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Water vapour and carbon dioxide fluxes in sugarcane grown in megathermal humid climate in Northeastern Brazil

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Abstract

The understanding about biophysical processes taking place between the crop and the atmosphere is essential to define the appropriate management practices in order to increase crop yield. The aim of the present study is to analyze water vapour and carbon dioxide (CO_2) fluxes in sugarcane crop between the development and the mid-season as an environmental variables function, as well as to assess the correction effects on fluxes. Latent heat flux (λE) and net ecosystem CO_2 exchange (NEE) micrometeorological measurements were performed through the eddy covariance technique (EC), between June7th and November 17th, 2013 in a sugarcane crop grown in Northeastern Brazil. Days were characterized according to cloudiness conditions through the clearness index (Kt). The λE and NEE, set through the EC technique, needed correction due to heat and water vapour transfer, because CO_2 and λE raw fluxes tend to overestimate and underestimate the values, respectively. Both λE and NEE followed the daily photosynthetic solar irradiance course, but maximum values were not recorded at the same time. Apparent quantum yield and water use efficiency were higher under partly cloudy skies; both variables can be applied to simulation models in order to improve management practices and increase yield.

Keywords: conductance; eddy covariance; *Saccharum spp* L.; solar radiation; water use efficiency.
Abbreviations: DAP_Days After Planting; EC_Eddy Covariance Technique; GHG_Greenhouse Gas Emissions; NEB_ Northeastern Brazil;

Introduction

Sugarcane (*Saccharum spp*.) is among the most important crops in the world, mainly because of its high agricultural potential for sugar and ethanol production. Ethanol is an alternative to fossil fuels and helps reducing greenhouse gas emissions - GHG (Beeharry, 2001). Sugarcane is grown in approximately 8.8 million hectares in Brazil, fact that turns the country into the largest producer in the world - 665 tons in the 2015/2016 harvest (Conab, 2016).

In Brazil, sugarcane cultivation includes regions presenting different soil and climatic characteristics. Crop yield is hampered in Northeastern Brazil (NEB), mainly in the Coastal Plains of Alagoas, by annual rainfall concentration between March and August. The total of 70% of the annual rainfall is recorded at this time of the year, which is a climate feature of the region. The rest of the year imposes water deficit in periods (September to February) of larger solar radiation (Souza et al., 2004; Abreu et al., 2013; Teodoro et al., 2015). Consequently, it reduced yield due to stomatal closure, which limits carbon dioxide (CO_2) assimilation (Chaves, 2002).

Sugarcane physiological responses to the environment are commonly assessed through CO_2 assimilation, stomatal conductance and transpiration measurements applied by means of techniques based on punctual measures (Gonçalves et al., 2010; Sales et al., 2012). Although useful, these measurements do not allow analyses to be conducted throughout the day, besides using individual leaves to represent the canopy. Thus, techniques enabling canopy continuous and representative measurements, such as the eddy covariance technique (EC), are essential.

The EC is the main micrometeorological method adopted to determine the flux of atmospheric properties (latent heat - λE, sensible heat - H and CO_2) over vegetated areas for prolonged periods-of-time. The main advantages of the method lie on less disturbance in the measurement environment, on continuous measurements and on the integration of most of the surface. The basic EC principle concerns setting the covariance between vertical wind fluctuations and air temperature, water vapour or CO_2 concentration, and obtainment H, λE and CO_2 fluxes, respectively, through the gross difference of the material moving between crop and atmosphere by using the sampling turbulent fluxes (Baldocchi et al., 1988; Baldocchi et al., 2003; Smith et al., 2010).

The EC has been used in many crops to characterize water vapour patterns and CO_2 fluxes in days with different weather conditions and in crop development stages (Anderson and Verma, 1986; Baldocchi et al., 1981). However, just as it happens in other micrometeorological methods, EC application requires a number of adjustments in the raw data and assumptions must be met in order to find consistent results (Mauder et al., 2013; Webb et al., 1980).

