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Evapotranspiration and control mechanisms in managed Amazonian forest in, Pará, Brazil

Diego Ribeiro de Aguiar[1]*, Raimundo Cosme de Oliveira Junior[2], Troy Patrick Beldini[3], Rodrigo da Silva[4] and Raphael Tapajós[4]

[1]Laboratório de Manejo Florestal, Instituto Nacional de Pesquisas da Amazônia (INPA), Manaus, Amazonas, Brazil.
[2]Napt Medio Amazonas, Empresa Brasileira de Pesquisa Agropecuária (Embrapa), Santarém, Pará, Brazil.
[3]Instituto de Biodiversidade e Floresta, Universidade Federal do Oeste do Pará (UFOPA), Santarém, Pará, Brazil.
[4]Instituto de Engenharia e Geociência, Universidade Federal do Oeste do Pará (UFOPA), Santarém, Pará, Brazil.

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This work examines whether management causes changes in evapotranspiration (ET) surface conductance (g_s), aerodynamic conductance (g_a) and the decoupling factor (Ω) in managed and natural forest sites in a tropical rain forest in the Amazon. The study was conducted in the Tapajós National Forest (FNT) in managed (logged) and natural (unlogged) forests, which have micrometeorological towers for data capture. For ET estimation, the Penman-Monteith (PM) and Eddy Covariance (EC) equations were used. The models were significantly different only for unlogged (PM 134.9±15.9 mm.month^{-1} and EC 100.9±11.1 mm.month^{-1}), while the means of the logged site were PM 111.1±15.7 mm.month^{-1} and EC 108.5±18.3 mm.month^{-1}. Each area has different characteristics for the surface variables, g_a, g_s and Ω, and therefore the sites were different from each other for the study variables. However, logged ET did not differ for the PM, while EC decreased in the year after the management intervention, and was then followed by an increase.

Key words: Tapajós, water vapor, surface, aerodynamic conductance, decoupling factor.

INTRODUCTION

The Amazon has a key role in regional and global climate systems, in large part due to contributions to evapotranspiration (ET) of the surface and therefore for the global carbon cycle. However, the Amazon forest currently faces risks due to deforestation pressure and climate change (Randow et al., 2014).

Forest management is a method of selective logging that limits damage to the forest by cutting lianas, doing road planning, using skidders with articulated wheels and conducting directional felling (Palace et al., 2007).

Historically, forest management research emphasized mainly silvicultural aspects and changes in species composition, but little has been investigated on post-operation changes in biogeochemical cycles and their

*Corresponding author. E-mail: dribeiroaguiar@yahoo.com.br.

effects on forest productivity (Hall et al., 2003).

ET is an essential component of the water cycle, due to the control it exerts on energy exchanges and biogeochemical cycles and the interaction of these with the atmosphere and terrestrial ecosystems (Katul et al., 2012; Wang and Dickinson, 2012), and globally ET returns more than 60% of annual precipitation to the atmosphere (Liu et al., 2013).

Changes in ET due to land cover changes or other land use practices have received special attention in the last ten years because of their potential effects on climate and water resources (Boisier et al., 2014).

The arboreal contribution to Amazonian regional hydrologic cycling represents a considerable portion of the regional water balance, therefore, changes in vegetation cover due to deforestation, leading to decreased ET, modified hydrologic balance, with consequences in the Amazon and neighboring regions (Correia et al., 2007).

Each type of vegetation has a different structure, and these differences effect gas exchange processes, so it is important to know whether interventions through forest management cause changes in the structure of vegetation that change ET. Thus, this work aims to determine the hydrologic aspects in a tropical rain forest in the Amazon, examining whether management creates differences in ET, surface and aerodynamic conductance, and decoupling factors for managed and natural forest sites.

MATERIALS AND METHODS

Study area

The study area is located in the Tapajós National Forest (FNT) - (3,017º S; 54,970º W) in the State of Pará, located about 70 km south of the city of Santarém, with an area of 6×10^5 ha and an average canopy height of 36 m.

The climate is classified as Ami (Köppen), with an average annual temperature of 25.5°C. The rainy season occurs between January and May, resulting in an average annual rainfall of 1,820 mm. The local relief is slightly hilly, with gently undulating wavy topography. The soil that is predominant in the study area is a dystrophic Yellow Latosol. The vegetation is classified as dense forest, characterized by the dominance of individual trees of large size (IBGE, 2012).

The FNT is limited by the Tapajós River to the west, and the Santarem-Cuiaba Highway (BR-163) to the east, extending from 50 to 150 km south of the city of Santarem, Brazil, Pará. The area of forest management (logged) is located at km 83 of the BR-163 and has a 67 m tall micrometeorological instrumental tower located 6 km west of the BR-163 highway and 6 km east of the Tapajos River. The site used as control (no forest management – unlogged) is an undisturbed primary forest that extends for tens of kilometers to the north and south located close to the FNT entrance at km 67 of the BR-163 and also has a 67 m tall micrometeorological instrumental tower located at 54°58 'W, 2º51' S.

The study site was an area of 18 ha that was harvested in three phases between August and December, 2001. The first phase occurred starting on August 18th with the felling of trees near the micrometeorological instrumental tower. These trees were felled in order to prevent accidental treefall onto the tower once harvesting activities were initiated and probably had little if any effect on subsequent measurements of the variables in this study. The second phase occurred during the month of September and was comprised of harvesting in an area that included nearly the entire 18 ha intensive harvesting area which was situated 1 km to the east, 0.1 km to the west, 0.1 km to the north, and 0.7 km to the south of the micrometeorological instrumental tower. The third phase occurred in November and December and included an area that extended up to 3 km from the measurement tower and encompassed the remainder of the 18 ha harvest area not included in the September harvest activities (Figueira et al., 2008).

