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Understanding the Local Carbon Fluxes Variations and Their Relationship to Climate Conditions in a Sub-Humid Savannah-Ecosystem during 2008-2015: Case of Lamto in Cote d'Ivoire

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Abstract

The temporal variations of the Gross Primary Productivity (GPP), the Total Ecosystem Respiration (TER) and the Net Ecosystem Exchange (NEE), and their responses to meteorological conditions (e.g. temperature, radiative flux and precipitation) at Lamto, in wet savannah region across Côte d'Ivoire are analyzed using GFED-CASA and daily meteorological data recorded over the 2008-2015 period. The study shows the links between these carbon fluxes and climate variability at Lamto that is subject to high anthropogenic pressures and seasonal bushfires. The correlative statistics from multiple regression methods were used to assess the different relationships and show how they change in time. The results show important seasonal variability in the Gross Primary Productivity and the Total Ecosystem Respiration mainly associated with the changes in temperature and radiative flux. In addition, the statistical analysis suggests a high correlation between meteorological conditions and the GPP and TER. These climatic conditions may explain 83% and 79% of the variances of GPP and TER respectively. Moreover, the interannual variability of the Net Ecosystem Exchange indicates that around Lamto, in the subhumid savannah, the ecosystem behaves as a carbon sink similar to other West African ecosystems. On the other hand, there is no clear link between the NEE and temperature, radiative flux and precipitation. This lack of connection may suggest a limited response of the NEE interannual dynamics related to the changes in climatic features.

Keywords

Carbon Flux, Ecosystem, Subhumid Savannah, Lamto, Climatic Conditions, Linear Models

1. Introduction

Previous studies and reports indicate an increasing effect of the changes and the variabilities in climate on earth [1] [2]. For example, in West Africa, it is showed that since the 1970s, rainfall and temperature have been subject to both temporal and spatial fluctuations [2] mainly due to global warming which is related to anthropogenic greenhouse gas (GHG) emissions [3], particularly CO_2 and CH4, which represent alone 90% of these anthropogenic emissions [4]. Nearly 25% of the GHG emissions are absorbed by terrestrial ecosystems since 1750 [5] [6] [7]. However, these ecosystems, particularly in Africa, characterized by strong spatial and interannual mutations linked in part to climate variability are not intensively studied [8]. On the other hand, in tropical regions, GHG emissions are mainly due to deforestation, biomass combustion and the agricultural exploitation of natural formations [9] [10]. It is worth noting that at a global scale, African continent contributes less than 4% of GHG emissions, compared to European countries, Asia and America [11] [12]. Irrespective of its negligible emission of GHG, West African region is one of the most and highly sensible to GHG impacts [13]. Across the region, the changes in the climate are much more manifested in the form of frequent occurrence of intense extreme event [14] [15] (e.g. Heat Waves, Drought, Wet and Dry Spells, etc.), thus affecting the socio-economic and health stability. Previous works like Reichstein *et al.* [16] and Chmura *et al.* [17] have shown that long periods of drought can significantly alter the carbon fluxes in the ecosystems and their carbon productivity, and even rapidly reverse sinks into carbon sources. However, in Africa, there are significant uncertainties in the carbon exchange assessment between the ecosystems and the atmosphere [18] [10] due to the low density of continuous measurement networks and the inaccessibility of high-quality regional information (*i.e.* Ground-based observation data). This leads to important uncertainties in the estimation in its over short and long-term future [19]. The existing observation and measurement stations (e.g. Lamto-Côte d'Ivoire, Assekrem-Algeria) and regional networks (e.g. Carbo-Africa) are currently being operated to improve our knowledge on carbon flux exchanges between ecosystems and the atmosphere across Africa [20] [21]. Despite these improvements, there still an important challenge in the evaluation and understanding of the carbon fluxes in Africa ecosystems. This lack maybe related to the seasonal anthropogenic activities which modify the interaction between these carbon fluxes and meteorological parameters.

Moreover, since the signature on June 12, 1992 and the ratification on November 29, 1994 of the United Nations Framework Convention on Climate

Change (UNFCCC) by Côte d'Ivoire, whose objective is to stabilize greenhouse gas concentrations in the atmosphere at a level that prevents dangerous anthropogenic interference with the climate system [22], the Lamto region has become an area of interest for research on climate change due to GHG. This region offers enormous environmental and socio-economic potential for Côte d'Ivoire and climate impacts are not well understood. In this context, the current study aims to analyse and understand the responses of carbon fluxes (*i.e.* GPP, TER and NEE) to climate variations (air temperature, precipitation and radiative flux) at Lamto using data from the GFEDv4.1 inventory [23] and ground-based observations. This is mainly done through the assessment of the possible links between the carbon fluxes and climate variability at Lamto using correlative statistics and the evaluation of the different relationships and how they change in time. In addition, the long and short-term trends in these carbon fluxes are also analyzed by a diagnostic approach based on linear regression by least square fit to detect the period of the significant changes in their variations.

