



# Article Interannual Variability of Energy and CO<sub>2</sub> Exchanges in a Remnant Area of the Caatinga Biome under Extreme Rainfall Conditions

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Abstract: Research focusing on energy, water vapor, and CO<sub>2</sub> exchanges over the Caatinga Biome is recent. Consequently, there exist research gaps on this topic that limit our ability to understand and project interannual and long-term variations in the CO<sub>2</sub> cycle of this environment. Thus, the objective of this study was to evaluate the behavior of the energy and CO<sub>2</sub> balances of the Caatinga Biome under extreme rainfall conditions (extreme drought and intense rainfall) using simulations of the SITE model (Simple Tropical Ecosystem Model). Meteorological data from the years 2009 (heavy rainfall) and 2012 (extreme drought) obtained from an INMET automatic station were used. Relationships between monthly GPP and NEE values and rainfall were also analyzed. Although the SITE model had been previously calibrated for the region, adjustments to the calibration were necessary for our study due to the extreme climatic values of the selected years. The results highlight the impact of rainfall on energy and mass exchanges over the Caatinga, particularly evident in the partitioning of the energy balance and the  $CO_2$  balance. In 2009 (during heavy rainfall), the fraction of Rn converted into LE was nearly 6% higher compared to the values observed in 2012 (during extreme drought). Regarding CO<sub>2</sub>, it was found that the Caatinga behaved as a sink, even under extreme drought conditions (2012), with annual average values of  $-1.86 \mu$ mol m<sup>-2</sup> s<sup>-1</sup> (2009) and  $-0.81 \mu$ mol m<sup>-2</sup> s<sup>-1</sup> (2012). Relationships between monthly GPP and NEE values and rainfall were also investigated, revealing an asymptotic relationship between the components of CO<sub>2</sub> balance and rainfall. It was evident that both the monthly values of GPP and NEE tend to stabilize when monthly rainfall volumes exceed 200 mm.

Keywords: caatinga; CO2 balance; energy balance

## 1. Introduction

Terrestrial ecosystems have served as substantial sinks for atmospheric carbon dioxide (CO<sub>2</sub>), absorbing an average of 25–30% of annual anthropogenic emissions [1,2]. Humid tropical forests, such as the Amazon rainforest, exemplify CO<sub>2</sub> sinks based on their 20-year average behavior. However, they have occasionally acted as neutral or even CO<sub>2</sub> sources [3] due to distinctive seasonal patterns of carbon exchange, meteorological variables, and water



Citation: Mendes, K.R.; Marques, A.M.S.; Mutti, P.R.; Oliveira, P.E.S.; Rodrigues, D.T.; Costa, G.B.; Ferreira, R.R.; Silva, A.C.N.d.; Morais, L.F.; Lima, J.R.S.; et al. Interannual Variability of Energy and CO<sub>2</sub> Exchanges in a Remnant Area of the Caatinga Biome under Extreme Rainfall Conditions. *Sustainability* **2023**, *15*, 10085. https://doi.org/ 10.3390/su151310085

Academic Editor: Matteo Gentilucci

Received: 8 March 2023 Revised: 31 May 2023 Accepted: 15 June 2023 Published: 26 June 2023



**Copyright:** © 2023 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/). use efficiency [4]. These differences arise from both inherent characteristics of the biome and the influences of extreme events and fire impacts in the region [5,6]. Therefore, further studies are necessary to comprehensively understand the intricacies of the biosphereatmosphere interaction within these environments.

The CO<sub>2</sub> concentration is currently increasing at a rate exceeding the worst projection of the Intergovernmental Panel on Climate Change [7]. Forests play a crucial role in regulating global climate change through both the emission of greenhouse gases into the atmosphere, either through burning or deforestation, as well as through the absorption of carbon from the atmosphere through growth. Forests are particularly important because they store a larger amount of carbon in their trees and soil than currently exists in the atmosphere [7]. Consequently, aspects of biogeochemical cycles have been the subject of increasing research, particularly using the eddy covariance technique (EC) to estimate in situ carbon fluxes [8–10].

Climate modeling studies predict that rainfall patterns in tropical dry forests will change, resulting in an overall reduction in rainfall and an intensification of dry intervals. These changes are expected to increase the susceptibility of these forests to drought [11–13]. In this context, it is crucial to comprehensively understand how forest carbon fluxes vary spatially, and their underlying control mechanisms. This understanding is essential for accurately assessing the global carbon balance [14].

