RESEARCH PAPER

THE RELATION BETWEEN NET PRIMARY PRODUCTIVITY AND HUMAN ACTIVITIES FOR THREE BIOMES IN BAHIA STATE, BRAZIL

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ABSTRACT. Brazilian biomes are hotspots of global biodiversity, important biomass producers and, consequently, help maintain the world's carbon balance. Net primary production (NPP) is a variable used to determine carbon uptake by land cover. As environmental factors and human activities vary, net primary production increases or decreases. This study aimed to evaluate NPP in three Brazilian biomes – Atlantic Forest, Cerrado, and Caatinga – in the state of Bahia for the last 17 years, and to understand its relationship with human activities by analyzing burned areas, as well as interrelated environmental factors, such as climate variability and soil heat flux, using remote sensing. Using the MOD17 dataset, we find evidence that the Atlantic Forest biome is the one that absorbs more carbon in comparison to the Caatinga and Cerrado biomes, with a mean annual net primary production in each one of these three biomes equal to 1,227.89 g C m^{-2}, 913.81 g C m^{-2}, and 803.56 g C m^{-2}, respectively. The years of El Niño influenced all biomes, and the results showed a strong relationship between climate and NPP in the studied biomes, especially in Caatinga, which is the most sensitive to climatic variations. Besides these results, we find evidence that, in all these biomes, the NPP dynamics have been affected by the increase in land use for agricultural and livestock activities, mainly because of deforestation and burning.

KEYWORDS: Atlantic Forest, Cerrado, Caatinga, MODIS, Carbon, Land use change

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INTRODUCTION

Vegetation in Brazilian biomes is considered one of the richest in the world (Forzza et al. 2012). The Cerrado and Atlantic Forest biomes are global biodiversity hotspots (Myers et al. 2000). Of the 20,000 plant species in the Atlantic Forest, an estimated 8,000 are endemic (Myers et al. 2000) and the flora and fauna of the biome may include 1%-8% of total world species (Silva and Casteleti 2003). The Cerrado biome is the largest and richest savanna in the neotropical region (Klink and Machado 2005; Mendonça et al. 2008). It covers around 2 million km^2 and it is home to a vascular flora of 12,300 species, of which 4,400 are endemic (Mittermeier et al. 2011). The Caatinga biome covers 70% of northeastern Brazil (Silva et al. 2017) and connects to the Cerrado, with which it shares many forest species (Teixeira et al. 2017). The biodiversity of Brazilian biomes comprises important biomass producers, and is, consequently, responsible for the world's carbon turnover (De Miranda et al. 2014; Althoff et al. 2016; Barni et al. 2016; Morais et al. 2017).

Net primary production (NPP) is an important variable for understanding carbon flow in different ecosystems (Chen et al. 2019; Novenko et al 2019; Zhang et al. 2019) and is defined as the difference between photosynthesis and autotrophic respiration of natural vegetation (Wang et al. 2018). NPP increases or decreases as variables such as precipitation and temperature (Liu et al. 2016; Delgado et al. 2018), solar radiation, diffuse light fraction and vapor pressure deficit (Wu et al. 2016), soil characteristics and water availability cause stress due to excess or scarcity to vegetation (Dyukarev et al. 2019; Chen and Yu 2019). Root depth and soil hydraulic redistribution can also determine NPP in drought periods (Oliveira et al. 2005). Moreover, climate change and human activity resulting in changes in land use and cover are intrinsically linked to variations in carbon uptake (Neumann et al. 2016; Chen et al. 2019).

In Brazil, human activity has caused many of the changes in land use and cover, mainly due to burning and deforestation (Barni et al. 2016; De Santana et al. 2020). Based on the annual deforestation report of the non-governmental organization MapBiomas, in 2019, an estimated 408,6 thousand ha were deforested in the Cerrado, 10,6 thousand ha in the Atlantic Forest and 12,1 thousand ha in the Caatinga. These data corroborate Brazil's position as the world's seventh-largest greenhouse gas emitter, with an average of 1,939 billion tons of Greenhouse Gases emitted per year (SEEG 2018). Another impact of burning and deforestation is that the increased levels of atmospheric aerosols from biomass burning, in addition to pollution, cause a reduction in diffuse radiation and, consequently, NPP (Oliveira et al. 2007; Rap et al. 2015). Also, regarding changes on land cover, the replacement of natural vegetation for areas of human occupation such as pastures, can alter water balance and, possibly, the water content in the atmosphere and rainfall patterns (Dias et al. 2002; Staal et al. 2018). Therefore, understanding the relationship between human activity and NPP is essential to mitigate present and future impacts in Brazilian biomes.

Changes in precipitation and climate anomalies play an important role in the regional and global carbon cycle (Wu et al. 2016; Fu et al. 2018). Some studies have shown a decline in global NPP due to deforestation and droughts in recent decades (Medlyn et al. 2011; Althoff et al. 2016), and due to El Niño anomalies (Gushchina et al 2019; Wigneron et al. 2020). On the other hand, in some specific cases, depending on the sort of land handling, an increase in NPP can be verified, despite the increase in the use of the soil for agriculture and the temperature rise (Li et al. 2017; Chen et al. 2019). Therefore, the effect of environmental factors on the dynamics of NPP can vary from region to region (Ji et al. 2020), which stresses the need to evaluate these factors. Few studies have been conducted in Brazilian biomes regarding the effects of climate events and human action on NPP.

Images of the Moderate Resolution Imaging Spectroradiometer (MODIS) have been used in numerous studies on NPP (including for model input) due to its accuracy and spatial and temporal representativeness (Liu et al. 2016; Neumann et al. 2016; Morais et al. 2017). MODIS can provide results to better understand the spatial dynamics of NPP and increase or decrease trends based on environmental and human factors in Brazilian biomes. Moreover, MODIS provides information on potential carbon areas and helps create environmental and socio-economic policies. Thus, this study aims (1) to evaluate the spatial and temporal dynamics of NPP in the Atlantic Forest, Caatinga and Cerrado biomes as a whole and for each land use and cover in the state of Bahia, Brazil, in the last 17 years, (2) understand the relationship between NPP and human activity through the analysis of burned areas in the biomes, and (3) verify the influence of environmental factors in net primary productivity of each biome (whole) through the study of climate variability and soil heat flux.

