International Journal of Science, Engineering & Environmental Technology (IJOSEET), 5(5): 42-53, 2020
ISSN 0794-9650
www.repcomseet.com

Net Ecosystem Exchange of CO_2 and C-Sequestration Potential of a North Alabama Forest during Different Seasons

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Abstract - An important issue in global climate change research is the carbon cycle of terrestrial ecosystems and forests play an important role in the terrestrial carbon budget.Net ecosystem exchange (NEE) of carbon dioxide (a measurement of how much carbon is entering and leaving the ecosystem) is a good estimate of gross primary production, the amount of biomass that primary producers produce in a given ecosystem. In this study, NEE measurement by using the eddy covariance (EC) technique has been used to characterize the fluxes in photosynthetic uptake of CO_2 by plants and ecosystem release of CO_2 by plant respiration and decomposition to analyze the seasonal variation and meteorological control of CO_2 flux in the mid-aged mixed temperate forest of Bankhead National forest (BNF) Alabama, USA dominated by Loblolly Pine/Shortleaf Pine, and Oak/Hickory. The results showed that the seasonal variations of net ecosystem exchange of CO_2 (NEE). Gross primary production (GPP) and ecosystem respiration (RE) display single-peak pattern. Also the diurnal trends showed Carbon (C) loss through respiration and maximum C accumulation as GPP during the afternoon periods of high radiation and optimum temperature. Average NEE for the months of January to March were-0.1154 and.0.31 µmol m^{-2} s^{-1}, in 2013 and 2014 respectively, whereas that of May-June were -0.82 and. -3.31 µmol m^{-2} s^{-1} for 2013 and 2014 respectively. This seasonal variation in the CO_2 exchange processes of the BNF reflected the mixed composition of the mid-aged temperate forest. In 2013 a cumulative value of 91.8 g C was lost by the ecosystem but the GPP/RE ratio was well above 1 to make the ecosystem a carbon sink. Cumulative NEE for the nine months of the study in 2014 was -344 g C m^{-2} of the ecosystem and the negative cumulative NEE made the BNF a C sink. The study in 2014 estimated the C sequestration potential of the BNF to be about 1,856 kg of carbon/acre/year.

Keywords: Net Ecosystem, Carbon dioxide, Respiration, Gross primary production, Vapor pressure deficit, relative humidity

1.0 Introduction

Atmospheric CO_2 concentration has been increasing since the industrial revolution (Watson and Verardo, 2000; Albritton *et al*., 2001) resulting in the changes in global carbon cycle and carbon budget, and induced climate warming as well as other global climate change problems, that threaten human survival and sustainable development (Yu et al., 2001). Terrestrial ecosystems are vital in climate systems, for they not only change passively with climate change, but have significant feedback on biogeochemical cycle. (Heijmans *et a*l., 2004). This makes it necessary to develop long-term monitoring to estimate precisely terrestrial ecosystem carbon budget.

Forests are a significant part of the global carbon cycle that plays an important role in alleviating the build-up of atmospheric CO_2 (Lohila *et al*., 2007; van Minnen et al., 2008). Forests store substantial amounts of carbon. The amount stored, however, changes over time as the forests grow and die. Carbon sequestration of forest has received wide attention, but the estimation of its carbon uptake is still a subject of much research (Valentini *et al*., 1996; Massman and Lee, 2002) due to variability of forest species and soils properties in the forests. Alabama having the third most timberland acreage in the 48 contiguous states with about 23 million acres of timberland accounting for 68% of the total land area in the state has much interest in forest productivity studies. Net ecosystem exchange (NEE) of carbon dioxide (a measurement of how much carbon is entering and leaving the ecosystem) is a good estimate of gross primary production, the amount of biomass that primary producers produce in a given ecosystem.

NEE measurement by using the eddy covariance (EC) technique has been utilized to characterize the fluxes in photosynthetic uptake of CO_2 by plants and ecosystem release of CO_2 by plant respiration and decomposition (Running *et al*., 1999; Canadell *et al*., 2000; Geider *et al*, 2001). Eddy covariance technique is scale-appropriate for forest ecosystems in particular because it can be used to assess net CO_2 exchange of an entire forest ecosystem, and it can continuously monitor the carbon fluxes between atmosphere and vegetation (Foken and Wichura, 1996; Baldocchi et al., 2000; Baldocchi, 2003).It has been suggested that old-growth forests may be only weak sinks for CO_2 because of reduced photosynthetic potential (Hubbard et al., 1999), and decomposition of accumulated woody detritus (Harmon et al., 1990).