The work is organized as follows: Section 2 describes the study area, data and methodology used. Section 3 presents a statistical analysis of the response of carbon flux components (GPP, TER, NEE) to temporal variations in air temperature, precipitation and radiative flux recorded at Lamto station. A conclusion and perspectives are provided at the end.

2. Material and Methods

2.1. Study Area

The ecosystem of Lamto (5˚02W and 6˚13N, **Figure 1**) is located in a tropical subhumid savannah across the Sudano-Guinean Transition Area [24]. The region is of about 160 km north of Abidjan and its climate is controlled by the West African Monsoon (WAM). The recorded annual mean rainfall is about 1200 mm, with important seasonal and interannual variability [24] while the mean annual temperature is ~27˚C with a seasonal temperature range of ±2˚C [25]. The main dry season extends from December to February and the wet season is from

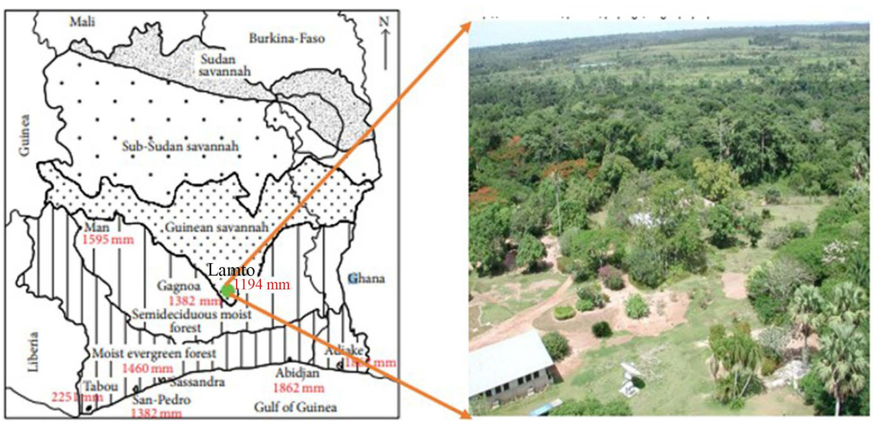


Figure 1. Study area: Lamto (6˚31N and 5˚02W), Côte d'Ivoire (adapted from Diawara *et al.*, 2014).

March to November, with a short dry season in August (**Figure 2**). The region is characterized by tropical ferruginous soils under savannah, ferralitic soils under forest, hydromorphic soils at the bottom of the hill and black soils over amphibolites [26]. All these features offer to the Lamto region significant environmental and socio-economic potential.

2.2. Data

2.2.1. GFED-CASA Data

The GFEDv4.1's database (Global Fires Emissions Database) consists of the CASA (Carnegie-Ames-Stanford-Approach) biogeochemical model output [27] [28] [29], developed to simulate the terrestrial carbon cycle using a combination of satellite and ground-based observation data [30] [31] at a monthly time scale. The biospheric fluxes in this database are composed of the Net Primary Production (NPP), the Heterotrophic Respiration (Rh) and the Fire Emissions (BB) in $gC/m^2/month$ at 0.25×0.25 spatial resolution over 1997-2015. In this work, only carbon exchanges (NPP and Rh) between land cover and the atmosphere are estimated over the 2008-2015 period because they allow calculating the other carbon fluxes variables such as Gross Primary Productivity (GPP), Total Ecosystem Respiration (TER) and Net Ecosystem Exchange (NEE). On the other hand, emissions due to fires (BB component) are not evaluated.

2.2.2. Ground-Based Observation Data

The meteorological data used in this study are air temperature (˚C), rainfall (mm) and radiative flux (J/cm^2) recorded daily at the geophysical station of Lamto over the 2008-2015 period according to WMO standards. These data have been used to document the climate variability at Lamto [24] [32] and are very often stress factors for vegetation.

2.3. Methods

This work is based on a statistical analysis of carbon fluxes (GPP, TER and NEE) in relation to climatic conditions (temperature, rainfall and radiative flux). The

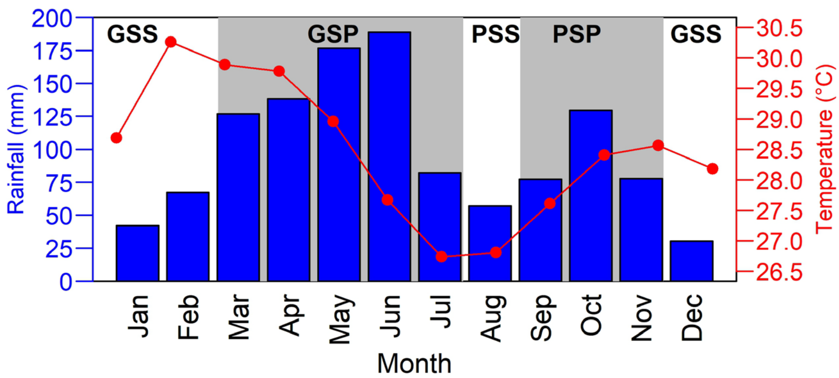


Figure 2. Precipitation-temperature diagram over 2008-2015 period. GSS, GSP, PSS and PSP are the great dry season, the great wet season, the short dry season and the short-wet season respectively.