Accordingly, the aim of the present study was to analyze water vapour and carbon dioxide fluxes in sugarcane crop between the development and the mid-season as an environmental variables function, as well as to assess the correction effects on fluxes.

Results and discussion

Weather conditions

Mean daily air temperature throughout the assessment period (73-236 days after planting - DAP) was 24.1 °C, minimum and maximum temperatures were 18.0 to 31.7 °C (Fig. 1a). Mean overall daily solar irradiation (Hg) was 16.5 MJ m^{-2} and ranged from 2.4 to 23.5 MJ m^{-2} (Fig. 1b). Mean vapour pressure deficit (VPD) was 0.76 kPa, it ranged from 0.26 to 1.19 kPa (Fig. 1C); minimum and maximum wind speeds at 2.0 m were 0.62 and 1.73 m s^{-1}, respectively, and the mean speed was 1.03 m s^{-1} (Fig. 1c). The total rainfall during the period was 1.103 mm, maximum daily rainfall was 81.5 mm (99 DAP); mean rainfall frequency was one event every 1.3 day (Fig. 1d). According to the SWC variation, the crop did not face water stress, since it recorded W_{uc} above the threshold (Fig. 1d). However, WSC decreased between 187 and 200 DAP due to lack of rainfall or to daily rainfall event below 2.0 mm associated with the highest air temperatures recorded during the period (Fig. 1d). Dry periods between September and October are common in the study region, other studies involving sugarcane also show water deficit up to 50 mm (Abreu et al., 2013).

Effect of flux corrections

The linear regression forced through the origin showed that the λEvalues resulting from EC were 9.9% lower than the corrected values; therefore, it was worth adopting the WPL correction procedures (Fig. 2a). The German study about pasture conducted by Liebethal and Foken (2003) evidenced that WPL corrections increase λE values from 2% to 3%, as well as that positive corrections at daytime are necessary and that negative ones are demanding at nighttime periods.

The NEE measured through the EC technique represents the difference between gross CO_2 assimilation and plant and soil component losses. Values were higher than those corrected by approximately 20% after NEE correction through WPL (Fig. 2b), according to Liebethal and Foken (2003), who reported reduction by 25% to 30% in pasture after WPL correction. Figure 2b makes it clear that the difference between the adjusted and obtained data increases as fluxes get higher. According to Liu (2005), WPL adjustments reduce NEE magnitude by 1.4 and 2.5 times at night and day periods, respectively. When λE and sensitive heat flux (H) are near zero in the transition between night and morning, for instance, adjustments are not necessary; therefore, gross NEE measurements are equal to the adjusted values, since adjustments are proportional to the heat and water vapour transfer.

Diurnal pattern of fluxes

The diurnal patterns of NEE, ET and IRf components were assessed for six days; different cloudiness conditions and growth rates were taken into account. There were fluctuations throughout the diurnal period according to the IRf variation when partly cloudy sky days were taken into account (89, 116 and 219 DAP). When IRf values were not maximum, maximum NEE values at 89, 116 and 219 DAP were recorded at 8:30 am (1.17 mg m^{-2} s^{-1}), 9:30 am (1.33 mg m^{-2} s^{-1}) and 12:30 pm (1.47 mg m^{-2} s^{-1}), respectively. However, maximum ET was recorded at 11:30 am (0.20 g m^{-2} s^{-1}), 13:30 pm (0.18 g m^{-2} s^{-1}) and 10:30 am (0.21) at 89, 116 and 219 DAP, respectively, similar to the maximum IRf. Overall, fluxes increased between morning and noon, and decreased in the afternoon at days of clear sky (96, 123 and 206 DAP). The NEE showed maximum values at 9:00 am during 96 (0.89 mg m^{-2} s^{-1}), at 206 DAP (1.61 mg m^{-2} s^{-1}); and 10:30 am, at 123 DAP (1.15 mg m^{-2} s^{-1}). Again, it did not meet the highest IRf values. Unlike partly cloudy days, the maximum ET meets the highest IRf, only at 123 DAP (0.21 g m^{-2} s^{-1}), at 11:30 am. Maximum ET was recorded at 11:30 am (0.19 g m^{-2} s^{-1}) and 9:30 am (0.21 g m^{-2} s^{-1}) at 96 and 206 DAP, respectively, at days other than the partly cloudy ones.

