Chapter

The Relevance of Maintaining Standing Forests for Global Climate Balance: A Case Study in Brazilian Forests

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Abstract

Estimate Net Ecosystem Exchange (NEE) is important to better understand carbon exchanges between terrestrial ecosystems and the atmosphere. Comprehend these dynamics is essential to better understand the responses of environments to ongoing climatic changes. This study aims to analyze, with AMERIFLUX and LBA network measurements, the variability of NEE and climate variables in four different tropical coverages: Pantanal, Amazonia, Caatinga and Cerrado (savanna). Furthermore, was estimate the Gross Primary Productivity (GPP). We found a distinct seasonality of meteorological variables and CO_2 fluxes in each site. Despite acting mostly as a CO_2 sink, some environments already show worrying source data in certain periods, pointed out as a direct effect of the reduction of photosynthesis caused by land use changes. The preserved forest plays an important role in maintaining rainfall at a regional and global level, and its maintenance makes it possible, by the way, an important tool in combating global warming via carbon sequestration by trees, which requires commitment and public policies of environmental preservation and recovery of degraded areas.

Keywords: net ecosystem exchange, carbon balance, climate change, deforestation, micrometeorology

1. Introduction

In 1998, the World Meteorological Organization (WMO), a United Nations agency, and the United Nations Environment Programme (UNEP) started actions of

Intergovernmental Panel on Climate Change (IPCC), which is composed of a large group of researchers from various nationalities with the aim of developing scientific knowledge about climate change and its impacts on society. It is agreed that the increase in the concentration of greenhouse gases (GHG) is mainly caused by the burning of fossil fuels and changes in land use, such as deforestation. These and other human activities are responsible for climate change [1]. The alert for these changes has promoted several lines of research within climate science to debate and create understanding about the GHG cycle and how man would be influencing this cycle, which still has great uncertainties. To decrease these uncertainties, in situ measurements are necessary to better understand the particularities of each environment [2], as these data can be used for the evaluation of soil-vegetation-atmosphere interaction models, [3, 4], as well as in the analyses of satellite products that estimate components of the water and/or CO_2 balance [5–7], which can provide reliable information to monitor CO_2 exchange in tropical forests that have little coverage of towers equipped with Eddy Covariance (EC) system, for example Brazil.

One practical way to mitigate the effects of climate change would be to increase the vegetation cover in dryland and devastated areas, both through the replanting of large forest covers in order to capture atmospheric CO_2, and through the effect of forests on the hydrological cycle. With the emerging trade in carbon credits in the global market, there are several enterprises that benefit from the reforestation of large areas of land and the banks of hydroelectric power generation dams. Although carbon credit trading is accused of being an ineffective way to mitigate CO_2 emissions, because some people pay to continue polluting, this would be an advantageous way of transitioning to an economy with a clean energy matrix, especially in a country like Brazil, with extensive areas of tropical forest.

Therefore, it would be more economically advantageous to preserve untouched forests than to devastate them for logging or to start immediately profitable agricultural and cattle ranching enterprises. However, the prognoses for Brazilian forested areas related to global warming [8, 9], especially the Amazon, are not very good: Global warming is expected to increase temperatures in this region, which may make the climate drier, causing savannization of this forest, i.e., parts of the forests should be altered, changing their structure and approaching the Cerrado physiognomy.

River levels may present a great reduction, and the air should become drier during dry periods, which increases the risk of fires. In addition, the advance of the agricultural frontier, if maintained at current levels, is expected to reduce forest cover to 53% of the original by 2050. The number of studies on the response of Amazonian and Cerrado flora and fauna species to climate change is still very small, but they indicate that with an increase of 02–03°C in average temperature, up to 25% of the trees in the Cerrado and about 40% of the trees in the Amazon could disappear by the end of this century [10]. For the planet's temperature not to exceed an increase of 1.5°C and thus avoid drastic changes in the climate, "rapid, vast and unprecedented changes" will be necessary at the global level, warned a report released on 08/10/2018 by the UN IPCC.

Micrometeorological studies to obtain data that help understand the role of Brazilian tropical forests in the planet's climate balance exist since the 1980s until the LBA (Large Scale Biosphere-Atmosphere Experiment in Amazon) [11]. Some works pointed in the Amazon forest a potential sink of atmospheric CO_2 [12–14] with micrometeorological measurements. Saleska et al. [15] compared micrometeorological estimates and biometric measurements in Santarém- PA and reported a CO_2 source to the atmosphere of 1.3 Mg C ha^{-1} $year^{-1}$, associated with the prevalence of emissions by necromass decomposition in preceding episodes of high tree mortality in the region. Miller et al. [16] reported slightly positive ecosystem fluxes of 0.4 Mg C ha-1 year-1, closer to neutral, corroborated by biometric measurements. Espírito Santo et al. [17] combined satellite estimates and field data to suggest that uptake by living trees exceeds emission by dead trees, reinforcing evidence of the upland forest acting as a carbon sink in aboveground biomass. The differences between the contributions of different Brazilian biomes have been consistently reported in the literature [2]. Evapotranspiration rates are highest and greatest at Cerrado and Pantanal sites in wetter months. Even in the month with the highest evapotranspiration rates (October), the values of the Caatinga sites do not reach the magnitude scale of the measurements of the other sites, showing the peculiarity of this site as to its BSh (Arid/Stepp/Hot) climate by Köppen's climate classification. Generally the measurements show that evapotranspiration in the dry season is higher than in the wet season and Rn is the main control of evapotranspiration in humid tropical rainforests (like the Amazon site), which does not apply for the more arid Caatinga region nor for the Cerrado and Pantanal sites, which differ from the Amazon by showing depletion of evapotranspiration throughout the dry season, culminating with lower values in drier months such as August and September, the same period where the Amazon site presents its maximum [2].

All these particularities directly influence the local and regional carbon balance, showing the need to create a better understanding of the biogeochemical cycles in these locations to try to show the importance of forest climate control on climate and greenhouse gas emissions, in order to prove that keeping the forest standing can be the most viable alternative for a public policy on climate change mitigation, results that will be discussed below.

2. Methodology

2.1 Data policy and use license

The Ameriflux platform integrates the data monitored in three biomes, with the identifications: BR-Sa1 (Amazon), BR-CST (Caatinga) and BR-Npw (Pantanal). The data from the Cerrado site (BR-BI, Bananal Island - Javaés) are available at https://daac.ornl.gov. The data made available by ORNL DAAC are shared freely, without restriction, in agreement with NASA's Earth Science Program. Ameriflux data is shared under a CC-BY-4.0 data usage license (Creative Commons by Attribution 4.0 International). The CC-BY-4.0 license specifies that data usage is free to share (copy and redistribute the material in any medium or format) and/or adapt (remix, transform and build upon the material) for any purpose. The citation of the data sites is: BR-Sa1 [18], BR-CST [19] and BR-Npw [20].