responses of carbon fluxes to these climatic conditions are evaluated with linear models using the multiple regression method. The correlative statistics and their significance (p-value) according to Pearson [33] were also calculated. To homogenous the climatic data time series into line with that of the GFED-CASA data, the daily meteorological parameter was averaged monthly. In addition, the GPP, TER and NEE components of the carbon flux were calculated from the NPP and Rh variables of the GFED-CASA database following Equations (1) [34], (2) [21] and (3) [17] below.

$$\mathrm{GPP} = \frac{\mathrm{NPP}}{\mathrm{CUE}}. \tag{1}$$

where, CUE (value without unit) refers to the Carbon-Use Efficiency by the considered ecosystem [35]. Its values are generally in the range [0.2 - 0.8] [34] [35] [36] [37]. In tropical regions, the Cue values are estimated in the range [0.40 - 0.53] with an average value of 0.43 [38] [37].

$$\mathrm{NEE} = \mathrm{NPP} + \mathrm{Rh}. \tag{2}$$

$$\mathrm{TER} = \mathrm{NPP} - \mathrm{GPP} + \mathrm{Rh}. \tag{3}$$

3. Results

3.1. Seasonal Variability and Trends

3.1.1. Seasonal Variability

Figure 3 shows the seasonal cycles of TER and GPP (in absolute values) observed at Lamto over the 2008-2015 period. The carbon flux TER representing the sum of autotrophic (*i.e.* CO_2 emission by the plant into the atmosphere) and heterotrophic (*i.e.* CO_2 emission from the decomposition of organic matter) respirations [36] shows a seasonal cycle with strong variations. These seasonal variations are characterized by a rapid decrease in flux values from April (182 $gC·m^{-2}·month^{-1}$) to August (118 $gC·m^{-2}·month^{-1}$) followed by an abrupt increase until November (185 $gC·m^{-2}·month^{-1}$) and a decrease until February (137 $gC·m^{-2}·month^{-1}$). In addition, the GPP (*i.e.* the total CO_2 captured by chlorophyll plants from the atmosphere through photosynthesis) [39] [29], shows a seasonal profile contrasted to that of the TER. As the TER, the GPP cycle is also characterized by a strong seasonal variation. However, there are two decrease phases in seasonal GPP values, from February (1883.35 ppb) to April (−204 $gC·m^{-2}·month^{-1}$) and from August (−94 $gC·m^{-2}·month^{-1}$) to November (−185 $gC·m^{-2}·month^{-1}$) and, two increase phases, from April (−204 $gC·m^{-2}·month^{-1}$) to August (−94 $gC·m^{-2}·month^{-1}$) and from November (−210 $gC·m^{-2}·month^{-1}$) to February (−120 $gC·m^{-2}·month^{-1}$). Globally, the seasonal cycle of GPP ranges from −213 $gC·m^{-2}·month^{-1}$ in November to −93 $gC·m^{-2}·month^{-1}$ in August. In addition, the breaks observed in seasonal trends of TER and GPP appear quite significantly during changes in rainfall regime (*i.e.* GSP/PSS/PSP/GSS/GSP). This behavior could probably be explained by the presence of favorable conditions (e.g. radiative flux, soil temperature, sensitive heat/latent heat ratio, biospheric mutation, etc.) to significant monthly variations in GPP and TER fluxes.

