Australian Journal of Crop Science
AJCS
AJCS 13(09):1422-1428 (2019) ISSN:1835-2707
doi: 10.21475/ajcs.19.13.09.p1257

Micrometeorological methods to estimate sugarcane evapotranspiration in coastal northeastern region of Brazil

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Abstract

The aim of the present work was to evaluate the performance of Bowen ratio-energy balance method, as well as the energy balance closure by Eddy covariance technique for a sugarcane crop in Brazilian northeastern region. Micrometeorological measurements were carried out between June 7th and November 17th, 2013. Latent and sensible heat fluxes were determined through Eddy covariance technique (EC) and by the Bowen ratio-energy balance method (BREB), considering two approaches. The first, estimated the air temperature and water vapour pressure gradient in two levels above the canopy. The second method measured the air temperature and water vapour pressure at the first level and the surface temperature from radiometric measurements. Latent heat flux was also estimated as energy balance residue from determinations of the sensible heat flux by Eddy covariance. The degree of energy balance closure was dependent on the time of the day considered. Bowen ratio - energy balance estimated from the first approach, showed the best agreement with the eddy covariance measurements to estimate latent heat flux, while in the second case, when the Bowen ratio was estimated using the surface temperature, the linear relationship was the most discrepant. Therefore, the Bowen ratio conventional method is more suitable for estimating latent heat flux in sugarcane.

Keywords: eddy covariance, Bowen ratio, energy balance, *Saccharum* spp.
Abbreviations: ET_Evapotranspiration; NEB_Northeastern Brazil; EC_Eddy Covariance Technique; BREB_Bowen ratio - energy balance; EBC_Energy balance closure; BREB_S_Bowen ratio – energy balance method with surface temperature, EC_R_residual eddy covariance technique

Introduction

The understanding of the biophysical processes that occur in the soil-plant-atmosphere system is critical for the determination of water needs and definition of management techniques in agricultural systems. Considering that water is a resource in great demand and that laws regulate its use, crop evapotranspiration (ET) is one of the variables of major interest in agriculture, especially in regions where the resource is a limiting factor (Jabloun and Sahli, 2008), like in Northeastern Brazil (NEB).

In NEB, sugarcane (*Saccharum s*pp) is one of the major crops and its production is restricted by the temporal-spatial heterogeneity of rainfall, in addition to the fact that the period of higher (lower) solar radiation coincides with lower (greater) water availability (Silva et al., 2013, Teodoro et al., 2015). Thus, the use of irrigation complementing rainfall is necessary to reach high yields.

The use of irrigation requires the correct determination of the crop water requirement for the rational use of water resources. ET can be quantified by means of approaches based on water balance, micrometeorological techniques and plant transpiration (Wilson et al., 2001). Micrometeorological techniques are widely used. However, their use is restricted to research for the validation of methods that are simple to use and adequate to the climatic conditions of each region (Liu et al., 2012; Er-Raki, et al., 2013). Among the micrometeorological methods, the Bowen ratio - energy balance (BREB) is widely used to estimate ET due to its simplicity. However, BREB has some problems associated with measurements of net radiation (Rn) and air temperature and humidity gradients, which results in invalid or inconsistent estimates (Ohmura, 1982; Silva et al., 2012).

BREB is commonly used in studies to estimate sugarcane ET (Silva et al., 2015; Nassif et al., 2014); however, due to the inherent problems of this method, other approaches and modifications such surface temperature from radiometric measurements can be used to improve the results (Lhomme et al., 1994; Norman et al., 2000). The validation of BREB to estimate ET has been performed considering as standard the measurements obtained by the Eddy covariance technique (EC). The principle of EC is to determine the average

covariance between vertical wind fluctuations and air temperature or water vapour concentration to obtain sensible (H) or latent heat fluxes (λE), respectively (Baldocchi, et al., 1988; Baldocchi, 2003). However, this method also presents a series of uncertainties resulting from unsatisfied assumptions and the chaotic nature of turbulence (Mauder et al., 2013), which results in discrepancy between available energy and heat fluxes (λE and H). In this case, the energy balance closure might be required (Twine et al., 2000).
According to the above, the aim of the present work was to evaluate the performance of BREB, as well as the energy balance closure by EC measurements under a sugarcane crop in the coastal region of the state of Alagoas, Northeastern Brazil.

