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Carbon exchange in a caatinga area during an unusually drought year

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ABSTRACT

The objective of this study was to analyze the daily and seasonal variation of the carbon balance components in a *caatinga* area during an unusually drought year. Data were collected from a turbulent vortices covariance system installed at an area in *Caatinga*, in the region of Petrolina Municipality, State of Pernambuco, Brazil. Carbon dioxide flux data were collected in the year 2012, and the partitioning between gross primary productivity (GPP) and ecosystem respiration (Re). The vegetation cover index, weather elements and the soil water content were monitored. It was observed that the daily emissions of CO_2 flux was dependent upon photosynthetically active radiation in the first days after rainfall events, being influenced by the water vapor pressure deficit with the reduction in the soil water content. The occurrence of up to 2 mm rainfall promoted peaks of Re after long periods of drought. The measured NEP was equal to 468.18 gC m^{-2} $year^{-1}$. So, it is concluded that in years with severe drought, Caatinga may act as a source of carbon to the atmosphere.

Introduction

The Brazilian semi-arid is characterized by high incidence of solar radiation, high temperatures and wide space-time variation of rainfall, which result in water deficiency over the year. The predominant native vegetation is *caatinga*, which has been considered the most resilient biome in Brazil (Giongo et al., 2011; Santos et al., 2011).

Although species exhibit tolerance to environmental conditions, anthropogenic action by means of deforestation increases the vulnerability of ecosystems to climate changes (Salazar et al., 2007). So, measurements of the energy balance, radiation and carbon are important for the analysis of the ecosystem response to socio-environmental variations (Zhang et al., 2015; Minderlein & Menzel, 2015; Silva et al., 2011).

Concerning to *caatinga*, there are studies that indicate the seasonality of the radiation and energy balance under different annual water availability conditions (Oliveira et al., 2006; Teixeira et al., 2008; Santos et al., 2011; Cunha et al., 2013; Souza et al., 2015a, Souza et al., 2015b). In turn, studies on carbon balance do not clarify source-drain action of such vegetation (Oliveira et al., 2006; Santos et al., 2011). On a daily scale, Cunha et al. (2013) verified carbon assimilation by the *caatinga* in the rainy season, and small release in dry season. Oliveira et al. (2006) evaluated the carbon exchanges at the caatinga-atmosphere interface, in one year with rainfall of 510 mm, demonstrating that it had a greater sink capacity in the rainy season than in the drought period. These two studies were carried out in years with average precipitation near to the historic annual of the region, and data on this balance are not available in extreme drought condition. In this meteorological condition, vegetation may have carbon partitions altered in gross primary productivity (GPP) and ecosystem respiration (Re), as it was seen in other ecosystems (Anderson-Teixeira et al., 2011). This type of study is essential because it includes information on ways to minimize carbon emissions and impacts of climate change (Yang et al., 2011; Chen et al., 2013), and enhances the understanding of the role of ecosystems in global carbon balance (Minderlein & Menzel, 2015; Anderson-Teixeira et al., 2011). The objective of this study was to analyze the daily and seasonal variation of carbon balance components in a *caatinga* area during an untypically drought year.

Material and methods

The experiment was carried out at Experimental Station of Caatinga, which belongs to Embrapa Tropical Semiarid (9.05°S; 40.19°W; 350m), in the municipality of Petrolina, State of Pernambuco, Brazil. The area complies 600 ha, which has been preserved for over 40 years and is composed of vegetation of a shrubby-arboreal, hyperxerophilic caatinga vegetation (average height of 5 m), with *Poincianella microphylla*, *Croton conduplicatus*, *Bauhinia cheilantha*, *Manihot pseudoglaziovii*, *Commiphora leptophloeos*, among others. The climate of the region is semi-arid with annual temperature of 26°C, average relative humidity around 65%, wind velocity of 2.2 m s^{-1}, and annual precipitation of 510 mm.