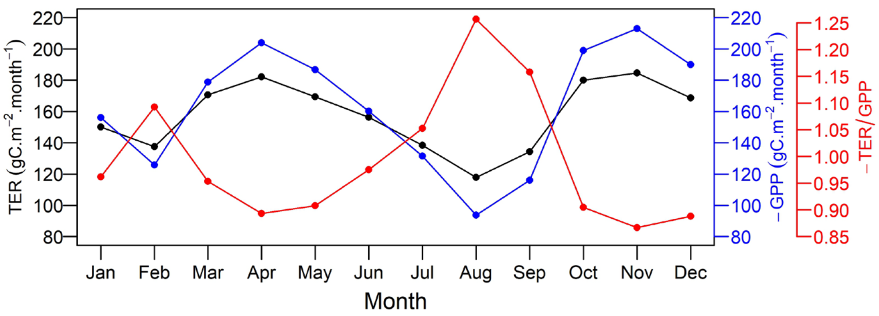
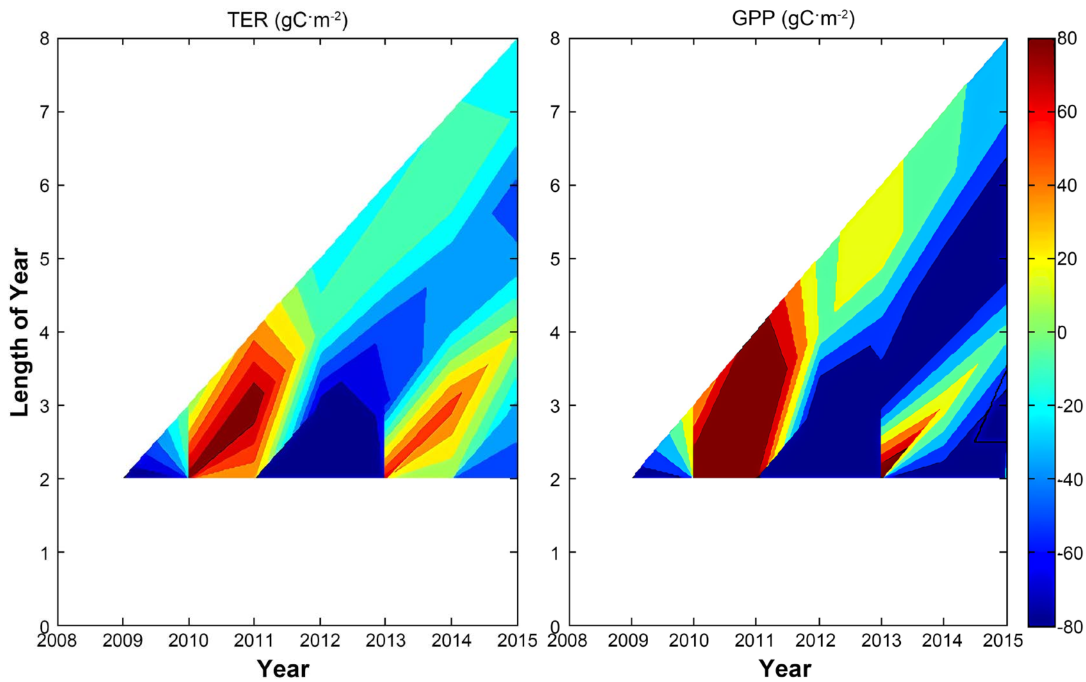


Figure 3. Mean monthly changes in TER (in black) and GPP (in blue) of the TER/GPP ratio (in red) observed at the Lamto station over 2008-2015.

However, a significant and important correlation ($R^2 = 0.985$ and p-value = $1.09 \cdot 10^{-9}$) is found between the monthly variation of TER and GPP (in absolute value). This result suggests that TER and GPP could be controlled by the same mechanisms such as drought. Indeed, Granier *et al.* [40] showed that drought decreases both GPP and TER fluxes, which is consistent with their seasonal trends associated to the recorded low values in the Lamto region over the study period (**Figure 3**). In addition, the seasonal variation in the observed TER/GPP ratio is very significant, ranging from 0.86 in November to 1.26 in August with a mean value of 0.99. This mean value is higher than the TER/GPP ratio obtained in other regions. For example, Janssens *et al.* [41] found a mean ratio value of 0.80 in 18 European ecosystems while Law *et al.* [42] obtained 0.83 on the interval [0.55 - 1.2] in various ecosystem types, including grasslands and crops.

3.1.2. Trends Analysis

An analysis of long and short-term trends in TER and in GPP is provided using a statistical diagnosis based on linear regression by least square fit [43]. This method objectively detects one or more trend breaks in the TER and GPP time series when they occur. **Figure 4** shows all trends for time segments from 2 to 8-years (total length of the time series), with a 95% confidence level by the Student t-test. The variations of TER (**Figure 4(a)**) and GPP (**Figure 4(b)**) are obtained by multiplying the coefficient of linear trends by the length of the time series. Thus, it is obvious that time segments of several years or less may have an excess or deficit of TER and GPP. There is also an increase (upward trend) and/or decrease (downward trend) for time segments less than or equal to 4 years for TER and GPP. In addition, time segments greater than 4 years systematically show a decrease in TER values ($<0\ gC \cdot m^{-2}$), while the GPP always shows an increase and/or a decrease. It should be noted that the 7-year variations observed between 2009 and 2015 indicate a decrease in TER ($\sim -10\ gC \cdot m^{-2}$) and in GPP ($\sim -30\ gC \cdot m^{-2}$) in the Lamto region. For a length of segment less than 3 years, a negative and significant trend in GPP ($\sim -45\ gC \cdot m^{-2}$) occurs from 2014 to 2015. However, two characteristic modes (*i.e.* high and low frequency variability) are observed and determine trends in variations. Low frequency variability (*i.e.* time segment ≥ 5 years) is linked only to a decrease in TER while high frequency



(a) (b)

Figure 4. Trends in the annual averages of TER (a) and GPP (b) obtained at Lamto over the 2008-2015 period. The black contour provides significance at a 95% confidence level from the student t-test.

variability (*i.e.* time segment ≤ 5 years) is related to an alternation of positive and negative changes that are associated to significant small-time scale fluctuations in TER and GPP.

