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ABSTRACT

This work studied the behavior and seasonality of evapotranspiration influenced by biotic and abiotic factors through analysis of diurnal variation of aerodynamic resistance (r_a), stomatal resistance (r_s) and decoupling factor (Ω). This index was proposed by Jarvis and McNaughton (1986) as an indicative of the control of these resistances on the evapotranspiration of vegetation. Selection of representative data from wet and dry seasons from a primary forest in Central Amazonia and a primary forest and a pasture sites in Southwestern Amazonia had shown that: (i) r_a is about 20 s.m^{-1} in both forests in both seasons, and ranges from 70 to 100 s.m^{-1} in the pasture site; (ii) r_s varies both throughout the day and seasonally, with medians increasing from 40 in the morning, to 150 s.m^{-1} in late afternoon, in the wet season in the forests and from 50 to 160 s.m^{-1} in the pasture. These values increase in the dry season, with the forests r_s ranging from 50 up to 500 s.m^{-1} and pasture r_s starting from 140 s.m^{-1} and reaching up to more than 1800 s.m^{-1} in the dry afternoons; (iii) Ω ranges from 0.5 to 0.8 during the wet season, and reduces to values below 0.5 in the afternoons during the dry season, indicating that, although a strong influence of net radiation in the evaporative loss is present, to a large extent the evapotranspiration fluxes are coupled to the biotic control of stomatal closure in the vegetation, especially in the pasture and during dry periods.

Keywords: aerodynamic resistance, decoupling factor, stomatal resistance.

Análise de controles biológicos e meteorológicos da evapotranspiração em áreas de florestas primárias e pastagem na Amazônia

RESUMO

O comportamento e a sazonalidade da evapotranspiração influenciada por fatores bióticos e abióticos foram estudados por meio da análise de variações diárias da resistência aerodinâmica (r_a), da resistência estomática (r_s) e do fator de desacoplamento (Ω), um índice proposto por Jarvis e McNaughton (1986) como um indicativo do controle das resistências na evapotranspiração da vegetação. A seleção de dados representativos de estações secas e úmidas de uma floresta primária na Amazônia Central, uma floresta primária e uma área de pastagem

no sudoeste da Amazônia, demonstrou que: (i) r_a é cerca de 20 s.m^{-1} nas florestas em ambas as estações, e varia de 70 a 100 s.m^{-1} na área de pastagem; (ii) r_s varia ao longo do dia e sazonalmente, com medianas passando de 40 no período da manhã, para 150 s.m^{-1} no final da tarde, na estação chuvosa na floresta e 50 a160 s.m^{-1} no pasto. Estas medianas aumentam na estação seca, com as r_s florestais que variam de 50 a 500 s.m^{-1} e r_s na pastagem a partir de 140 s.m^{-1} chegando a mais de 1800 s.m^{-1} nas tardes secas; (iii) Ω varia de 0,5 a 0,8 durante a estação chuvosa, e cai para valores inferiores a 0,5 nas tardes durante a estação seca, o que indica que, apesar de uma forte influência do saldo de radiação na perda evaporativa, em grande parte os fluxos da evapotranspiração são acoplados ao controle biótico pelo fechamento dos estômatos na vegetação, especialmente no pasto e durante períodos de seca.

Palavras-chave: fator de desacoplamento, resistência aerodinâmica, resistência estomática.

1. INTRODUCTION

The Amazonian rainforest is one of the most important biomes of the planet. It is of great relevance to the global climate and biodiversity, and it is considered the largest tropical rain forest of the world and a major contributor to surface evapotranspiration (Choudhury et al., 1998), influencing the global hydrological cycle and affecting atmospheric global circulation associated with tropical convection.

Besides being important for maintaining the regional climate and ecosystem, the Amazon forest also has an important role in the different regional climates of Brazil. The Amazonian ecosystem can be considered a source of water for other regions, as a significant amount of water vapor that evapotranspirates in Amazonia is transported to Center-west, Southeast and Southern regions of Brazil by low-level jets (Zemp, 2014; Arraut et al., 2012).

Although the Amazon forest is recognized as an important component of the regional and global climate system, the spatial and temporal variability of its hydrological functions is not completely understood; therefore, evaluating the seasonal and spatial variations of the water fluxes in the tropics is important (Werth and Avissar, 2004). These variations mainly depend on the characteristics of the vegetation, on energy processes and on water availability (Hasler and Avissar, 2007). Understanding of vegetation and climate interaction is commonly achieved by field measurements and by weather- and climate models simulations. These models use variables such as wind, air and soil temperatures, air humidity and soil moisture to estimate evapotranspiration through aerodynamic conductance and stomatal conductance. Werth and Avissar (2004) presented a review of four approaches to estimate evapotranspiration in Amazonia: the first is the relationship with radiation, the second is water balance, the third is global climate and the last is data assimilation. They observed the seasonality of ET in two groups: one that follows the seasonal cycle of net radiation, and another that follows the seasonal cycle of precipitation. This division motivates the following research questions: what controls the seasonal variation of ET in Amazonia? Is it mainly related to the available radiative energy or does the vegetation significantly control its variability, through its surface conductance that is susceptible to the seasonality of soil moisture?