At temperate latitudes, the period for carbon assimilation (growing season) can be restricted by temperature, light and moisture conditions, as well as by leaf phenology (Keeling et al., 1996; Myneni et al., 1997; White et al., 1999; Jackson et al., 2000) Respiratory carbon losses occur throughout the year and are generally dominated by soil respiration (Janssens et al., 2001). Both soil and ecosystem respiration are mainly regulated by temperature and moisture conditions (Lloyd and Taylor, 1994; Davidson et al., 1998; Raich and Tufekciogul, 2000), The interplay between assimilation (photosynthesis) and respiration determines the seasonal pattern, in phase and amplitude, of the net ecosystem carbon flux. Environmental conditions may differently influence assimilation and respiration. Assimilation (GPP) is mainly dependent on irradiation during the growing season when temperature is adequate for growth, whereas respiration (RE) is mainly dependent on temperature and moisture.

The Bankhead National forest (BNF), located in northwestern Alabama is about 180, 000 acre forest that contains stands of large old-growth hardwoods including oak, maple, beech, and black gum and is dominated by Loblolly Pine/Shortleaf Pine, and Oak/Hickory. As a typical temperate forest with less tree species diversity, and carbon than tropical forests, more than one-third of the carbon is stored in the vegetation, and nearly two-thirds in the soil. To our knowledge, there is a limited documented study about the productivity of Alabama forests especially with respect to estimating their C sequestration capacity. Therefore our objective was to use the eddy covariance flux data measured at the BNF site in 2013 and 2014 to estimate the seasonal variations of net ecosystem exchange of carbon dioxide and carbon sequestration potential in the mid-aged southern mixed forest located in the William Bankhead National Forest, Alabama, USA.

2.0 Materials and Methods

2.1 Experiment site

The experimental site is located at the William B. Bankhead National forest on 34.341221 N and 87.347807E and at an elevation of 293.8m (964ft) above sea level. This location is in Northwestern Alabama covering some 180,000 acres around the town of Double Springs. Bankhead is part of the Warrior Mountains, the western terminus of the Appalachian Mountains (Huey, 1993). The area receives nearly 60 inches of rain each year. The highest amount of rain reaches the region as afternoon thunderstorms in July, August and September. Summers are extremely hot and humid with temperatures frequently reaching above 100 ºF (37.8 ºC) but summer nights are slightly cool. Winter temperatures are mild, rarely dipping below 40 ºF (4.4 ºC) with the humidity level at its lowest in November and December. Spring brings mild temperatures and blooming trees and flowers. During the fall temperatures range from 65 ºF (18.3 ºC) to 85 ºF (29.4 ºC) with low humidity levels. The area is generally cooler than the south due to its higher elevations (references).

2.2 Instruments and measurements

The Eddy covariance setup mounted on a 130 ft tower to measure mass and energy fluxes over the forest (Fig3) at the BNF consisted of the CSAT-3, a Sonic Anemometer (CSI, Logan, Utah), to measure wind speed (m s^{-1}) in three-dimensional space, and sonic air temperature ($T_{s,}$ ºC); NR-LITE Net Radiometer, and a Photosynthetic Active Radiometer sensor; LI-7500 Open Path (OP) CO_2/H_2O infrared gas analyzer (IRGA) (LI-COR Inc., Lincoln, NE) to measure CO_2 and water vapor fluctuations as well as a CSI CR5000 Datalogger for data storage. The IRGA was slightly tilted (~ 15º from the vertical axis of the IRGA) to prevent rainwater accumulation and dew deposition on the measuring window and was displaced 0.15 m behind the CSAT-3, facing the dominant prevailing winds.

The data acquisition system, Data Logger (CR5000, Campbell Scientific Inc., Logan UT) collected high frequency data from the sonic anemometer, Gas analyzer and other sensors and was storing days of binary formatted data on a Memory Card International Association (MCIA) flash card. Prevailing wind direction of the whole year was predominantly south easterly (90-130º) with about 40% contribution from this direction and north westerly flow was contributing about 30%