Calculation of ET and surface variables

The vortices correlation technique (Eddy Covariance - EC) uses sonic anemometers and infrared gas analyzers (IRGA) for scalar measurements at high frequency involved in determining the turbulent flow and mass exchange (carbon dioxide and water vapor) and energy (latent heat and sensible heat) between the biosphere and atmosphere (Baldocchi, 2003).

The data collected from micrometeorological towers generated 30 min, 24 h and monthly averages calculated from the fluxes of momentum, heat, water vapor and carbon dioxide, and carbon dioxide storage in the air column (Miller et al., 2009).

ET is calculated by Eddy system as follows: ET and latent heat flux (LE) are both based on the water vapor flow measurements (M/H_2O) and represent the sum of surface evaporation, condensation and transpiration by plants. LE is calculated as the product of the latent heat of vaporization and the measurement of fluid stream of water vapor (F / H_2O) in $W.m^{-2}$. ET is the sum of half hour averages of F / H_2O in $mm.day^{-1}$, from evaporative transpiration (Hutyra et al., 2007).

ET calculations using the Penman Monteith equation (Kume et al., 2011) was done as follows:

$$ET=\frac{\delta(\mathrm{Rn}-G)+\rho_a c_p \frac{(e_s-e_a)}{r_a}}{\delta+\gamma\left(1+\frac{r_s}{r_a}\right)} \qquad (1)$$

Where: ET = actual daily evapotranspiration (mm day^{-1}); δ is the slope of the saturated vapor pressure curve of water (k Pa $°C^{-1}$); Rn = net radiation (W m^{-2}); L = heat flow in soil (W m^{-2}); ρa = mean density of air (1.292 kg m^{-3}); cp = specific heat of air at constant pressure (J kg^{-1} C^{-1}); γ = psychrometric constant (k Pa C^{-1}); r_s = stomatal resistance (s m^{-1}); r_a = air resistance (s m^{-1}); and = actual vapor pressure (k Pa); s = saturation vapor pressure (k Pa).

ET is influenced by the power available at the surface, by the vapor pressure gradient between the water surface and the air and the resistance to vapor transfer. The canopy exchange process with the atmosphere are characterized by biotic and abiotic factors, such as surface conductance (g_s), aerodynamic conductance (g_a) and the decoupling factor (Ω) (Pinto Jr. et al., 2009).

The control exerted by the stomata of the water flow path between the mesophyll in the leaf and the atmosphere is represented by stomatal conductance (g_s) (Costa et al., 2010) in Equation 2:

$$g_s = (r_s)^{-1} = \left\{\frac{\rho_a c_p \mathrm{DVP}}{\gamma \mathrm{LE}} - \frac{1}{g_a}\left(1-\frac{\delta \mathrm{H}}{\gamma \mathrm{LE}}\right)\right\}^{-1} \qquad (2)$$

Where: g_s is the stomatal conductance; DPV vapor pressure deficit (k Pa); ρa is the density of air (1.292 kg m^{-3}); cp is the specific heat of moist air (1,013 J Kg^{-1} $°C^{-1}$); γ is the psychrometric constant (k Pa $ºC^{-1}$); ra is the aerodynamic drag (s m^{-1}).

The aerodynamic conductance (g_a) is the inverse of aerodynamic resistance (r_a), which was calculated in accordance with Allen et al.

(1998), as shown in Equation 3.

$$(g_a)^{-1} = r_a = \frac{\ln\left\{\frac{z_m - d}{z_{om}}\right\}\ln\left\{\frac{z_h - d}{z_{oh}}\right\}}{k^2 U_z} \quad (3)$$

Where: zm is measured wind height (m), zh is moisture height measurement (m), d is zero plane displacement height (m), Zom is length of roughness governing the time of transfer (m), Zoh is length of roughness governing heat transfer and steam (m), k is the von Karman's constant, 0.41, Uz is the wind velocity at height z (m s^{-1}).

Atmospheric conditions were determined as in Campbell and Norman (1998), from the convection rate that produces mechanical air turbulence which can be used to estimate the atmospheric stability parameter (ζ) described in Equation (4).

$$\zeta = -\frac{0{,}4gzH}{\rho_a c_p T_k u^3} \quad (4)$$

Where in g is the acceleration of gravity (9.8 m s^{-1}), z is the surface height, H is the sensible heat flow, ρ is the density of air (k^{-3}), T_k is the air temperature (K), u is the air friction velocity (m s^{-1}), cp is the specific heat of moist air.

The atmospheric stability was used in the correction factor for the momentum flow (ΨM) and sensible heat flux (ΨH) as in Equation 5. For stable atmosphere (ζ ≥ 0):

$$\Psi_M = \Psi_H = 6\ln(1+\zeta) \quad (5)$$

For unstable atmosphere (ζ <0):

$$\Psi_H = -2\ln\left[\frac{1+(1-16\zeta)^{\frac{1}{2}}}{2}\right] \qquad \Psi_M = 0{,}6\Psi_H \quad (6)$$

The control of tree transpiration by the stomata is commonly described by the decoupling factor (Ω), which reflects the extent to which the canopy of trees is coupled to the atmosphere (Kumagai et al., 2004). The coefficient Ω of decoupling ranges between 0 and 1 (Wullschleger et al., 2000; Han et al., 2011).