Souza Filho et al. (2005) presented in their study evidence that supported the idea that the radiation and maybe other atmospheric variables are the main mechanism of control of the seasonal variation of ET in the Amazonia, while vegetation control plays a secondary role in ET. They used meteorological data from Caxiuanã, in Northeast Amazonia, to calculate the aerodynamic and surface conductance and the decoupling factor proposed by Jarvis and McNaughton (1986) during dry and wet periods. During the wet period surface conductance is higher than during the dry period (Souza Filho et al., 2005). On the other hand,

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VPD, aerodynamic conductance, and solar radiation are higher during the dry period. But, even while presenting a higher surface conductance during the wet season, the vegetation does not prevent the ET from being higher during the dry season. From this analysis, they concluded that the control of atmospheric conditions over ET is dominant, with a decoupling factor close to 1 in the wet and dry seasons.

Da Rocha et al. (2009) investigated the seasonal behavior of water vapor flux and sensible heat flux in 7 flux towers in Brazil. These tower sites included tropical humid and semideciduous forest, transitional forest, floodplain (with physiognomies of Cerrado), and Cerrado *sensu stricto*. The authors observed that the control of the seasonality of ET was different in each biome, where evaporative demand (mainly the net radiation) plays the most important role in the tropical humid forests and soil moisture variation plays the most important role in the Cerrado.

In a more complete evaluation of differences in control of evapotranspiration in wet forest and seasonally dry forests, Costa et al. (2010) found that the wet equatorial sites are mainly driven by environmental factors, while in seasonally dry forests, ET is also controlled by biotic factors. This poses the question of whether the wet equatorial sites will remain largely resilient to dry season water stress or may begin to present signs of larger biotic control of water loss by the vegetation in case of increasing frequency of extreme dry seasons as predicted by some climate models. Moreover, a large fraction of Amazonia is also under pressure of deforestation for pasture or agriculture, and it is interesting to investigate how a vegetation type like pasture grass compares to the pristine rainforest in terms of biotic control of evapotranspiration and experiences dry season water shortages.

In this context, the goal of this study was to analyze the diurnal and seasonal variations of the aerodynamic resistance, stomatal resistance and the decoupling factor of Jarvis and McNaughton (1986) for three sites in Amazonia: a primary forest in Central Amazonia and a primary forest and a pasture in Southwestern Amazonia. The data used in the present work are measurements of evapotranspiration and meteorological variables. In Central Amazonia, the data were collected in the Cuieiras Biological Reserve near Manaus, AM, while in Southwestern Amazonia, the data were collected in the Jaru Biological Reserve and at the cattle ranch, Fazenda Nossa Senhora (FNS), close to Ji-Paraná, RO.

2. METHODS AND SITE DESCRIPTION

2.1. Site description and instruments

This study is based on the data of three sites in Amazonia. The first is located at the Cuieiras Forest Reserve, about 50 km north of Manaus, Amazonas state, Brazil. The site is known as K34 (2º 36' 32" S, 60º 12' 33" W) and it is part of the LBA project, which is responsible for the maintenance and administration of the site. The second site is located at Jaru Biological Reserve (Rebio-Jaru), about 100 km north Ji-Parana, Rondônia state, Brazil (10º 4' S; 61º 56' W). The third site is a pasture located about 50 km northwest of Ji-Paraná, Rondônia state, Brazil. The site is a cattle ranch known as Fazenda Nossa Senhora Aparecida (FNS) (10º 45' S, 62º 22' W), deforested in the late 1970s. The second and third sites are also part of LBA project.

The K34 site is covered by primary forest, with diverse vegetation and a vast number of species. The leaf area index (LAI) of the area is about 5-6. The index is in accordance with that estimated by Hasler and Avissar (2007). The climate is classified as Af according to the Köpen classification (tropical rainforest climate), with temperatures varying from 19 to 39°C. The rainfall regime is divided into two seasons: rainy (November to May) and dry (August to October). The annual average precipitation varies from 1800 to 2800 mm year^{-1}. More information about the climate of the region is found in Araújo et al. (2002).

Besides conventional meteorological and short and long wave radiation sensors, an eddy covariance system is installed at a 53-m high tower measuring the energy, water and carbon fluxes of the K34 site. The system is composed of a tridimensional sonic anemometer (Solent 1012R2, Gill Instruments, UK) and a fast-response infrared gas analyzer ("Infra-Red Gas Analyzer", IRGA) (LI-6262, Li-Cor, EUA). The data was recorded in 10.4 Hz sampling (Araujo et al., 2002).

The Rebio Jaru is a "terra firme" forest, with relatively stronger rainfall variability than K34, which varies annually from 1250 to 2500 mm. The forest has a mean height of about 35 m, but some of the higher trees reach up to 45 m. The air temperature shows no clear seasonal pattern, ranging on average between 22 and 27°C; however, a significant drop in humidity and a reduction in rainfall is observed during the dry seasons. The same measurements as in K34 were collected, but at the height of 62.7 m (Von Randow et al., 2004).

The FNS is covered by *Brachiaria brizantha* (A. Rich.) Stapf. grasses, with an average LAI of 2.0 (Zanchi et al., 2009). The climate of the region is equatorial, warm and moist, with temperature varying from 17 to 32°C. The rainfall regime follows the same patterns as in Rebio Jaru. The measurements from FNS analyzed in this work are from an automatic weather station (AWS) installed in a 5.5 m tower, providing measurements of the most common meteorological variables. The tower counts with an eddy correlation system similar to the one installed at K34. Other details of the microclimatology of the region can be found in the work of Von Randow et al. (2004).