2.3 Flux calculation and data processing

2.3.1 Flux calculation

Using the eddy covariance technique (EC), CO_2, H_2O, and energy fluxes between the vegetation and the atmosphere were calculated with measured wind pulse and scalar pulse (Baldocchi *et a*l., 2001). The CO_2 flux (Fc; µmol CO_2 m^{-2} s^{-1}) was calculated as

$$Fc = \overline{Pw'c'}; \qquad (1)$$

where: P is air density, c is the concentration of CO_2, and w is the vertical wind speed. The over-bar represents the mean value; the prime indicates the instantaneous deviation from the mean value. The net ecosystem exchange of CO_2 (NEE; µmol CO_2 m^{-2} s^{-1}) represents the net CO_2 exchange between the ecosystem and the atmosphere. NEE was calculated as

$$NEE = Fc + Fs; \qquad (2)$$

where Fs is canopy storage of CO_2 (µmol CO_2 m^{-2} s^{-1}), By the micrometeorological convention negative NEE means the net CO_2 sequestration by vegetation from the atmosphere, while positive NEE indicates the CO_2 release from ecosystem to atmosphere.

2.3.2Data processing

Flux data of BNF in 2013 and 2014 were used in this study, and the measured data were processed with the following quality-control methods:(1) The triple coordinate rotation was used to align the coordinate system with the mean wind and to eliminate the effect of tilt (Wilczak *et al*., 2001). (2) The WPL method was adopted to adjust density changes resulting from fluctuations in heat and water vapor (Webb *et al*., 1980). (3) The canopy storage of CO_2 was calculated (Hollinger et al., 1994). (4) The eddy covariance flux data were screened for anomalous or spurious values outside the range normally encountered, which was possibly caused by sensor malfunction and interference from rain, dew, hoarfrost, birds, etc. The threshold of CO_2 flux was set to be (-2, 3) (µmol CO_2 m^{-2} s^{-1}). Nighttime data was screened by using a threshold of friction velocity (u*) identified as 0.2 m s^{-1} in this study (Baldocchi,2003; Gu et al., 2005).

2.3.3 Gap filling

In this study, the mean daily variation (MDV) method was used to fill the gaps of meteorological data, with a time window size of 7 days. Nonlinear regression method was adopted to fill the gaps of CO_2 flux. Small gaps (< 2 h) were linearly interpolated. For larger gaps, daytime missing NEE were estimated as a function of PAR using the Michaelis-Menten equation (Falge et al., 2001) with a 30-day moving window (Zhang et al., 2006):

$$\mathbf{NEE_{day}} = \mathbf{R_{day}} + \frac{\mathbf{A}_{\max}\,\alpha PPFD}{\mathbf{A}_{\max} + \alpha PPFD} \qquad (3)$$

where: PPFD is the photosynthetic photo flux density (µmol m^{-2} s^{-1}), α is the ecosystem photosynthetic photon yield (µmol CO_2 mol^{-1} photon), Amax is the maximum photosynthetic rate (µmol CO_2 m^{-2} s^{-1}), and R_{day} is the daytime ecosystem respiration (µmol CO_2 m^{-2} s^{-1}).
Nighttime missing NEE data were estimated from the empirical relationship between the ecosystem RE and air temperature with Eq. (4) (Falge et al., 2001), based on data for every two months in a group by using the regression method,

$$NEE_{night} = R_e = \beta_o \exp(\beta_1 T_s) \quad (4)$$

where: both β_0 and β_1 are fitted parameters (the empirical coefficients fit) for each growing season. The coefficient β_0 is the intercept of *R*e when *T*s is 0ºC, i.e., the base respiration rate at 0ºC, and β_1 is the sensitivity of respiration (RE) to a range of temperatures. Q_{10} is the sensitivity of respiration to temperature variation, the factor by which the RE rate increases for a 10ºC temperature increase. Q_{10} was computed using the equation:

$$Q_{10} = \exp(10\ \beta_1) \quad (5)$$

Using the daytime respiration estimation, the gross primary production (GPP; µmol CO_2 m^{-2} s^{-1}) of the vegetation could then be estimated from Eq. (6) (Valentini et al., 2000; Law et al., 2002; Baldocchi, 2003):

$$GPP = RE - NEE = RE + NEP \quad (6)$$

Thus C accumulation (NEE) is the balance between C gain (GPP) by photosynthesis, and C loss by respiration (RE). NEE = GPP + RE
GPP = Total C input into the ecosystem from photosynthesis and RE = Total C loss from the ecosystem through respiration.