On a global scale, seasonally dry tropical forests (SDTFs) are highly fragile, highly endangered, and poorly studied environments compared to wet tropical forests and savannas [10,15]. The Caatinga Biome occurs exclusively in Brazil, located in the northeast region of the country (NEB), and corresponds to the largest continuous area of seasonally dry tropical forest (SDTF) in South America [16]. This area is characterized by the occurrence of annual rainfall predominantly below 800 mm, which is spatially and temporally irregular. It experiences high temperatures, abundant solar radiation, and high evaporative demand, resulting in an almost permanent condition of water deficiency [10,17,18]. Despite recent studies on heat and mass exchange in the Caatinga Biome [10,19–23], there is still a lack of studies with broader spatial and temporal scopes on the soil-vegetation-atmosphere relationship, especially regarding CO<sub>2</sub>. Logically, the studies represent important milestones, but they are specific and cover limited time aforementioned periods. Further improvements are needed in understanding the behavior of the Caatinga in terms of CO<sub>2</sub> exchange during anomalous years (wet or dry, with high temperatures) and normal years. Additionally, there is a scarcity or near absence of studies on trends in the magnitude of  $CO_2$  balance components and their respective relationships with rainfall trends.

Typically, studies with larger spatial and/or temporal scales are conducted using remote sensing data [4,18,24,25] or via modeling [2,26–30]. Studies using soil-vegetation-atmosphere transfer (SVATS) models are a viable alternative for determining and evaluating energy and CO<sub>2</sub> fluxes in various ecosystems. This alternative is particularly valuable, considering the complexity and cost of setting up in situ experiments (such as EC flux towers) to assess the potential impact of climate change on ecosystem functioning [31,32].

The SITE (Simple Tropical Ecosystem) model is a simple point-based (offline) model that uses an integration interval (dt). It incorporates site-specific data on temperature, horizontal wind speed, specific humidity, and photosynthetically active radiation (PAR) [33,34]. The SITE model was originally developed to study the response of tropical ecosystems to varying environmental conditions while adequately representing the functioning of the ecosystem. It considers the main physical, chemical, and biological processes involved in energy and carbon fluxes.

It has been employed because of its biogeochemical and biophysical character that encompasses various surface processes, including infrared radiation balance above the canopy, solar radiation balance, aerodynamic processes, canopy physiology and transpiration, canopy water balance, mass and energy transfer in the atmosphere, soil heat fluxes in two layers, soil water, and carbon flux and equilibrium [23]. Studies carried out using the SITE model have yielded promising results both within its intended scope [35], and in an experimental site within a tropical semi-deciduous forest in the southern Amazon Basin [34] and the Caatinga ecosystem [21,23].

Little is known about how the Caatinga acts regarding  $CO_2$  exchanges under conditions of extreme drought and in years of heavy rainfall. Therefore, this study aims to assess the energy and  $CO_2$  balances of the Caatinga Biome when exposed to extreme rainfall conditions (including both extreme drought and heavy rainfall). Additionally, it aims to evaluate the source/sink dynamics of the Caatinga under these extreme conditions while demonstrating the compensation and saturation of gross primary productivity (GPP), net ecosystem exchange (NEE), and net ecosystem productivity (NEP) as influenced by monthly rainfall.

#### 2. Materials and Methods

### 2.1. Study Area

We used a dataset composed of two years of extreme climate behavior: heavy rainfall in 2009 and extreme drought in 2012. We chose 2009 and 2012 based on [18], which characterizes the climatic variability of the region. The study indicates that the annual rainfall totals in the region is typical of a tropical-arid climate, ranging between 400 mm and 800 mm. Considering a climatological perspective with 30 years of observation, 2009 was the rainiest year, while 2012 was the driest. To calibrate the SITE model, we used a set of two years (2014 and 2015) of EC data. The EC system was installed in a fragment of the Caatinga biome (Figure 1), located in the Seridó Ecological Station (ESEC-Seridó), where the exchanges of energy fluxes and  $CO_2$  were systematically and uninterruptedly monitored for two consecutive years (2014–2015) [10].



Figure 1. Geographical location of the micrometeorological tower installed in the ESEC-Seridó, Brazil.

The monitoring was performed using a flux tower equipped with an EC system, in addition to instruments for measuring soil heat flux, shortwave, and longwave radiative components. The tower belongs to the INSA (National Institute of the Semiarid) and is part of the NOWCDCB network (National Observatory of Water and Carbon Dynamics in the Caatinga Biome). The tower is situated at the ESEC-Seridó (6°34'42" S, 37°15'05" W 205 m above sea level) near the municipalities of Serra Negra do Norte and Caicó, in the State of Rio Grande do Norte, Brazilian Semiarid (Figure 1).

The climate in the region is semiarid, and the ESEC-Seridó exhibits a distinctive type of caatinga characterized by its dry and sparse nature, with bushes and trees reaching heights of up to 2 m. The soils of the Seridó region are formed on a crystalline shield and

have moderate natural fertility, especially in the alluvial lowlands. However, these soils are subjected to an irregular and limited distribution of rainfall. The vegetation develops on a shallow and stony soil, resulting in distinct physiognomies within the boundaries of the conservation unit. These variations are influenced by factors such the type of soil, water availability, and topography [36,37].

