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Ecosystem productivity and its response to environmental variable of moist Indian sal forest

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Abstract: The network of eddy covariance (EC) based flux-towers is growing rapidly in India to accurately account carbon source/sink capacity of forest and managed ecosystems. Sal (*Shorea robusta*) forests representing about 16% of the total Indian forested area, a very important component of Indian carbon budget. One year observation on ecosystem scale CO_2/H_2O flux and other micrometeorological observations were analysed for elucidating diurnal and seasonal pattern of fluxes along with their response to biophysical and environmental factors of an Indian sal forest. Daily average air temperature ranged between 10.31 °C to 32.36 °C. Maximum Net Ecosystem Exchange (NEE) of −5.51 g C m^{-2} day^{-1} occurred on the 244 DOY due to ideal condition for photosynthesis. Environmental factors governing carbon flux components agreed with the incident of maximum and minimum NEE, Gross Primary Productivity (GPP) and Ecosystem Respiration (R*e*) in Barkot Flux Site (BFS). Clear variation in monthly NEE, GPP and R*e* was observed during the study. Higher LAI and sufficient moisture condition resulted to higher absorption of carbon during September–March. During pre-monsoon (April–June) NEE was lowered due to reduce LAI and high VPD. During the rainy season (July–August) the carbon sequestration potential was highly reduced due to cloudy condition and rain accelerated R*e*. Annual GPP, R*e* and NEE of BFS was 2916.19 g C m^{-2} yr^{-1}, 2408.32 g C m^{-2} and −507.89 g C m^{-2} yr^{-1}.

Key words: Barkot flux site, eddy covariance, gross primary productivity, net ecosystem exchange, sal (*Shorea robusta*) forest.

Introduction

Forests influence climate through exchanges of energy, water, carbon dioxide, and other chemical species with the atmosphere (Bonan 2008). Among the terrestrial ecosystems, largest amount of carbon is stored in forest (Gray & Whittier 2014). Carbon exchange between the forest ecosystem and the atmosphere is one of the key processes that need to be assessed (IPCC 2001). Accurate quantification and deeper understanding of carbon exchange can guide climate policy makers during formulation of mitigation strategies (IPCC 2007). Forest are vulnerable to warmer and drier climate (Malhi *et al.* 2008) and may aggravate global warming through positive feedbacks (Betts *et al.* 2004). Hence, with the changing climate and global warming, the ability to monitor forest carbon fluxes is of increasing interest to better understand the influence of biosphere on global carbon cycle (Canadell *et al.* 2007).

In recent years, eddy covariance (EC) technique

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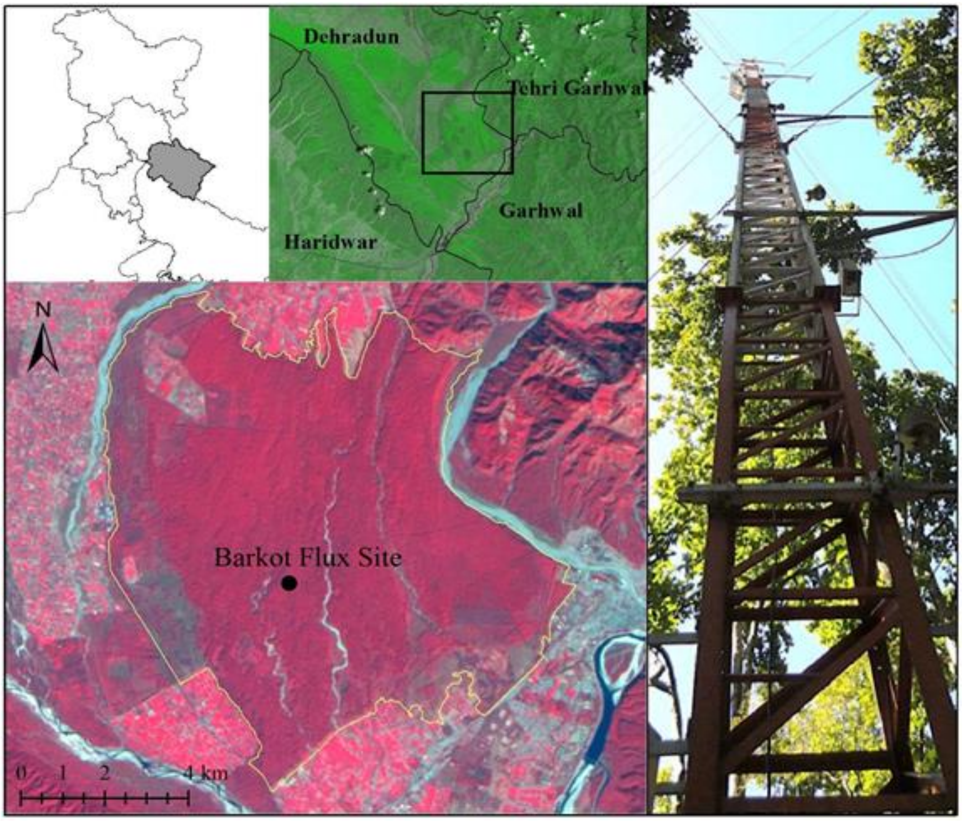