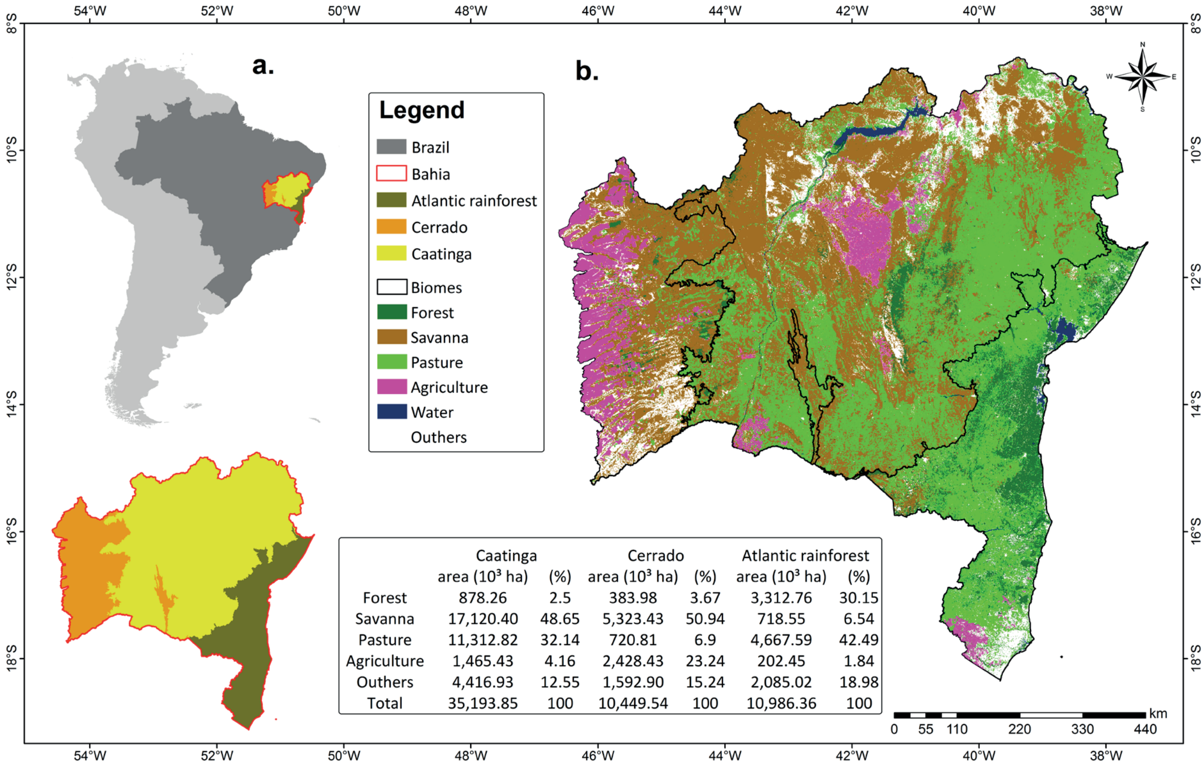
MATERIALS AND METHODS

Study area

The studied biomes are the Atlantic Forest, Caatinga, and Cerrado located in the state of Bahia, northeastern Brazil. The biomes cover an area of approximately 56 million hectares with 417 municipalities (Figure 1). Around 14 million people live in the areas of these biomes (IBGE 2021) and the territory is considerably occupied by productive activities.

The Atlantic Forest biome is characterized by dense, open, and mixed ombrophilous forests, and semi-decidual and decidual seasonal forests. In its latitudinal extent, it has tropical and subtropical regions, while in its longitudinal extent, it comprises different forest compositions due to the decreasing precipitation gradient from the coast to the interior (Ribeiro et al. 2009). Its climate, according to the new classification of Alvares et al. (2013), the climate is tropical without dry season (Af) on the coast, which covers 47% of the Atlantic Forest. Inland, climate is tropical monsoon (Am) and tropical with dry winter (Aw) in 10% and 24% of this biome, respectively. Moreover, the climate in the borders of the Caatinga biome has been recorded as humid subtropical (Cwa) in 3,7 % of its area, subtropical with hot summer (Cfa) (3%) and tropical dry summer (As) (10%), dry semi-arid (BSh) (0,71%), temperate with mild summer (Cfb) (1,11%), and dry winter and temperate summer (Cwb) (0,48%), respectively.

The Cerrado biome is composed of savannas with



	Caatinga		Cerrado		Atlantic rainforest	
	area (10^3 ha)	(%)	area (10^3 ha)	(%)	area (10^3 ha)	(%)
Forest	878.26	2.5	383.98	3.67	3,312.76	30.15
Savanna	17,120.40	48.65	5,323.43	50.94	718.55	6.54
Pasture	11,312.82	32.14	720.81	6.9	4,667.59	42.49
Agriculture	1,465.43	4.16	2,428.43	23.24	202.45	1.84
Outhers	4,416.93	12.55	1,592.90	15.24	2,085.02	18.98
Total	35,193.85	100	10,449.54	100	10,986.36	100

Fig. 1. Location map (a) biomes of the state of Bahia and (b) land use and cover of the biomes in the state of Bahia, Brazil in 2019

defined arboreal and shrub-herbaceous strata. The climate for the state of Bahia in 94% of the biome is tropical with dry winter (Aw), with heavy rainfall in summer. Only a small portion of its area, located to the east of the biome, is classified as As in 4,62% of its area, and Cwb in 1,38% of its area, respectively (Alvares et al. 2013).