3.2. Statistic Analysis of Carbon Fluxes

3.2.1. Parametric Approach by Linear Models

The equations are an exception to the prescribed specifications of this template. You will need to determine whether or not your equation should be typed using either the Times New Roman or the Symbol font (please no other font). In order to know the local meteorological variable(s) (*i.e.* explanatory variable) that control the carbon fluxes (e.g. GPP and TER) variability, linear models were established with the corresponding determination coefficients (R^2) and their significance (p-value) (**Table 1**). This approach is used to model carbon fluxes as a function of radiative flux and/or temperature and/or precipitation. The different linear functions (Equations (4)-(6), Equations (11)-(13)) obtained show that the monthly flux of GPP and TER are better correlated to local climatic conditions when the "pilot" variable is the radiative flux (Fr) (Equation (4) and Equation (11)) unlike temperature (Te) and rainfall (Pr). Indeed, the values of the correlation coefficient are important and very significant for GPP (R^2 = 0.50, p-value = 0.02) and TER (R^2 = 0.52, p-value = 0.008) with the radiative flux (Fr). However, there is no significant correlation between GPP and rainfall (R^2 = 0.13, p-value = 0.25) and temperature (R^2 = 0.25, p-value = 0.05), and also between TER and rainfall (R^2 = 0.17, p-value = 0.18) and temperature (R^2 = 0.28, p-value = 0.05).

Table 1. Linear Models showing relationships between mean monthly carbon fluxes (*i.e.* GPP and TER) and local meteorological conditions such as radiative flux (Fr), Air Temperature (Te) and Rainfall (Pr) recorded at the Lamto station during the 2008-2015 period, and their correlation coefficients (R^2) and significance (*p*-value).

	Linear Models	R^2	*p*-Value
(4)	$GPP = 0.12 * Fr - 14$	0.50	0.01
(5)	$GPP = 17.26 * Te - 324.94$	0.23	0.05
(6)	$GPP = 0.26 * Pr + 136.20$	0.13	0.25
(7)	$GPP = 0.45 * Fr - 68.95 * Te + 1466.18$	0.83	0.0004
(8)	$GPP = 0.12 * Fr + 0.14 * Pr - 14.62$	0.52	0.04
(9)	$GPP = 15.27 * Te + 0.21 * Pr - 288.40$	0.31	0.11
(10)	$GPP = 0.43 * Fr - 67.60 * Te + 0.04 * Pr + 1437.27$	0.80	0.002
(11)	$TER = 0.07 * Fr - 54.60$	0.52	0.008
(12)	$TER = 10.48 * Te - 138.83$	0.28	0.05
(13)	$TER = 0.17 * Pr + 140.33$	0.17	0.18
(14)	$TER = 0.23 * Fr - 35.29 * Te + 812.44$	0.79	0.00077
(15)	$TER = 0.07 * Fr + 0.10 * Pr + 54.15$	0.55	0.02
(16)	$TER = 0.07 * Fr + 0.10 * Pr + 54.15$	0.36	0.10
(17)	$TER = 0.22 * Fr - 33.78 * Te + 0.05 * Pr + 779.64$	0.81	0.003

On the other hand, the results are improved when linear models with two (Equations (7)-(9)) and three (Equations (14)-(16)) variables are used. As in a humid tropical ecosystem such as that of the Lamto region, where climate variables are dependent and interact strongly with each other [24], the three-variable linear model would then be more representative of the impact of these meteorological conditions on the variability of GPP and TER. However, Equation (7), Equation (10), Equation (14) and Equation (17)) show that the effect of rainfall is marginal for GPP and TER seasonal variations. Considering rainfall in the linear model reduces the determination coefficient by 0.03 for the GPP and increases it by 0.02 for the TER while reducing their degree of significance by increasing *p*-value. In addition, the less significant effects due to rainfall can be integrated into the constant term used in each two-variable linear model (Equation (7) and Equation (14)) involving radiative flux (Fr) and temperature (Te). These linear models would then be more representative of the exchanges between the Lamto ecosystem and the atmosphere. **Table 1** shows that GPP and TER are also better correlated under these conditions. Indeed, Equation (7) and Equation (14) explain 83% (*p*-value = 0.0004) and 79% (*p*-value = 0.000077) of the GPP and TER variances, respectively with high significance. In this case, the constant terms 1466.18 $gC \cdot m^{-2} \cdot month^{-1}$ in Equation (7) and 812.44 $gC \cdot m^{-2} \cdot month^{-1}$ in Equation (14) represent potential non-linear effects or coupled effects of radiative flux (Fr) or temperature (Te), such as those resulting from interactions with other variables. Equation (7) and Equation (14) obviously ignore other aspects of local meteorological conditions, such as rainfall, relative humidity, wind speed and non-climatic factors, such as soil type, soil moisture and vegetation type. They also represent a useful first-order estimate of the seasonal variability of carbon fluxes for the Lamto ecosystem over the 2008-2015 period.