Micrometeorological measurements were performed from January 1 to December 31, 2012, a period characterized as the driest year over the last 38 years. From January to April, which are the rainiest months in the region, the cumulative rainfall was only 71.0 mm, which resulted in the annual total of 92.24 mm (Figure 1). The other meteorological elements were over the historical average of the region.

Carbon dioxide concentration was measured by the turbulent vortices covariance system installed 16.9 m above the soil surface. A three-dimensional sonic anemometer (CSAT3, Campbell Scientific, Logan, UT, USA) and an open path infrared gas analyzer (LI-7500, Liquor, Lincoln, NE, USA) were used, connected to a datalloger (CR1000, Campbell Scientific, Logan, UT, USA). Simultaneously, the following meteorological elements were monitored: global solar radiation (pyranometer, model CM3, Kipp & Zonen, Delft, The Netherlands), temperature and air relative humidity (HMP45C, Campbell Scientific, Inc., Logan, UT, USA), and rainfall (CS700-L Hydrological Services Rain Gauge, Liverpool, Australia). The photosynthetically active radiation (PAR) was measured by means of four quantum sensors, out of which, two were located above vegetation, one face-up, and other face-down, to measure the incident and reflected PAR, respectively (PAR_T and PAR_R, LI-190SA, Li-cor, Nebraska, USA), and two laid under vegetation (PAR_B, LI-191SA, Li-cor, Nebraska, USA).

Soil water content was monitored by means of the gravimetric method, between the surface and 0.5 m depth, at each 0.10 m, at monthly average intervals in the drought period, or shortly after the occurrence of rainfall events from January to April. In addition, the determination of the plant cover index was performed at 15-day intervals, with 12 readings and 36 replicates using the AccuPar ceptometer (Decagon Devices Inc., 2001).

Half-hourly turbulent flux of CO_2 were processed using Alteddy software version 3.6 (Alterra, University of Wageningen, The Netherlands). Corrections were made to minimize the effect of lateral wind on sonic velocity, temperature and water vapor by means of the rotation of the coordinates. Conditions of atmosphere stability were characterized and filters were applied at the friction velocity ($u^* < 0.5$ m s^{-1}) to eliminate the advective conditions and low turbulence (Foken et al., 2004).

Analysis on data quality was performed based on the criteria proposed by Foken (2004) and the gaps were filled using the software proposed by Falge et al. (2001) and Reichstein et al. (2005), available at: *Eddy covariance gap-filling & flux-partitioning tool* (http://www.bgc-jena.mpg.de/~MDIwork/eddyproc/).

Covariance of fluxes and meteorological data (Reichstein et al., 2005) were used to fill the missing data by an average value in similar meteorological conditions within a seven-day time interval. This tool was also used to calculate the net carbon flux (NEE) partition in gross primary productivity (GPP) and ecosystem respiration (Re).

The daily emission of carbon balance components and meteorological elements were performed for representative days of different water availability conditions, with characteristics of foliar senescence and extreme drought. Seasonal analysis was done with the schedule data of net carbon flux (NEE) at half-hourly values and daily totals of net ecosystem production - NEP, GPP and Re. Where: NEP = GPP – Re.