The Caatinga biome has savannas with a predominance of semi-continuous canopy species, which are classified as woodland steppe savannas and woodland savannas. In the northern area of the Caatinga, the climate is semi-arid (BSh) in 53% of the biome. In the central region, the climate is Aw and As in 18% and 25% of the Caatinga, respectively. Small portions of the Caatinga have Cwb and Cfb climates, in 2,24% of its area, and 1,76% of its area, respectively (Alvares et al. 2013).

Net primary production

To achieve the Net Primary Production (NPP) between the years 2003 and 2019, were used MOD17A3 images from collection 6, which are provided in HDF format with an annual NPP layer and a pixel resolution of 500 meters. Net primary production is obtained from the difference between Gross Primary Production (GPP) and vegetation respiration. Initially, according to Eq. (1), to collect the GPP the algorithm is based on the concept of the efficiency of use of solar radiation by vegetation (ε). The gross primary production derives from absorbed photosynthetically active radiation (APAR). Where APAR is estimated by multiplying the fraction of photosynthetically active radiation absorbed by vegetation cover (FPAR) (from MOD15 images) and incident photosynthetically active radiation (PAR), assumed to be 45% of total incident solar radiation (Monteith 1972; Running and Zhao 2019), according to Eq. (2):

Due to the variability of vegetation cover and

$$GPP = \varepsilon \times APAR \quad (1)$$

$$APAR = PAR \times FPAR \quad (2)$$

environmental factors in large areas, it is difficult to find the efficiency of light use (ε). However, the model is based on a maximum efficiency value (ε_{max}), including the environmental contributions, where it assumes the minimum air temperature ($Tmin_{scalar}$) and the water status of the vegetation, found through the deficit of water vapor pressure (VPD_{scalar}) (Field et al. 1995; Running and Zhao 2019), as per Eq. (3):

However, to arrives at annual NPP, the maintenance

$$\varepsilon = \varepsilon_{\max} \times T\min_{scalar} \times VDP_{scalar} \quad (3)$$

(R_m) and growth respiration (R_g) are subtracted from GPP as the Eq. (4):

The MODIS tiles that cover the Atlantic Forest, Cerrado,

$$NPP = GPP - Rm - Rg \quad (4)$$

and Caatinga biomes of the state of Bahia, Brazil, are 13H and 09V, 13H and 10V, 14H and 9V, and 14H and 10V and they are available for free on the NASA website (https://search.earthdata.nasa.gov/). In the MODIS Reprojection Tool (MRT) software, the tiles were unified, with conversion from HDF to GeoTIFF and sinusoidal projection to WGS84. In ArcGis 10.4.1, the areas of each biome were cut off and the NPP layer was multiplied by the conversion factor of 0.1 to obtain the biophysical values (g C m^{-2}) (Running and Zhao 2019).

To estimate the carbon uptake of each annual land use and cover, the most relevant classes were selected in all studied biomes, forest, savanna, pasture and agriculture for MapBiomas year 2019 (https://mapbiomas.org/) (Figure 1). The images provided by MapBiomas have a resolution of 30 meters. For use in the overlap, the image was resampled to 500 meters using the nearest neighbor method.

Burned area

The MCD64A1 images of the burned area in the 500-meter spatial resolution MODIS sensor, collection 6, resulted from the algorithm that uses active fire observations and a burn-sensitive vegetation index, which identifies the date the burn occurred on each pixel (Giglio et al. 2016). MCD64A1 images are available with the layers: burn date; uncertain burn date; pixel quality control; and first day, and last reliable detection day of the year (last day) of burned areas (Giglio et al. 2016). The burn date layer made available for each month was used to obtain the values for each year between 2003 and 2019 in hectares for each biome. Given the accuracy of the burn date layer (Libonati et al. 2015; Fornacca et al. 2017), it was the only layer used in this study.

Climate data

To obtain the annual precipitation of each biome, the secondary GPM_3IMERGM 06B version of the Integrated Multi-satellite Retrievals (IMERG) algorithm of the Global Precipitation Measurement (GPM) program was used, available in GeoTIFF format at Giovanni-NASA (https://giovanni.gsfc.nasa.gov/). The IMERG algorithm is based on the analysis of cloud surface temperature, humidity, and pressure and provides precipitation estimates from images with resolution of approximately 10x10 km for the entire planet (Huffman et al. 2019).

MOD11A2 land surface temperature (LST) images of the MODIS sensor have been frequently used due to their accuracy and proximity with air temperature variations (Zhu et al. 2013; Aguilar-Lome et al. 2019). These images are available with the mean temperature of 8 days for each pixel and with spatial resolution of 1 km. For this study, land surface temperature (LST_day) and the pixel quality control indicator (QC_Day) were used.

The LST_day layer was multiplied using ArcGis 10.4.1 software by the scale factor of 0.02 and subtracted from 273.15 to obtain the temperature in Celsius (Eq. (5)) (Wan 2013). Then, for the entire study period, the LST_day band was multiplied by the quality layer with QC = 0, since quality control values equal to zero indicate greater accuracy of the data (Sun et al. 2017).

$$LSTDay = (P \times F) - 273.15 \quad (5)$$

where,

LST Day is the daytime surface temperature (°C), P is the original pixel value, F is the conversion factor (0.02).

Based on the eight-day mean values of the land surface temperature MOD11A2 images, annual means were obtained for the Atlantic Forest, Cerrado, and Caatinga biomes.

The water availability index (WAI) is estimated from the ratio of actual evapotranspiration to potential evapotranspiration (Reichstein et al. 2007; Chen and Yu 2019). The actual evapotranspiration and potential evapotranspiration bands of the MOD16A3 images were used to determine the index. The MOD16A3 images are available annually and have a resolution of 500 meters.