The highest diurnal NEE values were more often recorded in the morning shift, and such result did not meet the maximum IRf. The same result was found in other crops (soybeans and vine), and it was attributed to the fact that increased solar radiation and air temperature intensity at daylight ,at higher IRf, reduces stomatal conductance in order to avoid excessive water loss, which, consequently, decreases CO_2 assimilation by the leaves (Anderson et al., 1984; Guo et al., 2014.). With regard to the present study, maximum air temperatures were recorded between 11:30 am and 14:30 pm, close to the largest IRf magnitude (Fig. 3).

Regarding the cloudiness effects, the apparent quantum yield (α) was higher during partly cloudy sky days (Table 1) due to greater solar radiation scattering at days of higher cloudiness degree, which leads to better solar radiation use by adjacent leaves. These results corroborate those by Suyker et al. (2004), who analyzed the effect of diffuse solar radiation on CO_2 uptake in corn crops and found cloudy-days α 23% higher than in clear days. Other studies involving wheat, triticale, corn and sunflower in Southwestern France showed mean α in cultures at days of higher cloudiness degree 52% higher than in clear days (Béziat et al., 2009). In addition to α the highest WUE values were also recorded in partly cloudy sky days (Table 1), since water vapour losses reduced, and α was higher, under cloudiness condition. The WUE values between 11 and 13 mg CO_2 g^{-1} $(H_2O)^{-1}$ were recorded for sugarcane in São Paulo region, Brazil; however, gross CO_2 assimilation was taken into account (Cabral et al., 2013). Overall, α and β were 0.015 mg J^{-1} and 1.756 mg m^{-2} s^{-1}, respectively, when the rectangular hyperbolic was set between IR_f and NEE (Fig. 4). Both parameters are of paramount importance to estimate carbon assimilation through different mechanistic models, as suggested by Liu

Table 1. Daily net ecosystem CO_2 exchange values (NEE), crop evapotranspiration (ET), intercepted photosynthetic solar irradiance (IRf), water use efficiency (WUE) and apparent quantum yield (α) as a function of cloudiness.

	Sky condition	NEE	ET	IRf	WUE	α
DAP (DOY)	...	g CO_2 m^{-2}	g H_2O m^{-2}	MJ m^{-2}	mg CO_2 g^{-1} (H_2O)	g CO^2 MJ^{-1}
89 (174)	Partly cloud	22.3	3897.7	2.6	5.7	8.5
96 (181)	Clear	19.0	4299.6	3.5	4.4	5.5
116 (201)	Partly cloud	26.5	3671.5	4.5	7.2	5.9
123 (208)	Clear	29.7	4649.3	6.2	6.0	4.8
206 (291)	Partly cloud	35.2	3559.7	7.7	9.9	4.6
219 (304)	Clear	43.0	4451.3	9.9	9.7	4.3