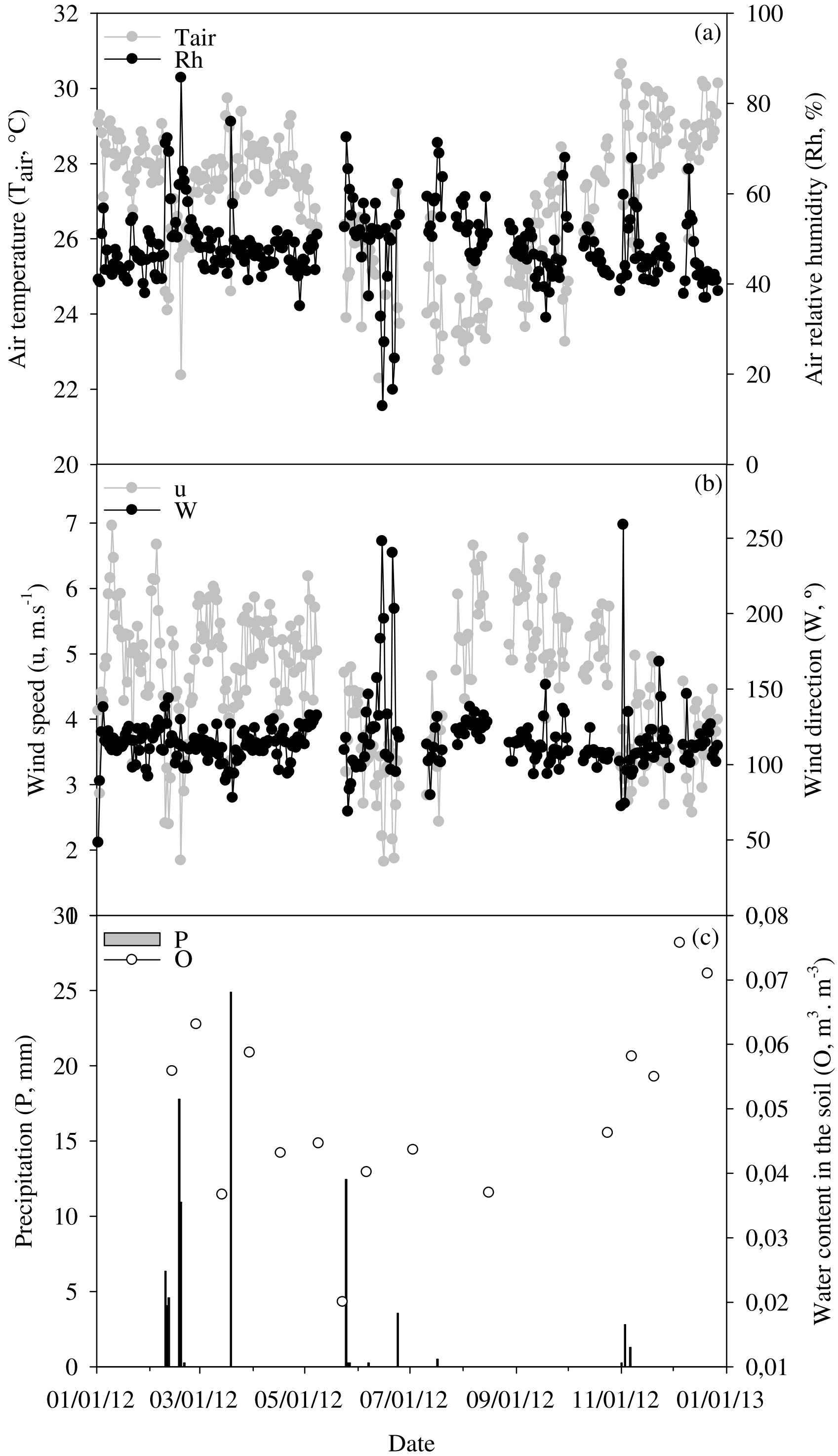

Figure 1. Variation of meteorological elements: temperature and air humidity (a), wind speed (b), rainfall and water content in the soil (c) in an area in *caatinga* over 2012, Petrolina-State of Pernambuco.