A Ω value closer to 1 indicates that transpiration is more dependent on the radiation balance; Ω values closer to 0 indicate that transpiration is more greatly controlled by the prevailing weather conditions that affect the physiological control of plants (Souza Filho et al., 2005).

$$\Omega = \frac{1}{1+\left(\frac{\gamma}{\delta+\gamma}\right)\cdot\left(\frac{g_a}{g_s}\right)} \quad (7)$$

Where Ω is the decoupling factor; g_a is aerodynamic-conductance (s.m^{-1}).

Statistical analysis

R version 3.2.3 was used to process and analyze data. Statistical analysis compared the managed and control forests as well as whether there are differences between the models and if each model differs between seasons. The data were submitted to the Kolmogorov-Smirnov normality test and comparison between models were made using ANOVA. The probability level of α = 0.05 was used for all comparisons, and for the post-hoc mean separation the Tukey test was used.

RESULTS AND DISCUSSION

Forest management causes a reduction of the impact on vegetation structure, and it can aid in faster return to evapotranspiration values of a primary forest reduced impact logging. The average ET calculated by Penman Monteith (PM) was 111.06 ± 15.71 and 108.52 ± 18.29 mm.$month^{-1}$ in the logged area. In the statistical analysis, data were normal, and when ET was compared the PM and EC data using a two-way ANOVA the two did not differ (F = 0.025, p = 0.87), but the fixed effect of seasons (wet and dry) showed a difference between models (F = 9.88; p <0.01); however, by the Tukey test these models did not significant differ (p = 0.87) for the logged site.

Annual average PM-ET was 1,322.98 mm while rainfall was 1,480.19 mm for 2001 to 2003 at the logged site. Similarly, Kume et al. (2011), working in a Malaysian tropical forest measured an annual average PM-ET of 1,323 mm. This shows that the level of ET for the current study area could be considered to be equal to those in an unmanaged tropical rain forest, and this result is important in order to evaluate the effect of forest management in the Amazon on ET levels.

The PM varied for seasonal periods, while the EC had a tendency to increase over time. This may be related to the features of each model used to calculate the ET (Figure 1). In the application of PM, the aerodynamic and surface resistances are two important parameters. When the canopy resistance is estimated, this model provides satisfactory results even if the ET is subject to changes, such as harvest history (Ebisu and Ogawa, 1993).

The PM results from 2000 to 2001 were 3.16 ± 0.28 mm day^{-1} and 3.85 ± 0.33 mm day^{-1} for the rainy and dry seasons, respectively, and the annual average was 3.51 ± 0.75 mm day^{-1} (Rocha et al., 2004) and 3.50 ± 0.46 mm day^{-1} for this study. In Manaus, in the Jarú Reserve, Costa et al., (2010) obtained ET values of 3.58, 3.57 and 3.11 mm day^{-1}. These data are similar to those from the current study and show that even with the loss of a few trees the managed site is able to maintain a level of ET equal to that of unlogged forest areas.

In the current study, PM ET had an average of 134.89 ± 15.94 mm $month^{-1}$ for the unlogged site, and there was an increase in the evapotranspiration rate for the dry season each year, while the EC had a more regular distribution with ET 100.89 ± 11.05 mm $month^{-1}$ (Figure 1).

The PM and EC showed a significant difference in two-way ANOVA (F = 162.87; p> 0.01) for the unlogged site, and the Tukey multiple comparison test showed that the models had significant differences. The seasons are different between models (wet and dry F= 45.08; p <0.01), and comparing season within the model, EC not differ between seasons (p = 0.91), while the PM had a difference (p <0.01). The global level of ET is around 1,500 mm (Kume et al., 2011), and at the unlogged site annual average ET was 1,618.71 mm for 2002 to 2005.

ET estimated by EC significantly decreased during the year after forest harvest (2001-2002) and then increased up to 2003. Since this technique is based on available energy, after forest harvest there was a decrease in

