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Study of CO_2 Flow and Energy Balance in a Transition Forest in Southwestern Amazonia by the Modified Bowen Ratio Methods and Eddy Covariance

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Abstract

Background: The study of CO_2 fluxes and energy between the surface and the atmosphere, contribute to investigate natural or anthropic effects on ecosystems. Meteorological and micrometeorological stations are usually equipped with instruments capable of measuring these flows directly or indirectly, using Eddy Covariance (EC) and Modified Bowen Ratio (MBR) methods, respectively. The coefficients of turbulent diffusivity are physical quantities directly correlated to magnitudes of flows, and difficult to measure.
Objective: The objective of this work was to evaluate the use of turbulent diffusivity coefficients in CO_2 flux estimates for the (MBR) method.
Methods: The experiment was conducted in Amazonia / Cerrado transition forest, where a meteorological tower was installed. The fluxes of CO_2, latent and sensitive heat obtained by the EC and MBR methods were compared by the Scheirer-Ray-Hare statistical test to detect possible differences between flows, seasons, and methods. The CO_2 flux, estimated by the Modified Bowen Ratio method, was tested as a function of turbulent diffusion coefficients of sensible and latent heat.
Results: In both Bowen ratio and Eddy Covariance methods, available net energy prioritized the latent heat flux during the dry season. The energy balance by Eddy Covariance method was underestimated in 30% in the humid season and 5% in the dry season. The energy balance by the Bowen ratio method closed at 100% during the dry season, but during the wet season it was underestimated at 4%.
Conclusion: The CO_2 fluxes measured by the Eddy Covariance method and estimated by the Modified Bowen Ratio method as a function of the latent heat turbulent diffusion coefficient, did not show significant differences between their estimates, between the seasons and between the methods. The sensible heat flux showed significant difference between the methods of Bowen ratio and Eddy Covariance, and between the seasons.

Keywords: turbulent diffusivity, atmospheric stability, atmosphere-biosphere interaction.

INTRODUCTION

The Amazon-Cerrado transition forest has been drawing special attention to studies aimed at quantifying energy exchanges, carbon balance and the search for assistance in the use of methodologies to estimate the different changes that occurred due to land use and occupation (DANELICHEN et al. to 2015). The analysis of the dynamics of the energy flows of the terrestrial surface allows to identify anthropic and natural alterations in an ecosystem (VELASQUE, et al., 2018).

Among the micrometeorological techniques of mass and energy measurement, the most used is the Eddy Covariance (EC) system and the Bowen Energy / Reason Balance (BERB) method (BOLINIUS et al., 2016). EC is a direct measurement method that determines the turbulent fluxes without any empirical assumptions being widely used to estimate fluxes of momentum, heat and trace gases.

The BERB method has been used to estimate the energy balance and evapotranspiration (ET) of vegetated surfaces (BIUDES et al., 2015). However, the use of this method in conjunction with trace gas concentration makes it possible to estimate its fluxes, especially CO_2 (WOLF et al., 2008).

The estimation of trace gas fluxes by energy balance is a technique known as the Modified Bowen Ratio (RBM) that follows the K-theory (PEREIRA et al., 2013). One of the assumptions of the BERB and RBM is to assume equality of the coefficients of turbulent diffusion (K), similarity theory, to the transport of energy and mass (FOKEN et al., 2006). In different atmospheric conditions, this technique can cause errors in the estimations of its flows (WOLF et al., 2008).

The closure of the energy balance obtained through EC and RBM methods during the day rests on two factors. The first factor is related to the accuracy of the measurement of surface energy fluxes, including the balance of radiation (Rn), soil heat flux (G), and canopy storage (S), which directly determines the magnitude of H + LE for the Bowen Reason system, which is a measure of energy balance closure in EC studies. The second factor is the different tendency of the two systems to partition the available energy towards the H and LE flows (WOLF et al., 2008; BOLINIUS et al., 2016).

1.1 Objective

Therefore, the objective of this work was to evaluate the use of the turbulent diffusivity coefficients kv and kh in the estimates of CO_2 fluxes between the Ratio Modified Bowen in Amazon-Cerrado transition forest.

2. MATERIAL AND METHODS

2.1. Study area

The study was conducted in a transition forest area, Amazonia-Cerrado, in the south of the Amazon forest, 50 km NE of the city of Sinop at 11 ° 24 '43.4 "S and 55 ° 19' 25.7" W , State of Mato Grosso, Brazil, at 423 m above sea level, where a meteorological tower of 42 m high was installed.