Results and discussion

On 02/20/2012, soil water content and vegetation cover index (VCI) reached their maximum magnitudes of 0.08 m^3 m^{-3} and 3.49 m^2 m^{-2}, respectively (Figure 2a). Under this condition, the ecosystem behaved as a CO_2 sink, with maximum carbon fixation (~ 9.0 µmol m^{-2} s^{-1}), represented by the NPP, at times of greater availability of photosynthetically active radiation (PAR) (Figure 2b), and GPP values with peaks close to 10.0 µmol m^{-2} s^{-1}. With the reduction of the PAR incidence, even with the increase in the atmospheric demand (DPV = 2.2 kPa), it was observed a decrease in GPP of around 2.0 µmol m^{-2} s^{-1} at 6:00 p.m. The response of CO_2 flux to PAR was also observed in several ecosystems (Oliveira et al., 2006; Aires et al., 2008). At night, (from 6:00 p.m. to 6:00 a.m.), CO_2 flux was mainly ascendant as a reflection of soil emissions and autotrophic and heterotrophic respiration, demonstrating that the

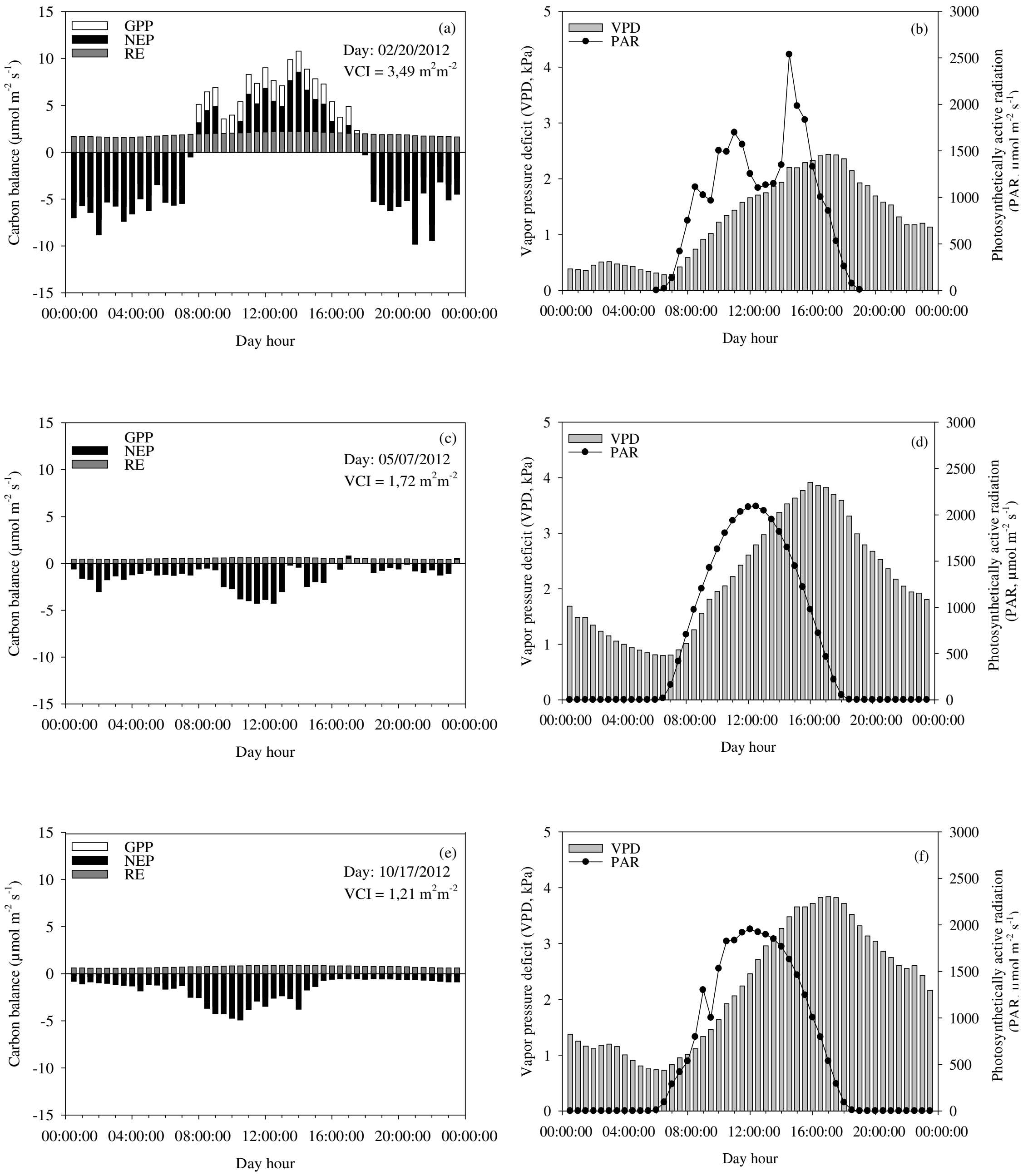

Figure 2. Daily partioning of carbon balance (a, c, e) in the net ecosystem production (NEP), gross primary production (GPP) and respiration of the ecosystem (Re), and photosynthetically active radiation and vapor pressure deficit (b, d, f), in days with different water availability and vegetation cover index in an area of Caatinga, Petrolina Municipality, State of Pernambuco, Brazil.