Results and discussion

Energy balance closure

The description of the environmental conditions as well as the daily patterns of the energy fluxes as a function of the meteorological conditions are described in Rocha et al. (2018). Therefore, in the present study the results will concentrate on discussing the estimation methods of energy balance components in sugarcane by micrometeorological technique. EBC by EC was assessed on daytime scale and during morning and afternoon shifts. The daytime index was 64% (Fig. 1A); during the morning 57% (Fig. 1B), and during the afternoon the value was maximum (76%) (Fig. 1C). The non-closure of the energy balance with the EC technique has been reported in several studies. Wilson et al. (2002) analyzed EBC from several measurement environments of the FluxNET research network and reached an average value of 80%, with higher index during the afternoon. This characteristic was attributed to the underestimation of storage terms, as heat retention in biomass, which are higher during the morning. The discrepancy between the Rn - G and λE + H relationship was also observed in other crops, such as cotton (0.76), potato (0.79) and maize (0.81) (Chavez et al., 2009; Parent and Anctil, 2012; Ding et al., 2010).
Achieving complete energy balance closure is not possible from experimental data (Foken et al., 2006). When it comes to the EC, the causes for discrepancy between energy availability and output fluxes are attributed to the occurrence of advection, loss of low frequency components, instrument limitations, heat retention in crop biomass and neglect of other energy balance terms (Barr et al., 1994; Meyers and Hollinger, 2004; Oncley et al., 2007; Li et al., 2005). Thus, when EBC by EC is not satisfactory, it is recommended to calculate λ by the relationship between λE and H obtained by EC, and to recalculate both fluxes by means of equations 2 and 3, respectively (Twine et al., 2000; Steinwand et al., 2006; Sànchez et al., 2009). The adoption of energy balance closure by the Bowen ratio has been adopted for sugarcane, including for EBC higher than the present study, such as < 70% in Sertãozinho, Brazil (Cabral et al., 2003) and 80% in Xicoténcat, Mexico (Zermeño-Gonzalez et al., 2012). Hence, the data referring to λE discussed in the present work will come from the energy balance closure by the previously described method.
After energy balance closure by the Bowen ratio (λ), we observed that 63% of the available energy (Rn-G) was used in the evapotranspiration process (λE), while the remaining 37% were used to heat up the air (H) (Fig. 2A). The use of most of Rn - G by λE was due to the soil water availability resulting from the various precipitation events during the measurement period, which did not limit the evapotranspiration process during most of the evaluation period. When considering the partitioning of available energy by the EC_R method, 76% of energy was consumed by λE and 24% for H (Fig 2B). The BREB method was the one that most approached the EC, with 66% for λE and 34% for H (Fig. 2C). BREB_S presented the greatest discrepancy in relation to EC, with 91% (λE) and 9% (H) (Fig. 2D).
When BREB was used in sugarcane under full irrigation, Silva et al. (2011) observed that 81% of Rn-G observed for λE, while the remaining 19% for H. Using the BREB method in sugarcane in coastal tablelands of Paraíba, Brazil, Azevedo et al. (2014) reported that 82% of Rn was consumed by λE, while H and G consumed 16% and 2.0 %, respectively.
The BREB and EC_R methods showed the lowest RMSE, 61.1 and 77.1 W m^{-2}, respectively, while the BREB_S had the highest, 130.9 W m^{-2}. The "d" followed the same RMSE pattern, with the highest index for the BREB method (0.97), followed by the EC_R (0.96) method and lower for the BREB_S (0.90) method. In general, according to the slope (b), the tendency of the BREB method was to overestimate λE determined by EC by approximately 6%. The EC_R and BREB_S methods also showed an overestimate tendency of 20 and 36%, respectively (Table 1). According to the t test ($p < 0.05$), only the BREB method presented no difference in relation to the EC method.
The values mentioned in the present study are in agreement with those observed for canopy forest in China, where RMSE and "b" were 61.4 W m^{-2} and 0.80, respectively, which were also reported an underestimate of BREB in relation to EC (Shi et al., 2008). In relative terms, EC measures tend to favor H, while BREB estimates favor λE (Barr et al., 1994). This disparity between EC and BREB can be attributed to the λE correction procedures, which tend to increase these fluxes disproportionately in relation to H, with direct effect on the H/λE (λ) ratio of EC (Wolf et al., 2008).