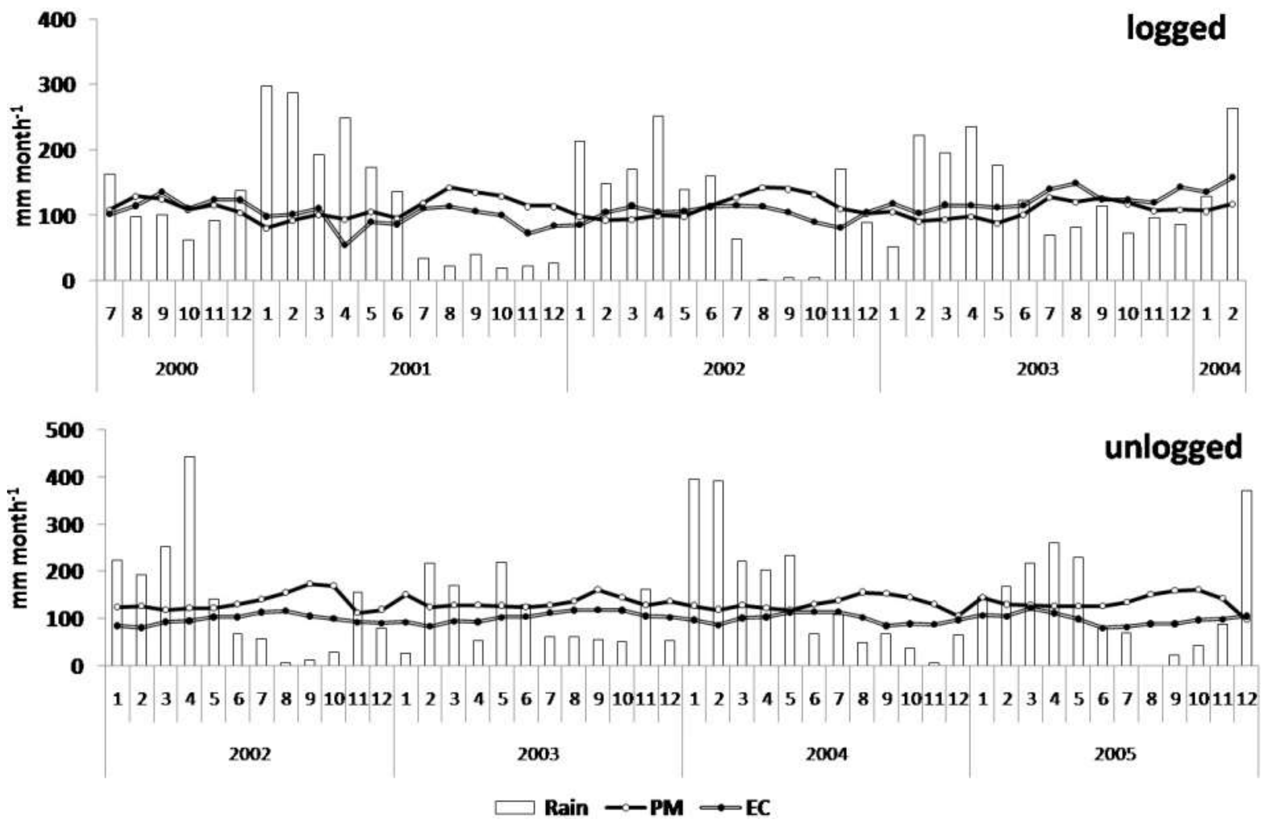

Figure 1. ET from PM, EC and precipitation for the logged and unlogged sites.

monthly average LE (121.09±7.9 and 100.68±12.85 $W.m^{-2}$) during the final five months comparing 2000 and 2001, which implied a reduction in ET. Afterward the forest recuperated LE and ET values and these levels increased during the next few years.

At the unlogged site the PM and EC had averages of 4.50±0.53 and 3.32±0.42 $mm.day^{-1}$, respectively. At the same site Hutyra et al. (2007) used water vapor flux to determine ET and the daily average during 2002 to 2005 was 3.07 $mm.day^{-1}$. This result demonstrates the extent to which model characteristics influence ET rates, and this is very important when studying forests that have different vegetation structures.

The PM ET rate for the unlogged site was 4.5 $mm.day^{-1}$ and was EC 3.32 $mm.day^{-1}$. Costa et al. (2010), using an energy balance analysis for both the logged and unlogged sites, found a value for ET of 3.49 $mm.day^{-1}$, and Vourlitis et al. (2008), calculating ET based on sap flow found a value of 3.01 $mm.day^{-1}$. ET values using PM in the current study were higher than those from most other reported studies probably due to the fact that the model aggregates variables such as r_s and r_a that influence vegetation interaction with the atmosphere, a relevant caveat when comparing distinct forests.

In the precipitation correlation analysis PM ET had an r = -0.63 in the logged site and r = -0.80 in the unlogged site; the EC ET showed no correlation (r = -0.06 and r = -0.21, logged and unlogged sites respectively). The precipitation in the Tapajós National Forest had an annual average of 1480.2 $mm.year^{-1}$ (logged site from 2001 to 2003) and 1618.71 $mm.year^{-1}$ (unlogged site from 2002 to 2005), and seasonal variations are very well defined in the region of the Amazon. Precipitation and ET are meteorological elements that move in opposite directions, expressed in millimeters of rainfall (Thornthwaite, 1948), so this trend is justified by the PM method. ET in the dry season is higher than in the rainy PM due to environmental conditions that favor the process. But as the real ET requires water availability, it can be considered that the ET values for the dry season would be the potential values and the real values are from the rainy season.

Comparison of sites

The distribution of ET over the two year period for the PM sites had the highest ET (unlogged) compared to the dry period. In the ANOVA sites had differences for the years of study ($F = 10.78$ and $p \leq 0.01$), and the Tukey test showed that sites had significant differences in seasonality. In the one-way ANOVA for ET EC was not