# 2.2. Micrometeorological Measurements and Application of the SITE (Simple Tropical Ecosystem) Model

The procedure for calculating hourly NEE values can be found in [21,38]. The CO<sub>2</sub> flux calculation involved a series of procedures that included: coordinate rotation correction using the planar fit method, sonic virtual temperature correction, corrections for density fluctuation (WPL-correction), and frequency response correction. After the calculations, a robust quality control and filtering process was performed to detect and exclude spikes and physically inconsistent data. Subsequently, gap-filling was performed. A detailed description of the complete methodology is described in previous research: [10,20,21,39]. The partitioning of CO<sub>2</sub> fluxes was performed using the algorithm reported in [40], which uses the nighttime period to divide NEE into Reco and GPP. During the night, GPP is assumed to be zero, and therefore, NEE is equal to Reco. The nighttime fluxes were adjusted with respect to air temperature through the Lloyd and Taylor equation [41]. In both the filtering and gap-filling procedures, we used an online tool from the Max Plank institute—https://www.bgc-jena.mpg.de/REddyProc/ui/REddyProc.php, accessed on 25 March 2022.

The energy balance, Rn and G, were directly measured, while LE and H were determined using high-frequency data measured by the EC system as described by [10,39].

Micrometeorological data measured at the tower, located 11 m above the surface, were used as input data SITE simulations. Observations included air temperature, rainfall, horizontal wind speed, downward shortwave and longwave radiation, and specific humidity.

The model was calibrated and validated for the study region considering the years 2014 and 2015 [32]. Energy balance data (Rn, LE, H, and G) were used, where Rn represents the radiation balance, H denotes the sensible heat flux (heating of the air near the surface), LE corresponds to the latent heat flux (evaporation of water from the soil and transpiration of plants), and G represents the heat flux in the soil (heating of the soil). The carbon balance (GPP, Reco, and NEE) was obtained using the EC method during two consecutive years (2014 and 2015) in the ESEC-Seridó.

For model calibration, ref. [32] adopted the sequential method, selecting parameters with the highest probability of influencing the model's outcome. These parameters include the initial soil moisture fraction ( $\theta g/\theta d$ ), stomatal conductance coefficient (m), maximum capacity of the Rubisco enzyme (Vmax), typical dimension of leaves (du), typical dimension of stems (ds), leaf width (w), and specific leaf area (SL), based on previous sensitivity analyses [34,42]. Table 1 presents the calibration parameters used for the Caatinga biome by [32].

The performance of the model was evaluated and analyzed using Taylor diagrams, which display the Pearson correlation coefficient (r), standard deviations (SD) between the observations and simulated data, and root mean square error (RMSE). Additionally, the model's performance was assessed using the following statistical measures: median absolute error (MAE) and Willmott's index of agreement (d). Further details regarding the model validation can be found in [32].

The SITE model was used to compute a multi-year series of the energy and  $CO_2$  balance of a Caatinga area within the ESEC-Seridó. In the present study, the model input data consisted of meteorological data observed in 2009 (1019.6 mm of rainfall), considered a wet year compared to the region's climatology which has an annual average below 800 mm, and in 2012 (198.2 mm of rainfall) was characterized as a year with extremely low rainfall. These measurements were obtained from an automatic weather station belonging to the INMET (National Institute of Meteorology) network.

**Table 1.** Calibrated parameters: specific leaf area (sla,  $m^2$  leaf kg<sup>-1</sup> C), typical dimension of leaves (du, m), typical dimension of stems (ds, m), leaf width (w, m), stomatal conductance coefficient (m, dimensionless), maximum capacity of the Rubisco enzyme (Vmax,  $\mu$ mol CO<sub>2</sub> m<sup>-2</sup> s<sup>-1</sup>), and initial soil moisture fraction ( $\theta g/\theta d$ , dimensionless).  $\theta g$  is the mass-based soil water content expressed in gravimetric soil moisture content,  $\theta d$  is soil moisture content.

Davamatars		Wet Season	Dry Season	Source	
raianteters	Initial	CO <sub>2</sub> Flux Calibrated		Source	
Specific leaf area (sla)	13.0	14.5	23.5	[32,43]	
typical dimension of leaves (du)	0.072	0.056	0.032	[32,44]	
typical dimension of stems (ds)	0.1	0.05	0.05	[32,44]	
Leaf width (w)	0.1	0.06	0.03	[32,44]	
Stomatal conductance coefficient (m)	10.0	8.0	4.0	[17,32,43,45]	
Maximum capacity of the Rubisco enzyme (Vmax)	$75  imes 10^{-6}$	$90  imes 10^{-6}$	$50  imes 10^{-6}$	[32,43,46]	
Initial soil moisture fraction ( $\theta g/\theta d$ )	0.36	0.225	0.105	[32,36,47]	

A regression analysis was conducted to examine the relationships between the monthly values of  $CO_2$  balance components (GPP, NEE, and NEP) and rainfall. The quality of the model fit was assessed through the coefficient of determination ( $R^2$ ) and significance (*p*-value < 0.05) using the R software, version 4.2.1 [48].