Temporal pattern of daily evapotranspiration

The ET daily course considered two specific days, one with clear sky and one partially cloudy. It indicated the same daily variation among methods (Fig. 3). Considering EC, maximum ET occurred at 13.5 h (0.33 mm 30 $min.^{-1}$) and 11.5 h (0.38 mm 30 min^{-1}) during days July 20th (partly cloudy) and July 27th 2013 (clear sky), respectively (Fig. 3A). For the EC_R method, ET peaks were observed at 13.5 h on July 20th (0.39 mm 30$min.^{-1}$) and at 11.0 h on July 27th (0.44 mm 30$min.^{-1}$) (Fig 3B). By the BERB method, during July 20th and July 27th, ET peaks were recorded at 13.5 h (0.31 mm 30 $min.^{-1}$) and 11.5 h (0.31 mm 30 $min.^{-1}$) (Fig. 3C), respectively. Considering BREB_S, maximum ET occurred at 13.5 h (0.40 mm 30 $min.^{-1}$) on July 20th and 11.5 h (0.45 mm 30 $min.^{-1}$) on July 27th, respectively (Fig. 4D).
The daily ET was evaluated from values accumulated during the days, in which EC determinations were valid. By the EC, the accumulation was 122.5 mm, with an average of 4.0 mm

Table 1. Wilmott's index of agreement (d), root mean square error (RMSE), slope coefficient (b) and Student's test (t) for the Bowen ratio - energy balance (BREB), Bowen ratio - energy balance with surface temperature and residual Eddy covariance technique (EC_R) in relation to the eddy covariance technique (EC). Mean evapotranspiration (ETa) and relationship with reference evapotranspiration (ET_0).

Method	Statistic index			Evapotranspiration	
	d	RMSE (W m^{-2})	b	ETa (mm d^{-1})	ET/ET_0
EC	-	-	-	4.0	0.89
BREB	0.97	62.1	$1.06^{n.s.}$	4.2	0.96
BREB_S	0.90	130.9	1.36^{*}	5.4	1.22
EC_R	0.96	77.1	1.20^{*}	4.6	1.04

*, n.s., significant and not significant by a t-test at a 5% probability level, respectively.

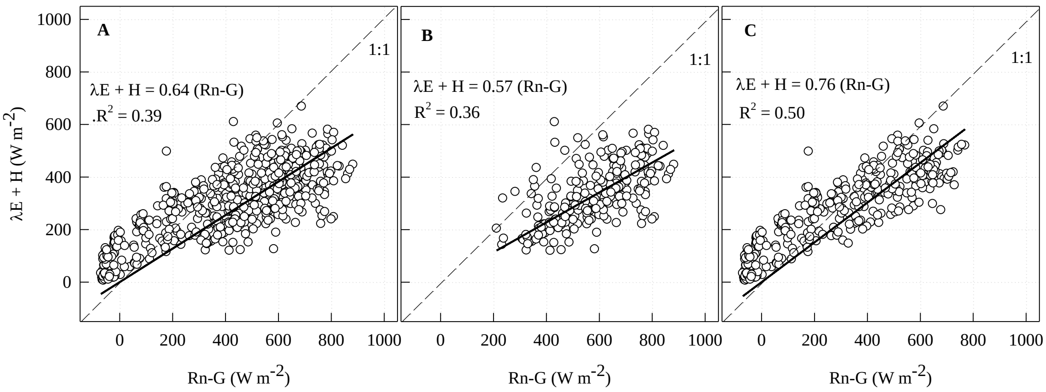

Fig 1. Energy balance closure by the Eddy covariance technique considering total daytime (A), morning (B) and afternoon fluxes (C) during sugarcane cultivation. Latent (λE) and sensible heat flux (H), net radiation (Rn) and soil heat flux (G).