3.0 Result and Discussion

In this study, CO_2 flux and meteorological data measured at BNF forest ecosystem research station in 2013 and 2014 were used to analyze the seasonal variation of CO_2 flux and its response to meteorological factors. The seasonal variations of NEE, GPP, and Re displayed single-peak patterns. The BNF forest was an evident carbon sink from April-July in 2013 and from April till the time of last data collection in September 2014. Maximum carbon sequestration appeared during May of 2013 (Figure.4a) but in 2014 May and July recorded the highest (Fig 4b). This trend probably accounted for the higher cumulative value of carbon in 2014. This year the cumulative GPP/RE ratio was 1.9 and the negative cumulative nature of NEE made the ecosystem a carbon sink unlike in 2013.

The diurnal trends showed C loss through Respiration and maximum C accumulation as GPP during the afternoon periods of high Radiation and optimum Temperature (Figure 4c) Average NEE for the months of January to March were -0.12 and 0.31 µmol m^{-2} s^{-1} for 2013 and 2014 respectively, whereas that of May-June were -3.3 and -3.31 µmol m^{-2} s^{-1} respectively (Fig 4a and b). This seasonal variation in the CO_2 exchange processes of the Bankhead National Forest reflected the mixed composition of the mid-aged temperate forest (Figures 5 and 6). Decrease in NEE in August 2014 was probably due to higher RE enhanced by high T; lower radiation, higher VPD with corresponding lower RH and lower GPP/RE ratio than previous months compared with 2013 (Figures 7 and 8; 9-12)

In 2013 a cumulative value of 91.8 g C was lost by the ecosystem. This loss might be due to the excessive respiration taking place in July and August of the year as earlier explained. However the cumulative values of GPP and RE were 1597.9 and 713 g C m^{-2} respectively and the GPP/RE ratio was well above 1 to make the ecosystem a carbon sink. Cumulative NEE for the period of study in 2014 was -344 g C m^{-2} of the ecosystem. The negative cumulative NEE made the Bankhead National Forest a C sink (Figures 13 and 14). Decrease in NEE in August was probably due to the fact that respiration (RE) was taking place at a higher rate than previous months. This study estimated the C sequestration potential of the Bankhead National Forest to be about 1,856 kg of carbon/acre/year.

The annual average RE/GPP was 61% and 81% in 2013 and 2014 respectively, showing a strong interannual difference. This indicated that, as a relatively mature forest the relative contribution of carbon release from ecosystem respiration to gross ecosystem carbon exchange varied interannually during the study period. The ecosystem carbon exchange was weak when the temperature was lower than 10±C, and it increased when the temperature was higher than 10±C. The Q_{10} value varied a little in 2013 and 2014 (being 1.32 and 1.43, respectively), and was slightly lower than the results in similar latitude forest (Schmid et al., 2000) and in a subtropical plantation (Wen et al., 2006). The response of CO_2 flux to temperature showed a hysteresis phenomenon. The peak carbon sequestration did not appear during the period of the highest temperature (Figures. 4a and 4b). This may be because the response of stomata opening and closing to temperature is hysteresis. The stomata movement activates when the temperature increases in spring and summer, but is weakened when the temperature decreases in Fall and winter. This also induces hysteresis appearing in the response curve of photosynthesis to temperature. The hysteresis of stomata movement to meteorological factors has been reported in some previous studies (Yu *et al*., 1998; Wang, 2004).

The ecosystem photosynthetic parameters A_{max} reached the maximum in May each year and showed a small interannual difference. The interannual differences of α and R_{day} were obvious, which were mainly ascribed to the differences of meteorological factors, such as radiation, vapor pressure deficit, precipitation, etc. The relationship between NEE and PPFD accorded with the rectangular hyperbola model on daily scale, showed a good linear correlation on monthly scale which was consistent with the results in other studies (Wang et al., 2004; Pilegaard *et al*., 2001). On the monthly scale, RE, GPP, and NEE increased with increasing VPD, and the trend slowed and even became stable when VPD was higher than 508Pa on the average. A higher VPD usually occurred during April- September in which photosynthesis and respiration of vegetation were active. When VPD was increasingly high, the trend of the ecosystem carbon exchange became weak. This was due to the key role of stomata in the regulation of the balance between transpiration water loss and photosynthetic carbon assimilation (Cowan, 1977; Cowan and Farquhar, 1977; Xu and Baldocchi, 2003). VPD had a distinct impact on stomata movement (Schulze and Hall, 1982). When VPD was too high, stomata closing occurred to decrease the stomata conductance, and photosynthesis and respiratory activities become less active.

