m along the planting lines, representing areas of 2.4 m². Subsamples containing 10% of the fresh weight were oven-dried at 60 °C until a constant weight was reached. The leaf area indices of green (L_g) and dead (L_d, senesced) leaves were calculated from the sampled dry biomass and the specific leaf area of green (10.2 m² kg⁻¹) and dead (9.6 m² kg⁻¹) leaves.

Gap filling

Missing half hourly fluxes amounted to 20% during the first year of measurements and 18% in the second year, within the

range reported for other sites (Falge et al., 2001; Cabral et al., 2010). The longest gap of 15 consecutive days was due to power failure after a lightning storm – a very common occurrence in this region. Due to the growth of the plants, for small gaps we used the mean diurnal variation (Falge et al., 2001) over a 5 day nonoverlapping window. When the sensible heat fluxes (H) were available, the missing LE were estimated from the energy balance as the residual (see energy balance closure results), if not LE was obtained from the relationships between LE and U*, fitted over variable time windows as a function of the data gaps.

The soil water content (SWC) was simulated during the periods when it was not available by the model Hydrus1D (Šimůnek et al., 2008), forced with the measured rainfall and evaporation data.

Bulk canopy and aerodynamic conductances

The bulk canopy conductance (g_c) was obtained from the inverse Penman–Monteith equation (Monteith, 1965) (see Cabral et al., 2003; Sakai et al., 2004), with the aerodynamic conductance for momentum transfer (g_u) being based on the wind speed and the sonic-anemometer friction velocity (u*), following Gash et al. (1999). The calculations were performed for daylight hours between 08:00 and 17:00 hours on dry days, i.e. without rainfall in the preceding 48 hours. Under these conditions, it can be assumed (based on the observed nearly exponential decay of soil evaporation) that evaporation came predominantly from the vegetation (see Grace et al., 1998; Ryu et al., 2008).

Wet canopy evaporation

The evaporation of intercepted rainfall was obtained as the residual (LE = R_n – H – G – S) in the energy balance equation (see Gash et al., 1999; van der Tol et al., 2003). We tested the performance of the sonic anemometer during rainfall based on the linear relationship between u* vs. the standard deviation of vertical wind speed (van der Tol et al., 2003; Cabral et al., 2010). The residual LE was summed during rainfall events with more than 0.5 mm h⁻¹ and after, as long as, the vapor pressure deficit was lower than 0.7 kPa, under the assumption that as the transpiration decreases during wet canopy conditions (see Tolk et al., 1996; Bosveld & Bouten, 2003; Kume et al., 2008), the measured fluxes represented water from intercepted rainfall.

Results

Fetch, flux corrections, and energy balance closure

The peak distance from the measuring point to the maximum contributing source area (Hsieh et al., 2000) estimated for a canopy height (h_c) of 0.5 m varied from 12 m (unstable conditions) to 120 m (stable conditions) and when h_c was 4 m, from 8 to 40 m, respectively. The fetch around the tower consisted of sugarcane plantation in all directions within a diameter of approximately 500 m. During unstable conditions, the cumulative source contribution achieved was >90%.

The ensemble normalized cospectra of water vapor fluxes (LE) are presented in Fig. 1a, calculated over three periods when the sugarcane was fully developed and therefore with the maximum attenuation of high frequency eddies. The estimated characteristic time constant of the first-order response sensor (τ_w) was 0.5 s when the closed-path tubing was new, observed just before the harvest in 2005; 0.85 s 1 year later (2006); and 1.5 s 2 years later (2007). In the worst cases which represented the maximum attenuation in heat fluxes obtained by the application of the estimated τ_w, the resultant water vapor flux losses were between 15% and 19%. However, the comparison between the LE fluxes measured with the closed-path without corrections (LI6262) vs. the open-path system (LI7500) during 30 days in April–May of 2007 and shown in Fig. 1b indicated that on average the closed-path LE fluxes were underestimated by 5%.

The slope of the energy balance closure relationship (H + LE = R_n – G – S) forced through the origin without LE flux corrections was 0.83 (R^2 = 0.902; P = 0.01), but after the data were spectrally corrected (Fig. 2), the closure achieved was 0.97 (R^2 = 0.88; n = 29624) and not significantly different from unity (P = 0.01).