In Rondônia, the topography is generally flat and the soil is classified as medium-textured red-yellow podzol (*Podzólico vermelho amarelo A moderado textura media*—Brazilian Soil Taxonomy, typic paleudult—or orthic acrisol—FAO).

2.2. Evapotranspiration

In the evaporation process of a vegetated surface two resistances can be considered as controlling factors: the stomatal resistance (r_s) and the aerodynamical resistance (r_a). In a vegetated surface, the path of turbulent diffusion from the surface to the atmospheric boundary layer is frequently analyzed through these two resistances. The stomatal resistance is related to the physiology of the plant. It is the mechanism that better represents the control of the evapotranspiration in the plant. The transpiration in the leaves accounts for approximately 90% of the water loss of the plant (Lambers et al., 2008), which reflects the importance of assessing this resistance.

The stomatal resistance was calculated by inverting the Penman Monteith (Equation 1).

$$r_s = \left[\frac{(\rho_a C_p VPD)}{\gamma LE} - r_a \left(1 - \frac{\Delta H}{\gamma LE}\right) \right] \tag{1}$$

where :

ρ_a is the air density (kg m^{-3}),

C_p is the specific heat of air at constant pressure (Jkg^{-1} °C^{-1});

VPD is given in hPa;

γ is the psychometric constant (hPa °C^{-1});

LE is the latent heat flux (Wm^{-2});

Δ is the slope of the saturation vapor curve (hPa °C^{-1}); and

H is the sensible heat flux (Wm^{-2}).

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On the other hand, the aerodynamic resistance is closely related to the planetary boundary layer and to the turbulent atmospheric processes. The aerodynamic resistance can be defined as the parameter that represents the resistance to the turbulent activity in the layer of air close to the surface. This turbulent activity is responsible for the transport of sensible and latent heat and water fluxes.

The aerodynamic resistance was calculated by Equation 2, following Costa et al. (2010).

$$r_a = \frac{\bar{u}}{u_*^2} \tag{2}$$

where:

$\bar{u}$ is the above canopy mean horizontal wind speed and

u_*^2 is the friction velocity.

This formulation is simpler than an explicit account of stability effects on the turbulence aerodynamics, but we prefer to use it to avoid large possible errors introduced in the calculation of stability functions in Amazonia and to make it more comparable to previous works of Hasler and Avissar (2007) and Costa et al. (2010). The unity that commonly represents the aerodynamic and surface resistances is s m^{-1}.

A useful tool to characterize the processes of exchange between the canopy and atmosphere and the control of these processes considering their seasonality is the decoupling factor (Ω) proposed by Jarvis and McNaughton (1986) as in Equation 3.

$$\Omega = \frac{1}{1 + [\gamma/(\delta+\gamma)](r_s/r_a)} \tag{3}$$

The decoupling factor is an index that allows evaluating whether the evapotranspiration process is mainly controlled by the vegetation or is decoupled from the surface and mainly limited by the energy available: the closer to 1 the greater the control of the atmospheric conditions (mainly available energy), while a value close to 0 indicates a strong influence of vegetation (strong coupling between the evapotranspiration and biological activity of stomata opening or closing).

The analysis in this work includes the wet and dry periods of 2000. In the three sites, the period analyzed was 90 days, from January to March (wet season) and also 90 days from August to October (dry season). These periods were chosen to represent the seasonality of the sites; therefore, we chose the months that the vegetation is most likely subject to contrasting wet/dry stress conditions (middle of wet season versus end of dry season).

All data were recorded in half-hour intervals and the calculations of the eddy fluxes were performed using an in-house developed software written in FORTRAN, which can be adapted to a number of different hardware configurations and program options. The program was configured to apply two-axis rotations to align the coordinate frame with the mean streamlines and force the mean vertical component (w) to zero and to perform standard frequency-response corrections. No detrending method was applied to the signals. Generally, for these sites and instrumental setup, apart from the coordinate rotations, the corrections are relatively small and do not represent large uncertainty factors in the final values (Kruijt et al., 2004).

Based on this information, the aerodynamical and stomatal resistances and the decoupling factors were calculated and only daytime periods (from 8 am to 6 pm) are presented, to focus the study on the analysis of time periods where the vegetation control of evapotranspiration would be greatest.

3. RESULTS AND DISCUSSION

In Central Amazonia, the maximum monthly precipitation registered during the year 2000 was 458 mm in April and the minimum was 89 mm in August. The total precipitation of the year was about 2620 mm. In Southwestern Amazonia, the total precipitation for the year was 1760 mm, while the highest monthly precipitation was 274 mm in October (which already indicates the beginning of the following wet season), followed by 264 mm in January. The driest month was August, reaching 30 mm.