4.0 Conclusion

The diurnal trends of NEE showed C loss through Respiration and maximum C accumulation as GPP during the afternoon periods of high Radiation and optimum Temperature (Figure 4). Seasonal variation exists in the CO_2 exchange processes of the BNF reflecting the mixed composition of this mid-aged temperate forest (Figs 5 and 6). Average NEE for January to March were-0.1154 and.0.31 µmol m^{-2} s^{-1}, in 2013 and 2014 respectively, whereas that of May-June was -3.3 and. -3.31 µmol m^{-2} s^{-1} for 2013 and 2014 respectively (Figures 7 and 8). Decrease in NEE in August 2014 was probably due to higher RE enhanced by high T; lower radiation, higher VPD with corresponding lower RH and lower GPP/RE ratio than previous months compared with 2013 (Figures 7 and 8: 9-12). Cumulative (Cum) NEE for the period of the study was -511g C m^{-2} and -344 g C m^{-2} of the ecosystem in 2013 and 2014 respectively. The negative cumulative NEE makes the Bankhead National Forest a C sink (Figures 13 and 14). This study estimated the C sequestration potential of the Bankhead National Forest to be about 1,856 kg of carbon/acre/year.

SITE/DATA

Figure 1. Lawrence County, Alabama

Figure. 2a. Oak/Hickory/Pine canopy

Figure 2b.130 ft tower erected in the middle of the forest.

Fig. 3. Eddy covariance sensors mounted on a 130 ft tower

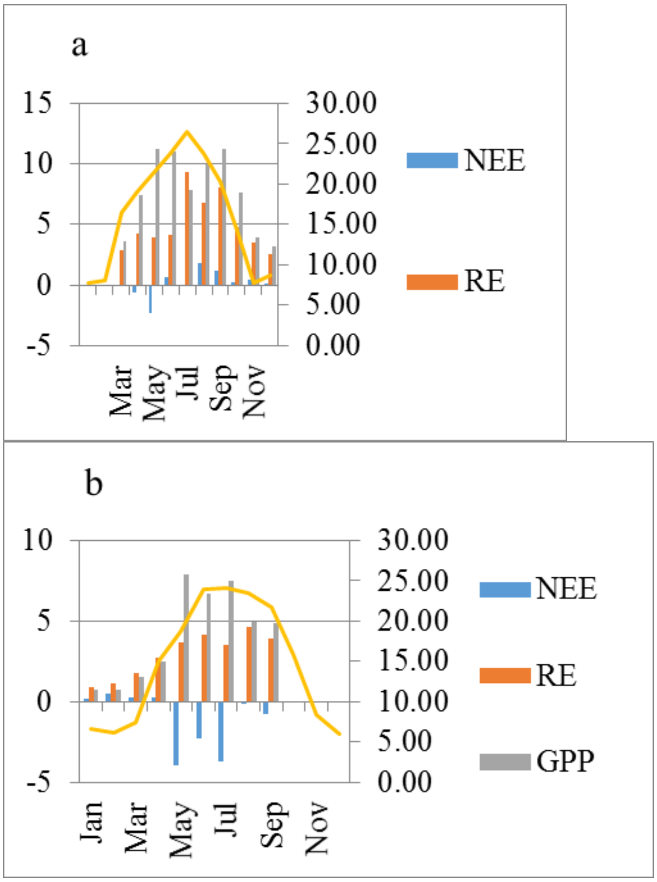


Fig 4a and b. NEE, RE, and GPP in relation with the average temperature for 2013 (a) compared with 2014 (b).