Soil

Soil heat flux and influence on NPP were analyzed using «GLDAS_NOAH025_» version 2.1 soil heat flux images of the Global Land Data Assimilation System (GLDAS-2.1) and spatial resolution of 0.25° x 0.25° (Rodell et al. 2004; Beaudoing and Rodell 2019). The images are available in GeoTIFF format at Giovanni-NASA (https://giovanni.gsfc.nasa.gov/)

Statistical analysis

For all the analyses we performed here, we use the mean of the interest variable for the geographical sub-areas of our investigation. To determine NPP for each land use and cover (forest, savanna, agriculture, and pasture) of the Atlantic Forest, Cerrado, and Caatinga biomes, one-way ANOVA and the Tukey test were performed, according to normal waste distribution and variance homogeneity requirements. One-way ANOVA and t-test methods have been commonly used for this type of analysis (Liu et al. 2016; Yang et al. 2017; Chen and Yu 2019). A decreasing/increasing trend analysis was also performed for the 2003–2019 time series in all the annual variables of this study, namely, NPP, precipitation, burned areas, land surface temperature, evapotranspiration, water availability index, and soil heat flux, based on the Mann-Kendall nonparametric test. A positive or negative Z value in the Mann-Kendell test indicates an increasing or decreasing trend, respectively (Mann 1945; Kendall 1975). All statistical analyses were performed using R 3.6.1 software, at a significance level of $\alpha < 0.05$. To verify the relationship of the variables with NPP, a series of regressions were also estimated.

RESULTS

Spatial and temporal analysis of net primary production

According to the results of the MOD17A3 images, the Atlantic Forest has the highest average NPP for the studied period in comparison to the other biomes. The Atlantic Forest, Cerrado, and Caatinga have a mean annual NPP of 1,227.89 g C m^{-2}, 913.81 g C m^{-2}, and 803.56 g C m^{-2}, respectively (Figure 2).

For the studied series (2003–2019), a sharp decrease in NPP was observed in 2015 and 2016 in the Atlantic Forest biome. For the Cerrado biome, lower NPP was recorded in 2003, 2007, 2012, and 2016, while, for the Caatinga biome, the most critical years for NPP were 2012, 2015, and 2017 (Figure 2).

The Atlantic Forest biome absorbed the most carbon, especially on the coast (Figure 3), which is known for having extensive forest remnants (Figure 1). In the west of the biome, high mean annual NPP values, between 1,500 and 1,750 g C m^{-2}, were also observed. In the west and the extreme south of the state, however, where agriculture is predominant (Figure 1), low mean annual NPP values were observed (Figure 3). In the Caatinga biome, to the north, values less than 250 g C m^{-2} were observed; nevertheless, in the center of the biome, some sites had a mean annual NPP of up to 2,500 g C m^{-2}. Chapada Diamantina, located in the center of the Caatinga biome, comprises a mixture of native vegetation, between savanna and forest, as observed in Figure 1. Throughout the Cerrado, mean annual NPP ranged from 750 to 1,250 g C m^{-2}.

Net primary production and land use and cover

Higher and lower NPP variations were observed for the forest areas of the Atlantic Forest, 1,434.55 g C m^{-2}, followed by the savanna areas of the Atlantic forest biome, 1,228.99 g C m^{-2}, and the forest areas of the Caatinga biome, 1,226.24 g C m^{-2}, and they do not differ statistically ($\alpha = 0.05$) (Figure 4).

Considering the division of these biomes in terms of land use for human activities, mean annual NPP in pastures observed in the Atlantic Forest (1,092.91 g C m^{-2}) and NPP in agriculture in the same biome (971.99 g C m^{-2}) are statistically equal to the NPP observed in the forest areas of the Cerrado biome (1,059.09 g C m^{-2}).

Moreover, mean annual NPP observed in the agricultural areas of the Atlantic Forest (971.99 g C m^{-2}), savanna of the Atlantic Forest (965.18 g C m^{-2}), grassland of the Cerrado (916.56 g C m^{-2}), and savanna of the Caatinga (858.11 g C m^{-2}) did not differ statistically. Agriculture of the Caatinga biome has a lower mean NPP (628.77 g C m^{-2}) and differs statistically from the other studied categories.

The NPP observed for each land use and cover in the different biomes varied throughout the study period (Figure 5). In the Atlantic Forest biome, in the years 2015 and 2016, reductions of 6% to 22% of NPP were observed in all land covers and uses with respect to the historical average value of the time series. In the agriculture area of this biome, a 21% reduction in NPP was observed in 2013, in comparison with the mean of all studied years.

For the Cerrado biome, annual NPP in all land use and cover was lower in 2003, 2007, 2012, and 2016, with reductions ranging between 10% and 22% with respect