2.2 Description of study áreas

2.2.1 Cerrado site

Measurements were made at an experimental floodplain site in Cantão State Park, 260 km west of Palmas, Tocantins, Brazil, in the context of the Large-Scale Biosphere-Atmosphere Experiment in Amazonia (LBA), at a micrometeorological tower with measurements of turbulent energy fluxes and meteorological variables. The tower was located 2 km east of the Araguaia river (9° 49′ 27.9“ S, 50° 08’ 92.8” W, at 120 m altitude), about 1 km east of Javaézinho river, on the northern border of Ilha do Bananal and south of the park. The region of the Araguaia plain, where Ilha do Bananal is located, stands out for its exuberant landscape with aspects of the Cerrado and Amazon biome with three conservation units, the Araguaia National Park, the Cantão State Park (PEC) and the Cantão Environmental Protection Area. Bananal island covers an area of about 21,000 km2 (approximately 80 x 260 km) and is the largest river island in the world, covered mostly by savannas and grasslands, in seasonal floods usually from February to June [21]. The measurement fetch area covers three types of physiognomy: cerradão and semideciduous forests (trees with an average height of about 20 m), cerrado s.s., and areas of clean field and isolated lagoons. The regional climate is hot and seasonally humid, with average annual precipitation of about 1466 mm year-1, approximately 90% of the annual rainfall in the rainy season between October and April [21] and therefore typical of the Cerrado biome in central-western Brazil. The measurements comprise the period from January 2004 to December 2006.

2.2.2 Caatinga site

The measurements were taken at a site managed by the Chico Mendes Institute for Biodiversity Conservation and the micrometeorological tower is part of the monitoring network of the National Observatory of Water and Carbon Dynamics in the Caatinga Biome (NOWCDCB) project. The period of measurements comprises January 1, 2014 to July 31, 2015. This project is located in a preserved Caatinga area (BR-CST), situated in the Pajeú river basin in Serra Talhada (7° 58′ 05.20“ S and 38° 23’ 02.62” W, 430 m), state of Pernambuco, northeastern Brazil. The climate is classified according to Köppen as BSwh (semi-arid), being characterized as hot and semi-arid, with summer rainfall concentrated between December and May (85%) according to Alcântara et al., [22]. The average annual precipitation is approximately 640 mm, and the average monthly air temperature ranges between 23.1 and 26.7°C [22]. The native species of the site are composed of Mimosa hostilis, Mimosa verrucosa and Croton sonderianus, and it is possible to find Anadenanthera macrocarpa, *Spondias tuberosa*, Caesalpinia pyramidalis and Ziziphus joazeiro, with a height of about 8.0 m [22].

2.2.3 Pantanal site

The study was conducted at the Brazilian Northern Pantanal Wetland (BR-Npw) flux tower (**Figure 1**) located approximately 35 km SE of Pocone, Mato Grosso, Brazil (16° 29′53.71” S: 56° 24′45.91” W; 120 m altitude). The site is part of a research station managed by the Federal University of Mato Grosso (UFMT) within a national reserve managed by the Brazilian Social Service of Commerce (SESC Pantanal) [23, 24]. Our data were collected from 1 January 2015 to 31 December 2016. Micrometeorological variables were measured 20 m aboveground, close to the eddy covariance sensors. Air temperature (*Ta*, °C) and relative humidity (*RH*, %) were measured using a thermohygrometer (HMP45AC, Vaisala Inc., Woburn, MA, USA). Precipitation (*Ppt*, mm) was measured 2 m above the ground using a micrometeorological station (WXT520, Vaisala Inc., Helsinki, Finland) installed in an open area to avoid interception by the tower or tree canopy. The flood stage was determined by measuring water levels (*WL*) above the ground at the study site. These inundation

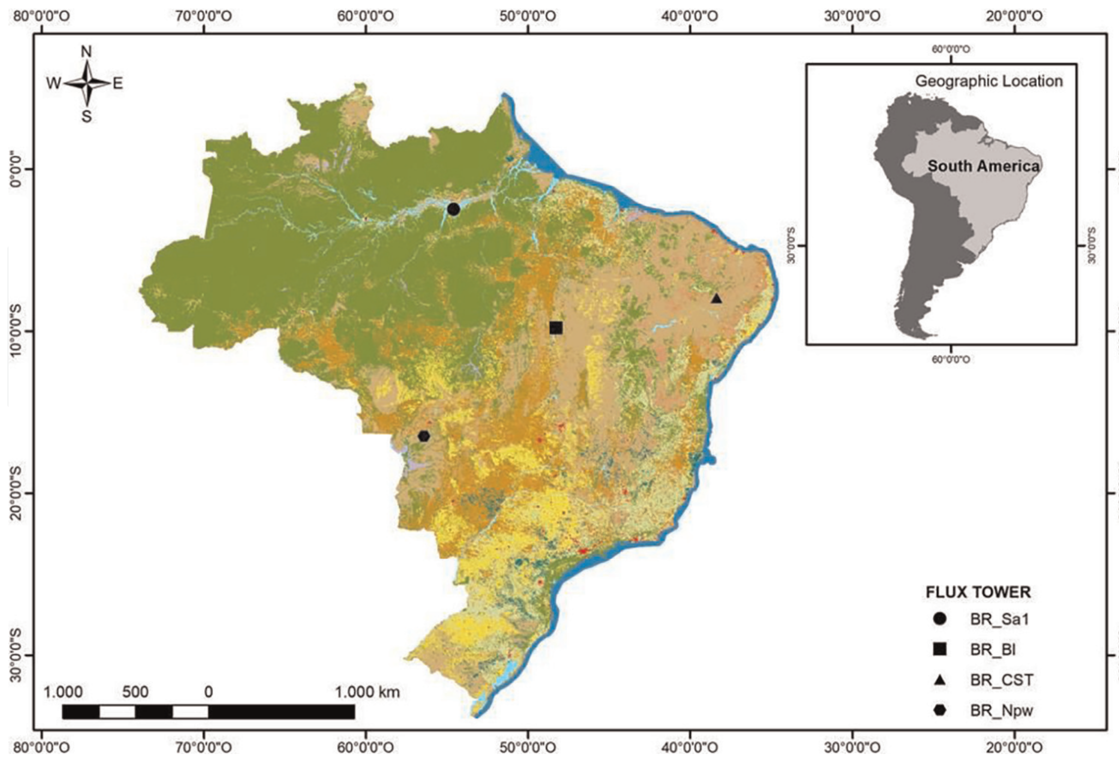

Figure 1.
Location of the study sites.

levels (± 1%) were measured along with water temperature (± 0.3°C using a CTD-10 [Decagon Devices Inc., Pullman, WA, USA], ± 0.05% full scale at 20°C) in 2015 and 2016. Due to instrument malfunction in 2014, the data for this year are not available. The start of each flood cycle began with the first reading of standing water at the site and ended when sensors indicated the absence of standing water. These flood cycles were then compared to the stage of the Cuiaba River collected by the RPPN-SESC Pantanal park rangers (pers. comm.) approximately 1 km away.