#### 3. Results and Discussion

Rainfall, Temperature and Radiation

The choice of the years 2009 and 2012 was based on previous analyses by [18], which identified these two years as having rainfall extremes. Specifically, 2009 exhibited a rainfall anomaly of approximately +400 mm while 2012 had an anomaly of approximately -400 mm in the ESEC-Seridó region. The selection of these years was primarily motivated by the influence of rainfall on energy and mass exchange (water vapor and CO<sub>2</sub>) in tropical regions, as demonstrated by studies conducted by [10,20,21].

Differences in rainfall amount and distribution were observed between the two study years (Figure 2). Annual rainfall in 2009 and 2012 were 1019.6 mm and 198.2 mm, respectively, while the mean annual climatological precipitation is 758 mm [32].



Figure 2. Average monthly rainfall (mm) observed during the years 2009 and 2012 in Seridó-RN.

The months from February to May showed the highest volumes and a greater regularity in 2009 (857 mm—84% of total rainfall) and 2012 (98.60 mm—50% of total rainfall). In the dry season (from July to December), rainfall rarely occurs, with negligible values recorded in 2009 (102.20 mm—10% of total rainfall) and 2012 (2.20 mm—1% of total rainfall).

Figure 3 illustrates the hourly cycle of global radiation (Rg) over the two years. It can be observed that Rg exhibited a similar behavior in both years. However, it is noteworthy that Rg was slightly higher in 2012 (490.20  $Wm^{-2}$ ) compared to 2009 (466.50  $Wm^{-2}$ ), which is likely associated with lower cloud cover in 2012. This is supported by the fact that rainfall in 2012 was substantially below both the climatological average and that of the year 2009 [18].



**Figure 3.** Annual mean hourly cycle of global solar radiation (Wm<sup>-2</sup>) observed during the years 2009 and 2012 in Seridó-RN.

As expected, the air temperature in 2012 was also higher than in 2009 (Figure 4). The hourly cycle reveals that not only was the average temperature observed in 2012 higher than in 2009, but the minimum and maximum temperatures were also higher (23.6 °C and 35 °C, respectively) compared to 2009 (23.3 °C and 32 °C, respectively). This difference in air temperature is probably associated with the difference in rainfall between the two years.



**Figure 4.** Hourly cycle of mean air temperature (°C) observed during the years 2009 and 2012 in Seridó-RN.

The daily cycle of meteorological variables is primarily influenced by Earth's rotation and, consequently, the daily cycle of solar radiation. However, the daily cycle of air temperature is also affected by longwave radiation, specifically terrestrial and atmospheric radiation. For this reason, the maximum daily temperature occurs between 2 and 3 pm, which is more than two hours after the maximum incidence of solar radiation.

According to [49], it is currently known that changes in climate are conditioned by temporal and/or spatial variations in temperature, and that these changes are in turn determined by the energy balance at the Earth's surface. Therefore, any change in the energy balance will directly impact the fluctuations in air temperature, winds, and possibly rainfall.

#### 4. Energy Balance

Figure 5 shows the average daily cycle of the simulated energy balance in the study area for the years 2009 and 2012. In general, the daily pattern of Rn agrees with that of solar radiation. This correspondence has been observed across different ecosystems and in regions with different climatic conditions [10,50,51]. Rn is negative or approaches zero during the nighttime, when radiative cooling of the surface dominates and presents positive values during the day because of the incidence of solar radiation.



**Figure 5.** Hourly cycle of the energy balance components (Wm<sup>-2</sup>) simulated during the years 2009 (**A**) and 2012 (**B**).

In general, the average daily behavior of the energy balance components (Rn, H, LE and G) agreed with the daily pattern of solar radiation in both years. The exceptions were H and LE during 2012 (Figure 5B). The maximum value of LE was reached at approximately 09:00, whereas the maximum value of H was observed around 14:00 local time. H increased continuously from 09:00 h until 14:00 h while LE decreased within the same time interval.

Maximum LE occurred at 09:00 h, coinciding with the daily period when the Caatinga exhibits the maximum stomatal opening, according to [20]. After this time, also according to [20], VPD steadily increases until 14:00 h. During this time interval, Caatinga plants exert greater control over evapotranspiration by progressively reducing stomatal aperture to prevent excessive water loss [20,21]. Consequently, most of the available energy within this period (from 09:00 to 14:00 h) is converted into H.

The soil heat flux (G) has negative values throughout most of the day and night. Positive values are only observed between 9:00 a.m. and 5:00 p.m. (local time), reaching a maximum of  $53.87 \text{ Wm}^{-2}$  in 2009 and  $53.14 \text{ Wm}^{-2}$  in 2012. In 2009, the values of G were higher compared to 2012.