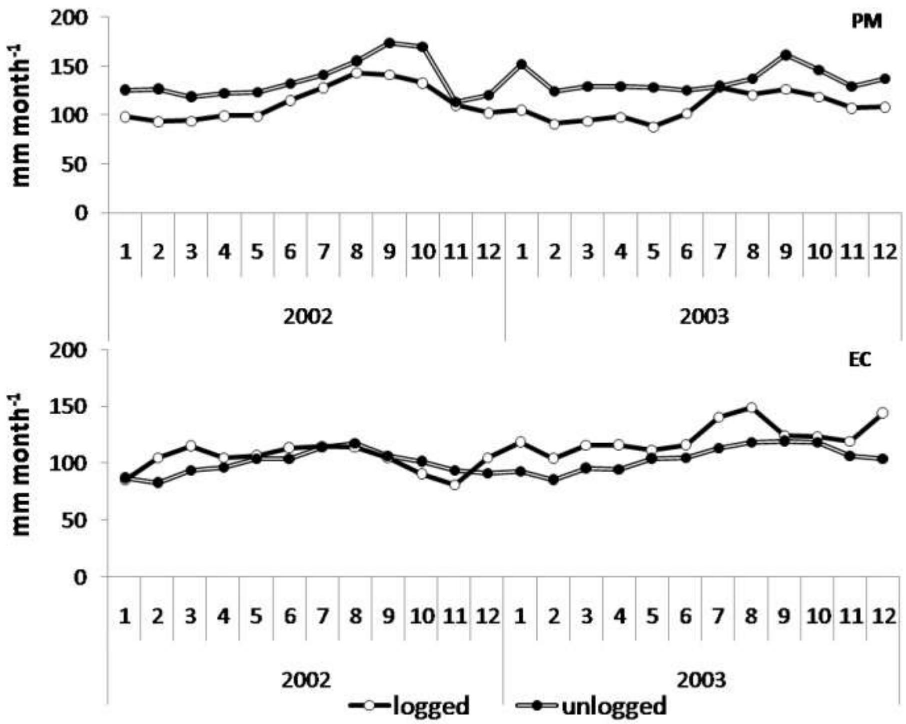

Figure 2. ET logged and unlogged for the period 2002 and 2003, using the PM and EC.

different (F = 0.025; p = 0.87) (Figure 2).

Seasonal comparisons showed that the dry period at the logged site in 2002 had lower average ET than in the rainy period. In the unlogged site the forest had a greater evapotranspiration in the dry season, and the variation of differences over the period was higher for the logged site.

The distribution of ET (PM) in comparison to the two sites has an unchanged distribution following the rainfall trend for respective sites. The peak in the distribution at the unlogged site in month 1 of the year 2003 is due to an extension of the summer season, wherein the average monthly rainfall was 52.3 mm.

When used for comparison of EC sites, the logged ET attained higher rates than in the unlogged (Figure 2), and also had higher rates of LE in the logged (113.00 ± 13.12 W m^{-2}) compared to unlogged (85.62 ± 8.16 W m^{-2}).

EC averages between study areas showed that the unlogged site was 101.82 ± 11.05 mm $month^{-1}$ for ET, while the logged was 113.16 ± 16.21 mm $month^{-1}$ with a difference of +11.34 mm $month^{-1}$ for the logged compared to the unlogged. The major variable involved in ET is the energy available at the surface and the way it regulates the transpiration of vegetation through their stomata (Avissar and Werth 2004). In the logged site high latent heat values were essential for obtaining higher monthly average than the unlogged. Therefore we can infer that the EC ET depends more on solar radiation balance than the ET process.

PM for the unlogged site had an ET rate higher than that of the logged site, with an annual average for the period of 135.03 ± 16.32 mm $month^{-1}$, while the other site was 110.35 ± 16.11 mm $month^{-1}$. This is due to the different structure of the canopy that influences atmospheric and physiological parameters, and aerodynamically regulates ET through features such as the activity of the stomata and roughness of the canopy (Matsumoto et al., 2008).

Using PM the daily average for the rainy season ranged from 4.1 ± 0.15 to 4.4 ± 0.34 mm day^{-1}, and the dry period from 4.8 ± 0.84 to 4.6 ± 0.40 mm day^{-1} for the unlogged site for the years of study. At the logged site the daily average for the rainy season was 3.3 ± 0.26 and 3.2 ± 0.21 mm day^{-1} and dry season had averages of 4.2 ± 0.55 and 3.9 ± 0 29 mm day^{-1}. ET ranged from 3.6 to 5.1 mm day^{-1} using the PM 2007 to 2009 in a tropical rainforest in Costa Rica (Cadol et al., 2012). The variation in the TNF is similar to that of other tropical forests when applying the PM model, since high temperatures and radiation create an evaporative demand in the Amazon region, which is usually 3 to 4 mm day^{-1} (Fisher et al., 2008).

Research conducted in tropical forests shows that the benefits of forest management are limited by the intensity of exploitation (Van Der Hout, 1999). Thus, one of the main impacts that can affect the ET is the opening of the canopy from the felling of trees.

The post-harvest growth rate was higher in the logged site with diameter increment of 0.6 $cm.year^{-1}$ before