2.2.4 Amazonia site

Measurements were made at a site located in the Tapajós National Forest (FNT, 2° 51' S, 54° 58' W), which is situated near the Santarém-Cuiabá Highway (BR-163), at km 67. The NTF is bounded by the Tapajós River to the west and the BR-163 highway to the east, extending 50 km to 150 km south of the city of Santarém-PA. On the eastern side of the BR-163 highway the landscape is extensively developed for agriculture. The tower was installed approximately 6 km west of the BR-163 highway. The data analyzed are CO_2 and energy fluxes associated with meteorological measurements. Measurements range from January 2009 to December 2011, with daily and monthly averages of hourly data. CO_2 fluxes were measured at 58 m using a closed path analyzer (LICOR- 6262) and a Campbell CSAT3 Anemometer was used for the three-dimensional wind measurements. The 65 m micrometeorological tower is located in an area emerging from within a primary forest with a closed canopy of approximately 40 m in height, and can reach up to 55 m with some emergent trees [25]. **Figure 1** shows the location of the four study sites.

2.3 Instrumentation and data processing

Site instrumentations are given in previous publications [21, 22, 24, 26]. The gaps arising from the exclusion of spurious data during the rigorous screening process, were filled using the gap-filling algorithm of marginal distribution sampling (MDS) described by Reichstein et al. [27], which takes into account the covariation of fluxes with meteorological variables and also the temporal self-correlation of fluxes. In this algorithm, three conditions are identified with their respective procedures: when flux data are missing, but meteorological data are available (Rg, Ta and VPD): the missing data is replaced by the average value under similar meteorological conditions in a 7-day window. If similar conditions are not available, the window is increased to 14 days; (2) when only radiation values are available: the missing data is replaced by the average value under similar meteorological conditions within a 7-day window; (3) when no meteorological data is available: the missing value is replaced by the average value of the last hour, thus considering the diurnal variability of each variable. If, after these steps, the data are not filled, the procedure is repeated with larger window sizes until the value can be filled. For filling the gaps, an automated online tool made available by the Max Plank Institute (Max Planck Institute for Biogeochemistry - http://www.bgc-jena.mpg.de/∼MDIwork/eddyproc/) was used.

2.4 Fluxes partitioning

Gross primary productivity (GPP) and ecosystem respiration (Reco) were partitioned from the CO_2 flux data (NEE). For the Cerrado and Pantanal sites, NEE is given as a proxy measure of turbulent flux (Fc). At the other sites NEE is composed of turbulent flux + storage. We used a nighttime-based flow partitioning method [27]. Since GPP =0 in night time, NEE corresponds to:

$$NEE = R_{eco}, \text{for night hours} \tag{1}$$

$$NEE = R_{eco} - GPP, \text{for daytime hours} \tag{2}$$

Reco (μmol m^{-2} s^{-2}) being the sum of autotrophic and heterotrophic respiration. Reco and GPP were calculated using the online tool provided by the Max Plank Institute (Max Planck Institute for Biogeochemistry - http://www.bgc-jena.mpg.de/∼MDIwork/eddyproc/).

Diurnal corrections for missing NEE data were modeled based on diurnal data using the common rectangular hyperbolic light response curve model [28, 29]:

$$NEE = \frac{\alpha \cdot \beta \cdot R_g}{\alpha \cdot R_g + \beta} + \gamma \tag{3}$$

where α (μmol C J^{-1}) is the light utilization efficiency and represents the initial slope of the light response curve, β (μmol C m^{-2} s^{-1}) is the maximum canopy CO_2 uptake rate at light saturation, γ (μmol C m^{-2} s^{-1}) is the ecosystem respiration and Rg (W m^{-2}) is the global radiation. GPP was calculated as:

$$\mathrm{GPP} = NEE + \mathrm{R_{eco}} \tag{4}$$

3. Results

3.1 Climate variables

Air temperature and precipitation are strong controls on ecosystem productivity [2], and all study sites showed effective seasonality in terms of rainfall and air temperature (**Figures 2–5**), with precipitation events (rainy days) more frequent in the Amazon and Cerrado sites. The distribution of average air temperature throughout the year is linked to the intensity of precipitation at the sites, with great variability throughout the year. The Caatinga and Pantanal sites are the warmest throughout the day and in the first months of the year (**Figure 6**), a pattern that is inverted from

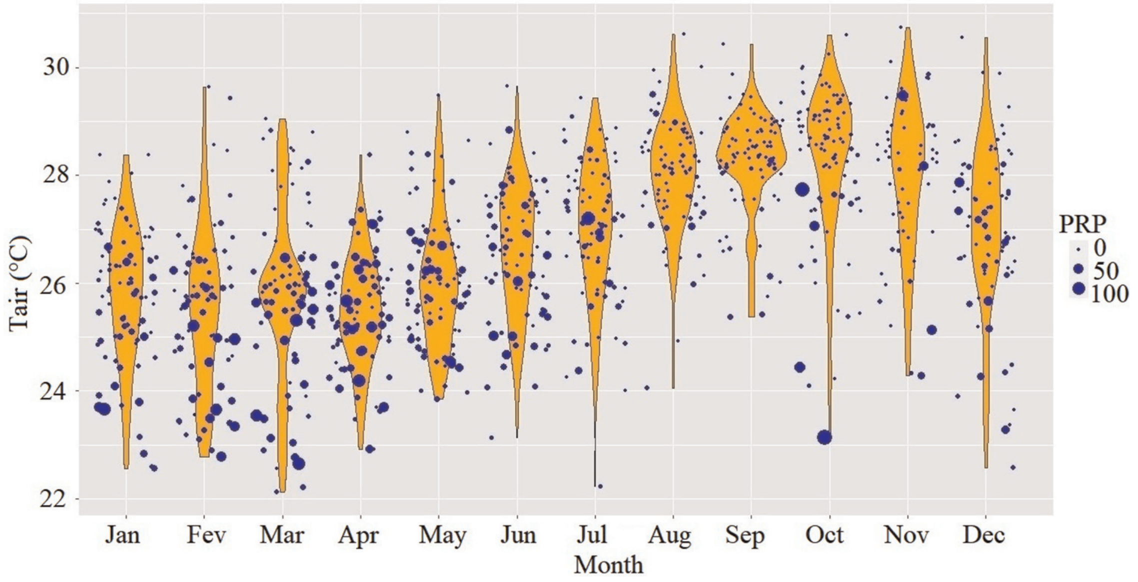

Figure 2.
Distribution of monthly air temperature data density by precipitation intensity at the Amazon site.