The climate, soil water content, and canopy development

Daily averages of air temperature, humidity, and saturation deficit are presented in Fig. 3a. The air temperatures, which ranged from 12 to 27 °C, did not limit the sugarcane development (Campbell et al., 1998; Keating et al., 1999). Vapor pressures as high as 2.6 kPa were recorded in summer, while in winter values as low as 0.7 kPa were attained, the corresponding saturation deficits varied from 0.12 to 2.4 kPa. The lower winter temperatures were a consequence of passing cold fronts and were followed by periods with rising temperatures, lower vapor pressures, and higher saturation deficits. The daily totals of rainfall (Fig. 3b) were characteristic of the region: summer rainfall days with some exhibiting more than 50 mm day⁻¹ and a dry winter disrupted by passing cold fronts as already noted above. The ranges of daily soil water content (SWC) in the three layers depicted in Fig. 3b were 89–217 mm (0–0.9 m), 169–379 mm (0–1.8 m), and 282–610 mm (0–3.0 m), respectively, and were recorded in the winter and summer of the second cycle.

The reflection coefficients (albedo) for PAR and Global fluxes were calculated as the ratios between daily totals of reflected and incident flux densities (see
Fritschen, 1967) and are presented in Fig. 3c. The comparison with the mean daily albedo obtained as the average of the measurements between 11 and 13 h gave somewhat smaller results for PAR (slope $= 0.95$; $R^2 = 0.98$) and global (slope $= 0.93$; $R^2 = 0.74$) radiation fluxes.

The estimated one-sided green ($L_g$) and senesced ($L_d$) leaf area indices, as well the canopy height, are shown in Fig. 3d. The PAR albedo ($\rho_{\text{PAR}}$) exhibited a steady decrease from 0.12, just after the previous harvest to 0.05 when the $L_g$ achieved was 3.2 $m^2$ $m^{-2}$. Besides the saturation in $\rho_{\text{PAR}}$, the $L_g$ still increased and this was detected by the global radiation albedo ($\rho_{\text{G}}$). Nonetheless, $L_g$ and $\rho_{\text{PAR}}$ data exhibited the significant relationship: $\rho_{\text{PAR}} = 0.0775 L_g^{-0.2255}$ ($R^2 = 0.88$, $P = 0.01$).

There was a delay in $L_g$ of nearly 2 months between cycles, because the minimum albedo ($\sim 0.05$) in the first cycle was observed in October 2005, whereas in the second cycle, it was recorded in January 2007; however, the $L_g$ values achieved were nearly the same 3.8 and 3.6, respectively.

The decrease observed during the final phase of the cycles (approximately the last 50 days) was the consequence of herbicide (glyphosate) aerial spraying; this is a common preharvest practice whose objective is to enhance the sucrose accumulation in sugarcane stalks (see Dalley & Richard, 2010).

**Available energy and turbulent fluxes**

The time series of daily totals (water equivalent, mm $day^{-1}$) of evapotranspiration ($E$) and available energy ($A_v = \frac{R_n - G - S}{C_0}$) are shown in Fig. 4. Low $E$ values (0.1 mm $day^{-1}$) were observed in the initial phase of the re-growth; the maximum attained was 5.3 mm $day^{-1}$ when the plantation was fully developed. The overall averages and standard deviations of $E$ in each cycle were $2.1 \pm 1.1$ and $1.8 \pm 1.4$ mm $day^{-1}$, respectively. The water equivalent of the sensible heat

fluxes \((H)\) is indirectly displayed in Fig. 4 as the difference between \(A_v\) and \(E\), and whose range was from \(-0.1\) to \(5.4\) mm day\(^{-1}\) with the overall averages being \(1.6 \pm 0.6\) and \(2.1 \pm 0.9\) mm day\(^{-1}\), respectively. Bowen ratios \((\beta = H/LE)\) as high as 5 were found at the beginning of the cycles, particularly in the second cycle, but a \(\beta\) of around 0.4 was representative of the fully developed plantation.

The monthly totals (water equivalent, mm month\(^{-1}\)) of fluxes are depicted in Fig. 5. The evapotranspiration \((E)\) followed the available energy \((A_v)\) and both were reduced in the summer by the cloudy conditions and rainfall. These conditions were more intense in the second cycle (2007).