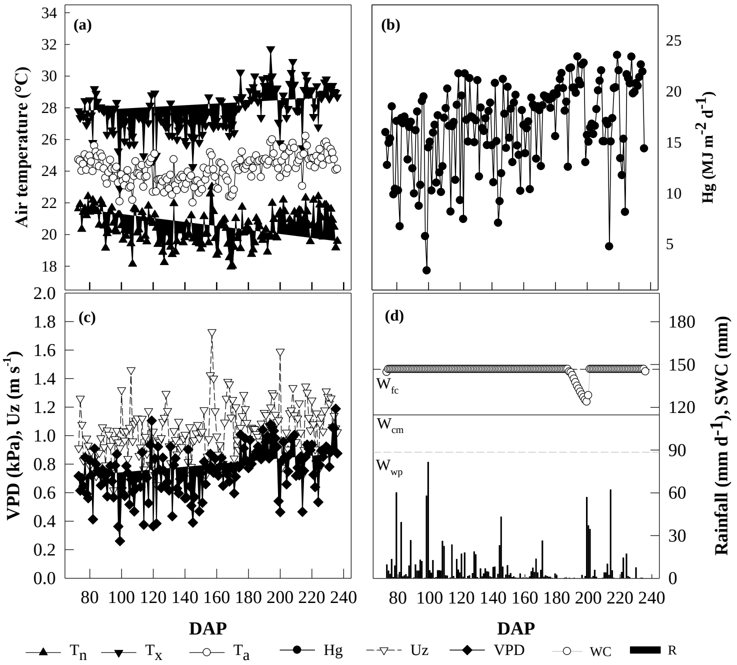


Fig 1. Daily variation in minimum - Tn, maximum - Tx and average air temperature - Ta (a), vapour pressure deficit - VPD (b), wind speed - u_z (c), soil water content - SWC and rainfall - P (d). Soil water content at field capacity (W_{fc}), critical moisture (W_{cm}) and permanent wilting point (W_{pw}).

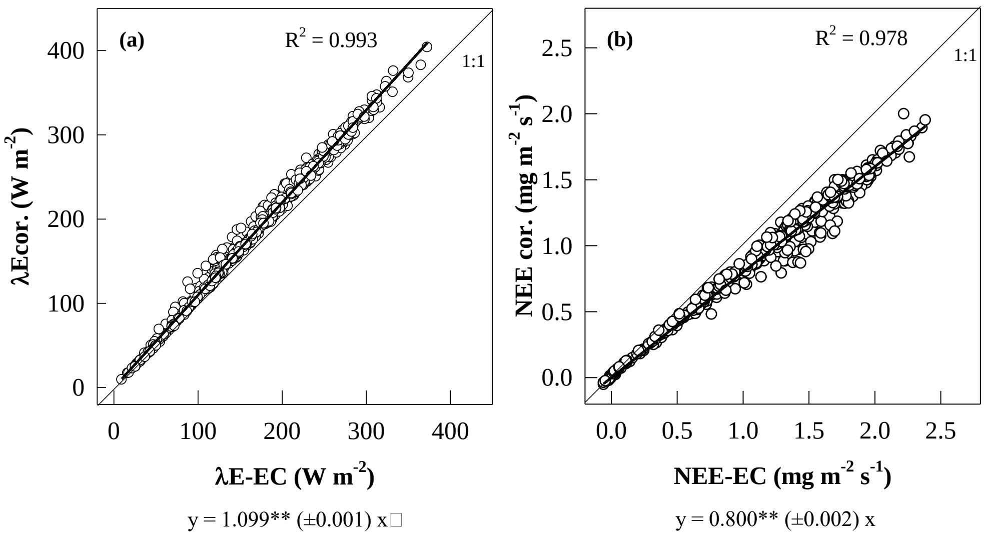


Fig 2. Relationship between latent heat flux (λ E-EC) (a) and net ecosystem CO_2 exchange (NEE-EC) (b) obtained by the eddy covariance technique and corrected by WPL (NEE-$EC_{cor.}$, λ E-$EC_{cor.}$) for sugarcane. Figures in brackets represent the standard error of estimate.