Table 2 presents the annual and seasonal averages (dry and wet seasons) of the components of the energy balance and their respective partitions. It can be noted that the annual and seasonal averages of Rn varied little, from 163.4 to 170.2  $Wm^{-2}$ , which is a difference of less than 5%. This small difference is due to little seasonal variation in solar radiation, the main modulator of Rn [10,50,51]. Such radiation behavior is typical of tropical regions, especially at low latitudes (below 10°). The fact that the year 2009 was rainier does not substantially alter the partition of energy fluxes compared to 2012 in this biome. As demonstrated in previous studies [4], the water use efficiency and evapotranspiration patterns respond more strongly to consecutive wet days rather than the amount of water precipitated in a given month, which can occur on isolated days.

**Table 2.** Annual averages of Rn, LE, H, and G, in addition to the closure residual (R) and partitioning of the energy balance.

	2009 (Heavy Rainfall)			2012 (Extreme Drought)		
	Annual	Wet Season	Dry Season	Annual	Wet Season	Dry Season
$Rn (Wm^{-2})$	166.4	170.2	166.7	163.4	167.4	164.4
LE (Wm <sup>-2</sup> )	42.6	59.0	35.9	32.8	43.5	26.0
${ m H}({ m Wm^{-2}})$	60.6	41.8	88.8	80.4	53.8	115.6
$G(Wm^{-2})$	0.9	0.8	0.7	0.7	0.3	0.6
$R (Wm^{-2})$	62.3	68.6	41.3	49.5	69.8	22.2
ED (Wm <sup>-2</sup> )	165.6	169.4	166.0	162.7	167.1	163.8
EBC	0.62	0.60	0.75	0.70	0.58	0.86
LE/Rn (%)	25.6	34.0	21.5	20.0	26.0	16.0
H/Rn (%)	36.4	24.5	53.3	49.2	32.1	70.3
G/Rn (%)	0.5	0.48	0.4	0.4	0.2	0.3
R/Rn (%)	40	20	40	30	20	40

Additionally, according to Table 2, it can be observed that the energy balance closure (EBC) simulated by the SITE model showed a seasonal variation ranging from 0.58 to 0.86, with an overall average of ~0.70 for the two years. This value is considered satisfactory, albeit lower than the values obtained experimentally using the EC method [10,39,52,53]. The relatively modest closure observed with the SITE model simulations is likely associated with discrepancies between the model's results and the observed values, as reported by [34,35]. Although these studies were conducted in different environments, they revealed a consistent pattern in the SITE simulations: an overestimation of LE and an underestimation of H. Additionally, ref. [32] also noted that, in general, the SITE model overestimates Rn and underestimates G, which theoretically implies a higher available energy compared to observed values.

Studies indicate that in the Caatinga, the majority of available energy is converted into sensible heat flux during the dry season, and the partitioning of energy flux is directly associated with vegetation characteristics and changes in land use [10,19,23]. In fact, the SITE model struggles to represent the variability of latent heat (LE) and sensible heat (H) throughout the day, likely due to the model's failure to account for daily changes in certain

environmental parameters such as soil moisture fraction and diurnal variations in the stomatal opening and closure of plants.

In relation to LE and H, Table 2 shows a condition of nearly constant water deficiency in the region, as H consistently surpasses LE, even during the comparatively wetter year of 2009. This behavior of LE and H in the Caatinga has been previously investigated and discussed in the scientific literature [10,19,22].

Table 2 also clearly shows the influence of rainfall on the seasonality of the energy balance components and their partitions. During the wet season, the portion of Rn converted to LE is nearly 60% higher compared to the dry season. On the other hand, the portion of Rn converted to H during the dry season is almost twofold higher than in the wet season. The role of rainfall is also illustrated in the interannual relationship. In 2009, a year characterized by higher rainfall, H was almost 50% higher than LE on an annual basis. Similarly, in 2012, H exceeded LE with a difference of more than 100%. The portion of Rn converted to H was slightly above 35% in 2009 and 20% in 2012. In contrast, the portion of Rn converted to H was slightly above 35% in 2009 while it reached nearly 50% in 2012. These seasonal and interannual variations in the values of the energy balance components and their respective partitions have also been widely reported in the literature within tropical and/or semiarid environments [10,22,39].

In relation to G, results indicate that the mean annual value was higher in 2009 compared to the value simulated in 2012. This difference is likely attributed to more intense rainfall, which interfered with the temperature differences between the atmosphere and the soil, as well as runoff. These factors are important parameters for quantifying G in the model, as they represent energy loss from the soil to the atmosphere. Despite these differences, their absolute values did not affect the difference between available energy (Rn–G) for both years, since the difference was similar to those observed in the Rn values. This implies that, in terms of energy availability, both years were practically equal.

The absence of rainfall during the dry season in the Caatinga can lead to changes in the energy balance, causing an increase in H fluxes and a decrease in LE fluxes. These changes modify the turbulent exchanges of heat and moisture that occur between the surface and the atmosphere [54–56].