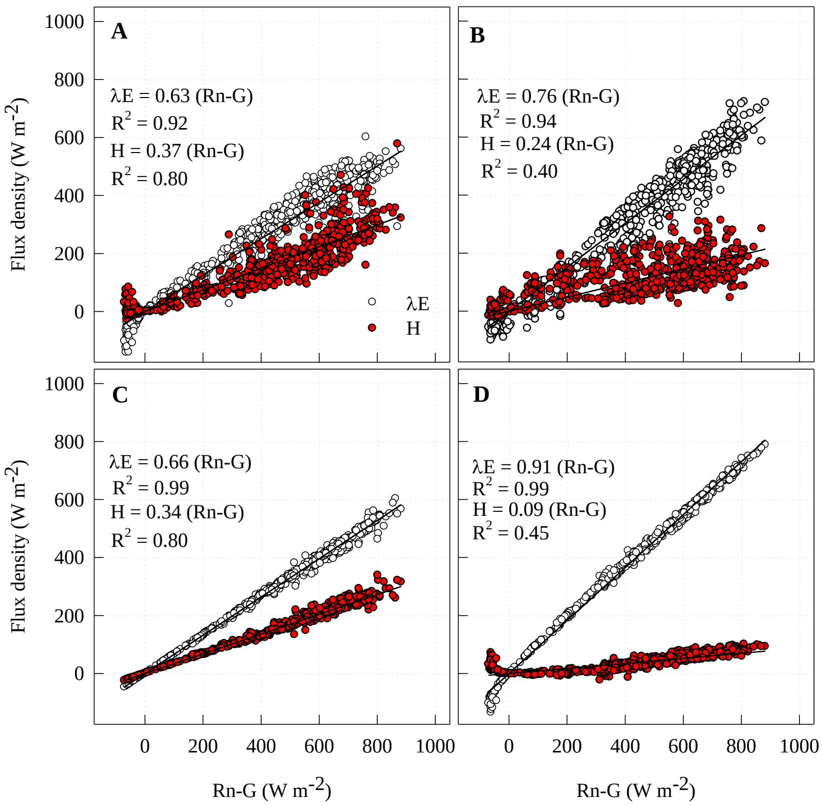

Fig 2. Partition of the available energy (Rn-G) during sugarcane cultivation between latent (λE) and sensitive heat flux (H) with Eddy covariance technique - EC (A), residual eddy covariance technique EC_R (B), Bowen ratio- energy balance - BREB (C) and Bowen ratio - energy balance with surface temperature - BREB_S (D).

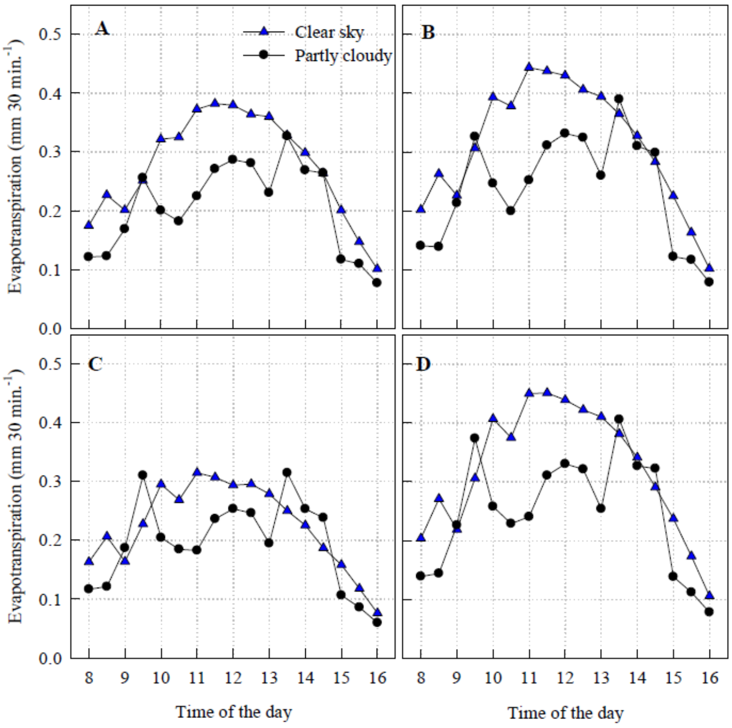

Fig 3. Instantaneous evapotranspiration of sugarcane during the days 07/20 (partly cloudy) and 07/27/2013 (clear sky) with Eddy covariance technique - EC (A), residual eddy covariance technique - EC_R (B), Bowen ratio - energy balance - BREB (C) and Bowen ratio - energy balance with surface temperature - BREB_S (D) methods.