ecosystem acts as a source of CO_2 during this period, when there is vegetation cover. Similar trends are cited by Yang et al. (2011) in temperate climate steppe ecosystem in the Mongolian desert, China.

As the water availability in the system was reduced, and leaf senescence increased (05/07/2012, Figure 2c), changes were observed in the daily emissions of CO_2 balance in relation to the period of greatest water regime. The highest values of the NPP, around 4.0 µmol m^{-2} s^{-1}, were verified between 9 a.m. and 1 p.m.. Then, with the increase in the vapor pressure deficit (Figure 2d), a decrease in NEP (~1,0 µmol m^{-2} s^{-1}), was observed, reaching almost null values. In this case, the reduction in water availability promoted a reduction of foliar biomass and, consequently, to autotrophic (vegetation) respiration.

Under extreme drought (10/17/2012, Figures 2e, 2f), although the magnitude of the NEP was not much modified compared to the previous period, it is observed an anticipation of carbon dioxide emission for the hours between 7 a.m. and 2 p.m., with minimum values of -3.0 µmol m^{-2} s^{-1}. In addition, at night, the release of CO_2 is virtually null. Moreover, GPP (~2.0 µmol m^{-2} s^{-1}) shows negative values throughout the day, indicating that part of the CO_2 was used by the ecosystem for its maintenance. High temperatures associated with the absence of rainfall promoted a reduction of the CO_2 efflux of the soil, in the