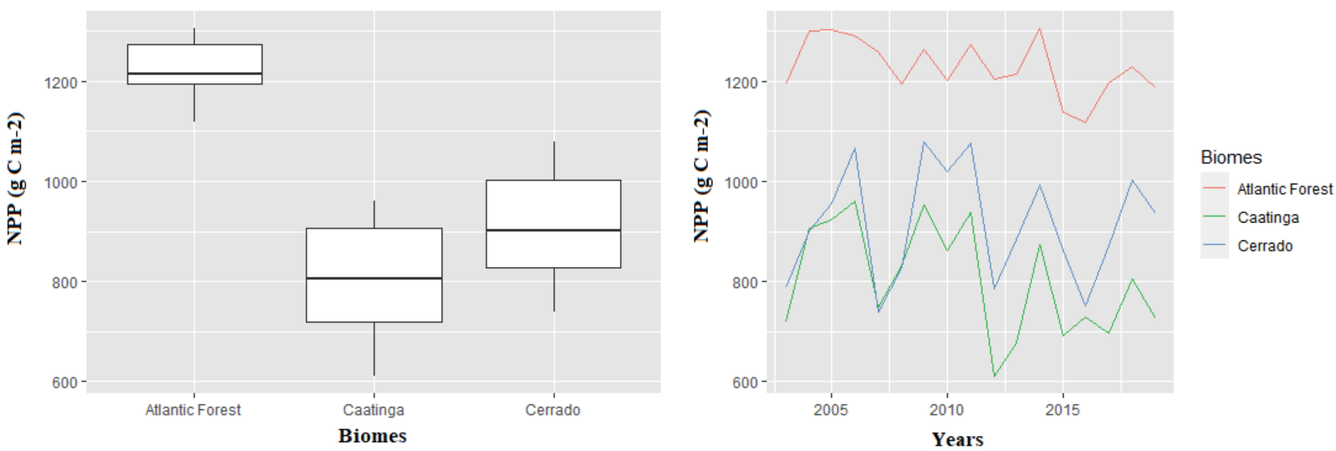


Fig. 2. Annual average and temporal variation of NPP in the Atlantic Forest, Cerrado, and Caatinga biomes of state Bahia, Brazil between 2003-2019

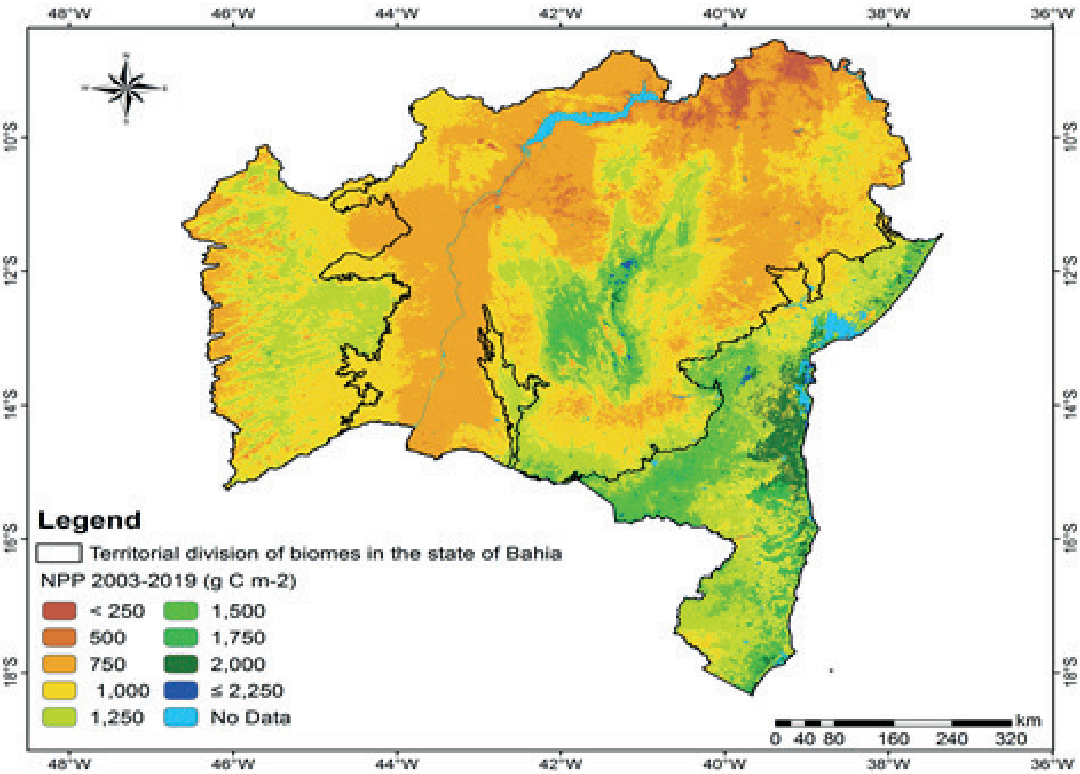


Fig. 3. Spatial mean NPP in the Atlantic Forest, Cerrado, and Caatinga biomes of state Bahia, Brazil between 2003-2019

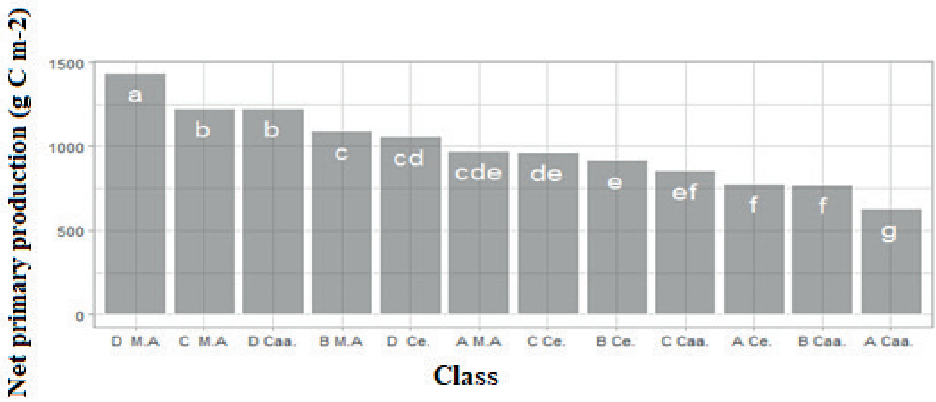


Fig. 4. One-way ANOVA and the Tukey test applied to NPP of class A, Agriculture; B, pasture; C, savanna; and D, forest; in M.A, Atlantic Forest; Ce, Cerrado; and Caa, Caatinga biomes of Brazil