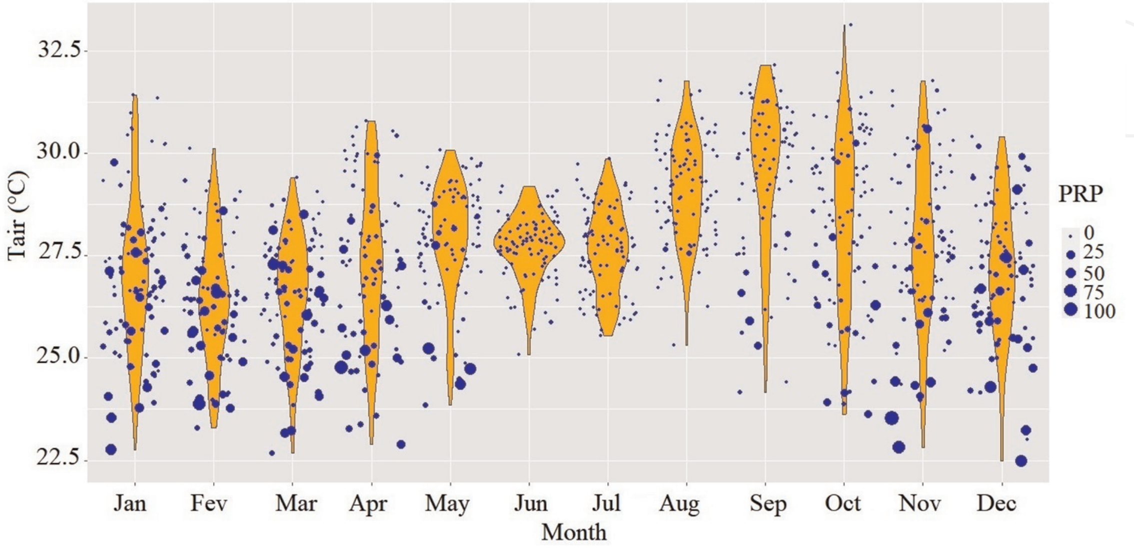

Figure 3.
Distribution of monthly air temperature data density by precipitation intensity at the cerrado site.

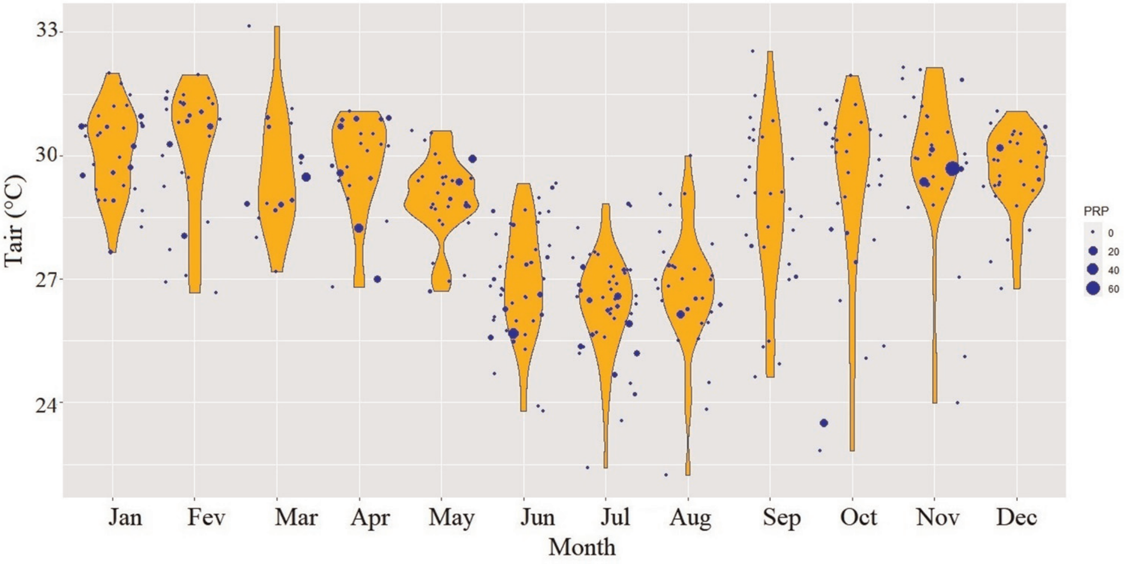

Figure 4.
Distribution of monthly air temperature data density by precipitation intensity at the Caatinga site.

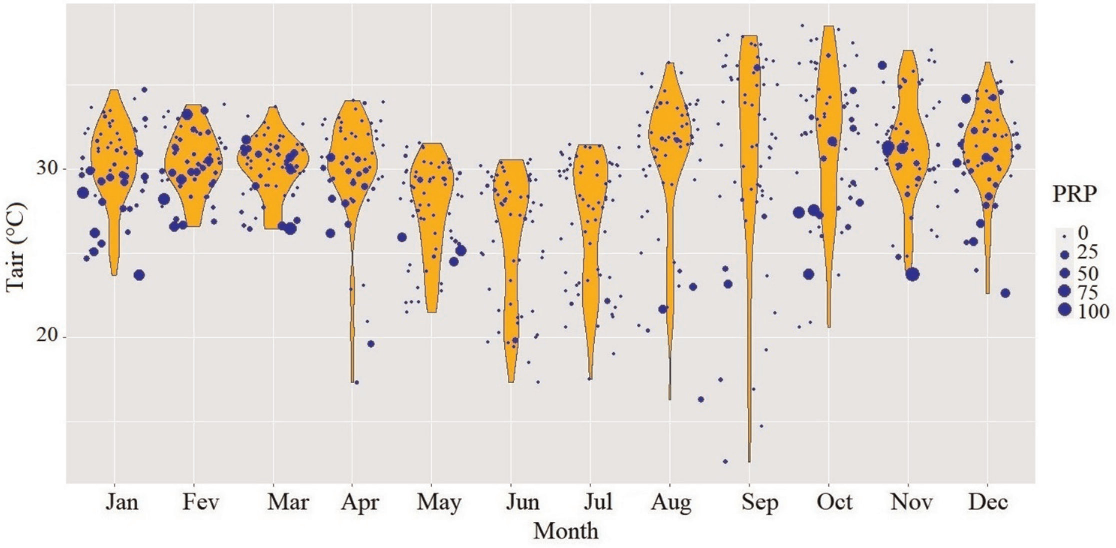

Figure 5.
Distribution of monthly air temperature data density by precipitation intensity at the Pantanal site.