2.2. Instrumentation used

The radiation balance (Rn) over the transition forest canopy was measured by means of a radiometer balance (Net Radiometer, Kipp & Zonen Delft, Inc., Holland) at 40 m height. The air temperature (Tar) and relative humidity (RH) gradients were obtained by two thermohygrometers model HMP54AC (Vaisala, Inc., Helsinki, Finland) installed at heights of 41 and 28 m. Soil heat flux (G) was obtained by two soil heat meters (HFT-3.1, REBS, Inc., Seattle, Washington) installed at a depth of 5 cm. The carbon dioxide concentration was measured at 41 and 28 m in height by a closed-loop infrared gas analyzer (LI-820, LI-COR, USA). The data for analysis were obtained between January and December of the year 2007. Data were separated in two seasons, one wet (January to April) after (October to December), and one dry (May to September).

2.3. Estimation of Latent and Sensitive Heat Flows by the Ratio Bowen Method

Bowen (1926) formulated the ratio β between the sensible heat flux H and the latent heat flux LE on a surface as a function of the vertical gradients of temperature and humidity. The criteria for acceptance of estimates of the Bowen method followed Perez et al. (1999). The latent (LE) and sensitive (H) heat flux can be calculated using the following equations:

$$LE = \frac{-R_n - G - \Delta S}{1 + \beta} \tag{1}$$

$$H = -R_n - G - \Delta S \quad \frac{\beta}{1 + \beta} \tag{2}$$

where ΔS is the energy stored in the canopy and the biomass was calculated according to the parameterization proposed by Moore and Fisch (1986)

2.4. Estimation of CO_2 Flow by the Modified Ratio Bowen Method

The coefficient of turbulent diffusion of the latent heat (k_v; m^2 s^{-1}) and sensitive (k_h; m^2 s^{-1}), were calculated by means of the equations:

$$K_v = \left(\frac{LE}{\rho_a \lambda}\right) \cdot \left(\frac{\Delta z}{\Delta q}\right) \tag{3}$$

$$K_h = \left(\frac{H}{\rho C_p}\right) \cdot \left(\frac{\Delta z}{\Delta T}\right) \tag{4}$$

where ρ is the air density (mg m^{-3}), Cp is the specific heat at constant pressure (1,00467 J g^{-1} k^{-1}).

The net CO_2 flux of the transition forest (F_c; µmol $m^{-2}s^{-1}$) was estimated by the equation (Pereira et al., 2013; Araújo et al., 2010):

$$F_c = K_c . \left(\frac{\Delta C}{\Delta z}\right) \cdot \left(\frac{1000}{44}\right) \tag{5}$$

in which k_C is the turbulent diffusion coefficient of the CO_2 flux (m^2 s^{-1}), ΔC is the difference of CO_2 concentration (mg m^{-3}) between the two heights considered. Applying the similarity theory for turbulent transport, we considered $k_C = k_v = k_h$ (WOLF et al., 2008).

2.5. Estimation of CO_2 Flow by the Eddy Covariance Method

The Eddy Covariance (EC) method calculates the correlation between the high-frequency temporal deviations of the wind speed with the horizontal wind speed temporal deviations and the scalar concentration. The turbulent fluxes of CO_2 (Fc), LE and H were measured by the following equations:

$$F_c = \rho\overline{w'C'} \tag{6}$$

$$LE = \rho\lambda\overline{w'q'} \tag{7}$$

$$H = \rho c_p\overline{w'T'} \tag{8}$$

where w' is the variation of the vertical component of the wind velocity with respect to its mean, q is the specific air humidity, T is the air temperature, C is the CO_2 concentration, c_p is the specific heat of the air at pressure constant, ρ is the dry air density at 20 ° C and λ is the latent heat of evaporation (BOLINIUS et al., 2016).

2.6. Atmospheric Stability

The atmospheric instability was evaluated using the dimensionless parameter (Z/L), which reflects the relative influence of dynamism and shear on the conduction of the vertical mixture (WOLF et al., 2008).

$$\frac{Z}{L} = -\frac{KgHZ}{\rho C_p T U_*^3} \tag{9}$$

where L is the Monin-Obkholve height method, Z is the height of the temperature sensor, ρ is the air density at temperature T, C_p is specific heat capacity at constant pressure, U_* is the wind friction velocity , K is the Von-Karmam constant, H is the sensible heat flux, and g is the acceleration of local gravity (MOHAN and SIDDIQUI, 1998).

2.7. Statistical analysis

Robust regression and Kendall's Tau correlation was used to better understand flow dynamics and Hir. The Scheirer-Ray-Hare nonparametric statistical test was used to detect possible differences between stations, methods and interactions between stations and methods (Table 1). All processing was done using the R language in the CoCalc cloud processing environment.