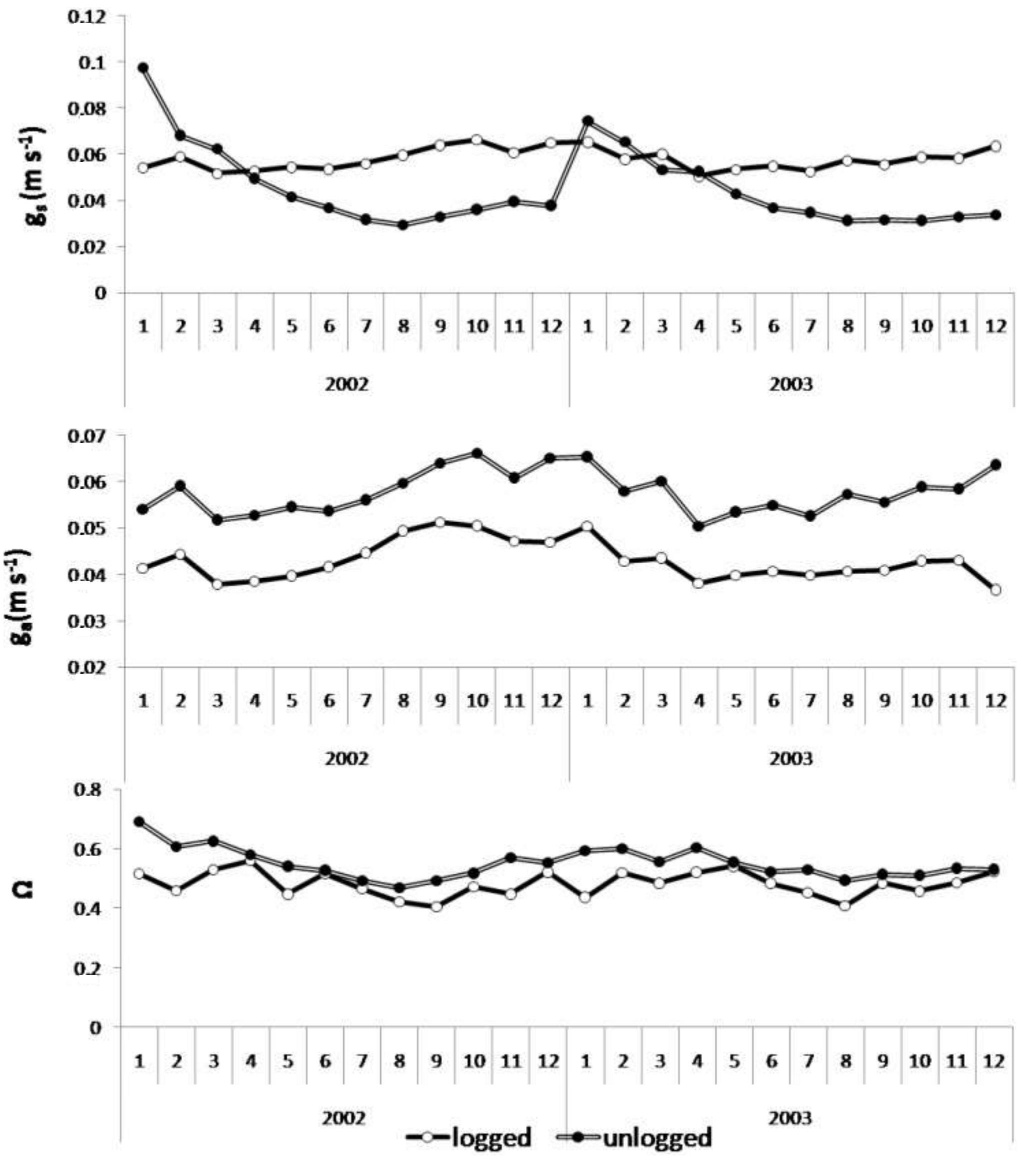

Figure 3. Surface conductance (g_s), aerodynamics (g_a) and decoupling factor (Ω) for the logged and unlogged for the period 2002 and 2003.

management to 1.21 cm.year^{-1} after three years; while the unlogged site diameter increment ranged from 1.04 to 1.34 cm.year^{-1} (Miller et al., 2011). The logged site had a greater increase, which is linked to factors such as the ecology of the species involved in colonization and canopy openness, which should consequently influence biogeochemical processes of forests, such as evapotranspiration.

Control mechanisms

Surface conductance

The gas fluxes in the study areas were different, in which the logged has a regular distribution over the years, while the unlogged has high values for the first half of the year (Figure 3). In ANOVA, this variable was significant for a difference between the sites (F = 12.06 and p≤0.01) and was significant according to the Tukey test at α = 0.05. The sites had means of 0.058 ± 0.005 m s^{-1} for the logged site and 0.045 ± 0.017 m s^{-1} for the unlogged site for the years 2002 to 2003. The logged site had an annual average of 0.058 ± 0.005 m s^{-1} for 2002 and 0.057 ± 0.004 m s^{-1} for 2003 and the unlogged site had 0.047 ± 0.02 and 0.043 ± 0.014 m s^{-1} for the respective years. The conductance (g_s) to the boundary layer ranged from 0.01 to 0.02 m s^{-1} in Sarawak, Malaysia (Lim et al., 2009), values lower than those from this work. Thus, by analyzing the parameter for the g_s (logged), it can be inferred that the canopy structure provides smaller variations throughout the study period (minimum 0.050 m s^{-1} and a maximum of 0.066 m s^{-1}). In contrast, the unlogged site has well defined peaks in the distribution with peaks at the start of each year and having higher values with a minimum of 0.029 m s^{-1} and a maximum of 0.097 m s^{-1}.

The vegetation of the two sites in question have different structural characteristics, due to changes in forest cover from harvest activities, which causes changes in physiological and structural characteristics of the vegetation (Arora, 2002). To calculate the ET, it must be taken into account that the different composition of the forest canopy will influence the variables used to calculate the g_s.

As the unlogged site (2002 to 2003) has an average of g_s 0.045 m s^{-1} at 0.057 m s^{-1} the logged site can thus be said to exert a greater control on transpiration in the high g_s area. The difference between the gs for unlogged and logged sites can be influenced by the proximity of the unlogged tower to the plateau slope. For the Flona Caxiuanã the g_s values were 0.060 m s^{-1} for the rainy season and 0.045 m s^{-1} for the dry season (Souza Filho et al., 2005). For a mangrove forest in the Amazon region the g_s ranged from 0.01 to 0.04 m s^{-1} (Rodrigues et al., 2011). Since this variable represents the canopy surface roughness it can give different responses for different vegetation types, and this is important in order to define the level of interaction between the forest and the atmosphere.