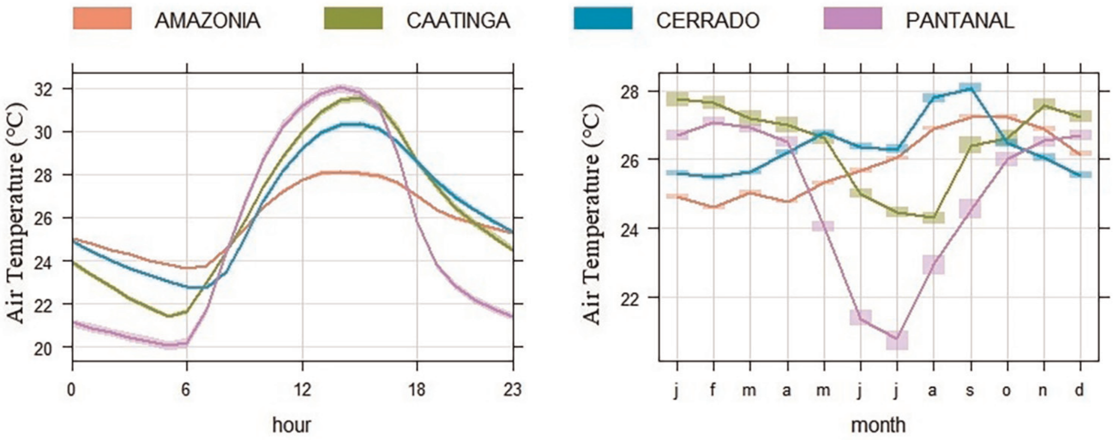

Figure 6.
Hourly (left) and monthly (right) variation of air temperature at the analyzed sites.

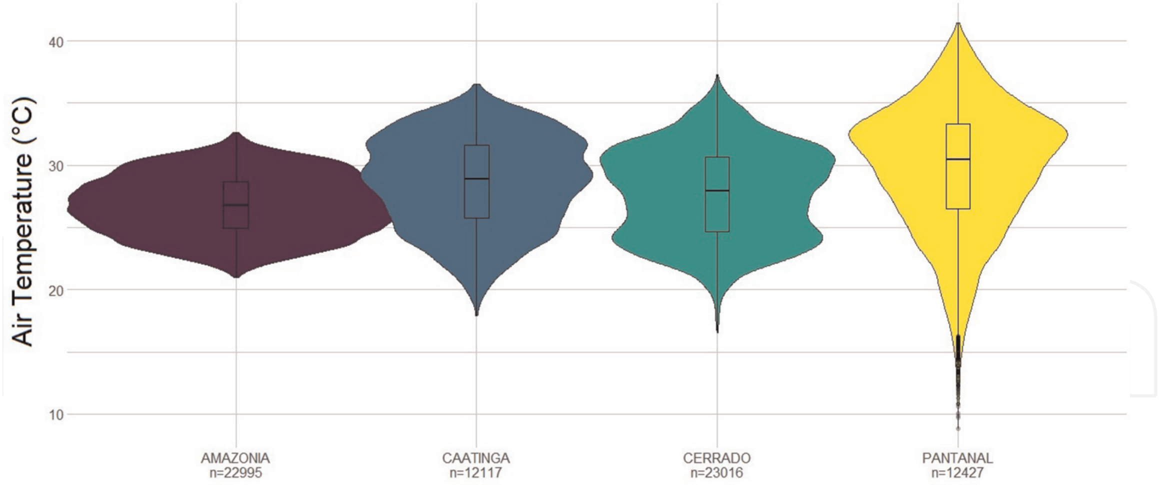

Figure 7.
Violin plot of air temperature at the analyzed sites.

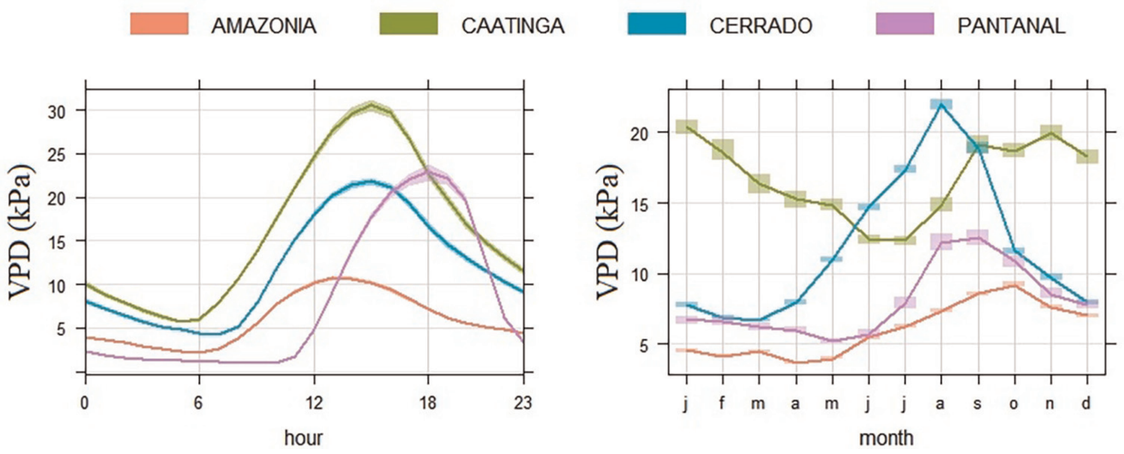

Figure 8.
Hourly (left) and monthly (right) variation of vapor pressure deficit at the analyzed sites.

June until October, when the Amazon and Cerrado sites are warmer than the others. The site with the highest average daily temperature is the Pantanal (**Figure 7**), with 31.6°C in October, while the Amazon site has the lowest temperatures (25.4°C) in April.

Despite being warmer during the day, the Pantanal site is colder at night, and due to its geographical location being susceptible to cold front events, it presents the lowest temperatures in the months of June to August. The Caatinga and Cerrado sites present values up to 3 times higher in VPD (**Figure 8**) than the others, while the Pantanal is close to the Amazon site in this variable. The VPD in the Amazon site practically doubles in value until October, concomitant with the lower precipitation rates and higher air temperature in the year.