Figure 1 presents the monthly values of precipitation minus reference evapotranspiration (P-ETo), as calculated using FAO standard recommendations (Allen et al., 1998) for the three sites. We observe that the sites in Southwestern Amazonia (Jaru and FNS) are subject to drier conditions during June through August, with significantly negative values of P-ETo.
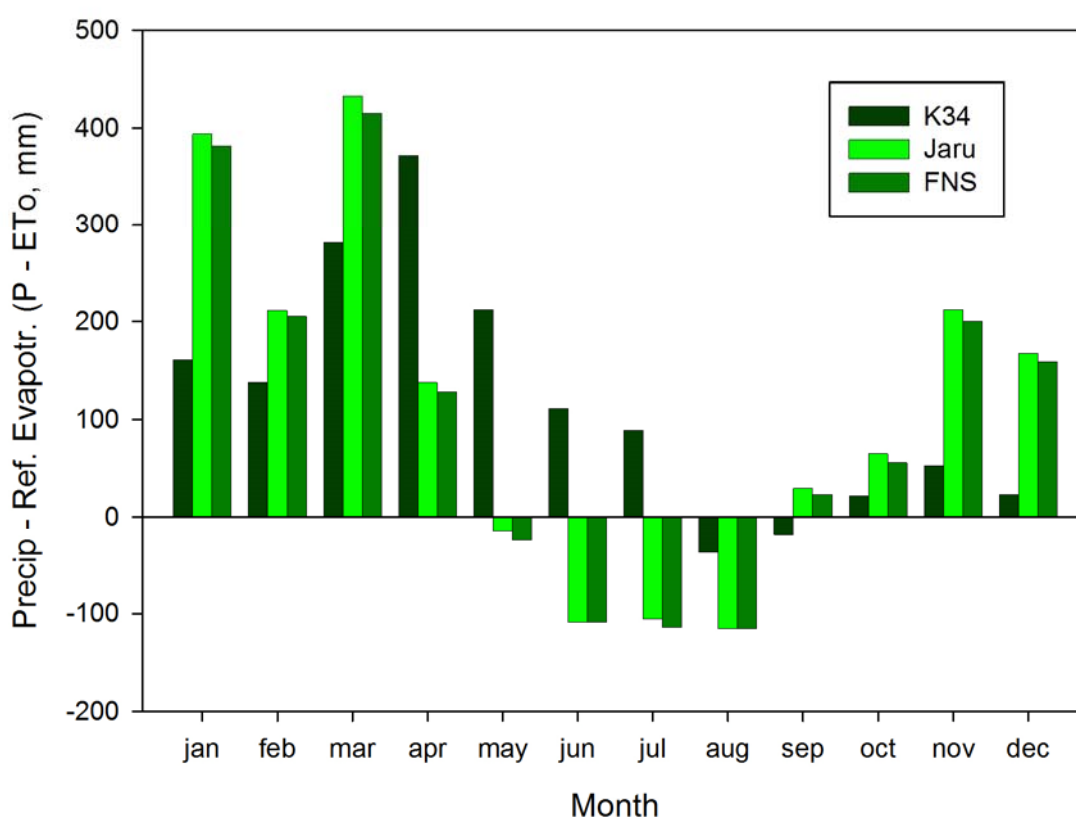

Figure 1. Monthly totals of the difference between precipitation and reference evapotranspiration (P – ETo), computed using FAO standard method.

Daily averages of the net radiation in K34 from January to March vary between 24 and 223 Wm^{-2} (not shown). This variation is slightly lower in the period from August to October, when the net radiation varied from 59 to 207 Wm^{-2}. Corresponding values in Rebio Jaru vary from 30 to 243 Wm^{-2} (wet period) and from 40 to 205 Wm^{-2} (dry period). In the pasture site, the net radiation variation is lower when compared to the forests. The highest variation in daily average net radiation in the pasture also happened from January to March, but in a lower range: from 42 to 202 Wm^{-2}, and during the dry months (June to August), varied from 37 to 149 Wm^{-2}.

Results of the measurements of vapor pressure deficit (*VPD*), aerodynamic resistance (r_a), stomatal resistance (r_s) and decoupling factor (Ω) during wet and dry season periods are presented in Figures 2 to 4. Each point in the line graphs is the median of observed values at each half hour, and the bars present the interval between the first and third quartiles. In this way, the values presented within the bars include 50 percent of the observations at each time.

Figure 2 shows the diurnal median values for the K34 forest site, which is located in Central Amazonia (Amazonas state). Figures 3 and 4 show the same variables, but measured at the Jaru forest site and FNS pasture site, which are located in Southwest Amazonia (Rondônia state). In general, results from the two forest sites are similar, but some changes in the values are noted in the pasture vegetation.

First observing the measurements at the forest sites (Figures 2 and 3), clear effects of the dry season are noted in the measurements of VPD (Figures 2a and 3a), where the maximum diurnal values reach ~ 20 hPa in both forests, compared to less than 10 hPa during the wet season. The r_a, on the other hand, almost does not change from the wet to the dry season (Figures 2b and 3b), remaining below 30 s/m during daytime hours. This means that the turbulent activity and roughness characteristics change little from one season to the other at those forests.

The forest stomatal resistances also vary significantly between seasons (Figure 2c and 3c). During the wet season, the daily variation is lower than during the dry season, ranging from around 30 to 150 s/m in the wet season and from 50 to 500 s/m in the dry season (with higher dispersion of values at Jaru, Figure 3c).