The total rainfall recorded in the first cycle (1194 mm) was below the long-term average minus one standard deviation \((1517 \pm 274\) mm) as well 12% lower than the total observed in the second cycle (1353 mm) which was considered normal, i.e. within one standard deviation of the long-term average. However, the cumulative rainfall during the initial 120 days of the first cycle (203 mm) was six times the recorded total in the second cycle. The long-term averages and standard deviations relative to April–July and May–August totals, which represent the first 120 days of each cycle, were \(190 \pm 96\) and \(142 \pm 85\) mm, respectively. Thus, while the initial 120 day period of the first cycle received the average rainfall, the second cycle received rainfall (32 mm) well below the average.

The cumulative \(E\) measured by the eddy-covariance system (Table 1) during the first (392 days) and second (373 days) cycles was 829 and 685 mm, respectively. These figures represent the second and third year re-growth of a sugarcane plantation. The total \(E\) in the first cycle accounted for 69% of rainfall, while it was 51% in the second cycle despite the total rainfall (1353 mm) being 13% greater. The evaporative fraction \((E/A_v)\) varied between 0.17 and 0.72, and the overall averages and standard deviations in each cycle were \(0.57 \pm 0.07\) and \(0.45 \pm 0.19\), respectively.

Because the wet canopy evaporation (Fig. 5) was obtained as the residual in the energy balance equation, we tested the performance of the sonic anemometer during rainfall for 573 rainy 30 min periods; the fitted slope of the linear relationship between \(u^*\) vs. the standard deviation of vertical wind speed was 1.20 \((R^2 = 0.83)\), close to the ‘universal’ value and assuring the sonic anemometer was not affected by the rainfall. The number of days in each cycle with rainfall was 112 (28%) and 141 days (38%), and the amount of rainfall recorded overnight represented 58% (697 mm) and 64% (641 mm) of the total rainfall in each cycle, respectively.

In terms of the parameters of Gash’s analytical rainfall model.
interception model (Gash et al., 1995), the overall average rainfall ($\bar{R}$) and wet canopy evaporation rate ($\overline{E_w}$) were 3.6 and 0.15 mm h$^{-1}$, respectively. The observed maximum monthly total interception (Fig. 5) was 33 mm in January 2007, and the cumulative interception losses in each cycle were 88 and 90 mm, respectively, accounting for approximately 7% of the total rainfall (see Table 1).

Sugarcane yields
Since planting in 2003, the observed sugarcane yields (stalks fresh weight, Table 2) reached the regional averages during the first three harvests (UNICA, 2011), despite the inter-annual variation in the total rainfall. However, the second-cycle yield (61.5 ± 4.0 t ha$^{-1}$) was 26% lower than the first cycle as well lower than the average for the third ratoon (76 t ha$^{-1}$).

The amount of rainfall received during the initial 120 days of growth (Table 2) gives us an indication why the expected yields were achieved with the exception of the third ratoon. The cumulative $E$ recorded during the initial 120 days of the first cycle was 157 mm (Fig. 5), therefore as long as the cumulative rainfall approximately attained this amount (157 mm) or the soil water content at the beginning of the cycle was nearly the field capacity (~140 mm m$^{-1}$) the probability of achieving the average yield increases.

The water use efficiency (WUE) calculated as Yield/$E$ was 101 kg ha$^{-1}$ mm$^{-1}$ in the first cycle and 90 kg ha$^{-1}$ mm$^{-1}$ in the second, implying a reduction of 11% in WUE.

The total rainfall received over the hypothetical fourth ratoon (Table 2) was normal (1710 mm), as was the amount of rainfall recorded for the initial 120 days of re-growth (204 mm).