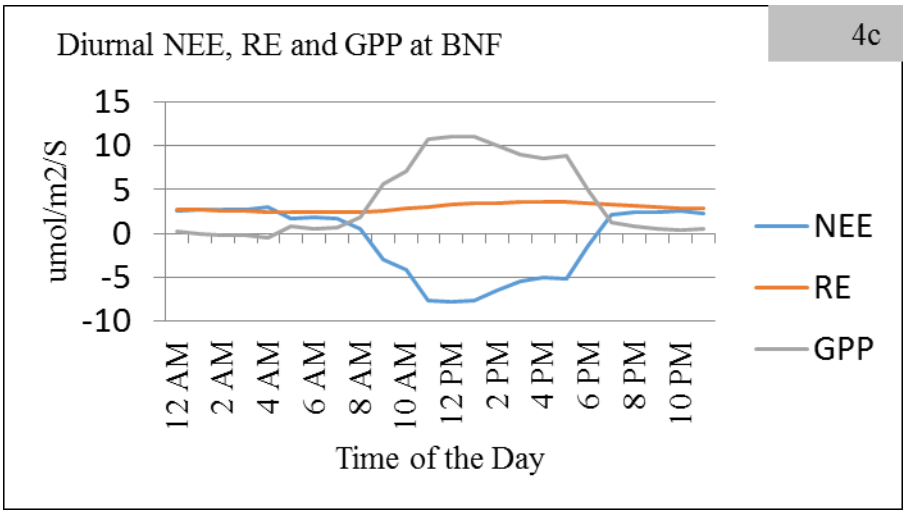
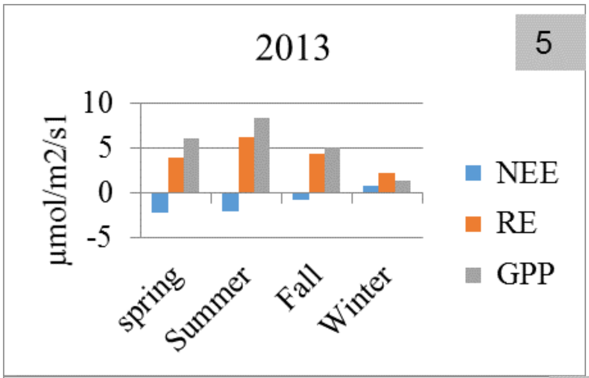