When comparing LE between seasons, it was observed that the averages with greater amplitudes occurred during the wet season, reaching almost  $60 \text{ Wm}^{-2}$ . In contrast, during the dry season, these values remained below  $40 \text{ Wm}^{-2}$  throughout the year 2009. The lower LE rates observed in the dry season can be attributed to reduced water availability for plants, resulting from lower rainfall rates [10,57,58]. Table 2 shows that, in most cases, the residual values are higher than the fluxes.

Regarding the behavior of H, substantially higher values were observed during the dry season (88.8  $Wm^{-2}$  in 2009 and 117.8  $Wm^{-2}$  in 2012) compared to the wet season (41.8  $Wm^{-2}$  in 2009 and 53.6  $Wm^{-2}$  in 2012). It is noteworthy that H values during the year of intense drought surpassed those observed during the year of intense rainfall. This distinction is due to the influence of biomass in regulating the energy exchanges between the atmosphere and the surface in the Caatinga. The ecosystem experiences alternating periods of high and low biomass, which are entirely controlled by rainfall [20,59].

Another noteworthy result shown in Table 2 refers to the residual of the energy balance, R, which accounted for 40% of Rn in 2009 and approximately 30% of Rn in 2012. In other observational studies, this residual is approximately 25% [10,19]. Energy balance calculations in tropical forests have exhibited higher residues, with values fluctuating between 16% and 25% [8]; in FLUXNET towers, the range is wider, ranging from 4% to 36% [60]. The SITE model has consistently demonstrated a tendency to underestimate H values, particularly during the dry season, as reported by [32] in the Caatinga and [34] in the Amazon.

Caatinga plants close their stomata in response to low water availability, which effectively reduces water transfer to the atmosphere, resulting in decreased evapotranspiration. Consequently, the energy consumption required to heat the air (H) increases [61]. According to the literature, the annual proportion of Rn converted into H in the Caatinga varies from approximately 40% to 60% [10,19,22]. Similar ranges of values have also been observed by [62] in the semiarid region of the Loess Plateau in China and by [61] in the Mongolian Plateau. In the present study, this percentage was less than 40% during the dry season in both years, indicating values lower than those reported in the literature. This finding strongly suggests that the SITE model tends to underestimate H.

According to [56], the characteristics of Caatinga vegetation directly influence the daily cycle of thermohygrometric variables and the variables that compose the energy balance. In addition, atmospheric conditions also play a decisive role in the variations of H and LE values at different times of the year in the Caatinga.

#### *CO*<sub>2</sub> *Balance*

The hourly averages of GPP and NEE simulated by the SITE model for the years 2009 and 2012 are presented in Figure 6, illustrating the observed effect of rainfall on both variables. The maximum daily mean gross  $CO_2$  fixation (GPP) during 2009 was approximately 64% higher than in 2012. On the other hand, the maximum daily average net fixation was almost three times higher than the corresponding value in 2009.



Figure 6. Hourly cycle of GPP (A) and NEE (B) simulated during the years 2009 and 2012.

Figure 6 also shows that maximum assimilation of  $CO_2$  (both gross and net) occurred between 09:00 h and 10:00 h local time, which corresponds to the period of stomatal opening in Caatinga species as reported by [20]. This coincides with the time of day when maximum  $CO_2$  assimilation rates are observed. Maximum stomatal opening suggests that the SITE model satisfactorily represents the physiological mechanisms of Caatinga plants regarding  $CO_2$  exchange. Nevertheless, in some experimental studies conducted in the region, the agreement between periods of maximum stomatal opening and maximum assimilation of  $CO_2$  was not observed. Instead, the maximum assimilation (both gross and net) coincided with the peak availability of radiation [21,39]. These studies suggest that, besides plant physiological mechanisms, meteorological variables, especially VPD and solar radiation, exert significant influences [20,21].

Maximum NEE values were  $-8 \,\mu mol \, m^{-2} \, s^{-1}$  in the wetter year (2009) and  $-4 \,\mu mol \, m^{-2} \, s^{-1}$  in the dry year (2012). The maximum hourly NEE values in our study are similar to those reported by [4,19,21] in fragments of preserved Caatinga and by [63] in China's typical forests [64] in a savanna forest in southeastern Brazil. Ecophysiological studies indicate that CO<sub>2</sub> assimilation can be influenced by the diurnal cycle [65] of air temperature, RH and VPD. In this study, the decline in GPP and NEE after noon can be attributed to the increase in air and soil temperature [21]. Thus, it can be argued that the coupling of the physiological mechanisms of Caatinga plants to the diurnal cycles of environmental factors is crucial for determining CO<sub>2</sub> fluxes in the biome.

A typical diurnal pattern was observed in all seasons, where GPP and NEE increased shortly after dawn, reaching their maximum values between 09:00 h and 10:00 h, and subsequently declining after noon to reach the lowest values (near zero) in the late afternoon. This positive behavior of GPP can be attributed to the absorption process associated with photosynthesis. The positive values of  $CO_2$  flux and NEE during the night indicate that the ecosystem is releasing  $CO_2$ .