d^{-1}, which resulted in ET/ET_0 ratio of 0.89, close to estimates by the BREB method, which presented total ET of 131.5 mm, mean of 4.2 mm d^{-1} and ET/ET_0 ratio of 0.96. Estimates by EC_R and BREB_S methods show a larger difference from observations, with averages of 4.6 and 5.4 mm d^{-1} and ET/ET_0 ratios of 1.22 and 1.04, respectively (Table 1).
Regarding BREB, the values agree with those reported by Nassif et al. (2014) for sugarcane in the region of São Paulo, Brazil, where the mean ET/ET_0 ratio was 0.87, with a variation between 0.9 and 1.1. Silva et al. (2012) reported mean ET of 4.7 mm d^{-1}, with ET/ET_0 ratios between 0.65 and 1.10 using BREB in the Brazilian semi-arid. ET obtained by EC was superior to that reported by Denmead et al. (2009) in two regions of Australia, where the mean ranged from 3.3 to 3.7 mm d^{-1}.

Materials and methods

Experimental area and plant materials

Micrometeorological measurements were conducted between June 7th and November 17th, 2013 in commercial sugarcane growing area (17.1 ha) (9°28'04"S, 35°47'34" W and 137 m), sugarcane plant cycle, cultivar RB867515, with planting carried out on March 25, 2013. The climate of the region, according to the Thornthwaite and Matter method, is characterized as humid, megathermal, with great water excess in the winter and moderate deficiency in the summer. The average annual rainfall is 1789 mm, with air temperature and relative humidity of 25.4 °C and 81.8%, respectively. The soil is classified as Yellow Latosol with medium-clay texture and flat topography (Ferreira Junior et al., 2014).

Radiometric measurements

Measurements to determine the net radiation (Rn) were obtained by a net radiometer installed above the crop canopy (CNR1, Kipp and Zonen, The Netherlands) and connected to an automatic data acquisition system (CR1000, Campbell Scientific Inc., Logan, USA) programmed to record the radiation every 10 seconds and store averages every 5 min. The short-wave balance (SWB) was obtained by the difference between global (Rg) and reflected solar irradiance (Rr). The long-wave balance (LWB) was determined by the difference between surface (Rs) and atmosphere emittance (Ra). Subsequently, Rn was calculated by the difference between SWB and LWB (Allen et al., 1998). 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).

Eddy covariance technique (EC)

The eddy covariance system (EC) was installed in the center of the crop in the predominant wind direction with fetch above 1:100 m. Vertical wind fluctuations and sonic temperature were measured using a three-dimensional sonic anemometer (CSAT3A 3D, Campbell Scientific Inc., Logan, USA). The water vapour concentration was quantified using an infrared gas analyzer (EC150, Campbell Scientific Inc., Logan, USA). In both devices, data were obtained at a frequency of 10 Hz and corrected for density effects due to the transfer of water vapour and heat (Webb et al., 1980). λE and H fluxes were determined by the covariance between vertical wind fluctuations and water vapour concentration or sonic temperature fluctuations, respectively, in averages of 30 min (Baldocchi, 2003; Li et al., 2008).

The quality of the measurements of fluxes by EC was quantified by the degree of energy balance closure (EBC), represented by the relationship between output fluxes (λE + H) and the available energy (Rn - G). The data obtained by the EC were submitted to quality control, with the exclusion of physically inconsistent data, during rainfall events and malfunctioning of the EC equipment (Hernandez-Ramirez et al., 2010; Schmidt et al., 2012). For comparison purpose, λE was also calculated as the residue (EC_R) of the energy balance equation (λE = Rn - G - H), considering the H values of EC and soil heat fluxes densities (G) (Twine et al., 2000), which estimated of Rn (1.4%). This represents the average value obtained from sugarcane studies in the region (Santos, 2009).