Figure 4: Diurnal trends of NEE, RE and GPP in both 2013 and 2014



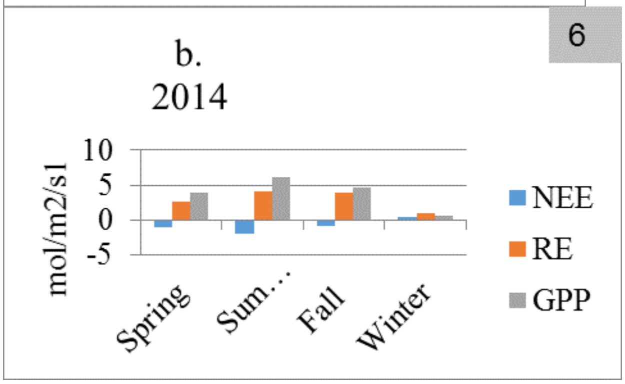


Figure5: Seasonal variation, 2013 Figure 6: Seasonal variation 2014

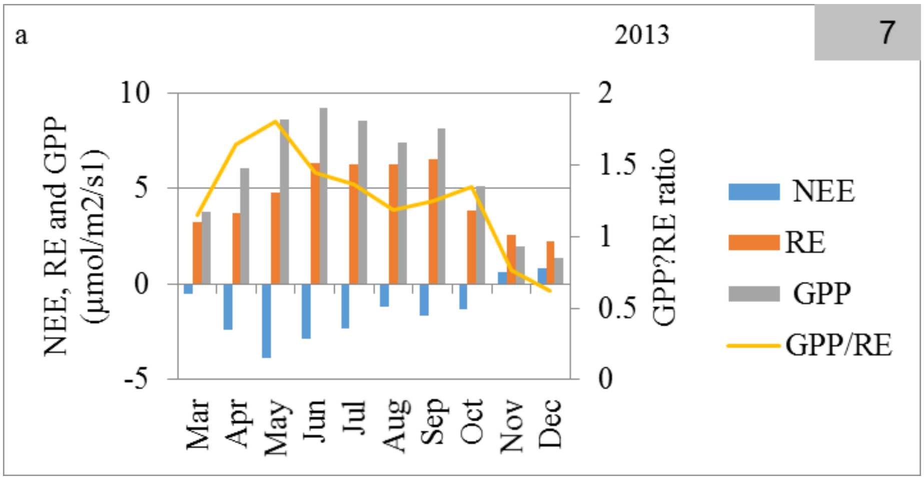


Figure7: Monthly variation,2013

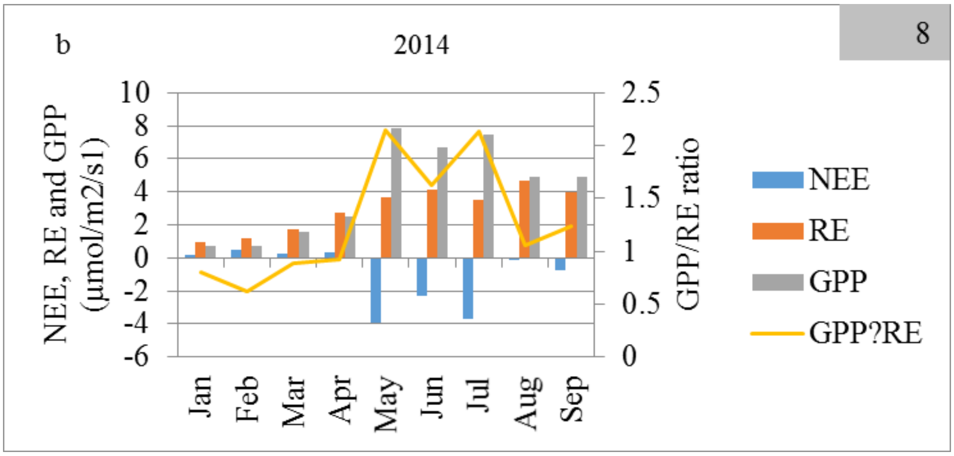
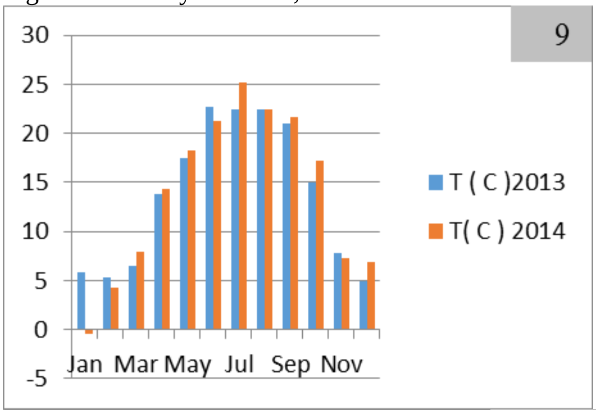