3.2 CO_2 fluxes

Monthly averages of NEE and GPP are presented in **Figure 9**, where seasonal changes in NEE are shown to be more intense in the Caatinga and Pantanal sites than in the Amazon and Cerrado sites. The maximum monthly mean GPP values exceed

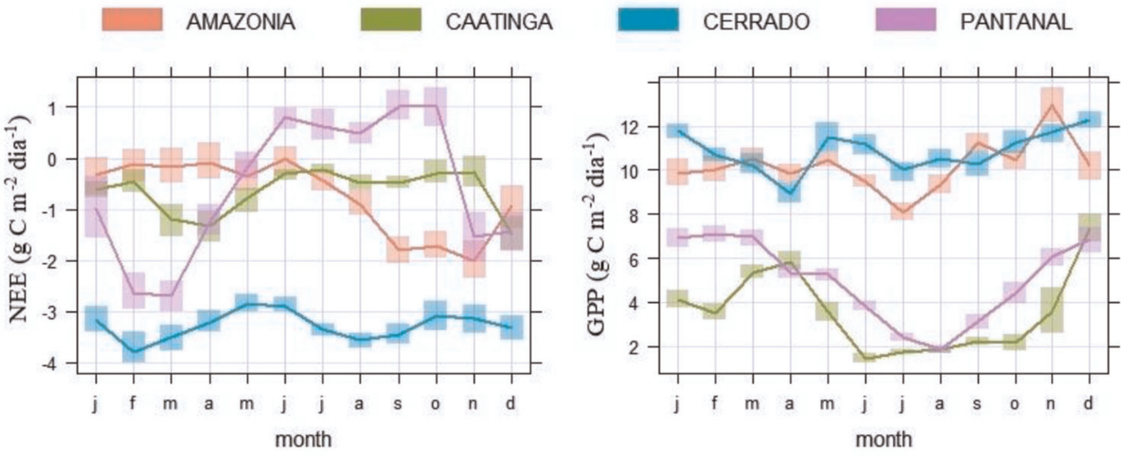

Figure 9.
Monthly variation of NEE (left) and GPP (right) at the analyzed sites.

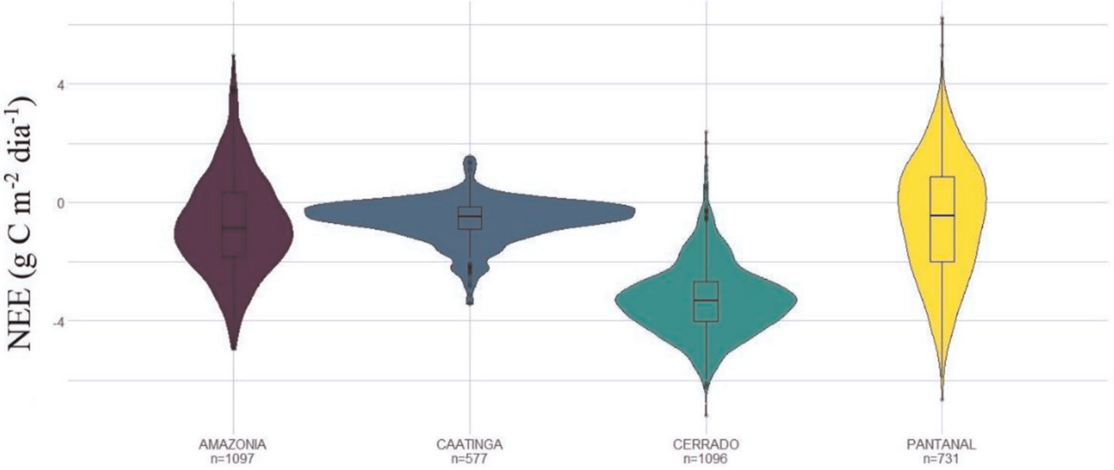

Figure 10.
Violin plot of air temperature at the analyzed sites.

14.0 gC m^{-2} d^{-1} in the Cerrado and Amazon sites, while the lowest GPP values reach about 1.0 gC m^{-2} d^{-1} in the Caatinga site. The seasonality and magnitude of the CO_2 exchange values found in the Amazon and Cerrado resemble each other, while the Caatinga and Pantanal patterns show very close values and variability. The maximum assimilation of the sites occurs in the month of February, when Pantanal and Cerrado show assimilations close to 4.0 gC m^{-2} d^{-1}, and the minimum is very close to 0.5 gC m^{-2} d^{-1} in the month of August at the Pantanal site, after the coldest and least rainy month of the site. Sites susceptible to seasonal flooding [21, 30] in the early months of the year (Cerrado and Pantanal) show increases in assimilation (more negative NEE) between January and February, while Amazon and Caatinga sites have marked increases in assimilation in the warmer months of the year. The density of NEE data (**Figure 10**) shows that most sites act as CO_2 sinks, with higher variability at the Pantanal site and lower variability at the Caatinga site. The medians of GPP (**Figure 11**) are higher in the Amazon, Cerrado and Pantanal sites compared to Caatinga. However, the same does not occur for NEE, where the medians of the Caatinga site have higher values compared to the other sites. Despite this, the large density of data below 0 gC m^{-2} d^{-1} indicates that the Caatinga biome is much more

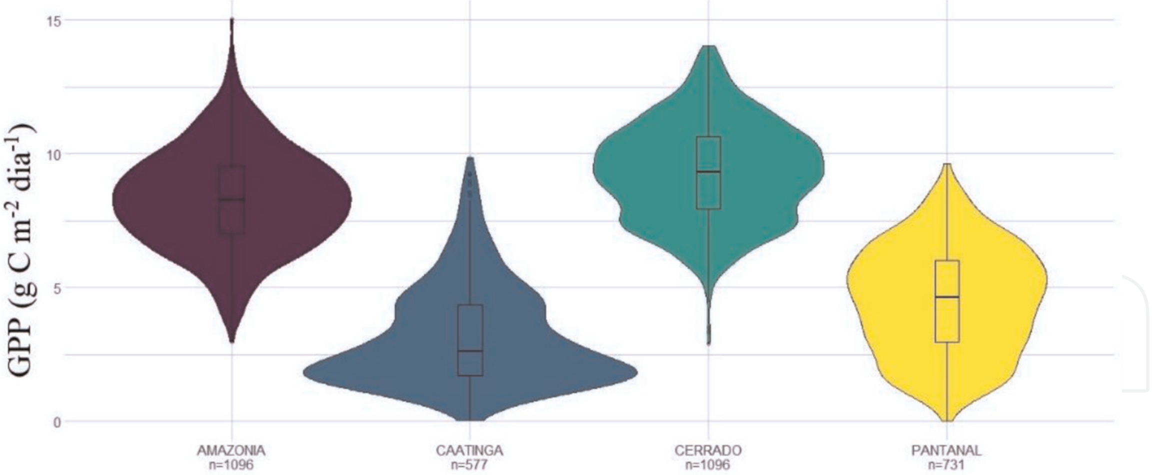

Figure 11.
Violin plot of air temperature at the analyzed sites.

firmly established as a CO_2 sink, despite its smaller vegetative size, than the Amazon site, for example, which have a bimodal NEE data density distribution pattern, showing a secondary maximum above 0 gC m^{-2} d^{-1}, indicating that the biome can act as a source in some seasons, probably controlled by CO_2 emissions higher than assimilation due to the intensification of wildfires in the region, included within the arc of deforestation of the Amazon.