3. RESULTS AND DISCUSSION

The coefficient of determination (R^2) between (LE + H + G + ΔS) versus (Rn) was 0.96 and 0.69 for the RB and EC method during the wet season, respectively (Figure 1A and B). During the dry season, it was 1.00 for the RB method and 0.95 for the EC, with p-value> 0.01 (Figure 1C and D). The non-closure of the energy balance by the RB method during the wet season may be related to the meteorological conditions (low-temperature amplitude, which underestimates H), since it closed at 100% during the dry season (Figure 1A).

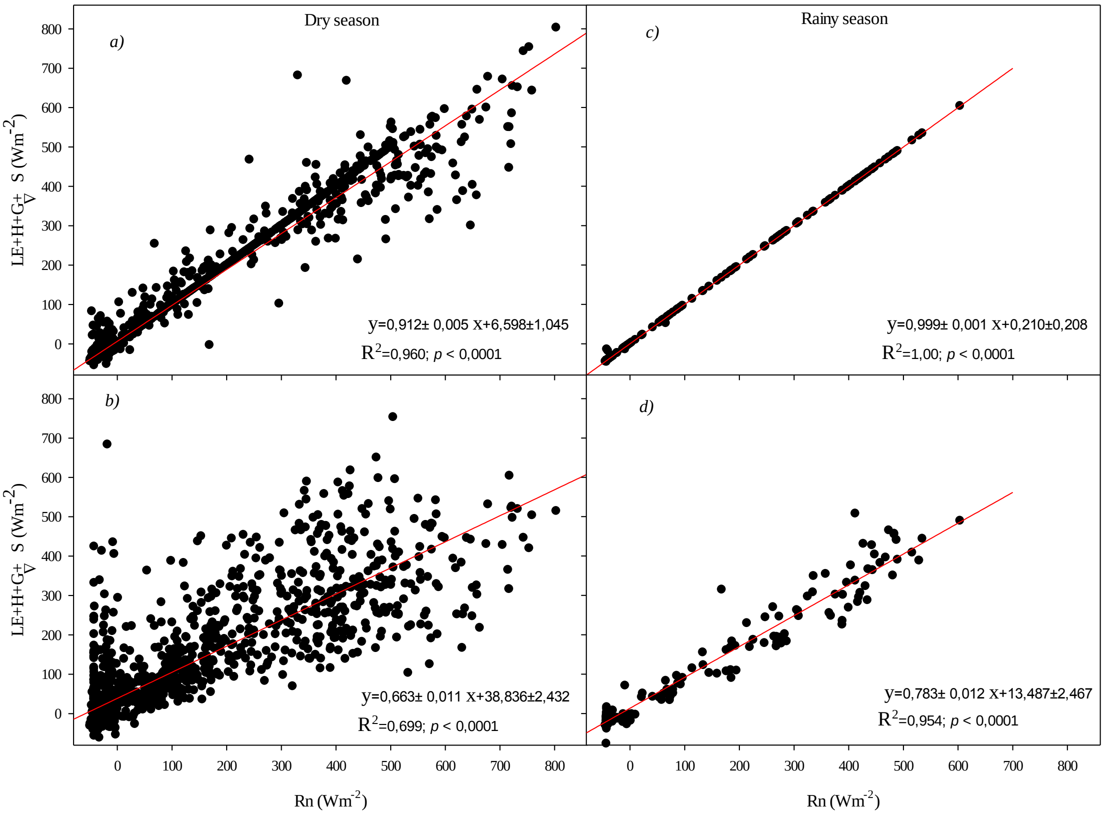

Figure 1: The relationship between the available net energy (Rn) and the latent heat (LE), sensible (H), soil (G) and biomass (ΔS) energy stocks. During the wet season for the methods of Bowen Ratio (RB) (a), Eddy Covariance (EC) (b) and dry season for (RB) (c) and (EC) (d) methods.

The correlation between the fluxes estimated by the RBM method in contrast to the atmospheric stability parameter showed a significant correlation of 0.094 for correlation between (F_{K_h}x *Z/L*) and -0.143 for (F_{K_v}x *Z/L*) (Table 1).

The Scheirer-Ray-Hare test detected differences between the mean ranks of the CO_2 flows F_{EC,K_h}, *LE* and *H* in relation to the station factor (dry and wet). For the method factor (EC, RB e RBM), there was a difference between the mean ranks of the CO_2 flows F_{EC,K_h} and *H*, but did not present a difference between the average ranks of the CO_2 flows F_{EC,K_v} and LE. For the interaction factor (station and method), there was no difference between the mean ranks of the flows.