Figures 2d and 3d present the diurnal variation of Ω for both forests. During the wet season, Ω shows a decreasing trend throughout the day, ranging from 0.8 to 0.5. During the dry season, Ω remains around 0.6 in the morning at K34 (Figure 2d), then drops to 0.4 in the afternoon. However, it drops significantly lower at Jaru throughout the day (Figure 3d). According to Jarvis and McNaughton (1986), this means that for both forests the evapotranspiration in the wet season is mainly controlled by the available energy, especially during morning hours, but trending to some influence of stomatal resistances during the day. During the dry season, the stomata play a stronger role in controlling forest transpiration, especially in the afternoon hours. Understanding mechanisms of how evapotranspiration is controlled in vegetated surfaces is of crucial importance, since the evapotranspiration processes connect the vegetation function and regional climate via their role in the partitioning of radiative energy into heat and moisture supply from the surface to the atmosphere.

The measurements at the pasture site are even more sensitive to the seasonal variations (Figure 4). Median VPD reaches 23 hPa in the dry season (Figure 4a), while remaining below 11 hPa in the wet season. Variations in r_a are also more pronounced than in the forests (Figure 4b), but these seasonal changes are more complex to interpret, because they are largely sensitive to grazing by cattle, which alters the roughness of the grass vegetation not necessarily consistent with our selection of wet and dry periods. Still, it can be observed that in the pasture r_a is higher than in the forests in both seasons, as a result of higher roughness of the forest vegetation.

The seasonal variations in r_s at FNS are similar to those in the forest sites in the wet season, varying from 50 to 150 s/m, while in the dry season the variation is much higher, from 100 to 1000 s/m (~2000 at 6 pm, Figure 4c), pointing to more intense water stress during the dry season in the pasture vegetation.

The behavior of Ω at the pasture is also different than in the forests, although also qualitatively indicating the higher control of transpiration by stomatal resistance during the dry periods (Figure 4d). Ω remains high (~ 0.8) during the whole day in the wet season and drops significantly (from 0.8 to 0.3) during the day in the dry season.
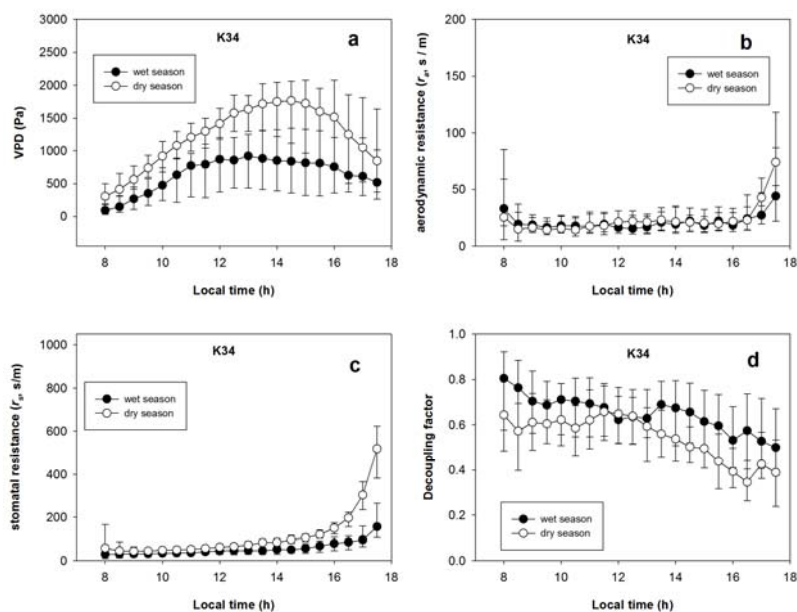
Figure 2. Distribution of hourly measurements of (a) vapor pressure deficit (VPD), (b) aerodynamic resistance, (c) stomatal resistance and (d) the decoupling factor, Ω, during the daytime, observed in wet and dry periods of 2000 at K34 forest site. Symbols represent the median of observations in each hour and the vertical bars represent the interval between 1st and 3rd quartiles.