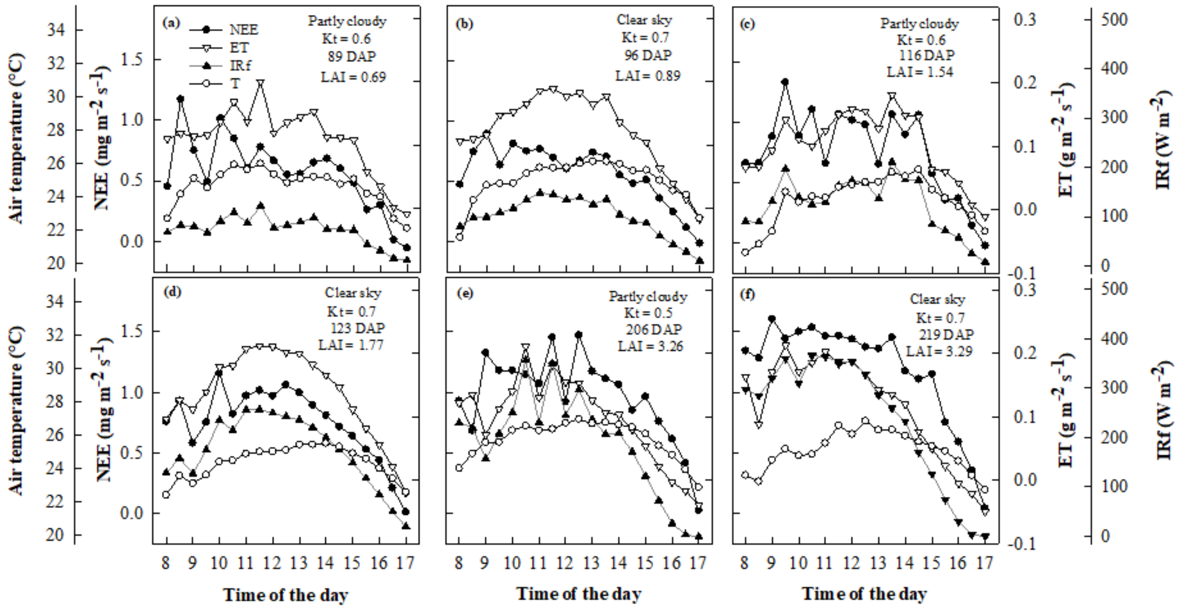
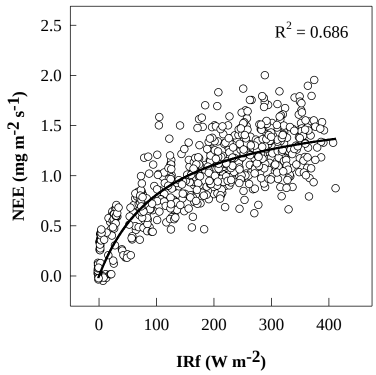
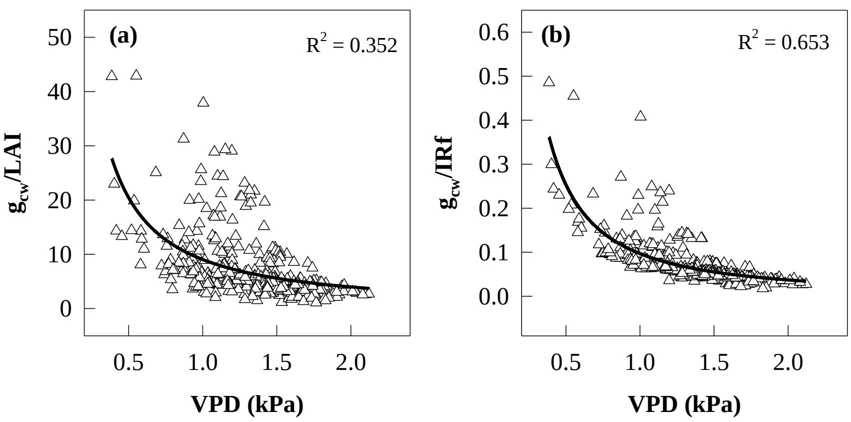