Fig. 1. Location of study area.

has emerged as promising technique to measure net CO_2 ecosystem exchange (NEE) (Wu *et al.* 2011; Baldocchi *et al.* 1996). Gross primary production (GPP), a key indicator of potential carbon assimilation and quantifiable on regional, continental or global scales (Prince & Goward 1995; Running *et al.* 1999), can be estimated from EC data by partitioning directly measured NEE into GPP and ecosystem respiration (R*e*). GPP exhibits daily, seasonal, annual and inter-annual difference (Falge *et al.* 2002). Increasing number of EC towers provide the best opportunity for estimating GPP, concurrent measurements of meteorological variables provide unprecedented datasets for investigating the dynamics and driving variables of GPP and are useful information for development and calibration of Light use efficiency (LUE) models (Yuan *et al.* 2007).

Most of the existing EC flux-tower networks are mainly confined to the northern hemisphere mid-latitudinal locations (Andrew 2012) leaving vast area of forest ecosystems unexplored despite their prominent role in global carbon budget. In recent years, few EC tower over selected Indian ecosystems has been initiated (e.g. Bhattacharyya *et al.* 2014; Jha *et al.* 2013; Patel *et al.* 2011; Watham *et al.* 2014). Nevertheless, systematic use of EC technique for accurately quantifying carbon balance of sal (*Shorea robusta*) forest has not been explored. Sal forest representing about 16% of the total Indian forest area (Tewari 1995) and a very important component of Indian carbon budget.

In view of the significance highlighted above, the present study explores two-fold objectives: (i) to establish EC tower and provide unique and accurate datasets of carbon exchange over an Indian sal forest ecosystem and (ii) to examine daily and seasonal variations in NEE and its component fluxes with respect to prevailing meteorological conditions. The obtained results can be used for development, calibration, and validation of empirical as well as process based ecosystem model used in carbon estimation.

Materials and Methods

The study was conducted on the Barkot Flux Site (BFS) in Barkot-Rishikesh Reserve Forest (30° 03′52′′–30°10′43′′N and 78°09′49′′–78°17′09′′E) (Fig. 1), classified as *North Indian Tropical Moist*

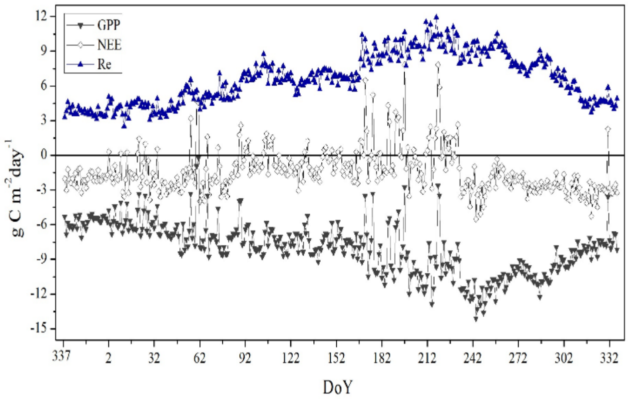

Fig. 2. Daily average gross primary productivity (GPP), net CO_2 ecosystem exchange (NEE) and ecosystem exchange (R*e*) (for better view the GPP value was assigned negative).

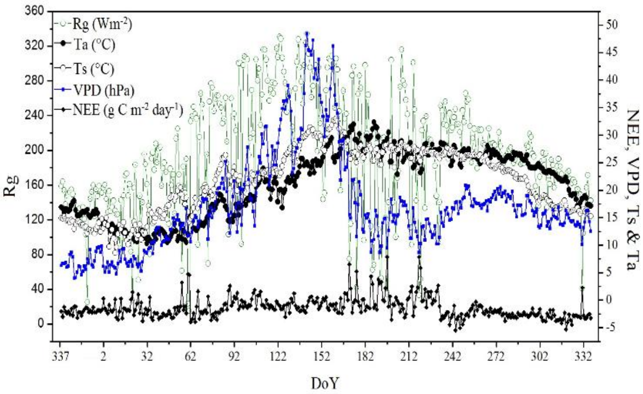

Fig. 3. Daily average net CO_2 ecosystem exchange (NEE) vs. meteorological condition.