Figure 3. Distribution of hourly measurements of (a) vapor pressure deficit (VPD), (b) aerodynamic resistance, (c) stomatal resistance and (d) the decoupling factor, Ω, during the daytime, observed in wet and dry periods of 2000 at Jaru forest site. Symbols represent the median of observations in each hour and the vertical bars represent the interval between 1st and 3rd quartiles.
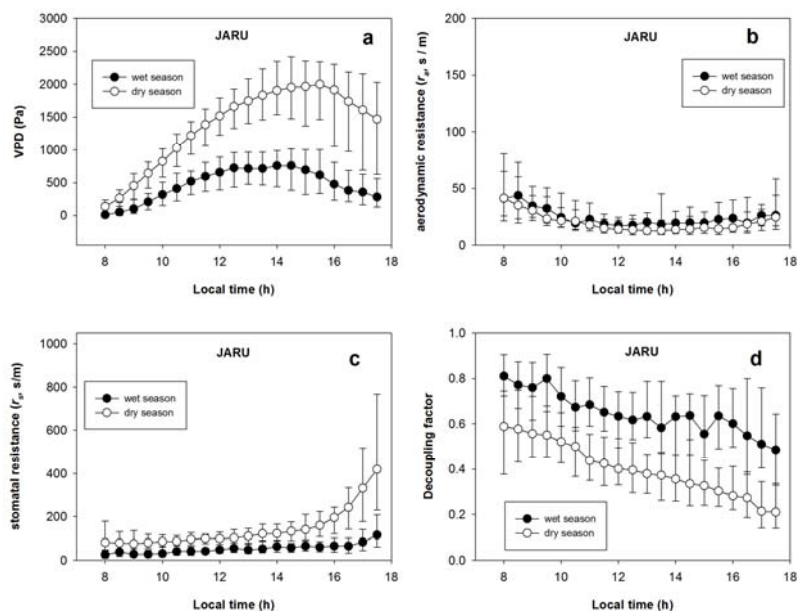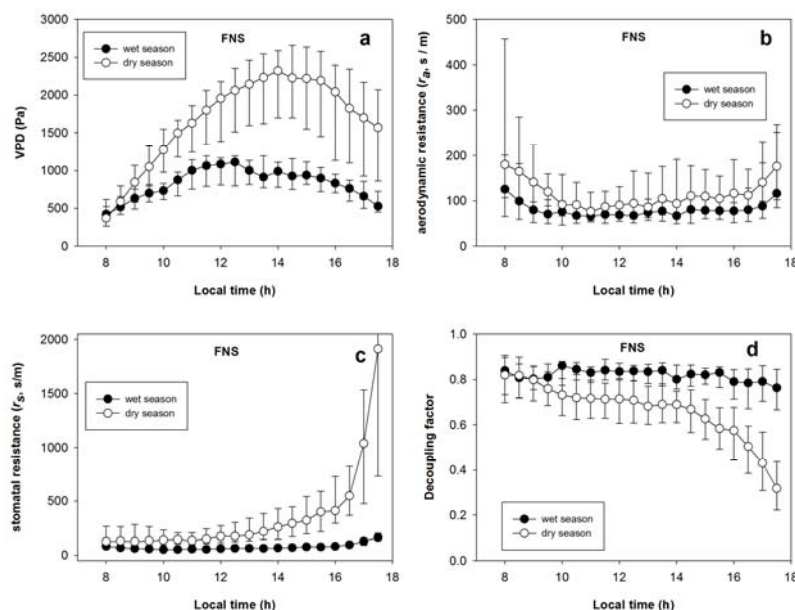
Figure 4. Distribution of hourly measurements of (a) vapor pressure deficit (VPD), (b) aerodynamic resistance, (c) stomatal resistance and (d) the decoupling factor, Ω, during the daytime, observed in wet and dry periods of 2000 at the FNS pasture site. Symbols represent the median of observations in each hour and the vertical bars represent the interval between 1st and 3rd quartiles.

For reference use in the climate models, in Table 1 we synthesize recommended values of the aerodynamic and stomatal resistances in the three sites. The r_a values were estimated from an approximate average of the medians from 9:00 to 16:00 h, to avoid the hours of transition to nighttime. The r_s reference values are presented as a range from lower resistances recommended for use in the morning time to higher resistances to represent stronger stomatal control during the afternoon.

Table 1. Reference values for aerodynamic and stomatal resistances, estimated in this study.

	r_a (s/m)	r_s (s/m)
Forest K34, wet season	20	40 – 150
Forest K34, dry season	20	50 – 500
Forest Jaru, wet season	20	40 – 100
Forest Jaru, dry season	20	90 – 400
Pasture (FNS), wet season	70	50 – 160
Pasture (FNS), dry season	100	140 –1800

Previous studies in the Amazon region have identified that evapotranspiration is directly connected to available energy, but also to aerodynamic transport mechanisms and biological control of transpiration, and that these controls vary according to the vegetation type or depending on periods of seasonal water deficits (e.g. Souza Filho et al., 2005, Hasler and Avissar, 2007, Costa et al., 2010, Von Randow et al., 2012, Christoffersen et al., 2014). Hasler

and Avissar (2007) analyzed the seasonality of evapotranspiration in 8 sites in Amazonia; three of them are the K34, Rebio Jaru and FNS sites. However, the authors used a preliminary version of the dataset, which was possibly subject to large uncertainties due to problems in data collection and incomplete quality assessment. We now update and extend the analyses to address in more detail how these mechanisms vary throughout the daytime and seasonally in the two contrasting vegetation types of rainforest and pasture in the same region, and in a rainforest in a wetter climate.

Results obtained in this study show that the biological control of transpiration (represented by the stomatal resistance) presents both diurnal and seasonal variability. Daily, a low resistance marks it in the morning, increasing throughout the day to reach high values in the evening. Since the stomatal resistance is related to the opening or closure of stomata, these results indicate that there is restriction of transpiration related to water deficit in the plants.

Analyzing the aerodynamic resistances, we also found that turbulence caused by the roughness of the surface can be an important secondary factor and almost invariable from the wet to dry seasons in the production of evapotranspiration in the sites, especially in the forest. This is indicated by the low aerodynamic resistance observed, or, in its turn, high aerodynamic conductance related to high roughness of the forest surface.