In the state of Mato Grosso a tower located in an area covering intact forest, selectively logged forest, and pasture, the average g_s value was 0.006 ± 0.002 m s^{-1} for the period from August 1999 to July 2000 calculated from EC Covariance (Vourlitis et al., 2002). Since the study area is surrounded by a larger area with intense human disturbance, the value for g_s in Vourlitis et al. (2002) was lower than that found in the current study in the TNF. Thus, the conductance of the canopy surface features of the exchange process with the atmosphere is controlled at various times by biotic and abiotic factors (Souza Filho et al., 2005).

Conductance aerodynamics

The sites had different averages (ANOVA, F = 131.60 and p≤0.01) and these were significant (Tukey). The unlogged site had higher values than the logged site (Figure 3). g_a in the study by Rocha et al. (2004) in the logged site from July 2000 to June 2001 was 0.0287 ± 0.0073 m s^{-1} while the current work for the same period had an average of 0.041 ± 0.005 m s^{-1}. According to Rennó (2003), Monteith suggests a value of 0.1 m s^{-1} for a very rough surface such as foliage of forests. In the TNF the average values were 0.043±0.004 m.s^{-1} for the logged site and 0.057±0.004 m.s^{-1} for the unlogged site from 2002 to 2003.

For an area subject to grazing management for the years 1993 and 1994, the g_a values were in the range of 0.034 and 0.027 m s^{-1} for the respective periods (Dirks and Hensen, 1999). In the present study the g_a levels were higher for the forest (0.057 m s^{-1} in unlogged and 0.043 m s^{-1} for logged).

For the rainy and dry seasons, respectively, the values for the year 2002 in the unlogged site were 0.054 m s^{-1} and 0.062 m s^{-1} and at the logged site they were 0.040 m s^{-1} and 0.048 m s^{-1}. In an intact forest in Mato Grosso g_a was 0.046 m s^{-1} and 0.052 m s^{-1} for the rainy and dry seasons, respectively (Pinto Júnior et al., 2009). With this typical seasonal variation, during the rainy season g_a is generally greater, and therefore changes in atmospheric variable will also cause different responses of g_a for each study site. This seasonal trend is the same for other work done in the Amazon region (Souza Filho et al., 2005; Vourtilis et al., 2008).

In an ecosystem of transition between the Cerrado and the Amazon in Sinop, Mato Grosso, the average g_a for the rainy season was 0.042 and 0.048 m s^{-1} for the dry season (Silva and Sanches, 2011). In the Atlantic Forest, a fragment of forest had average g_a of 0.099 m s^{-1} (Pereira et al., 2010), higher than other tropical forests.

Factor decoupling

The variation of Ω (Figure 3), had different monthly averages for the study area. ANOVA showed a difference between sites (F = 24.67 and p ≤ 0.01) and the Tukey test showed differences in means (p<0.05). In this figure, it can be seen that the decoupling sites have different patterns indicating that the conditions of interaction of the vegetation with the atmosphere are not the same for the two areas. Thus, the logged site, with an average of Ω = 0.48, depends more on solar radiation than the ET process. The unlogged site had a Ω = 0.55 meaning that this area is more decoupled from the atmosphere. The Ω for the rainy season was higher than the dry season in the unlogged forest (Table 1).

The Ω the annual figures tend to vary for forests in the two sites of the FNT, and the logged site obtained Ω = 0.48 ± 0.05 and Ω = 0.48 ± 0.04 for 2002 and 2003, while in the unlogged site the values were Ω = 0.55 ± 0.06 and Ω = 0.54 ± 0.03 for the years in question. In a forest of *Pinus sylvestris* L., for a period of 11 years, there were annual maximum and minimum values of Ω = 0.43 to Ω = 0.19 with a final average of Ω = 0 32 (Launiainen, 2010). Thus, the sites have different decoupling characteristics with the atmosphere, wherein these depend on different conditions for evapotranspiration; while the logged site depends more on the vegetation, the control site depends more on weather conditions.

The range of maximum and minimum for the managed site was Ω = 0.56 to Ω = 0.40 for study years compared

Table 1. Monthly average for rainfall data (P) mm, ET (PM, EC) (mm $month^{-1}$), g_a (m s^{-1}), g_s (m s^{-1}), Ω and standard deviation (SD) for the logged and unlogged sites.