3.2.2. GPP and TER Responses to Radiative Flux and Temperature as Predictors in a Multiple Linear Regression

In this section, approach by multiple regressions previously made (section 3.2.1) shows that linear models with two parameters and using radiative flux and Temperature (*i.e.* Equation (7) and Equation (14)) as predictors better explain the seasonal variations in GPP and TER in the Lamto region. In addition, the Equation (7) and Equation (14) show that any increase in temperature (Te) systematically leads to decreases in GPP and TER fluxes with rates of −68.75 $gC{\cdot}m^{-2}{\cdot}month^{-1}{\cdot}{}^{\circ}C^{-1}$ and −35.29 $gC{\cdot}m^{-2}{\cdot}month^{-1}{\cdot}{}^{\circ}C^{-1}$ respectively. These results indicate that when temperature increases (resp. decreases), the ecosystem's carbon requirements (*i.e.* GPP flux) are reduced (resp. increased) to favour (resp. inhibit) the respiration mechanisms inducing a significant increase (resp. decrease) of TER exchanges between the ecosystem and the atmosphere. On the other hand, any increase (or decrease) in the radiative flux (Fr) also leads to an increase (or decrease) in the GPP and TER with rates of +0.45 $gC{\cdot}m^{-2}{\cdot}month^{-1}{\cdot}J^{-1}{\cdot}Cm^2$ et +0.23 $gC{\cdot}m^{-2}{\cdot}month^{-1}{\cdot}J^{-1}{\cdot}Cm^2$ respectively. These results clearly indicate that the radiative flux (Fr) favours the atmosphere-ecosystem exchanges and show the GPP and TER responses to these radiative flux effects.

3.3. Annual Carbon Sequestration

Figure 5 shows the interannual variations of climatic variables (*i.e.* radiative flux, rainfall and temperature) and the Net Ecosystem Exchange (NEE) in the Lamto region. The annual values of NEE obtained using Equation (2) are negative and in the range [−97.95; −42.16] gC/m^2/year. This range of values indicates that the Lamto ecosystem behaves as a carbon sink on an interannual time scale over the 2008-2015 period. In addition, the interannual variations show an increase in the NEE flux from ~51.50 gC/m^2/year (in 2008) to ~97.95 gC/m^2/year (in 2011) followed by a decrease until ~57.49 gC/m^2/year (in 2015) except in 2013 when the NEE flux is equal to ~87.29 gC/m^2/year. These results are related to a global decrease in radiative flux (Fr) from ~1535.20 $J{\cdot}Cm^{-1}$ (in 2008) to ~1350.7 $J{\cdot}Cm^{-1}$ (in 2015) and an increasing trend in temperature from ~27.94˚C (in 2008) to ~28.59˚C (in 2015) with rate of 0.10˚C/year. In addition, the rainfall interannual variations show an upward trend from 2008 (~1211.15 mm) to 2010 (~1406.1 mm) followed by a significant decrease until 2014 (~991.6 mm) and an increase in rainfall in 2015 (~1480.7 mm). However, the interannual variations in NEE do not show a general clear trend with rainfall (Pr), radiative flux (Fr) and temperature (Te). Nevertheless, over short time segments, there is a similar fluctuation (*i.e.* increase) between the NEE and the rainfall variations (over 2008-2010) and a decrease in the radiative flux related to an increase in the NEE

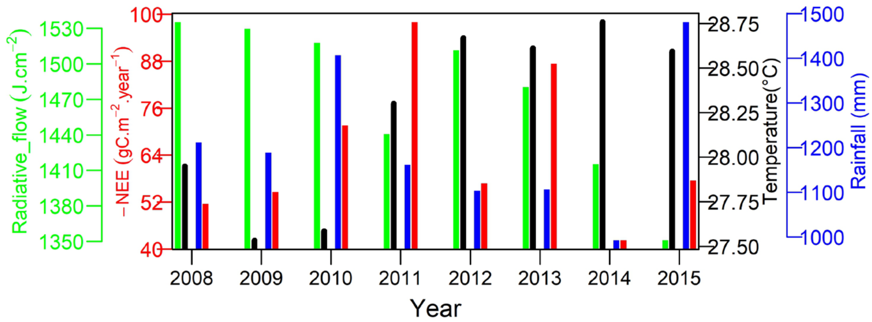


Figure 5. Interannual Variations of NEE (red) and Temperature (black), rainfall (blue) and radiative flux (green) in the Lamto region over the 2008-2015 period.