Bulk canopy and aerodynamic conductances
We have calculated the hourly averages of aerodynamic conductance ($g_a$) and bulk canopy conductance ($g_c$) over days within distinct $L_g$ intervals, the results are shown in Fig. 6(a, b). The mean $g_a$ (Fig. 6a) increased from 20 to approximately 80 mm s$^{-1}$ in part in response to the change in canopy structure (Fig. 3d), but also due to the decrease in the distance between the canopy top and the sonic anemometer (9 m). The hourly averages of $g_c$ ranged from 1 to 60 mm s$^{-1}$ (Fig. 6b) and followed the increase in $L_g$ (see Fig. 3d). To verify whether there was a relationship between $g_c$ and saturation deficit ($D$), the estimated hourly $g_c$ values obtained under high irradiance conditions (PAR > 1000 μmol m$^{-2}$ s$^{-1}$) were normalized by the daily green leaf area index ($L_g$) from Fig. 3d; these results are displayed in Fig. 7. The ratio, $g_c/L_g$, represents the canopy conductance on a leaf area basis, and the averages calculated over $D$ intervals exhibited a strong potential relationship ($g_c/L_g = 16.0D^{-0.8904}, R^2 = 0.8345$).

The mean hourly aerodynamic conductance ($g_a$) calculated over friction velocity ($u_*$) intervals also exhibited a good relationship with $u_*$ as shown in Fig. 8. The linear fittings were obtained on days covering two intervals of $L_g$ which represented the initial and fully

developed phases of the sugarcane plantation. $u^*$ was also well correlated with the wind speed ($u$), the fit was given by $u^* = 0.097u + 0.088$, $R^2 = 0.9876$. The dependence of evapotranspiration on $g_c$ (see autocorrelation issue, Suyker & Verma, 2008) was assessed by plotting the ratios of daily measured $E$ against the FAO reference crop evapotranspiration ($E_o$) using Eqn (6) of Allen et al. (1998) with the measured available energy (Fig. 9). The ratios exhibited a sharp decrease for $g_c < 15$ mm s$^{-1}$ ($L_g \sim 2$) and achieved values around unity for the fully developed canopy.

**Discussion**

**Flux corrections**

The spectral corrections were comparable with the corrections reported by Sakai et al. (2004) above grassland and Mammarella et al. (2009) during the summertime in a forest, from 10% to 15%, increasing with the $u^*$ (Aubinet et al., 2001) and the relative humidity (see Ibrom et al., 2007; Mammarella et al., 2009); at the sugarcane site although the relative humidity was higher during the summer, the LE fluxes were also higher, which decreases the relative magnitude of the corrections.

**Surface characteristics**

The early senescence and reduced $L_g$ (Fig. 3d) observed in the second cycle are typical responses to water stress in sugarcane (Inman-Bamber & Smith, 2005). As reported by Roberts et al. (1990), this response can be reversed by a compensatory growth after re-watering. However, the effects during the establishment of the crop possibly have more pronounced consequences for production (Robertson et al., 1999), perhaps because at that time the deep roots were yet to be reestablished (see Smith et al., 2005; Battie Laclau & Laclau, 2009). Based on the soil water drying period in the winter of 2006 (Fig. 3b), we found that the root system extracted water from a layer of 2.1 m depth just before the harvest, and from 1.2 m afterward.

**Conductance**

The daily patterns of sugarcane canopy conductance for a given $L_g$ varied little; similar results were found by Roberts et al. (1990) and Inman-Bamber & McGlinchey (2003) who used a fixed value of 25 mm s$^{-1}$ when estimated the sugarcane reference evaporation. The relationship between $g_c$ and the saturation deficit ($D$, Fig. 7) showed that for $D$ greater than 1.5 kPa the canopy conductance was lower than 12.5 mm s$^{-1}$ which is characteristic in C$_4$ plants (Polley et al., 1992). The evapotranspiration was significantly reduced (Fig. 9) when $g_c$ was lower than 15 mm s$^{-1}$ ($L_g \sim 2$), this has already been observed in C$_4$ crops (Steduto & Hsiao, 1998; Suyker & Verma, 2008). Based on the ratio ($E/E_o$) which represents a measure of the crop coefficient (Allen et al., 1998), the maximum attained sugarcane evapotranspiration approached the reference evapotranspiration; this result contrasts with that from Inman-Bamber & McGlinchey (2003) who found a coefficient of 1.25 was representative of the fully developed crop (see Denmead et al., 2009).