Years	Month	Logged						Unlogged					
		P	PM	EC	Ω	g_a	g_s	P	PM	EC	Ω	g_a	g_s
2002	1	213.11	98.27	85.17	0.52	0.041	0.054	223.01	125.72	86.31	0.69	0.054	0.097
2002	2	147.72	93.29	104.71	0.46	0.044	0.059	192.53	126.67	82.09	0.61	0.059	0.068
2002	3	169.67	94.01	114.32	0.53	0.038	0.052	252.48	118.54	93.85	0.63	0.052	0.062
2002	4	251.46	99.39	104.54	0.56	0.039	0.053	442.47	122.48	96.33	0.58	0.053	0.049
2002	5	139.95	99.09	106.04	0.45	0.039	0.054	141.22	123.44	103.94	0.54	0.054	0.041
2002	6	160.02	114.90	112.96	0.52	0.041	0.054	68.83	131.86	104.01	0.53	0.054	0.037
2002	7	64.01	127.78	114.79	0.47	0.044	0.056	58.17	141.41	114.08	0.49	0.056	0.032
2002	8	1.52	142.90	114.16	0.42	0.049	0.060	6.86	155.47	117.44	0.47	0.060	0.029
2002	9	3.81	140.95	104.69	0.41	0.051	0.064	13.46	173.92	106.46	0.49	0.064	0.033
2002	10	5.08	132.63	89.74	0.47	0.050	0.066	29.46	169.98	100.82	0.52	0.066	0.036
2002	11	170.94	110.05	80.84	0.45	0.047	0.061	155.19	113.35	93.48	0.57	0.061	0.039
2002	12	88.39	102.47	104.86	0.52	0.047	0.065	79.76	120.07	91.16	0.55	0.065	0.038
2003	1	52.32	105.47	117.89	0.44	0.050	0.065	27.69	152.36	92.95	0.59	0.065	0.074
2003	2	222.50	90.83	103.41	0.52	0.043	0.058	217.42	124.47	84.66	0.60	0.058	0.065
2003	3	195.83	94.12	115.85	0.49	0.043	0.060	169.67	129.40	95.08	0.56	0.060	0.053
2003	4	234.95	97.97	115.48	0.52	0.038	0.050	52.83	129.42	94.47	0.60	0.050	0.052
2003	5	176.28	88.26	111.72	0.54	0.040	0.053	220.22	128.12	103.26	0.55	0.053	0.043
2003	6	123.70	101.67	115.50	0.48	0.041	0.055	129.29	125.40	104.82	0.52	0.055	0.037
2003	7	69.85	128.19	140.41	0.45	0.040	0.052	62.23	129.52	113.12	0.53	0.052	0.035
2003	8	81.79	120.56	148.78	0.41	0.041	0.057	61.72	137.36	118.56	0.49	0.057	0.031
2003	9	113.79	126.28	124.19	0.49	0.041	0.056	55.88	161.51	118.79	0.51	0.056	0.031
2003	10	71.88	118.69	123.41	0.46	0.043	0.059	51.05	146.30	118.35	0.51	0.059	0.031
2003	11	97.03	107.03	119.23	0.49	0.043	0.058	161.04	129.10	106.21	0.53	0.058	0.033
2003	12	85.85	108.42	143.42	0.52	0.036	0.063	54.36	136.87	103.66	0.53	0.063	0.034
Mean		122.56	110.13	113.17	0.48	0.04	0.06	121.95	135.53	101.83	0.55	0.06	0.05
SD		73.35	16.12	16.21	0.04	0.00	0.00	101.32	16.32	11.05	0.05	0.00	0.02
Total		2941.47	2643.20	2716.13	11.57	1.03	1.38	2926.84	3252.75	2443.90	13.19	1.38	1.08

to the control site, which despite having an average near to that of a pine forest (Launiainen, 2010) the minimum value was greater and there was less amplitude between the data. Furthermore, Vourlitis et al. (2002) found a Ω of 0.27 ± 0.07 in Sinop, Mato Grosso, Brazil.

The control site in 2002 to 2003 averaged 0.51 ± 0.02 in the dry season and 0.58 ± 0.04 for the rainy season. In the logged site the values for the respective seasons were 0.32 ± 0.03 and 0.33 ± 0.04. The variation of Ω for the dry season was 0.2 to 0.3 and 0.5 for a rainy semi-deciduous forest in Mato Grosso, Brazil (Vourlitis et al., 2008), and in Rodrigues et al. (2014), working in a Mato Grosso, Brazil, the Ω averaged 0.48 during the rainy season and declined to a low of 0.21. In an ecosystem of transition between the Cerrado and the Amazon in Mato Grosso, Silva and Sanches (2011) described a Ω = 0.4 for the rainy season and Ω = 0.2 in the dry season. This demonstrates that as with other control mechanisms, Ω is influenced by seasonal changes at these study sites.

Generally, the forest has an Ω value indicative of the importance of the energy available to the process of ET during the wet season, wherein there is relatively less importance of stomatal control, because the leaf area index (LAI) is high (Wullschleger et al., 2000).

Typical values for Ω range from 0.1 in conifers, while for stomatal conductance this increases to 0.5 or greater in broadleaf trees, and values are higher in dense herbaceous vegetation (Wood et al., 2008). In rainforest in French Guiana Granier et al. (1996) obtained a value of Ω = 0.38. In the current study, the uncoupling of the unlogged site (Ω = 0.55) and logged site (Ω = 0.48) is consistent with hardwood vegetation. The monthly averages for 2002 and 2003 are shown in Table 1.

Conclusions

The PM ET did not change after forest management over the years, while EC increased for the logged site over the years, and this may be related to variation in LE. When compared to the unlogged site, values were higher for

PM and did not differ in EC. The PM model results capture the influence of rainfall in these study areas, and therefore the PM model can be considered better at evaluating the interaction of the forest structure with the atmosphere. As the forest is growing after the management operations, it should not decrease ET rates due to higher growth rates provided by opening of the canopy, which increases the incidence of light on the trees in the lower strata. When the surface parameters such as g_a, g_s and Ω were analyzed, it was revealed that the sites have different structural characteristics that influence the forest ET process.

CONFLICTS OF INTERESTS

The authors have not declared any conflict of interests.

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