Bowen ratio-energy balance method (BREB)

We estimated the Bowen ratio - energy balance, in addition to determining λE by EC and EC_R methods (Bowen, 1926). Thus, two air temperature and relative humidity sensors (HMP45C, Campbell Scientific, Logan, Utah) were installed at two levels above the vegetated surface. The first one at 0.25 m above the crop canopy and the second one at 3.20 m from the first. The Bowen ratio (β) was determined by the following equation:

$$\beta = \frac{H}{\lambda E} = \gamma \frac{\Delta T}{\Delta e} = \gamma \frac{t_1 - t_2}{ea_1 - ea_2} \qquad (1)$$

where: ΔT and Δe represent the difference of air temperature and the current air-water vapour pressure (kPa) between the two measurement levels, respectively; t_1 and t_2 indicate the air temperature (°C) at levels 1 and 2, respectively; $\gamma = c_p P/\varepsilon\lambda$ is the psychrometric coefficient; P is the atmospheric pressure (kPa); ε is the molecular weight ratio of dry air water vapour (0.622); ea_1 and ea_2 are the current water vapour pressures at levels 1 and 2 (kPa), respectively (Allen et al. 1998). λE and H fluxes by BREB were calculated by the following equations:

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

$$H = \frac{\beta}{1 + \beta}(Rn - G) \qquad (3)$$

The consistency analysis of data provided by BREB was based on Unland et al. (1996), who recommends data exclusion when the absolute difference between air water vapour pressures of the two measurement levels is less than 0.005 kPa and β values close to -1, specifically for the range of |1 + β| < 0.3.

Bowen ratio–energy balance method with surface temperature (BREB)

The BREB method was also applied considering the surface temperature obtained by radiometric measurements (BREB_S), according to Penman (1948):

$$\beta = \frac{H}{\lambda E} = \gamma \frac{\Delta T}{\Delta e} = \gamma \frac{t_o - t_2}{es_o - ea_2} \qquad (4)$$

Where; es_0 is the saturation vapour pressure (kPa) obtained by radiometric measurements and t_0 is the surface temperature (°C), determined from the following equation:

$$t_0 = \sqrt[4]{\frac{E_0}{\varepsilon_0 \sigma}} \qquad (5)$$

Where; E_0 is the emittance of the sugarcane canopy (W m^{-2}); ε_0 is the emissivity of sugarcane leaves, 0.995 (Idso et al., 1969); σ is the Stefan-Boltzman constant (5.67 10^{-8} W m^{-2} K^{-4}). At the end, the instantaneous λE values were integrated (MJ m^{-2} day^{-1}) and the sugarcane ET (mm day^{-1}) was calculated by the division between λE and the water vaporization latent heat (2.45 MJ kg^{-1}).

The daily reference evapotranspiration (ET_o, mm d^{-1}) was determined by the Penman-Monteith-FAO method, parameterized to a hypothetical culture, as described in FAO Bulletin No. 56 (Allen et al., 1998):

$$ET_0 = \frac{0{,}408\ \Delta\ (Rn - G) + \left(\gamma \frac{900}{T + 273}\right) u_2 (e_s - e_a)}{\Delta + [\gamma\ (1 + 0{,}34)\ u_2]} \qquad (6)$$

Where; u_2 is the wind speed at 2 m height (m s^{-1}); T is the air temperature at 2 m height (°C); e_s is the air-water saturation vapour pressure (kPa); and Δ is the slope vapour pressure (kPa $°C^{-1}$). Meteorological data required for the determination of ET_0 were obtained from the automatic agrometeorological station (Campbell Scientific, Logan, Utah, USA) located close to the field area.

Statistical analysis

The comparison of λE values was based on statistical index and considered the fluxes determined by EC as the standard (observed). The accuracy was represented by Root Mean Square Error (RMSE) and Wilmott's index of agreement (d), which varies between 0 and 1, and the closer to 1, the greater the approximation between estimated and observed data (Willmott, 1982). The tendency of estimates in relation to the observations was determined by the slope (b) forced to pass through the origin and the precision evaluated by determination coefficient (r^2). The Student's test (t) ($p < 0.05$) was used to verify difference between estimated and observed means.

Conclusions

The energy balance closure using the Eddy covariance technique showed higher value during the afternoon than in the morning. Latent heat flux estimates by the energy balance - Bowen ratio were closer to fluxes obtained by the Eddy covariance technique, followed by the residual Eddy covariance technique.

Acknowledgements

The authors would like to thank the Coordination for the Improvement of Higher Education Personnel (CAPES) for the scholarships and Santa Clotilde Plant S/A for offering the study area.

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