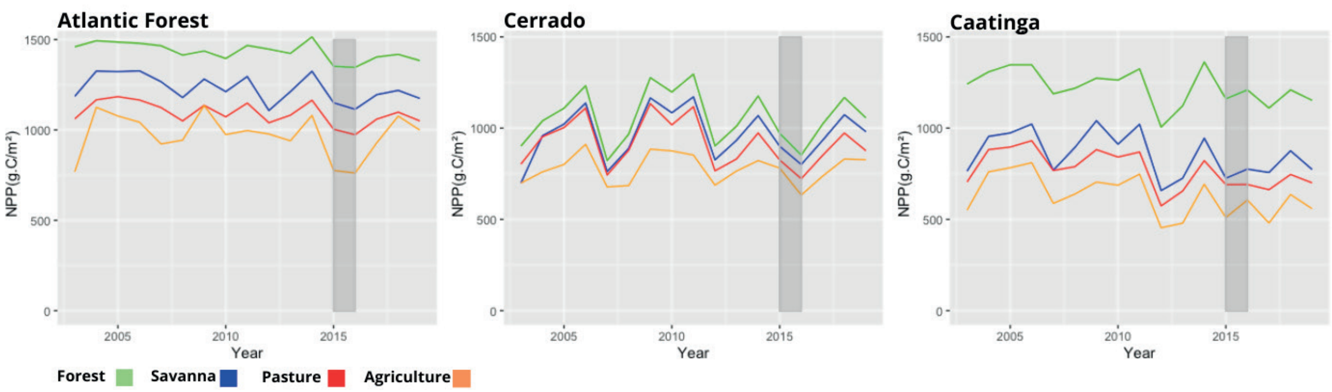


Fig. 5. Temporal variation between 2003 and 2019 of net primary production for each land use and cover (forest, savanna, agriculture, and pasture) in the Atlantic Forest, Cerrado, and Caatinga biomes, with gray markings for periods of high intensity El Niño events in Brazil available at http://enos.cptec.inpe.br/ (INPE, 2020)

to the annual mean, except for the savanna, in which a 27% reduction in NPP was observed in 2003, compared to the mean. In the Caatinga biome, 2012 was more critical, with reductions between 18% and 28% in NPP and annual values of 454.24 g C m^{-2} for agriculture, 573.92 g C m^{-2} for pasture, 657.78 g C m^{-2} for savanna, and 1,005.58 g C m^{-2} for forest.

The high intensity El Niño event in Brazil in the 2015–2016 period (INPE 2020) is related to the decrease in NPP in all biomes, especially the Atlantic Forest. Other low-intensity occurrences of El Niño were observed in Brazil in the periods 2002–2003, 2006–2007, and 2009–2010 (INPE 2020).

Decreasing/increasing trend

The Mann-Kendall statistical test results for the 2003 to 2019 time series showed statistically significant decreasing trend in carbon flux for the categories NPP forest Atlantic Forest, NPP Atlantic Forest pasture and NPP Caatinga pasture (Table 1). For environmental factors, an increasing trend was observed for Caatinga LST, Cerrado LST and Cerrado HF. Moreover, a decreasing trend was observed for Caatinga Precipitation. No statistically significant results were observed for overall NPP and burned areas of the Atlantic Forest, Caatinga, and Cerrado.

Effects of environmental and human factors on NPP

Regarding to the variables that controls the Net Primary Production, in the Caatinga biome there was a greater and positive relationship between NPP and precipitation than in the Atlantic Forest and Cerrado biomes (Figure 6). For the evapotranspiration variable, a strong positive relationship was found in the Cerrado (R^2 =0.97, p-value = 4.56e-13) and Caatinga (R^2 =0.94, p-value = 4.84e-11) biome. The water availability index shown to be the most important variable for net primary production in all biomes, with a positive and extremely significant relationship. The surface temperature was more significant for the Caatinga biome and negatively related to NPP. While, the heat flux variable, negatively impacts the NPP of the Atlantic Forest and Cerrado biomes. However, there are no statistically significant relationship between burned areas and net primary production in all biomes evaluated.

DISCUSSION

Spatial and temporal dynamics of net primary production

The spatial and temporal analyses of NPP in the 17 studied years showed that the Atlantic Forest biome has higher carbon stock and lower variation than the Cerrado and Caatinga biomes. Similar results were found in other studies (Bazame et al. 2019; Gomes et al. 2019). The forest of the Atlantic Forest biome in the state of Bahia, Brazil, is exceptionally superior to savannas and cultivated areas in terms of carbon uptake, with annual NPP of 1,434.55 g C m^{-2}, which is higher than the global average NPP of 1,032 g C m^{-2} in tropical forests and 577 g C m^{-2} in temperate forests (Li et al. 2017). This result demonstrates the importance of conserving the natural vegetation of the Atlantic Forest biome for regional and global carbon flux.

Significant NPP differences between natural vegetation areas and human occupation areas were found. The forest NPP of the Atlantic Forest biome is approximately 50% higher than the agricultural NPP of the Caatinga biome, this is the biggest difference found between land use and cover, and it is similar to results found in China when comparing areas of natural and unnatural vegetation (Yang et al. 2017). In contrast, the natural vegetation of the savannas of the

Table 1. Mann-Kendall test Z-statistics for the variables of interest (Time-series period 2003–2009)

Area	NPP	LST	Prec.	WAI	Eta	HF	BA
Atlantic Forest (whole)	-1.60 (0.11)	1.11 (0.27)	-1.36 (0.17)	-1.36 (0.17)	-0.37 (0.72)	1.24 (0.22)	-0.62 (0.54)
Atlantic Forest class Forest	-2.59 (0.0094*)						
Atlantic Forest class Savanna	-1.69 (0.091)						
Atlantic Forest class Pasture	-2.02 (0.043*)						
Atlantic Forest class Agriculture	-0.62 (0.54)						
Cerrado (whole)	0.042 (0.97)	2.18 (0.029*)	-1.94 (0.052)	0.00 (1)	0.12 (0.90)	2.14 (0.032*)	-1.11 (0.26)
Cerrado class Forest	0.20 (0.83)						
Cerrado class Savanna	0.45 (0.65)						
Cerrado class Pasture	-0.53 (0.59)						
Cerrado class Agriculture	0.041 (0.96)						
Caatinga class (whole)	-1.36 (0.17)	2.59 (0.094*)	-2.26 (0.023*)	-1.60 (0.1)	-1.68 (0.091)	1.41 (0.15)	-1.27 (0.20)
Caatinga class Forest	-1.77 (0.076)						
Caatinga class Savanna	-1.19 (0.23)						
Caatinga class Pasture	-2.02 (0.043*)						
Caatinga class Agriculture	-1.60 (0.10)						

NPP, net primary production; LST, land surface temperature; Prec, precipitation; WAI, water availability index; ETa, actual evapotranspiration; HF, soil heat flux; and BA, burned area;. P-value in parentheses, where (*) stands for the 5% significance level.