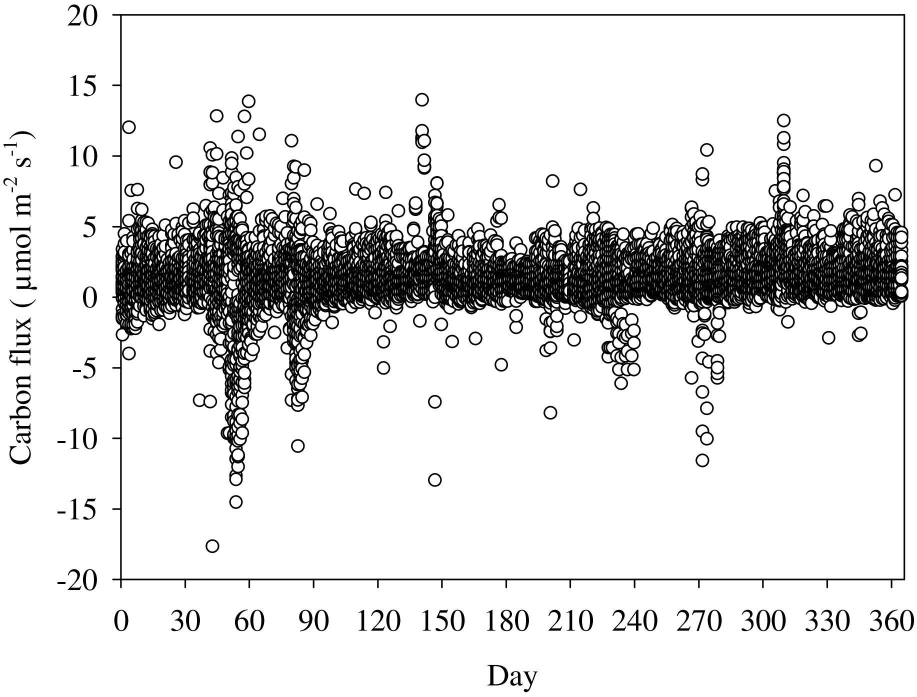

Figure 3. Seasonality of the CO_2 net flux measured at half-hourly intervals in a preserved *caatinga* area during a drought year in Petrolina Municipality, State of Pernambuco, Brazil.

hours of lower atmospheric demand.

The year began with NEE values ranging between -1.0 and 5.0 μmol m^{-2} s^{-1}, in January, with an average of 1.17 μmol m^{-2} s^{-1} (Figure 3), indicating that that month, although the VCI was high, due to reduced water availability, the CO_2 flux occurred from the vegetation to the atmosphere, through the respiratory process. Similar behavior was observed by Oliveira et al. (2006), for the *caatinga* vegetation between July 2004 and July 2005, when total precipitation was 501 mm, which resulted in the ecosystem acting as CO_2 source for the atmosphere.

During February and March, as a result of precipitation events that totaled 68.8 mm (75% of the annual total), the emission of CO_2 into the atmosphere occurred less intensely (NEE = 1.01 μmol m^{-2} s^{-1}). Among these months, peaks of NEE ranging from 13.93 to -17.69 μmol $m^{-2}s^{-1}$ (Figure 3) were observed, representing the maximum release and assimilation of atmospheric CO_2, respectively. With the beginning of leaf senescence, which occurred in May, it was observed an increase in NEE, which reached 1.65 μmol m^{-2} s^{-1} with peaks up to 8.00 μmol m^{-2} s^{-1}. These results may be associated with the release of CO_2 as a result of the decomposition of organic matter, the action of the microbiota (Aires et al., 2008), as well as respiration by heterotrophic organisms, as reported by Holanda et al. (2015), it may be favored by the increase in the temperature and water supply in the soil.

Between June and September, larger reductions of NEE were observed (Figure 3), presenting an average value equal to 1.06 μmol m^{-2} s^{-1}, due to loss of leaf biomass as a result of the water deficit in the system, and to reductions in air and soil temperatures (Figure 1), which regulates carbon exchange in ecosystems (Scott et al., 2012). This trend can be confirmed in the following period, between October and December, when an increase occurred in the NEE (1.48 μmol m^{-2} s^{-1}), due to the increase in temperature, which according to Xu and Baldocchi (2004) and Anderson-Teixeira et al. (2011), may cause an increase in the respiration of the ecosystem because it promotes increases in the metabolism.

The partition of the net carbon exchange during the year of 2012 revealed that the low rainfall volume induced the *caatinga* to act as a carbon source for the atmosphere (NEE = 1.3 gC m^2 d^{-1}) (Figure 3). At the beginning of the year, the vegetation presented a relatively high ICV. However, the reduced water availability promoted an increase in the surface resistance to water efflux (rs = 903 s m^{-1}) and, therefore, the influx of CO_2 into the vegetation. Under these conditions, Souza et al. (2015) demonstrated a strong coupling of the surface with atmosphere, in which the transfer of water to the atmosphere and, consequently, the influx of CO_2 dependent upon the vapor pressure deficit and the surface resistance (r_s).