flux (over 2008-2011). The small amplitudes of the calculated annual variations of temperature (<1.26˚C) and radiative flux (<120 J·Cm^{-1}, except for the year 2015) maybe due to a lack of a relationship between climatic parameters (*i.e.* temperature and radiative flux) and the NEE flux. In addition, seasonal variations of standardized NEE flux anomalies (**Figure 6**) and climatic parameters (*i.e.* temperature, radiative flux and rainfall) show low correlation values; R = −0.29 and R = −0.42 for rainfall and temperature respectively. However, the correlation coefficients (in absolute value) are much better between the radiative flux and the NEE (R = −0.65). These results indicate that the seasonal variability of NEE is particularly influenced by variations of the radiative flux.

4. Discussion

The impact of climatic conditions (*i.e.* rainfall, radiative flux and temperature) on carbon fluxes (*i.e.* GPP and TER) is analyzed over the 2008-2015 period in the Lamto region. The results show strong seasonal variations of TER and GPP (**Figure 3**) that are consistent with the climatic seasons [24] (**Figure 2**). Indeed, climatic variables (e.g. radiative flux and temperature) that control these fluxes also have strong seasonal variations patterns. Similar trends are also observed in many studies [44] [45] [46] [47] on various regions (e.g. France, China, Germany, Italy, Finland and Belgium). In fact during the growth period of plant, the GPP flux that characterizes photosynthetic activities is important [29] [35] [48] [49] [50] in response to the seasons of increasing and decreasing temperature. In addition, many authors as Lafleur *et al.* [51], Zhang *et al.* [52] and Lee *et al.* [48] pointed out that low temperatures limit photosynthetic activity in ecosystems and reduce GPP flux. These seasonal variations of temperature also influence the TER flux characteristic of respiration during the year [11] [53]. They also show lagged peaks behind the peaks of GPP and TER fluxes during the December-January-February dry season (**Figure 2** and **Figure 3**), probably due to a hysteresis effect whose underlying mechanisms and processes are not totally explained in many studies [46] [54] [55] [56]. This phenomenon of hysteresis has already been mentioned in the work of Zeppel *et al.* [57]. These authors underline that hysteresis occurs when an increase in a given independent variable *a*

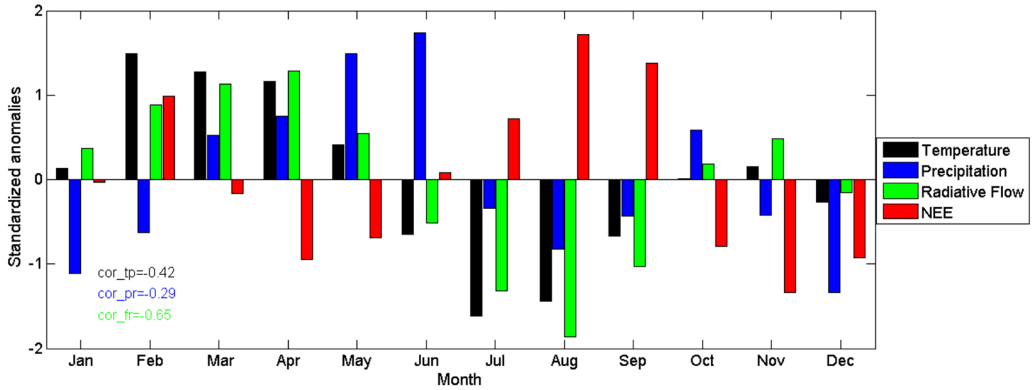


Figure 6. Mean monthly variations of standardized anomalies of the NEE flux (red) and Temperature (black), rainfall (blue) and radiative flux (green) and, their associated correlation coefficients over the 2008-2015 period.

does not lead to the same response scale in a dependent variable *β*, compared to a decrease in the variable α of the same magnitude.

In addition, the role of temperature at the plant stage has been the topic of much investigation [53] [58] in a context of climate and agricultural development. These authors have shown the importance of temperature in the interactions between vegetation and the atmosphere. Indeed, temperature determines water needs and strategies to ensure its availability to fulfill demand. However, Niu *et al.* [46] point out the importance of taking into account both radiative transfer and temperature in the response of the GPP flux.