Table 1: The correlation matrix of Kendall's Tau, where *Z/L* is the atmospheric stability parameter, F_{K_h} and F_{K_v} are the CO_2 fluxes estimated by the RBM as a function of the turbulent diffusivity coefficient of the Sensitive and Latent Heat respectively, Rn is the available net radiation and F_{EC} is the CO_2 flux measured by the EC. * p-value <0.05.

Variable	Z/L	F_{K_h}	F_{K_v}	R_n	F_{EC}
Z/L	1,000				
F_{K_h}	0,094*	1,000			
F_{K_v}	-0,143*	0,201*	1,000		
R_n	-0,434*	-0,024	0,150*	1,000	
F_{EC}	0,367*	0,111*	-0,032	-0,403*	1,000

The flow measured by the EC system had a mean variation, better pronounced than the flow estimated by the RBM method. Both the CO_2 flux estimated as a function of k_v and k_h, showed oscillations throughout the daily period. Another characteristic of RBM in relation to EC is that during both seasons (wet and dry), the CO_2 flux reached positive peaks in the first hours of the morning. This may have been a result of the accumulation of CO_2 stored below the canopy (VOURLITIS et al., 2011; ARAUJO et al., 2010), because during the night period the atmosphere presents conditions of low air turbulence, causing errors in the EC system estimates (Miler et al., 2004). At dawn, with the beginning of the convective process, the stored CO_2 is released, resulting in a peak in the CO_2 flow between 6 and 9h (PEREIRA et al., 2013 CHAPIN et al., 2011). Due to different methodologies (EC and RBM), the RBM method was more sensitive to the increase of the CO_2 concentration, near the canopy surface, in the first hours of the morning than the EC. Regarding the RBM method, CO_2 flow was lower during the wet season -4. 0μmolm^{-2}s^{-1} at 12h. During the dry season th,e fluxes were -16. 0μmolm^{-2}s^{-1} and -22. 0μmolm^{-2}s^{-1} both at 14h, estimated as a function of the turbulent diffusivity coefficients k_h and k_v respectively. Another distinction between the flows estimated by the RBM method is that there were more pronounced oscillations during the wet season. These oscillations may be due to the variation of the sky cover during the wet season. The flow measured by the EC was -22.0 and -20. 0μmolm^{-2}s^{-1} at 12h during the wet and dry seasons, respectively.

The flow of CO_2 measured on the canopy of a vegetated area is a result of the dynamics between the ecosystem and the atmosphere due to the prevailing meteorological conditions (PEREIRA et al., 2013).

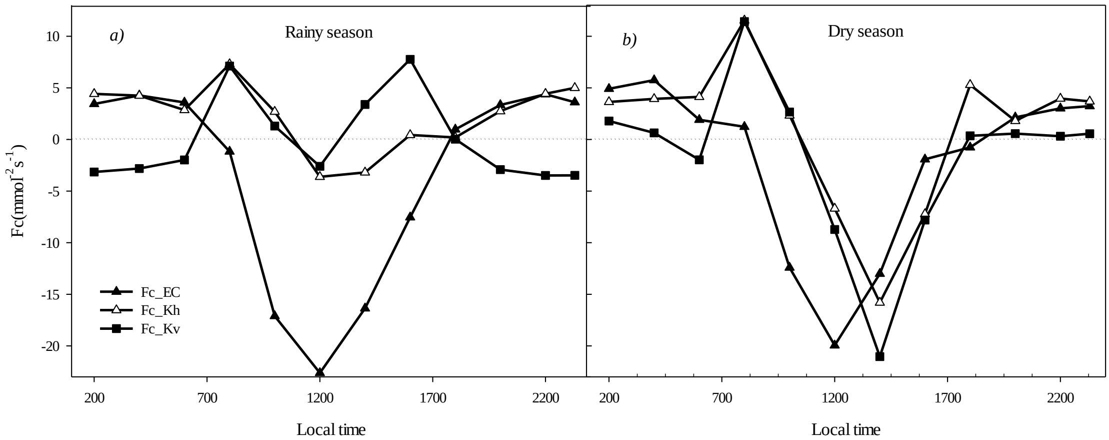

Figure 2: Daily cycle of the CO_2 flux by the methods of the EC and RBM as a function of the coefficients of turbulent diffusivity k_h and k_v. During the wet and dry seasons (a and b).

Pereira et al. (2013) estimated the daily CO_2 flux through the RBM method, during days of different sky cover in cambará forest in the northern Pantanal in Brazil, observed that the highest flow values occurred in days of clear sky and that during the period of sky covered by clouds occurred the major events of oscillations of the flow of CO_2, LE and PAR radiation. They argue that these variables were strongly correlated with the disposition of solar radiation.