Figure8: Monthly variation, 2014



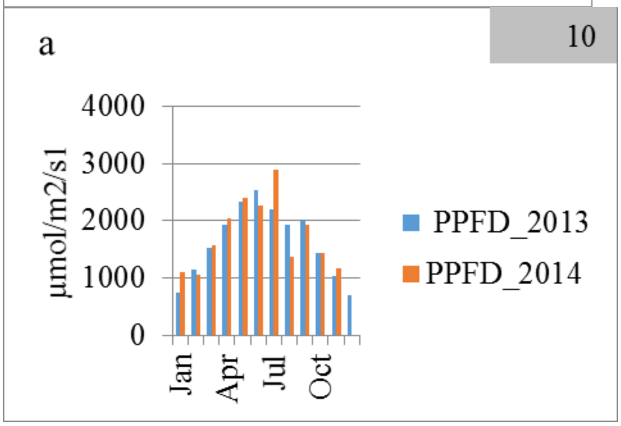


Figure9: Monthly average temperature

Figure10: Monthly average Radiation

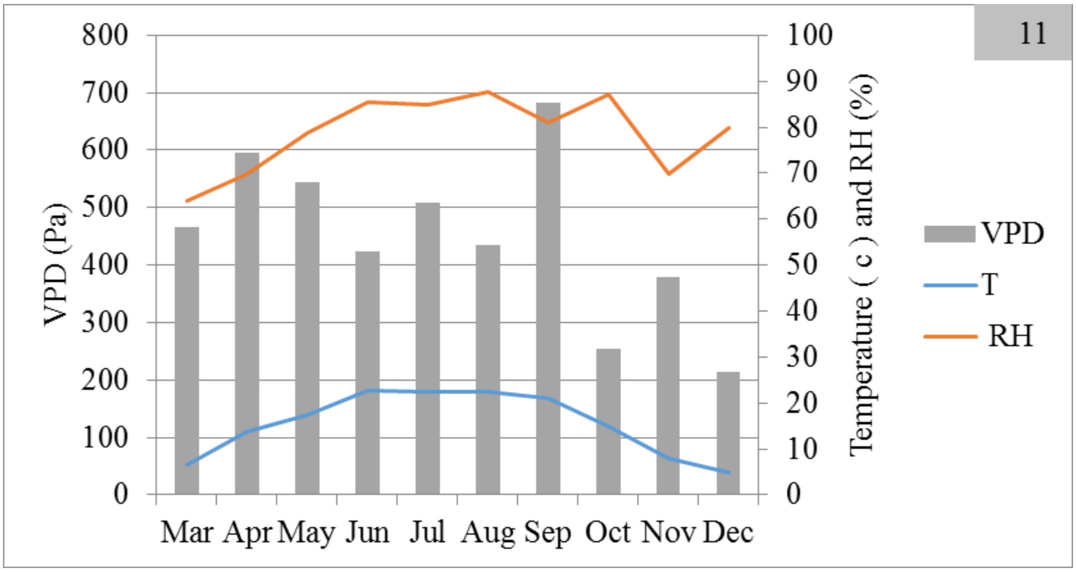


Figure 11: Monthly VPD,RH,T,2013

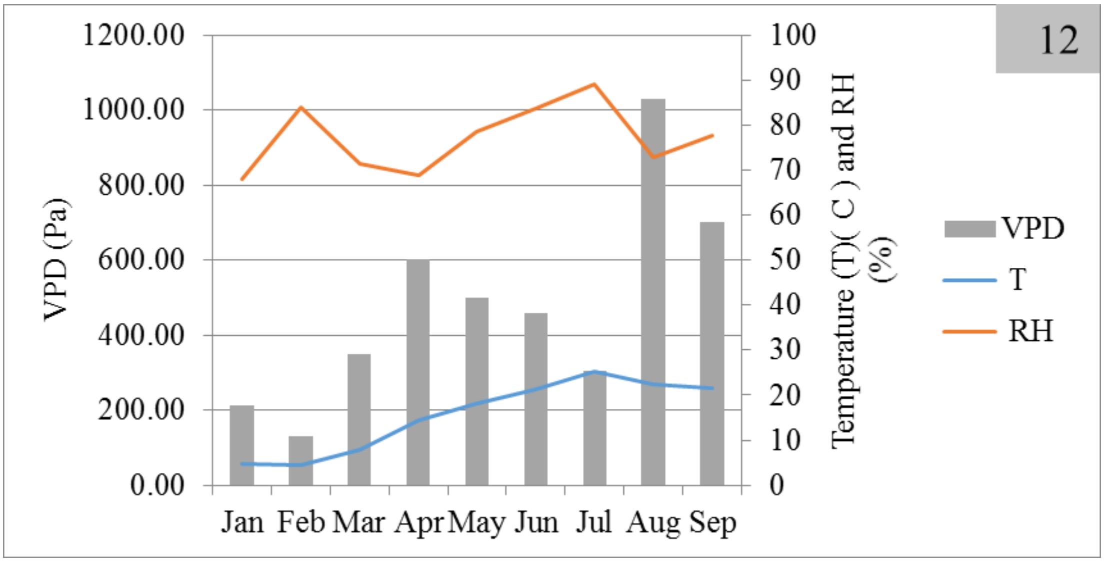
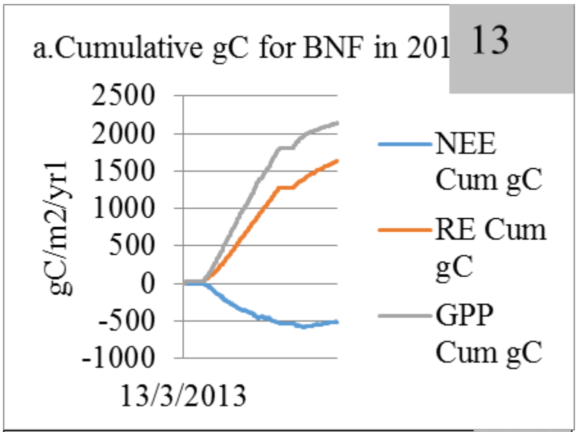


Figure12: monthly VPD, RH, T, 2014



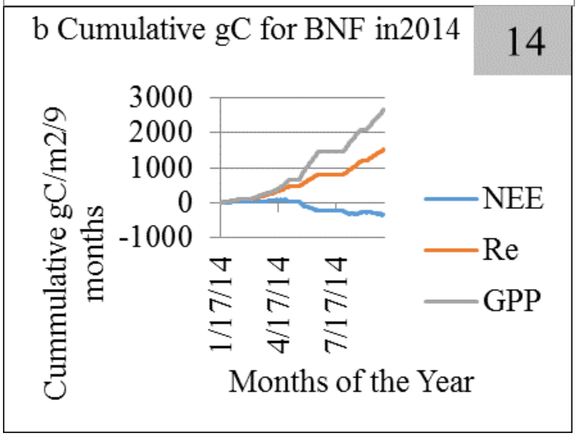


Figure13: Cum. NEE,RE,GPP,2013

Figure14: Cum. NEE, RE, GPP, 2014

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