In addition, the models defined by Equation (7), Equation (10), Equation (14) and Equation (17) (**Table 1**) indicate that the different responses of GPP and TER fluxes to environmental factors can be linear. These two- and three-variable equations involving on the one hand, radiative flux and temperature, and radiative flux, temperature and precipitation on the other hand explain most of the seasonal variation in carbon fluxes. Among these environmental factors, the radiative flux is the one that shows the most significant effect (*i.e.* pilot variable) on carbon fluxes, by explaining respectively 50% and 52% of the seasonal variances of GPP and TER (Equation (4) and Equation (11)). On the other hand, the results are improved when the radiative flux (Fr) and temperature (Te) are considered (Equation (7) and Equation (14)). In this case, these two variables explain 83% and 79% respectively of the seasonal variations in GPP and TER fluxes. These observations show the important and significant role of temperature and radiative flux in seasonal carbon fluxes responses. In contrary, the explicit consideration of rainfall (Pr) in the different linear models (Equation (10) and Equation (17)) does not show significant changes in the variance rates of these carbon fluxes. However, several studies [59] cited by [60]-[68] which analyzed the impact of climate variables on GPP and TER fluxes in several terrestrial ecosystems, showed the main role of precipitation in the seasonal and/or interannual dynamics of these carbon fluxes. Indeed, precipitation contributes to increasing 1) autotrophic respiration through increased vegetative growth [63] [65] [69], and

2) heterotrophic respiration through soil moisture [53] [66] [70]-[75].

Moreover, in the case of this study, the results clearly indicate that only the combined effects of radiative fluxes and temperature explain most of the seasonal variability of carbon fluxes. These results also show the particular behaviour of the Lamto region compared to other ecosystems [59] [62] [65] by its geographical position (in the Sudano-guinean transition area at 6˚31N and 5˚02W) and its rainfall regime (very marked two rainy and dry seasons) and by the strong interannual variability of its climate, which can change from humid to subhumid [24]. The response of carbon fluxes to environmental factors (*i.e.* radiative flux, temperature and rainfall) can be estimated by linear models with two or three variables depending on local conditions; for example, in regions where rainfall is highly seasonal (especially in regions where rainfall is low or non-existent for several months), linear models with two variables involving radiative flux and temperature (*i.e.* Equation (7) and Equation (14)) could be considered. Otherwise, in regions where rainfall is very high, three-variable models involving radiative flux (Fr), temperature (Te) and rainfall (Pr) could be used to take into account the effects of this rainfall. In addition, the interannual variability of the Net Ecosystem Exchanges (NEE) shows negative values (**Figure 5**) in the range [42.16; 97.95; −42.16] gC/m^2/year (in absolute value), indicating that the ecosystem in the Lamto region behaves as a carbon sink. This behaviour is also observed in several modeling studies and direct and/or indirect in-situ measurement on various West African ecosystems, such as Niger/Wankama1 [59], Senegal/Dahra [76], Burkina-Faso/Nazinga [68] and Benin/Nalohou [66].

These studies have shown the singular nature of these mentionned ecosystems which behave as carbon sinks.In addition, the absence of a well-defined relationship between annual NEE and environmental factors (e.g. temperature, rainfall and radiative flux) could be due to the fact that: 1) there are several sources of carbon (CO_2) for ecosystem respiration [53], and each source has its own control factors, such as soil moisture, extreme pedological conditions [38] [53] [76]-[81]; 2) the observed interannual variations in temperature and radiative flux have small amplitudes less than 1.26˚C and less than 120 J·Cm^{-1} respectively [21] [82].

5. Conclusion

This study assessed the different responses of carbon fluxes (*i.e.* GPP, TER and NEE) to meteorological factors (*i.e.* Temperature, Radiative flux and Rainfall) over the 2008-2015 period around Lamto region. A statistical approach using multiple regressions highlighted the seasonal variations of GPP, TER and NEE. In addition, the analysis based on linear models established with one climatic variable, show that the radiative flux, by explaining 50% and 52% of the variances of GPP and TER respectively, seems to be the most important environmental factor affecting the carbon fluxes. On the other hand, using linear model based on two climatic variables as predictors, the combined effects of the radiative flux and temperature are suggested to key role in the variation of carbon fluxes by explaining 83% and 79% of the variances of GPP and TER respectively. The seasonal changes in rainfall for its part, seems to have a negligible impact on the variation of the carbon fluxes. This is in agreement with previous studies which show that the interannual variability of carbon fluxes in West Africa is related more to the annual rainfall than the seasonal rainfall. This low impact could be linked to the fact that seasonal rainfall is low or sometimes non-existent over several months. In addition, the interannual variability of Net Ecosystem Exchange (NEE) has shown that the Lamto region behaves like a carbon sink similar to other West African ecosystems. However, there is no clear link found between NEE flux and temperature, radiative flux and rainfall. This absence of link suggests that the dynamics of NEE could either exhibit threshold responses to the effects of climatic factors or could not be determined mostly by climatic factors, but much more by exogenous parameters such as soil temperature, vegetation type, soil type, anthropogenic pressure and canopy structure. In order to better understand the main mechanisms responsible for the variability of carbon fluxes and to significantly reduce the uncertainties on the carbon balance in West Africa in a context of climate variability and change, it is necessary to take into account all these above-mentioned parameters which are beyond the scope of the current study.

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Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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