Fig 3. Diurnal variation of net ecosystem exchange (NEE), crop evapotranspiration (ET) and intercepted photosynthetic solar irradiance (IRf) under partly cloudy and clear sky conditions.



$$NEE = \left\{ \frac{1.756^{**} (\pm 0.001)\ 0.015^{**} (\pm 0.058) IRf}{1.756^{**} (\pm 0.001) + 0.015^{**} IRf\ (\pm 0.058)} \right\}$$

Fig 4. Relationship between net ecosystem CO_2 exchanges values (NEE) and intercepted photosynthetic solar irradiance (IR_f) during the sugarcane cycle. Figures in brackets represent the standard error of estimate.



$g_{cw}/LAI = 9.043^{**} (\pm 0.296)\ VPD^{-1.176^{**} (\pm 0.076)}$ $g_{cw}/IRf = 0.097^{**} (\pm 0.002)\ VPD^{-1.386^{**} (\pm 0,047)}$

Fig 5. Relationship between vapour pressure deficit (VPD) and canopy water vapour conductance normalized by the leaf area index -LAI (a) and photosynthetic solar irradiance intercepted - IRf (b) during the sugarcane cycle. Figures in brackets represent the standard error of estimate.

(1996), who adopted α and β 0.011 mg J^{-1} and 1.570 mg m^{-2} s^{-1} for sugarcane, respectively (Harrt and Burr 1967). Moreover, models used to estimate biomass production also adopt this parameter, so that its determination in different locations and cultivars makes simulation more efficient.

Canopy conductance

Studies in the literature have often assessed the VPD influence on g_{cw} by normalizing VPD through LAI. It is done in order to find conductance on leaf area basis (Cabral et al., 2012); moreover, conductance can be normalized through photosynthetic solar irradiance, since the radiation is a primary incentive to stomatal opening, whereas VPD is a closure stimulant (Grantz and Meinzer, 1991; Grantz et al., 1987). Thus, g_{cw}/IAF showed the trend to decrease as VPD increases, so that values close to 1.5 kPa g_{cw}/IAF decrease to approximately 10 mm s^{-1} (Fig. 5a). These results corroborate those by Cabral et al. (2012) in their study about sugarcane cultivation in São Paulo region, Brazil, wherein VDP 1.5 kPa resulted in g_{cw}/IAF lower than 11.5 mm s^{-1}. When g_{cw}/IRf was taken into account, 1.5 kPa decrease was also observed (Fig. 5b).

Higher adjustment was observed between VPD and $g_{cw,}$ when g_{cw} was normalized through LAI (R^2 = 0.663) (Fig. 5a), whereas when only the LAI was taken into account, the adjustment was lower (R^2 = 0.32) (Fig. 5b). Thus, it should be noticed that IRf, besides incorporating the effect from light - which exerts direct influence on conductance, also encompasses the effect from LAI, which is directly linked to the capacity of intercepting solar radiation.

Materials and methods

Plant materials

The study was carried out between June 7th and November 17th, 2013 in the Coastal Plains of Alagoas, in a sugarcane cultivation area (approximately 17.1 ha), Rio Largo County, Alagoas State, Northeastern Brazil (9° 28' 04" S; 35° 47' 34" W, 137 m). The soil in the region was classified as argisolic distrocohesive Yellow Latosol of intermediate/clayey texture and flat topography. The volumetric soil moisture at field capacity (θ_{fc}) and wilting point (θ_{wp}) were 0.244 and 0.147 m^3 m^{-3}, respectively. These values were determined through soil water retention curve; the overall density was 1.500 kg m^{-3} to profile 0.6 m. The climate was classified as megathermal humid, with moderate water stress in summer, and large water excess in winter, according to Thornthwaite and Mather´s classification. The mean annual rainfall is 1800 mm and the mean air temperature is 25.4 °C - ranging from 19.4 °C (August) to 31.8 °C (January); mean relative air humidity is 70% (Souza et al., 2004).