The results obtained from the analysis of the Jarvis and McNaughton (1986) decoupling factor (Ω) may bring further insight into our discussion. The parameter varies between 0 and 1, with values close to 1 indicating that the conditions of evapotranspiration are decoupled from surface resistances (that is, evapotranspiration is mainly related to the amount of available energy), and values close to 0 indicating a strong coupling between evapotranspiration and the atmospheric turbulent conditions and biological activity (that is, evapotranspiration is controlled not only by energy, but also by vegetation and other atmospheric conditions). Our results show that Ω presents not only a diurnal variation, but also a seasonal variation for both forests. During the wet season, evapotranspiration is controlled by atmospheric conditions, especially during the morning, dropping to around 0.5 at the end of the afternoon in both forest sites. On the other hand, in the dry season, stomata is responsible for controlling the transpiration in both forests, mainly at the end of the afternoon, with Ω dropping from around 0.6 to less than 0.4. A strong drop occurs in Rebio Jaru, which is lower than 0.5 already at the end of the morning. This indicates that, although energy limitation is a strong influence, there is a significant contribution of the biotic factors to the variability of evapotranspiration. FNS, in turn, shows that its evapotranspiration is controlled by the atmospheric conditions in the wet season, as well as in the dry season. However, during the dry season, Ω presents a diurnal variation, dropping to lower than 0.5 at the end of the afternoon, showing once more the restriction of transpiration related to water deficit in the plants during this period.

The radiative energy provided by solar radiation is the main forcing of the biophysical processes of interaction between the biosphere and the atmosphere, acting as the primary driver of evapotranspiration in Amazonia. This has been observed before, especially in the more 'equatorial' sites of Amazonia, such as the K34 (e.g. Da Rocha et al., 2009, Costa et al., 2010). However, there is also indication that some species in equatorial sites are sensitive to water stress if the dry season is prolonged or in artificial rainfall exclusion experiments (Meir et al., 2009). Our results further highlight the strong sensitivity that a land use change to pasture vegetation would cause: the pasture site clearly shows a large increase in stomatal resistance and transpiration control by the vegetation during the dry season.

Da Rocha et al. (2009) and Costa et al. (2010) discussed in their results a general seasonal behavior in evapotranspiration in different sites in Amazonia, corroborating the main control of evapotranspiration by abiotic / environmental conditions of available energy. The climate conditions that produce the tropical forests are generally characterized by frequent and

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abundant rainfall, which is certainly the case of forest in Central Amazonia near Manaus, and this makes less likely the occurrence of severe water stress. Due to this and also due to the large soil depth that tree roots may reach in the region, it is expected that these forests will remain resilient to annual dry seasons in the near future. However, if the occurrence of anomalous dry years increases in frequency due to climate change or a combination of climate change and increasing pressures of land use change substantially affect the ecosystem, it is realistic to expect a significant degradation of the forest into a less resilient forest type.

4. CONCLUSIONS

Analyzing measurements of vapor pressure deficit, aerodynamic resistance, stomatal resistance and of the decoupling factor, we studied the diurnal and seasonal variability of control of evapotranspiration in contrasting sites in Amazonia: a pristine rain forest in Central Amazonia (K34 site), a pristine forest (Jaru) and a pasture (FNS) in Southwestern Amazonia. Seasonal variations in precipitation minus reference evapotranspiration totals are similar conditions in the sites, however the pasture presents slightly higher vapor pressure deficit (drier conditions) in the dry season, and, especially because of the shallower roots in the pasture vegetation, we observe that these conditions reflect a different seasonal behavior of the evapotranspiration in the pasture compared to the forest sites.

Aerodynamic resistance does not change significantly from wet to dry season in either forest site, but it is higher in the pasture compared to the forests due to its lower roughness, and it is sensitive to cattle grazing. Stomatal resistance, on the other hand, exhibits large changes both throughout the day and from the wet to the dry seasons at the three sites. Daily, stomatal resistance shows low values in the morning, increasing to reach its maximum in the afternoon and early evening, which highlights the effect of increasing stomatal control of evapotranspiration as the day progresses. This effect is even more pronounced in the dry season, which evidences the occurrence of water stress in the pasture vegetation. During the wet season, soil water conditions are likely much more favorable, and the stomatal resistance is similar in the two vegetation types.

Results obtained for the decoupling factor also corroborate conclusions from previous studies that evapotranspiration is primarily driven by the conditions of available energy in Amazonia (decoupled from surface conditions) in the wet season, but, still, a significant biological control of transpiration by plants is observed in the dry season, especially in the pasture cover and in the afternoon.

5. REFERENCES

ALLEN, R. G.; PEREIRA, L. S.; RAES, D.; SMITH, M. **Crop evapotranspiration-Guidelines for computing crop water requirements**. Rome: FAO, 1998. (FAO Irrigation and drainage paper, 56).

ARAÚJO, A. C.; NOBRE, A. D.; KRUIJT B.; ELBERS, J. A.; DALLAROSA, R.; STEFANI P. et al. Comparative measurements of carbon dioxide fluxes from two nearby towers in a central Amazonian rainforest: The Manaus LBA site. **Journal Geophysical Research: Atmospheres**, n. 107, p. 58-1–58-20, 2002. http://dx.doi.org/10.1029/2001JD000676

ARRAUT, J. M.; NOBRE, C.; BARBOSA, H. M.; OBREGON, G.; MARENGO, J. Aerial rivers and lakes: looking at large-scale moisture transport and its relation to Amazonia and to subtropical rainfall in South America. **Journal of Climate**, v. 25, p. 543–556, 2012. http://dx.doi.org/10.1175/2011JCLI4189.1

IPABH

CHOUDHURY, B. J.; DIGIROLAMO,N. E.; SUSSKIND,J.; DARNELL,W. L.; GUPTA, S. K.; ASRAR, G. A biophysical process-based estimate of global land surface evaporation using satellite and ancillary data II. Regional and global patterns of seasonal and annual variations. **Journal Hydrology**, n. 205, p. 186–204, 1998. http://dx.doi.org/10.1016/S0022-1694(97)00149-2