**Wet canopy evaporation**

The average wet canopy evaporation ($\overline{E_w} = 0.15$ mm h$^{-1}$) observed above the sugarcane plantation was

### Table 1

<table>
<thead>
<tr>
<th>Cycle</th>
<th>Rainfall (mm)</th>
<th>Evapotranspiration (mm)</th>
<th>Available energy (mm)</th>
<th>Rainfall interception (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (393 days)</td>
<td>1194</td>
<td>829</td>
<td>1429</td>
<td>88</td>
</tr>
<tr>
<td>2 (374 days)</td>
<td>1353</td>
<td>685</td>
<td>1339</td>
<td>90</td>
</tr>
</tbody>
</table>

### Table 2

Sugarcane yields (stalks fresh weight) measured by the mill (Usina Santa Rita) and the regional averages (UNICA, 2011). The hatched columns exhibit the cycles measured in this work.

<table>
<thead>
<tr>
<th>Cane plant</th>
<th>1st ratoon</th>
<th>2nd ratoon cycle 1</th>
<th>3rd ratoon cycle 2</th>
<th>4th ratoon</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yield at mill (t ha$^{-1}$)</td>
<td>101.8 ± 4.91</td>
<td>95.9 ± 4.7</td>
<td>83.4 ± 5.5</td>
<td>61.5 ± 4.0</td>
</tr>
<tr>
<td>Regional average</td>
<td>104.8</td>
<td>94.2</td>
<td>83.1</td>
<td>71.3</td>
</tr>
<tr>
<td>Total rainfall (mm)</td>
<td>1950</td>
<td>1475</td>
<td>1194</td>
<td>1353</td>
</tr>
<tr>
<td>Initial 120 days rainfall (mm)</td>
<td>177</td>
<td>257</td>
<td>203</td>
<td>32</td>
</tr>
</tbody>
</table>

*Mean and standard deviation of five plots around the flux tower.
the same as the optimized value obtained by Finch & Riche (2010) in a Miscanthus plot and within the range (0.1–0.2 mm h⁻¹) of estimates based on the Penman-Monteith equation (van Dijk & Bruijnzeel, 2001). However, we measured the sugarcane interception loss at 7%, which was much lower than the 25% found by Finch & Riche (2010) and the 18% reported by van Dijk & Bruijnzeel (2001) for a maize, cassava, and rice mixed-crop growing in humid tropical conditions; although these authors also measured an interception loss of 8% in another plot of mixed maize and cassava, closer to our results. These high interception losses may be a consequence of the measurements being taken in

Fig. 6 Hourly averages of (a) aerodynamic and (b) bulk canopy conductance calculated over distinct time periods as given by the mean green leaf area index ($L_g$): $L_g = 0.2$ (black circles); $L_g = 0.7$ (empty squares); $L_g = 1.1$ (empty circles); $L_g = 2.3$ (black diamonds); $L_g = 3.8$ (gray squares); $L_g = 5.8$ (black triangles). For clarity, the figures contain the standard errors only for upper and lower values of conductance.

Fig. 7 Canopy conductance ($g_c/L_g$) divided by the leaf area index ($L_g$) during high insolation conditions (PAR > 1000 μmol m⁻² s⁻¹) vs. saturation deficits ($D$, kPa). The black circles represent the averages over saturation deficits intervals and the bars are the standard errors.

Fig. 8 Mean aerodynamic conductances ($g_a$, mm s⁻¹) vs. friction velocity ($u_*$) calculated when $L_g < 0.5$ (circles) and $L_g > 4$ (triangles).
small plots with more exposure to the wind, in contrast to the extensive area of sugarcane used here.

The energy balance equation terms are prone to uncertainty, an issue which must be addressed to give confidence in the residual LE estimates. During daylight rainy conditions, the typical values of fluxes were approximately: $R_n \sim 200 \text{ W m}^{-2}$; $S \sim 4 \text{ W m}^{-2}$; $G \sim 20 \text{ W m}^{-2}$, and $H \sim 60 \text{ W m}^{-2}$. The other estimated errors are in: $R_n$ of 5% (Kohsiek et al., 2007); $S$ and $G$ of 10 W m$^{-2}$ (Oncley et al., 2007), and $H$ of 10% (Mauder et al., 2007). Assuming that the errors are independent, the maximum residual LE error would be approximately 18 W m$^{-2}$ or 16% of LE (116 W m$^{-2}$). However, the rainfall interception measurements also have large uncertainties as argued by Muznylo et al. (2009); for an accuracy of 2.5% in gross rainfall and throughfall, and with the interception loss being 7% of gross rainfall, the expected error in the measured interception is approximately 22%.