Sugarcane planting, cultivar RB867515, was held in March 25th 2013, at 84 DOY (day of the year), in double row spacing (0.4 x 1.4 m). Soil preparation consisted of subsoiling and harrowing; fertilization was composed of 52 kg ha^{-1} of N, 143 kg ha^{-1} of P_2O_5 and 130 kg ha^{-1} of K_2O. Crop growth was characterized by the canopy height and leaf area index (LAI) throughout the cycle; LAI was calculated as the ratio between the leaf area of all green leaves (Hermann and Câmara, 1999) and the soil area occupied by plants.

Radiometric measurements

Global solar irradiance (Rg) was measured with the aid of a pyranometer (CM3, Kipp & Zonen, The Netherlands). Measurements taken to determine net radiation (Rn) were performed in a net radiometer (CNR1, Kipp & Zonen, The Netherlands) installed 0.30 m above crop canopy and connected to a datalogger (CR1000, Campbell Scientific, Inc., Logan, USA). The datalogger was programmed to perform measurements every 10 s, and to store the means taken every 5 min. Irradiation (MJ m^{-2}) was calculated through the integration between irradiances (W m^{-2}). The daily clearness index (Kt) was determined through the ratio between global solar radiation (Hg) and extraterrestrial solar radiation (Ho) (Allen et al., 1998) by adopting the following classification: Kt ≤ 0.3 – cloudy sky, 0.3 < Kt <0.7 - partly cloudy sky and Kt ≥ 0.7 - clear sky (Iqbal, 1983).

The photosynthetic solar irradiance (Rf) was estimated as 44% of the Rg (Ferreira Junior et al., 2012), which is the mean value for the region; transmitted photosynthetic irradiance (TRf) was calculated based on Beer's Law (Hipps et al., 1983):

$$\mathrm{TRf} = \mathrm{Rf}\ \exp^{(-\mathrm{K}\ \mathrm{IAF})} \quad (1)$$

where:

K = sugarcane light extinction coefficient equals to 0.58 (Inman-Bamber 1994).

Thus, the photosynthetic solar irradiance intercepted by canopy (IRf) was set through the difference between Rf and TRf.

Micrometeorological measurements

The EC system was assembled on a micrometeorological tower, at height 5.0 m, above soil surface in the prevailing wind direction (Baldocchi et al., 2003). It was composed of three-dimensional sonic anemometer (3D CSAT3A, Campbell Scientific, Inc., Logan, USA) and by infrared gas analyzer (EC150, Campbell Scientific, Inc., Logan, USA). The three-dimensional sonic anemometer was used to measure vertical wind fluctuations and the sonic temperature. The infrared gas analyzer was the equipment of choice to measure water vapour and CO_2 concentrations at frequency 10 Hz. Both, the λE and the net ecosystem CO_2 exchange (NEE) were set according to the covariance between vertical wind fluctuations, and water vapour and CO_2 concentrations, respectively (Baldocchi 2003; Li et al., 2008.). These variables were corrected for air density fluctuations after the measurements were taken due to heat and water vapour transfer, as suggested by Webb, Pearman and Leuning - WPL (Webb et al., 1980). Subsequently, these data were stored for 30 min, on average, in datalogger (CR3000, Campbell Scientific, Inc., Logan, USA).

Canopy water vapour conductance (g_{cw}, mm s^{-1}) was determined through the Penman-Monteith equation (Steduto and Hsiao, 1998):

$$g_{cw} = \frac{\gamma \lambda E g_{aw}}{s\ (-Rn - G) + \rho_a c_p g_{aw}\ \mathrm{VPD} - \lambda E (s + \gamma)} \quad (2)$$

Where;

γ psychrometric constant;
s = slope vapour pressure (kPa °C^{-1});
ρ_a = air density (kg m^{-3});
c_p = specific air heat capacity at constant pressure (J kg^{-1} °C^{-1});
VPD = vapour pressure deficit (kPa).