CHRISTOFFERSEN, B. O.; RESTREPO-COUPE, N.; ARAIN, M. A.; BAKER, I. T.; CESTARO, B. P.; CIAIS, P. et al. Mechanisms of water supply and vegetation demand govern the seasonality and magnitude of evapotranspiration in Amazonia and Cerrado. **Agricultural and Forest Meteorology**, n. 191, p. 33-50, 2014. http://dx.doi.org/10.1016/j.agrformet.2014.02.008

COSTA, M. H.; BIAJOLI, M. C.; SANCHES, L.; MALHADO, A. C. M.; HUTYRA, L. R.; DA ROCHA, H. R.; AGUIAR, R. G.; DE ARAÚJO, A. C. Atmospheric versus vegetation controls of Amazonian tropical rain forest evapotranspiration: Are the wet and seasonally dry rain forests any different? **Journal Geophysical Research: Biogeosciences**, n. 115, p. 1-9, 2010. http://dx.doi.org/10.1029/2009JG001179

DA ROCHA, H. R.; MANZI, A. O.; CABRAL, O. M.; MILLER, S. D.; GOULDEN, M. L.; SALESKA, S. R. et al. Patterns of water and heat flux across a biome gradient from tropical forest to savanna in Brazil. **Journal of Geophysical Research: Biogeosciences**, n. 114, p. 1-8, 2009. http://dx.doi.org/10.1029/2007JG000640

HASLER, N.; AVISSAR, R. What Controls Evapotranspiration in the Amazon Basin? **Journal of Hydrometeorology**, n. 8, p. 380-395, 2007. http://dx.doi.org/10.1175/JHM587.1

JARVIS, P. G.; MCNAUGHTON, K. G. Stomatal control of transpiration: Scaling Up from Leaf to Region. **Advances in Ecological Research**, n. 15, p. 1-49, 1986. http://dx.doi.org/10.1016/S0065-2504(08)60119-1

KRUIJT, B.; ELBERS, J. A.; VON RANDOW, C.; ARAUJO, A. C.; OLIVEIRA, P. J.; CULF, A. et al. The robustness of eddy correlation fluxes for Amazon rain forest conditions. **Ecological Applications**, n. 14, suppl. 4, p. S101–S113, 2004. http://dx.doi.org/10.1890/02-6004

LAMBERS, H.; CHAPIN, F. S.; PONS, T. L. **Plant physiological ecology**. New York: Springer, 2008. 605 p.

MEIR, P.; BRANDO, P. M.; NEPSTAD, D.; VASCONCELOS, S.; COSTA, A. C. L.; DAVIDSON, E. et al. The effects of drought on Amazonian rain forests. In: KELLER, M.; BUSTAMANTE, M.; GASH, J.; SILVA DIAS, P. (Eds.). **Amazonia and Global Change**. Washington D.C: American Geophysical Union, 2009. p. 429-449. (Geophysical Monograph Series, v. 186).

SOUZA FILHO, J. D. C.; RIBEIRO, A.; COSTA, M. H.; COHEN, J. C. P. Mecanismos de controle da variação sazonal da transpiração de uma floresta tropical no nordeste da amazônia. **Acta Amazônica**, n. 35, p. 223-229, 2005. http://dx.doi.org/10.1590/S0044-59672005000200012

VON RANDOW, C.; MANZI A. O.; KRUIJT, B.; OLIVEIRA, P. J.; ZANCHI, F. B.; SILVA, L. et al. Comparative measurements and seasonal variations in energy and carbon exchange over forest and pasture in South West Amazonia. **Theoretic al and Applied Climatology**, n. 78, p. 5–26, 2004. http://dx.doi.org/10.1007/s00704-004-0041-z

IPABHí

VON RANDOW, R. C. S.; VON RANDOW, C.; HUTJES, R. W. A.; TOMASELLA, J.; KRUIJT, B. Evapotranspiration of deforested areas in central and southwestern Amazonia. **Theoretical and Applied Climatology**, n. 109, p. 205-220, 2012. http://dx.doi.org/10.1007/s00704-011-0570-1

WERTH, D.; AVISSAR, R. The Regional Evapotranspiration of the Amazon. **Journal of Hydrometeorology**, n. 5, p. 100-109, 2004. http://dx.doi.org/10.1175/1525-7541(2004)005%3C0100:TREOTA%3E2.0.CO;2

ZANCHI, F. B.; WATERLOO, M. J.; AGUIAR, L. J. G.; VON RANDOW, C.; KRUIJT, B.; CARDOSO, F. L. et al. Estimativa do Índice de Área Foliar (IAF) e Biomassa em pastagem no estado de Rondônia, Brasil. **Acta Amazônica**, v. 39, n. 2, p. 335–348, 2009. http://dx.doi.org/10.1590/S0044-59672009000200012

ZEMP, D. C.; SCHLEUSSNER, C.-F.; BARBOSA, H. M. J.; VAN DER ENT, R. J.; DONGES, J. F.; HEINKEL, J. et al. On the importance of cascading moisture recycling in South America. **Atmospheric Chemistry Physics**, v. 14, p. 13337–13359, 2014. http://dx.doi.org/10.5194/acp-14-13337-2014

IPABH