The vegetation acted as a CO_2 sink at times after precipitation events, when, according to Souza et al. (2015), reductions in surface resistance (r_s = 53 s m^{-1}), were observed, promoting higher CO_2 consumption by vegetation. The maximum daily totals of NEP, GPP and Re were equal to 1.07, 3.2 and 2.3 gCm^{-2} d^{-1}, respectively, in this order, occurring up to five days after occurrence of rainfall

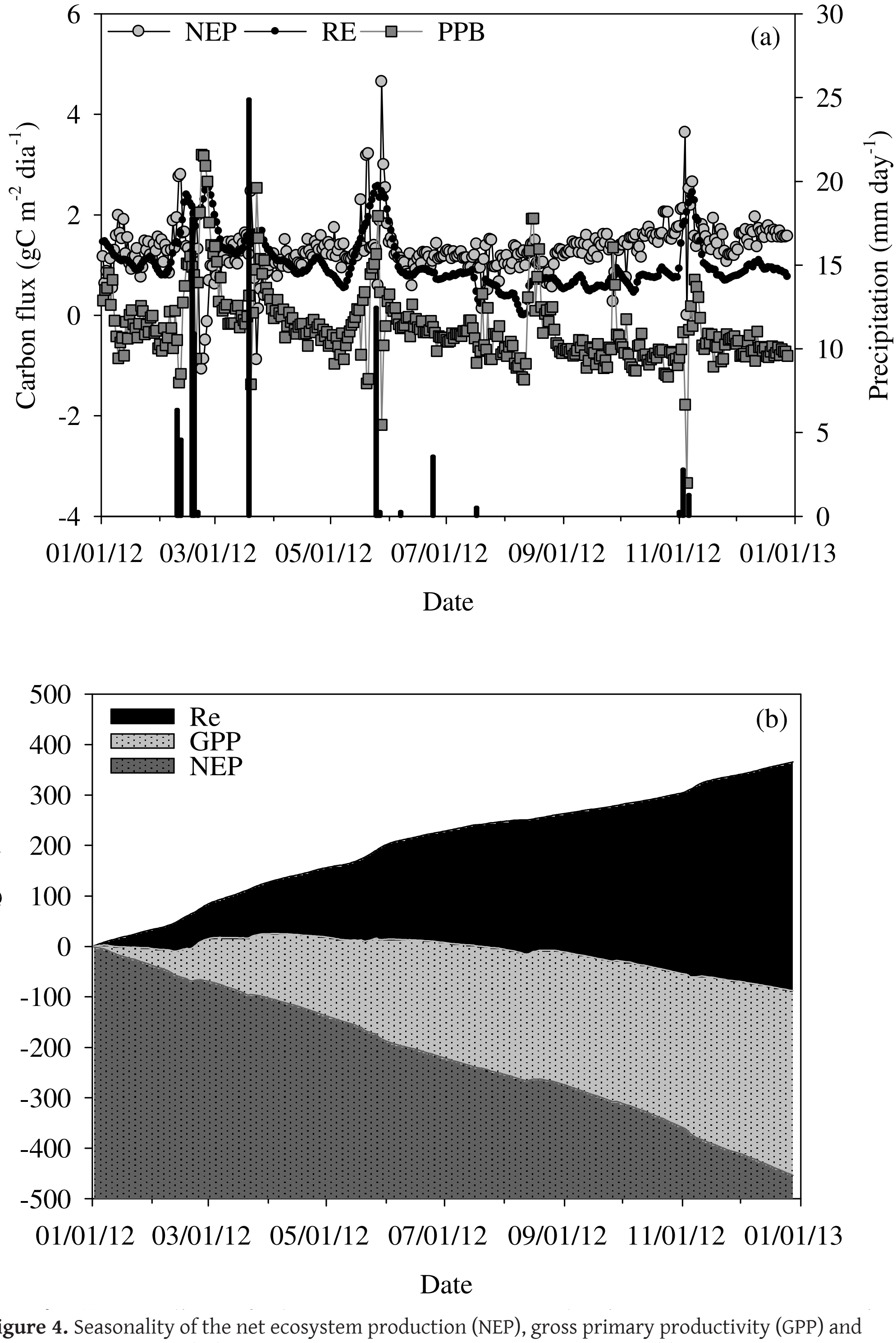

Figure 4. Seasonality of the net ecosystem production (NEP), gross primary productivity (GPP) and ecosystem respiration (Re) components of the carbon balance and rainfall (a) and cumulative flux values (b) in a *Caatinga* area during a dry year, Petrolina, State of Pernambuco.