The estimated 7% interception loss implies that approximately 93% of the rainfall reaches the soil either directly as throughfall or indirectly as stemflow. The soil evaporation measured by Denmead et al. (1997) in a sugarcane plantation without mulching accounted for approximately 40% of total evaporation while the green leaf area index ($L_g$) was <2.5; however, the total leaf area is greater because the senesced leaves also remain attached to the stalks in the sugarcane (see Fig. 3d) and therefore contribute to the canopy closure (Singles et al., 2008). Thus, practices like the system of trash-blanketing (Denmead et al., 2010; Farine et al., 2011), as opposed to the burnt-cane system representative of the conditions in Brazil, can effectively reduce this nonproductive water loss (see Pereira et al., 2006).

Even though the sugarcane originated in the tropics, cultivation is spread over 70 countries with significant production in subtropical regions where the growth is limited by periods of the year exhibiting low temperatures and rainfall (Campbell et al., 1998). The data presented here showed that rain-fed, sugarcane evapotranspiration was driven by the available energy when the canopy was fully developed and the maximum attained $E$ approached the reference evapotranspiration.

The total $E$ achieved in the water limited second cycle of the sugarcane (690 mm) was similar to the annual $E$ obtained in an Amazonian pasture (647 ± 144 mm) by Sakai et al. (2004) and represented 41% of the annual rainfall (1597 mm), while the total $E$ measured in the first sugarcane cycle was 20% greater and exhibited the same order of the increase (0.43 mm day$^{-1}$) estimated by Loarie et al. (2011) on conversion of other crops or pasture to sugarcane.

Based on the stalks moisture content (approx. 70%), the sugarcane WUE on a dry-weight basis (WUE$_d$) was 36.6 and 26.7 kg ha$^{-1}$ mm$^{-1}$ in each cycle, respectively. These values are comparable with soybean (average 31 kg ha$^{-1}$ mm$^{-1}$) reported by Suyker & Verma (2009) and maize (29.7 kg ha$^{-1}$ mm$^{-1}$) by Hickman et al. (2010) who also obtained considerably lower WUE$_d$ for two perennial grasses: Miscanthus (19.7 kg ha$^{-1}$ mm$^{-1}$) and Switchgrass (9.7 kg ha$^{-1}$ mm$^{-1}$). However, Suyker & Verma (2009) also observed higher WUE$_d$ in maize (52 kg ha$^{-1}$ mm$^{-1}$). High irrigated sugarcane yields (260–299 t ha$^{-1}$) were obtained in the northeast of Brazil characterized by low precipitation and high solar radiation due to low cloudiness (Waclawovsky et al., 2010). Although irrigation can be used to increase the yields of dryland crops, it is likely to be preferentially used in the production of high-value food agriculture instead of biofuel feedstocks (Farine et al., 2011).

These results should be representative of evapotranspiration under the conditions found in the areas where sugarcane expansion is planned in Brazil, and the crop is not traditionally grown, as in the central region and parts of the northeast (Marin et al., 2011), with some of them having low rainfall (Manzatto et al., 2009).

As pointed out by Hickman et al. (2010) and already observed by Loarie et al. (2011) large-scale plantings of bioenergy crops could potentially increase $E$, thereby decreasing surface temperatures, increasing humidity, precipitation, and cloud cover.

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These indirect land-use changes effects (Zenone et al., 2011) could be enhanced, because the sugarcane is one of the crops whose productivity is not expected to decline due to the climate change predictions (Buckridge et al., 2011) as the increase in temperature, and the CO₂ fertilization effect which would delay the onset of drought due to the reduction in the stomatal conductance (Oliver et al., 2009).

However, our results showed that the sugarcane agricultural system is less adapted to adverse growing conditions (see Schwalm et al., 2010) because the lack of soil water resulting from the low rainfall at the initial phase of the sugarcane re-growth limited the evapotranspiration.

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References


SUGARCANE WATER USE