 $CO_2$  fluxes and GPP were higher in 2009. By analyzing the hourly cycle of NEE, one can observe that the ecosystem absorbs  $CO_2$  (negative values) during the day and emits  $CO_2$  (positive values) during the nighttime, while also responding to rainfall patterns. GPP showed high values until July, corresponding to the peaks of observed rainfall. GPP values decreased later on with the progression of the dry season, reaching their lowest values in November, indicating that water availability largely influences GPP patterns and the conditions for  $CO_2$  capture.

The mean diurnal value (06:00 h–17:00 h) of NEE was  $-3.98 \ \mu mol \ m^{-2} \ s^{-1}$  in 2009 and  $-1.91 \ \mu mol \ m^{-2} \ s^{-1}$  in 2012. The nocturnal values (05:00 h–24:00 h) were 1.42  $\ \mu mol \ m^{-2} \ s^{-1}$  in 2009 and 1.19  $\ \mu mol \ m^{-2} \ s^{-1}$  in 2012. These results indicate minimal variability in CO<sub>2</sub> emissions to the atmosphere during the night. During the day, there was a predominant uptake of CO<sub>2</sub> with a maximum peak observed at 10:00 h in both years. The values of this peak were  $-8.14 \ \mu mol \ m^{-2} \ s^{-1}$  in 2009 and  $-4.09 \ \mu mol \ m^{-2} \ s^{-1}$  in 2012, showing a remarkable variability between the two years. This finding is consistent with the expected pattern of lower NEE variability at night and higher variability during the daytime.

Figure 7 shows the mean monthly values of GPP and NEE in 2009 and 2012, respectively, evidencing the existence of distinct seasonal variability. The annual mean GPP varied from 7.52  $\mu$ mol m<sup>-2</sup> s<sup>-1</sup> in 2009 to 4.62  $\mu$ mol m<sup>-2</sup> s<sup>-1</sup> in 2012, showing an increase at the onset of the wet season, especially in April. The annual average NEE was  $-1.86 \mu$ mol m<sup>-2</sup> s<sup>-1</sup> in 2009 and  $-0.81 \mu$ mol m<sup>-2</sup> s<sup>-1</sup> in 2012. With the onset of the dry season in May, the GPP reduced in magnitude. In 2009, GPP values were higher compared to 2012. The monthly variation of GPP in the study area was influenced by the seasonality of rainfall.



Figure 7. Monthly average of GPP (A) and NEE (B) simulated during the years 2009 and 2012.

This behavior of GPP has been reported by [56], who explains that it is attributed to the response of Caatinga plants' phenological dynamics to the increased availability of water for leaf development. Thus, a more robust leaf area enhances the capacity for light absorption and the photosynthetic uptake of  $CO_2$ , leading to higher vegetation productivity, as previously shown by [66].

Figure 8 shows the relationships between the monthly values of the CO<sub>2</sub> balance components (GPP, NEE and NEP) and rainfall. According to [67], NEP is the net production of the ecosystem, which accounts for the net primary production minus carbon losses due to heterotrophic respiration. NEP is essentially the diurnal NEE, reflecting carbon uptake during the day. It is calculated from 08:00 h to 16:00 h, resulting in negative values.



**Figure 8.** Regression analysis of simulated CO<sub>2</sub> flux components with monthly accumulated rainfall during the years 2009 (blue) and 2012 (red). Equations: (**A**) GPP 2009 =  $6.102 + 0.025x - 4 \times 10^{-5}x^2$  R<sup>2</sup> = 0.488, GPP 2012 = 3.305 + 0.065 R<sup>2</sup> = 0.750, (**B**) NEE 2009 =  $-0.900 - 0.019x + 4 \times 10^{-5}x^2$  R<sup>2</sup> = 0.761, NEE 2012 = -0.264 - 0.033x R<sup>2</sup> = 0.912, (**C**) NEP 2009 =  $-3.545 - 0.038x + 8 \times 10^{-5}x^2$  R<sup>2</sup> = 0.701, NEP 2012 = -2.864 - 0.045x R<sup>2</sup> = 0.722.

It is possible to observe that during the wettest year (2009), the saturation of GPP, NEE, and NEP occurred at approximately 300 mm of monthly rainfall, followed by a subsequent stabilization of the fitted curve. On the other hand, the fitted curve in 2012 was almost linear, without reaching saturation for GPP, NEE, or NEP due to the low rainfall rates.

The variation in CO<sub>2</sub> flux was significantly adjusted with rainfall during the wet season ( $R^2 = 0.488$ ) for GPP, NEE ( $R^2 = 0.761$ ), and NEP ( $R^2 = 0.701$ ). In extreme drought conditions, the coefficients of determination were also significant for GPP ( $R^2 = 0.750$ ), NEE ( $R^2 = 0.912$ ), and NEP ( $R^2 = 0.722$ ). Therefore, rainfall has exerted a significant influence on the behavior of the CO<sub>2</sub> flux components.