The soil heat flux (G) was estimated at 1.4 % of the Rn, which represents the mean value collected from sugarcane studies conducted in the region. The aerodynamic water vapour conductance (g_{aw}) resulted from the following equation: (Thom, 1972; Steduto and Hsiao, 1998):

$$g_{aw} = \frac{u_z\ k^2}{\left[\ln\left(\frac{z-d_0}{z_0}\right)\right]^2 + \left(1{,}35u*^{1/3}\right)\ k\ \ln\left(\frac{z-d_0}{z_0}\right)} \quad (3)$$

Where:
z = height above the ground (m),
u_z = wind velocity at height z (m s^{-1});
u* = friction velocity measured in sonic anemometer (m s^{-1});
d_0 = zero plane displacement (m);
z_0 = roughness length (m);
k = von Karman constant (0.42).

The d_0 and z_0 were calculated at 0.13 and 0.64 canopy height, respectively.

Both the NEE and λE measurements, which included spurious data exclusion during rainfall events, equipment malfunction and u* lower than 0.15 m s^{-1} (Zhao et al., 2007; Hernandez-Ramirez et al., 2010, Schmidt et al., 2012), were subjected to quality control. Energy balance closure was set through the Bowen ratio (Twine et al., 2000; Sanchez et al., 2009), because the closure degree was 0.64. The NEE response to IRf was assessed by adjusting the rectangular hyperbolic function (Suyker et al., 2004):

$$\mathrm{NEE} = \left\{\frac{(\beta\alpha\mathrm{IRf})}{[\beta + (\alpha\mathrm{IRf})]}\right\} \quad (4)$$

Where:
β = NEE value at light saturation (mg CO_2 m^{-2} s^{-1});
α = apparent quantum yield or initial slope of the light response curve (mg CO_2 J^{-1}).

Water use efficiency [(WUE, mg CO_2 g $(H_2O)^{-1}$)] was calculated through the ratio between NEE and crop evapotranspiration (ET), which was found by dividing λE by the vaporization latent heat (2.45 MJ kg^{-1}).

Soil water content measurements

Soil volumetric moisture (θ) was measured in TDR-type probes (Time Domain Reflectometry, CS16 model, Campbell Scientific) vertically equipped with rods at depths 0.0-0.3 and 0.3-0.6 m, and calibrated to the local ground (Varble and Chávez, 2011). Available water capacity (WAC, mm) was calculated by multiplying the difference between θ_{fc} and θ_{wp} by root system depth (0.6 m). Soil water content (SWC, mm) resulted from the product between θ and depth. Easily available water (EAW, mm), which is defined as the water fraction the crop extracts from the soil without stress, derived from the product between WAC and water availability factor (p), which was equal to 55 % (Allen et al., 1998). Finally, storage at critical moisture (W_{cm}) was calculated from the difference between WAC and EAW. The other meteorological data resulted from the automatic weather station of Federal University of Alagoas, which is located close to the crop.

Statistical analyzes were based on linear and non-linear regressions and the Student's test (t) was used to check adjustment coefficient significance.

Conclusion

Corrections made in the net ecosystem carbon dioxide exchange indicate that the raw measurements performed through the eddy covariance technique were overestimated, whereas water vapour fluxes were underestimated. The diurnal patterns of carbon dioxide, and water vapour fluxes, showed the trend of photosynthetic solar irradiance intercept; however, maximum values were not recorded at the same time, so that other variables, such as air temperature and vapour pressure deficit, may help stomatal closure and reduce conductance at maximum irradiance hours. Canopy conductance normalization to water vapour through photosynthetic solar irradiance intercept allowed better explaining the vapour pressure deficit influence on this variable. The apparent quantum yield and water use efficiency in sugarcane at days of partly cloudy skies are higher than in clear sky days.

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