events that totaled water depths higher than 10.0 mm (Figure 4). In this condition, the emergence of phytomass was favored, similar to that observed by Anderson-Teixeira et al. (2011). On the other hand, in the period of extreme drought, between September and December, the occurrence of rainfall events with intensity less than 2.0 mm day^{-1}, promoted respiration peaks up to 2.4 gC m^{-2} d^{-1}. Several studies cite the occurrence of respiratory peaks, shortly after precipitation events during the drought season (Zhao et al., 2006; Jarvis et al., 2007, Aires et al., 2008). Aires et al. (2006) cite that these phenomena occur because the increase in water content stimulates microbial respiration. Fraser et al. (2016) demonstrated that this effect may be attributed not only by microbial respiration but also by the contribution of remaining enzymatic pathways outside the cell membranes, thus becoming a phenomenon of biological and biochemical nature.

The annual carbon balance of the *caatinga* indicated CO_2 release of 468.18 gC m^{-2} year^{-1} and Re equals to 371.73 gC m^{-2} year^{-1}. This trend was similar to that obtained by

Aires et al. (2008), in a study conducted in a pasture area during two years with different water regimes (751.2 mm $year^{-1}$ vs 363 mm $year^{-1}$), which in deficit conditions acted as CO_2 source (NEE = 49 gC m^{-2} $year^{-1}$). In relation to *caatinga*, some studies have demonstrated its potential sink in conditions of water availability (Oliveira et al., 2006; Oliveira et al., 2005), different from that observed in this study. Therefore, the increase in temperature and the occurrence of increasingly frequent and prolonged droughts, as a reflection of climate change, may intensify the release of CO_2 by the *caatinga* and, consequently, potentiate the changes in the climate. This statement was also cited by Aires et al. (2008).

Conclusions

Under extreme drought conditions, the daily emissions of the Caatinga carbon dioxide flux was altered, being influenced by the intensity of photosynthetically active radiation in days immediately after rainfall events, and by the water vapor pressure deficit in days with low content of water in the soil. The Caatinga respiration exceeded the primary gross productivity, indicating that it acted as CO_2 source for the atmosphere.

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Trocas de carbono em uma área de caatinga durante um ano atipicamente seco

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semiárido

RESUMO

Objetivou-se analisar a variação diária e sazonal dos componentes do balanço de carbono em uma área de Caatinga durante um ano atipicamente seco. Os dados foram coletados a partir do sistema de covariância dos vórtices turbulentos, instalado em uma área de Caatinga, em Petrolina, PE, Brasil. Os dados dos fluxos de dióxido de carbono foram coletados no ano de 2012, e particionados em produtividade primária bruta (GPP) e respiração do ecossistema (Re). Os elementos meteorológicos, o índice de cobertura vegetal e o conteúdo de água no solo foram monitorados. Observou-se que, a marcha diária do fluxo de CO_2 foi dependente da radiação fotossinteticamente ativa nos primeiros dias após os eventos de precipitação, sendo influenciada pelo déficit de pressão de vapor d'água com a redução do conteúdo de água no solo. A ocorrência de precipitação de até 2 mm após longos períodos sem chuvas promoveram picos de Re. O NEP medido foi 468,18 gC m^{-2} ano^{-1}. Logo, conclui-se que em anos com seca extrema, a Caatinga atua como fonte de carbono para a atmosfera.

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