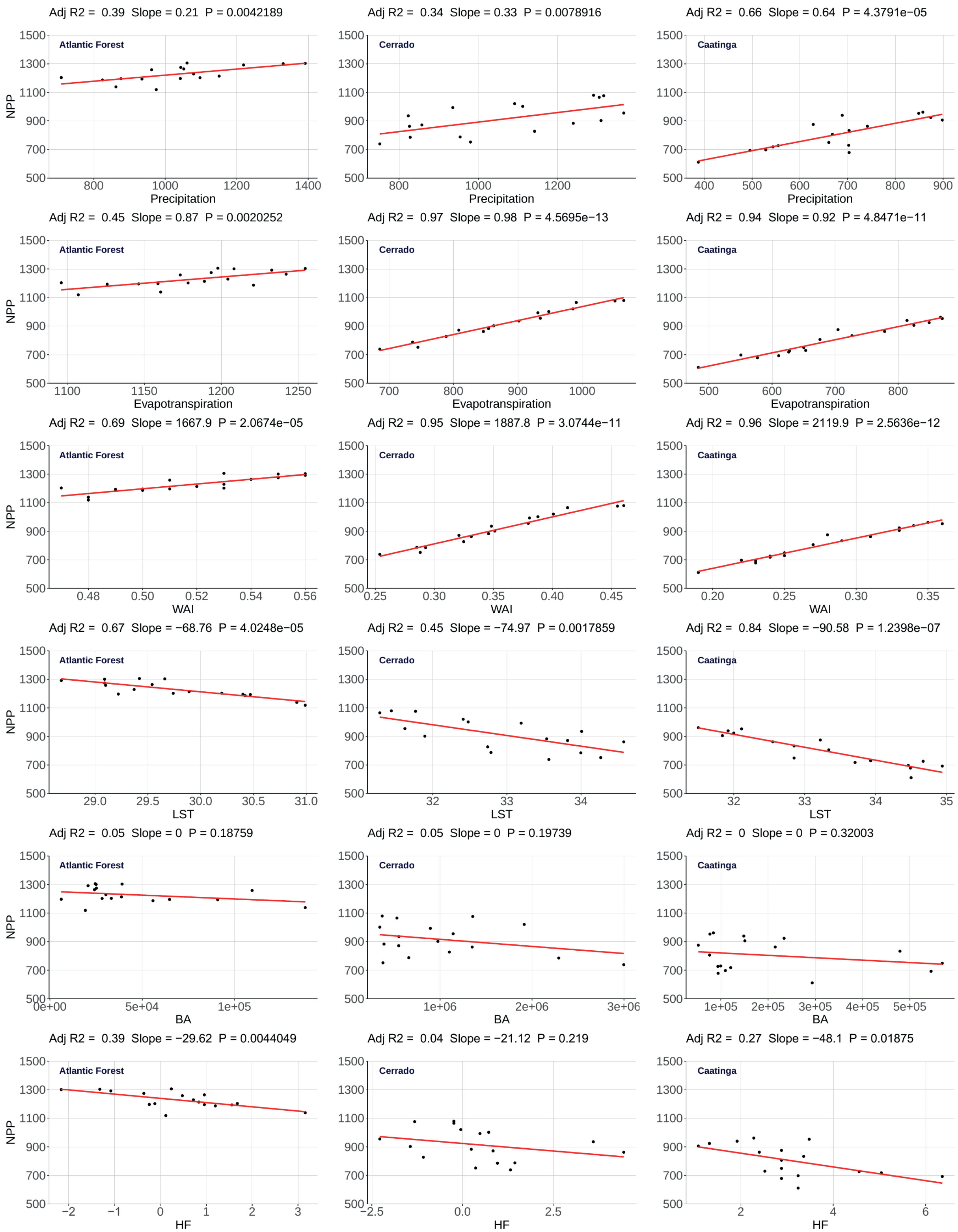


Fig. 6. Linear regression between NPP and controllers in biomes Atlantic Forest, Cerrado and Caatinga. NPP, net primary production (g C m^{-2}); Precipitation (mm); Actual evapotranspiration (mm); WAI, water availability index (mm mm^{-1}); LST, land surface temperature; BA, burned area (ha) and HF, soil heat flux (W m^{-2})

Cerrado and Caatinga biomes resemble areas with human occupations of agriculture and pasture. Similar results are reported by Morais et al. (2017), who observed similar NPP values in the savannas of the Caatinga to those found in irrigated areas. According to Chen et al. (2019), control of favorable conditions such as irrigation and nutrient supply in the soil has increased the leaf area and the «greening» of plantations, which are fundamental components for carbon flux.