4. Discussion

The results show that most of the sites act as CO_2 sink, corroborating works in the literature [12, 23, 31, 32]. There are data of higher CO_2 emissions (positive NEE) mainly at the Amazon site, where other work has shown the possibility of the environment acting as a moderate source [26, 33]. The overall magnitude of the carbon source/sink is generally highly sensitive to the choice of filter u∗ (to measure turbulence intensity), and even with all the corrections recommended by the literature, the pattern was reinforced by biometric measurements [16], which makes us look for alternative explanations for this unusual pattern, since the vast majority of forest sites in different areas of the same biome, point to a CO_2 sink. Heyek et al. [33] suggested that continuous integrated responses to changes in meteorology, with increased humidity and decreased sunlight, rather than a temporary disturbance, were responsible for the high carbon source at the site. The authors also suggested that reduced photosynthesis, rather than increased respiration, contributed to the high NEE source in specific years at the site. This suggests that partial drought-induced damage to still-living trees can adversely affect ecosystem-wide photosynthesis for several years, which is consistent with results from forest biometric studies at regional and global scales [34, 35]. Tian [36], analyzing series from 1980 to 1994, notes that the carbon balance of the Amazon forest can have great variability, sometimes positive and sometimes negative, depending on variables such as sunlight incidence, CO_2 concentration in the atmosphere and rainfall volume. Gatti et al. [37] point out that regions of the Amazon forest, such as the site region of this study, are affected by environmental degradation and are leading the Amazon as a whole to emit more carbon than it can absorb. The authors point out that a secondary effect of deforestation has been created: the indirect carbon emission caused by the impact of reduced rainfall on photosynthesis, corroborating what was pointed out [33]. Indirect emission happens because deforested regions have a greater loss of rainfall, especially in the dry season (August to October). With the drop in rainfall volume, the temperature rose 2°C in the northeast of the forest and 2.5°C in the southeast, and this "stress" affected photosynthesis, causing the trees to emit more CO_2 than in normal situations to compensate for the imbalance, showing the importance of maintaining the forest, including for the maintenance of rainfall important for agriculture and cattle ranching in the region.

5. Conclusions

The study showed an important meteorological control on the carbon cycle in the biomes studied, which infers that changes in surface cover will directly affect these variables and, consequently, the local carbon balance. Despite acting mostly as a CO_2 sink, some environments already show worrying source data in certain periods, pointed out as a direct effect of the reduction of photosynthesis caused by land use changes. The preserved forest plays an important role in maintaining rainfall at a regional and global level, and its maintenance makes it possible, by the way, an important tool in combating global warming via carbon sequestration by trees, which requires commitment and public policies of environmental preservation and recovery of degraded areas.

Acknowledgements

The authors are also thankful to the Coordination for the Improvement of Higher Education Personnel (CAPES) for the postdoctoral funding granted to KRM and to the National Council for Scientific and Technological Development (CNPq) for the research productivity grant of C.M.S.S (Process n° 303802/2017-0), the financial support of CNPq, through undergraduate research project (PIBIC-UFOPA for L. B. V and G. V. A) and the project NOWCDCB: National Observatory of Water and Carbon Dynamics in the Caatinga Biome (INCT-MCTI/CNPq/CAPES/FAPs 16/2014, grant: 465764/2014-2) and (MCTI/CNPq N° 28/2018, grant 420854/2018-5).

Conflict of interest

The authors declare no conflict of interest and the funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

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References

[1] Intergovernmental Panel On Climate Change - IPCC. Climate Change 2007: The Physical Science Basis. Geneva: Intergovernmental Panel on Climate Change; 2007

[2] Costa GB, Santos e Silva CM, Mendes KR, dos Santos JGM, Neves TTAT, Silva AS, et al. WUE and CO_2 estimations by Eddy covariance and remote sensing in different tropical biomes. Remote Sensing. 2022;**14**:3241. DOI: 10.3390/rs14143241

[3] Bai Y, Li X, Zhou S, et al. Quantifying plant transpiration and canopy conductance using eddy flux data: An underlying water use efficiency method. Agricultural and Forest Meteorology. 2019;**271**:375-384

[4] Mendes KR, Campos S, Mutti PR, Ferreira RR, Ramos TM, Marques TV, et al. Assessment of SITE for CO_2 and energy fluxes simulations in a seasonally dry tropical Forest (Caatinga ecosystem). Forests. 2021;**12**:86. DOI: 10.3390/f12010086

[5] Fonseca LDM, Dalagnol R, Malhi Y, Rifai SW, Costa GB, Silva TSF, et al. Phenology and seasonal ecosystem productivity in an Amazonian flood-plain Forest. Remote Sensing. 2019; **11**:1530

[6] Moreira AA, Ruhoff AL, Roberti DR, de Arruda Souza V, Da Rocha HR, Paiva RCD. Assessment of terrestrial water balance using remote sensing data in South America. Journal of Hydrology. 2019;**575**:131-147

[7] Laipelt L, Ruhoff AL, Fleischmann AS, Kayser RHB, Kich EM, da Rocha HR, et al. Assessment of an automated calibration of the SEBAL algorithm to estimate dry-season surface-energy partitioning in a Forest–savanna transition in Brazil. Remote Sensing. 2020;**12**:1108

[8] Marengo Jose A, Souza Carlos M, Kirsten T, Chantelle B, Kate H, Betts Richard A, et al. Changes in climate and land use over the Amazon region: Current and future variability and trends. Frontiers in Earth Science. 2018;**6**:1

[9] Marengo JA, Drought F. Climate change, and Forest loss in the Amazon region: A present and future danger? Frontiers for Young Minds. 2020;**7**:147

[10] Nobre C, Sampaio GS. Mudanças climáticas. In: Mudanças climáticas e mudanças socioambientais globais: reflexões sobre alternativas de futuro. Brasília: UNESCO, IBECC; 2008. pp. 15-31

[11] Nobre CA, Marengo JA Artaxo P Understanding the climate of Amazonia: Progress from LBA. In: Keller M, Bustamante M, Gash J, Silva Dias P. (Orgs.). Amazonia and Global Change. Geophysical Monograph Ser. Vol. 186. Washington, D.C.: American Geophysical Union Books; 2010. pp. 145-147

[12] Araújo AC, Nobre AD, Kruijt B, Elbers JA, 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 of Geophysical Research. 2002;**107**:8090

[13] Grace J. Carbon dioxide uptake by an undisturbed tropical rain forest in Southwest Amazonia. Science. 1995: 778-780

[14] Malhi Y. Carbon dioxide transfer over a central Amazonian rain forest.