According to Machado et al., (2004), when studying 25-year data of the diurnal and seasonal variability of the convective cover over the Amazonian forest, Cerrado and deforested area verified that during the rainy season, the atmosphere is close to the saturated adiabatic ratio, or humid, because of the large area covered by convective clouds. And that during the transition from drought to the rainy season, there is a catabolic flux of air mass, due to the decrease in temperature and an inversion of atmospheric equilibrium conditions (Z/L), increasing and reaching its maximum value, probably due to the increased surface temperature and humidity.

Makarieva et al. (2013) examined and contributed to the theory of how condensation influences atmospheric pressure by removing water mass from the vapor phase, latent heat flux. From the fundamental physical principles, they show that condensation is associated with the lowering of the air pressure in the lower atmosphere and that the water vapor supplied to the atmosphere by means of evaporation represents potential energy storage available to accelerate the air, thus causing the winds.

The interaction between the interior of the forest and the overlying air occurs entirely at night. Therefore, it is during the intermittent, convective events that much of the CO_2 from the sub-forest respiration is transferred into the atmosphere (OLIVEIRA et al., 2013).

Hollinger and Richardson (2005), when comparing two EC systems in a forest ecosystem observed that the uncertainty between the flows of LE and CO_2 increased during the period of growth (leaf area index) in the rainy season, but the uncertainty in H was not affected by the phenological state of the vegetation. This suggests that the sources and sinks of heat, water, and CO_2 on the surface are spatially distinct and have different functional controls. It is controlled by the thin layer of the elements (leaves, stems, and soil), heat exchange, as well as the temperature gradient between these elements and the atmosphere. Contrast LE is composed of transpiration, which is controlled by conductance between leaf mesophyll and leaf layers, water vapor pressure deficit, evaporation which in turn is controlled by soil moisture and litter layer (SANCHES et al., 2009). Photosynthesis is almost entirely governed by plant response to light, temperature, relative humidity, and air velocity, and may vary on small spatial and temporal scales depending on cloud cover and microclimate (MIRANDA et al., 2005). The transport of CO_2 from the soil to the atmosphere depends on the respiration of the soil itself, which is influenced by temperature, humidity, texture, and diffusivity within the soil itself (PINTO Jr. et al., 2009), and its conductance above the surface, depending on air pressure and velocity (REICHSTEIN et al., 2005).

Cooper et al. (1992), using five EC systems and two RBMs to measure evaporation on agricultural land, found that LE in a short time varied by 20% at a distance of 50m between the instruments, and up to 35 % at a distance of 100m. The observed variation between the instruments was compared with the variation of the vapor pressure deficit, so they verified that the difference between the instruments was due to the spatial variability in the gas exchanges underlying the ecosystem rather than an instrumental error.

The analysis of Barr et al. (1994) concluded that the turbulent diffusivity coefficients used in the RBM method were unequal in atmospheric neutrality conditions due to non-correlation between K_h and K_v during this period.

In grazing area in Kazakhstan, Wolf et al. (2008) compared the flow data, using two EC systems and an RBM system find an R^2 of 0.72 between H flows, between LE was 0.71 and 0.59 for the CO_2 flux, they found that most of the differences between the flows occurred under conditions of atmospheric neutrality, that is, when (Z/L) tends to zero, when there was also great variation in the correlation coefficient between scalars. As they estimated the CO_2 flux by the RBM method, only as a function of K_h, they claim that the dissociation between the turbulent diffusivity coefficients (K_h, K_v and K_{CO_2}) during the turbulent transport of these scalars introduces the possibility that the coefficient K_h calculated from the vertical temperature gradient $(\Delta T/\Delta Z)$ in equation 4 may not apply to CO_2 and LE emissions, when there is a low correlation between $(\Delta T/\Delta Z)$ and CO_2 emissions.

CONCLUSION

The sensible heat flux showed a significant difference between RB and EC, and between dry and wet seasons. The difference between the CO_2 fluxes by the EC and RBM methods as a function of K_v, (F_{EC,K_v}) did not show a significant difference between the stations and between the methods.

In both RB and EC methods, available net energy prioritized the latent heat flux (LE) even during the dry season. The non-closure of the energy balance by the EC method is within the limits found in the literature, 10 to 30%, which during the wet season was underestimated by approximately 30% and in the dry season by 5%. The energy balance by the RB method closed at 100% during the dry season, but during the wet season, it underestimated at 4%.

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