The NPP temporal variation analysis indicated that high-intensity El Niño events in the 2015–2016 period and low-intensity El Niño events in 2003 and 2007 impacted the NPP of the studied biomes. A cross-continent analysis showed that the severe drought in 2015–2016 mainly affected the carbon stock of America's humid forests, which, by the end of 2017, forests showed slight signs of recovery (Wigneron et al. 2020). Also regarding temporal variation, a decreasing trend of NPP for the forest of the Atlantic Forest biome was observed and can be linked to deforestation and burning. Based on the non-governmental organization Mapbiomas, between 2003 and 2019 there was an increase of approximately 215,000 hectares of agricultural areas in the Atlantic Forest biome, for the Cerrado and Caatinga biome the expansion of agricultural and pasture areas was 1.5 million and 1 million hectares, respectively. A global analysis revealed that 5% of Earth is in a «browning» process, mainly caused by human activity; in Brazil, the loss of leaf area of natural vegetation, which is an essential attribute of this process, has been reported, with consequences for carbon flux (Chen et al. 2019). For the pastures of the Caatinga and Atlantic Forest biomes, decreasing trends of NPP were also found, triggered by the large-scale degradation of pastures in the state of Bahia and Brazil. Based on the Digital Atlas of Brazilian Pastures, in 2019, 51% of the pasture areas in the state of Bahia were classified as «severe degradation» Brazil has approximately 41 million hectares of degraded pasture, which directly affects the health of vegetation and soil and disturbs carbon absorption. An analysis in the Cerrado biome compared the carbon stock between improved brachiaria grassland, degraded brachiaria grassland and savanna areas and showed that improved grassland areas store more carbon in more than half of the value found for degraded grassland, while for the savanna, the carbon stock values were close to those of improved brachiaria grassland (Rosendo and Rosa, 2012). These results highlight the importance of conservation and the need for proper management of cultivated areas for carbon flux.

Relation of NPP with environmental and human factors

The results reveal different responses of NPP to environmental changes in each studied biome. The correlations between precipitation and NPP in the Atlantic Forest and Cerrado biomes found in this study are lower than the same correlations for the Caatinga biome. An intuitive explanation for this stems from the fact that Caatinga has systematically lower annual mean precipitation than the other biomes studied. Therefore, small variations in terms of precipitation have a greater impact on NPP (Figure 6). In 2012, the Caatinga suffered the most severe drought in the last 50 years, which led to 57% lower precipitation in some localities of the biome than the historical mean of 606.4 mm (Gutiérrez et al. 2014). Also in 2012, NPP in the savannas of the state of Pernambuco suffered a reduction of 42% (NPP = 400 g C m^{-2}) (Morais et al. 2017), while in the state of Bahia, our results showed a reduction of 23% (NPP = 657.78 g C m^{-2}) in this atypical year.

Land surface temperature had a negative relationship with NPP for all biomes, with greater negative correlation in the Caatinga biome. As indicated in the literature, extreme temperature variations cause forest mortality (Pau et al. 2018) and, associated with water restriction, may be a limiting factor in carbon uptake (Wu et al. 2016). Doughty and Goulden (2008) indicate that forests decrease photosynthesis and carbon uptake when leaf temperatures are near or exceed 35°C. High temperatures are related to increased vapor-pressure deficit, which in turn induces stomatal closure and, thus, reduces carbon absorption and evapotranspiration (Lloyd and Farquhar 2008). This relationship between carbon absorption and evapotranspiration was also observed in the present study, in which a positive linear relationship with NPP was observed in all biomes. In addition to evapotranspiration, the water availability index showed a positive and strong correlation with NPP, perhaps the most important variable studied here, especially in the Caatinga and Cerrado biomes, where the water availability index is often half the value observed in the Atlantic Forest biome and increases strongly control NPP. The importance of water availability was also observed in Europe and Asia (Reichstein et al. 2007; Chen and Yu 2019). In addition to these results, an increasing trend for LST was identified in the Cerrado and Caatinga biomes and a decreasing trend for precipitation in the Caatinga biome, climatic conditions that, if confirmed over time, may threaten NPP in these biomes. According to Yang et al. (2017), low soil moisture and high temperatures of some arid and semi-arid regions hinder vegetation growth, which directly reduces NPP.

Regarding soil heat flux, which is an important component in studies on thermal properties of soils and soil-plant-atmosphere interactions (Singh et al. 2020), no strong correlations were found with NPP. However, lower heat flux values were observed in the Atlantic Forest biome, suggesting cover conditions with lower soil heating capacity.

Although no significant results were found between burned areas and NPP for the Atlantic Forest, Cerrado, and Caatinga in this study, loss of carbon stock by burning vegetation and deforestation, induced mainly by agricultural expansion (De Santana et al. 2020), and the consequent increase in atmospheric carbon has been reported in the biomes of Brazil (Silva Júnior et al. 2020). In that regard, we believe our time-series statistics, regarding the association of NPP and the burned areas, should be analysed with caution. One step ahead in our research agenda consists in exploring this issue by accessing longer time series to make it possible to address this issue with different methods. Based on future projections, a decrease in CO_2 emissions in the Brazilian biomes is not expected, and these emissions will exceed 5.7 Gt of CO_2 by 2030, which compromises Brazil's emission reduction targets set by the Paris Agreement (Silva Júnior et al. 2020).

CONCLUSION

The analyses conducted in this study provided valuable insight into the dynamics of NPP in the Brazilian biomes Caatinga, Cerrado, and Atlantic Forest of the state of Bahia. Of all the studied land covers and uses, the forests of the Atlantic Forest biome are the most important for regional and global carbon flux; however, a decreasing trend was identified by the Mann-Kendall test for NPP in this type of cover, which may be associated with deforestation. Moreover, the NPP of the savanna areas of the Caatinga and Cerrado biomes resembles that of the areas of human occupation for pastures and agriculture.

The results showed a strong relationship between climate and NPP in the studied biomes, especially in the Caatinga biome, which was more sensitive to variations of the studied climate variables. In the time series, reductions in NPP were observed resulting from El Niño (2015–2016) and atypical climate years, such as the 2012 drought in the Caatinga biome. Finally, the results can shed light on the dynamics of NPP in response to possible future climate change, enable management of potential carbon areas, and support future environmental and socioeconomic policies.

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