#### 5. Conclusions

In summary, the SITE model satisfactorily reproduced the seasonal variability of both energy and carbon balance. This is a pioneering study on the analysis of CO<sub>2</sub> exchange under conditions of extreme drought (2012 with 198.2 mm) and heavy rainfall (2009 with 1019.6 mm) in relation to the climatology (758.0 mm). It reveals the impacts of contrasting precipitation years on the intra- and interannual variability of energy fluxes and CO<sub>2</sub> fluxes in the Caatinga biome. In general, the results showed the relationship between rainfall seasonality, energy balance partitioning, and the dynamics of the CO<sub>2</sub> balance in the Caatinga. The annual mean GPP varied from 7.52 µmol m<sup>-2</sup> s<sup>-1</sup> in 2009 to 4.62 µmol m<sup>-2</sup> s<sup>-1</sup> in 2012, and the NEE was 57% higher in the wettest year (2009) compared to the extremely dry year (2012) due to surface water scarcity.

H and LE exhibited significant differences between the studied years, even during the dry and wet seasons, with H consistently higher regardless of the time of year. Even in the year with above-average rainfall, H remained higher than LE. However, this predominance is likely associated with the tendency of the SITE model to underestimate fluxes, mainly due to the model's limitation in capturing LE peaks during periods of extreme drought. On the other hand, net radiation showed seasonality linked to variations in solar radiation, which was similar in the years 2009 and 2012. The direct influence of rainfall on  $CO_2$  exchanges is shown through the strong relation ( $R^2 > 0.48$ ) observed in the regression analyses between GPP, NEE, NEP, and rainfall.

The monthly values of the  $CO_2$  balance components exhibit an asymptotic relationship with rainfall during the wet season, stabilizing after a monthly rainfall threshold of 300 mm. GPP, NEE, and Reco are directly influenced by the occurrence of rainfall in the Caatinga biome. In the year with high rainfall values (2009), the release of  $CO_2$  to the atmosphere was reduced. On the other hand, in the year with low rainfall values (2012), the peaks of carbon uptake were lower, but this was offset by a reduction in Reco. Nevertheless, the Caatinga biome continued to act as a sink for  $CO_2$  even during the year of extreme drought.

Given the importance of terrestrial carbon sinks to the global climate, attention is needed to create and strengthen policies to mitigate greenhouse gas emissions and to restore and protect seasonally dry tropical forests.

Author Contributions: Conceptualization, K.R.M., A.M.S.M., C.M.S.e.S. and B.G.B.; methodology, K.R.M., A.M.S.M., B.G.B. and C.M.S.e.S.; validation, K.R.M., A.M.S.M., C.M.S.e.S., B.G.B., P.R.M., P.E.S.O., D.T.R., G.B.C., R.R.F., A.C.N.d.S., L.F.M., J.R.S.L., A.C.D.A. and R.S.C.M.; formal analysis, K.R.M., A.M.S.M., C.M.S.e.S., B.G.B., P.R.M., P.E.S.O., D.T.R. and G.B.C.; writing—original draft preparation, K.R.M., A.M.S.M. and B.G.B.; writing—review and editing, K.R.M., A.M.S.M., C.M.S.e.S., B.G.B., P.R.M., P.E.S.O., D.T.R. and G.B.C.; writing—original draft preparation, K.R.M., A.M.S.M. and B.G.B.; writing—review and editing, K.R.M., A.M.S.M., C.M.S.e.S., B.G.B., P.R.M., P.E.S.O., D.T.R. and G.B.C.; visualization, K.R.M., A.M.S.M., C.M.S.e.S., B.G.B., P.R.M., P.E.S.O., D.T.R., G.B.C., R.R.F., A.C.N.d.S., L.F.M., J.R.S.L., A.C.D.A. and R.S.C.M. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research was funded by National Council for Scientific and Technological Development (CNPq) grant number 420854/2018-5 and for the productivity grant conceded to the authors C.M.S.e.S. and B.G.B. (grant n° 310781/2020-5 and 314257/2021-7, respectively), and to FUNPEC/UFRN for financial support (Project n° 372022). To National Council for Scientific and Technological Development (CNPq) for the research productivity grant of the author C.M.S.e.S. (Process n° 303802/2017-0) and the financial support in the NOWCDCB project: 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).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: The authors are thankful to the Brazilian National Institute of Semi-Arid (INSA) for funding the project which originated the EC data used in this study. We are also thankful to ICMBio (Chico Mendes Institute for Biodiversity Conservation) for providing access to the experimental site and to ESEC-Seridó (Ecological Station of Seridó) for supporting experimental activities.

Conflicts of Interest: The authors declare no conflict of interest.

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