Journal of Geophysical Research-Atmospheres. 1998:593-612

[15] Saleska SRSR, Miller SD, Matross DM, Goulden ML, Wofsy SC, Rocha HR, et al. Carbon in Amazon forests: Unexpected seasonal fluxes and disturbance-induced losses. Science. 2003:1554-1557

[16] Miller SD, Goulden ML, Menton MC, Da Rocha HR, De Freitas HC, Figueira AMS, et al. Biometric and micrometeorological measurements of tropical forest carbon balance. Ecological Applications. 2004:S114-S126

[17] Espírito-Santo FDB, Gloor M, Keller M, Malhi Y, Saatchi S, et al. Size and frequency of natural forest disturbances and the Amazon forest carbon balance. Nature Communications. 2014;**5**(3434):1-6

[18] Saleska S. AmeriFlux BASE BR-Sa1 Santarem-Km67-Primary Forest, Ver. 5-5, AmeriFlux AMP, (Dataset). 2019. DOI: 10.17190/AMF/1245994

[19] Antonino ADCD. AmeriFlux BASE BR-CST Caatinga Serra Talhada, Ver. 1-5, AmeriFlux AMP, (Dataset). 2019. DOI: 10.17190/AMF/1562386

[20] Vourlitis G, Dalmagro H, Nogueira JS, Johnson M, Arruda P. AmeriFlux BASE BR-Npw Northern Pantanal Wetland, Ver. 1-5, AmeriFlux AMP, (Dataset). 2019. DOI: 10.17190/AMF/1579716.

[21] Borma LS et al. Atmosphere and hydrological controls of the evapotranspiration over afloodplain forestin the Bananal Island region, Amazonia. Journal of Geophysical Research: Biogeosciences. 2009; **114**:G01003. DOI: 10.1029/2007jg000641

[22] Alcântara LRP, Coutinho AP, dos Santos Neto SM, de Gusmão C, da Cunha Rabelo AE, Antonino ACD. Modeling of the hydrological processes in Caatinga and pasture areas in the Brazilian semi-arid. Water. 2021;**13**:1877

[23] Dalmagro HJ, Zanella de Arruda PH, Vourlitis GL, Lathuilliere MJ, de Nogueira SJ, Couto EG, et al. Radiative forcing of methane fluxes offsets net carbon dioxide uptake for a tropical flooded forest. Global Change Biology. 2019;**25**:1967-1981

[24] Da Silva JB, Valle Junior LCG, Faria TO, Marques JB, Dalmagro HJ, Nogueira JS, et al. Temporal variability in evapotranspiration and energy partitioning over a seasonally flooded scrub Forest of the Brazilian Pantanal. Agricultural and Forest Meteorology. 2021;**308–309**:108559

[25] Stark S, Leitold V, Wu J, Hunter M, Castilho C, Costa F, et al. Amazon forest carbon dynamics predicted by profiles of canopy leaf area and light environment. Ecology Letters. 2012;**15**:1406-1414

[26] Hutyra LR, Munger JW, Saleska SR, Gottlieb E, Daube BC, Dunn AL, et al. Seasonal controls on the exchange of carbon and water in an Amazonian rain forest. Journal of Geophysical Research. 2007;**112**

[27] Reichstein M, Falge E, Baldocchi D, Papale D, Aubinet M, Berbigier P, et al. On the separation of net ecosystem exchange into assimilation and ecosystem respiration: Review and improved algorithm. Global Change Biology. 2005;**11**:1424-1439. DOI: 10.1111/j.1365-2486.2005.001002.x

[28] Falge E, Baldocchi D, Olson R, Anthoni P, Aubinet M, Bernhofer C, et al. Gap filling strategies for defensible annual sums of net ecosystem exchange.

Agricultural and Forest Meteorology. 2001;**107**:43-69

[29] Lasslop G, Reichstein M, Papale D, Richardson AD, Arneth A, Barr A, et al. Separation of net ecosystem exchange into assimilation and respiration using a light response curve approach: Critical issues and global evaluation. Global Change Biology. 2010;**16**:187-208

[30] Rebellato L, Nunes Da Cunha C. Efeito do fluxo sazonal mínimo da inundação sobre a composição e estrutura de um campo inundável no Pantanal de Poconé, MT, Brasil. Acta Botanica Brasilica. 2005;**19**(4):789-799

[31] Mendes KR, Campos S, da Silva LL, et al. Seasonal variation in net ecosystem CO_2 exchange of a Brazilian seasonally dry tropical forest. Scientific Reports. 2020;**10**:9454

[32] Fu Z et al. The surface-atmosphere exchange of carbon dioxide in tropical rainforests: Sensitivity to environmental drivers and flux measurement methodology. Agricultural and Forest Meteorology. 2018;**263**:292-307

[33] Hayek MN, Longo M, Wu J, Smith MN, Restrepo-Coupe N, Tapajós R, et al. Carbon exchange in an Amazon forest: Fromhours to years. Journal of Geophysical Research: Biogeosciences. 2018;**15**:4833-4848. DOI: 10.5194/bg-15-4833-2018

[34] Anderegg WRL, Schwalm C, Biondi F, Camarero JJ, Koch G, Litvak M, et al. Pervasive drought legacies in forest ecosystems and their implications for carbon cycle models. Science. 2015;**349**: 528-532

[35] Brienen RJW, Phillips OL, Feldpausch TR, Gloor E, Baker TR, Lloyd J, et al. Long term decline of the Amazon carbon sink. Nature. 2015;**519**: 344-348. DOI: 10.1038/nature14283

[36] Tian H, Melillo JM, Kicklighter DW, McGuire AD, Helfrich JVK, Moore B, et al. Effect of interannual climate variability on carbon storage in Amazonian ecosystems. Nature. 1998; **396**:664-667

[37] Gatti LV, Basso LS, Miller JB, Gloor E, Domingues LG, Cassol HLG, et al. Amazonia as a carbon source linked to deforestation and climate change. Nature. 2021;**595**:388-393