Deciduous Forest (Sub-Group 3C), forest type being *Moist Bhabar Dun Sal Forest* (3C/C2b) (Champion & Seth 1968).

The continuous 10 Hz measurements of CO_2/H_2O and wind speed were made at 46 m height using IRGASON (Campbell Scientific). Fluxes were calculated half-hourly using EddyPro 5.1 (LI-COR, Lincoln) software. The flux calculation process is described in detail by Burba (2013). Night-time filtering and subsequent gap filling was done using marginal distribution sampling (MDS) (Reichstein *et al.* 2005). Obtained NEE was partitioned into GPP and R*e* (Falge *et al.* 2002). As standard procedure, GPP was calculated as the sum of NEE and R*e* as: GPP = −NEE + R*e*. Monthly LAI and litter were measured at 5 permanent plots (0.1 ha), one at the tower location and four at 500 m distance from tower in all four direction.

Results and Discussion

Variation of carbon exchange

During the year-long study, the effect of photoperiodism was clearly visible. CO_2 uptake rapidly increased after sunrise and peaks at 1130 hours and zero at 1730 hours. Jia *et al.* (2015) also found peak CO_2 assimilation between 1100 and 1200 hours. Recorded daytime peak NEE was −27.841 μmol CO_2 m^{-2} s^{-1}, slightly lower than −29.5 CO_2 m^{-2} s^{-1} reported by Watham *et al.* (2014) and higher than −25 CO_2 m^{-2} s^{-1} reported by Jha *et al.* (2013) from Indian forests.

In an attempt to understand seasonality of carbon fluxes, daily GPP, NEE and R*e* is illustrated in Fig. 2. Environmental factors (Fig. 3) governing the flux components agrees with the incident of maximum and minimum NEE, GPP and R*e*. For example, maximum NEE of −5.51 g C m^{-2} day^{-1} on 244 DoY can be attributed to high LAI, high incoming solar radiation (Rg = 247 W m^{-2}), suitable temperature (air temperature, T_a = 27.6 °C, soil temperature, T_s = 26.9 °C) and vapour pressure deficit (VPD = 17.75 hPa) for carbon uptake, maximum release of carbon on 219 DoY (NEE of +7.83 g C m^{-2} day^{-1}) was due to very low Rg (33.27 Wm^{-2}), lowest GPP of 0.21 g C m^{-2} day^{-1} on 61 DoY was a product of lowest Rg (15.38 Wm^{-2}). In all the cases, except during ≈ 91–170 DoY, NEE was close to zero or positive when Rg < 100 Wm^{-2}. However, positive NEE during ≈ 91–170 DoY was due to high VPD, phenological constrain and lower Rg (but Rg >100 Wm^{-2}). During this period, LUE of the ecosystem was reduced due to flowering and water stressed condition, therefore, little drop in Rg had significant effect on NEE.

Monthly GPP, NEE, and R*e* is shows in Table 1. Except in July, BFS acted as sink of carbon with magnitude ranging between −4.078 to −91.73 g C m^{-2} $month^{-1}$. Higher NEE during post monsoon (September–March) compared to dry season (April–June) and monsoon season (July–August) was due to ideal climatic conditions for photosynthesis- clear sky, high LAI, and adequate water for photosynthesis. Sky conditions affect light quality, meteorological conditions and influences photosynthesis (Law *et al.* 2002; Gu *et al.* 1999). Rainfall intensity and frequency decreased with start of September months (Table 2). Yan *et al.* (2009) found higher NEE during wet season (October–March) than in dry season (April–September) in Dinghushan Biosphere Reserve, this one month shift in event of higher NEE was

Table 1. Monthly budget of Gross primary productivity (GPP), net CO_2 ecosystem exchange (NEE), and ecosystem respiration (R*e*).

Month	GPP	R*e*	NEE
JAN	175.04	127.53	−47.51
FEB	185.45	126.43	−59.02
MAR	205.23	163.66	−41.57
APR	224.88	211.90	−12.97
MAY	232.58	204.20	−28.38
JUN	231.08	225.88	−5.20
JUL	286.08	288.10	2.03
AUG	303.25	299.17	−4.08
SEP	337.06	265.61	−71.46
OCT	314.25	231.53	−82.72
NOV	238.90	147.16	−91.74
DEC	182.39	117.13	−65.26
Annual total	2916.19	2408.32	−507.89

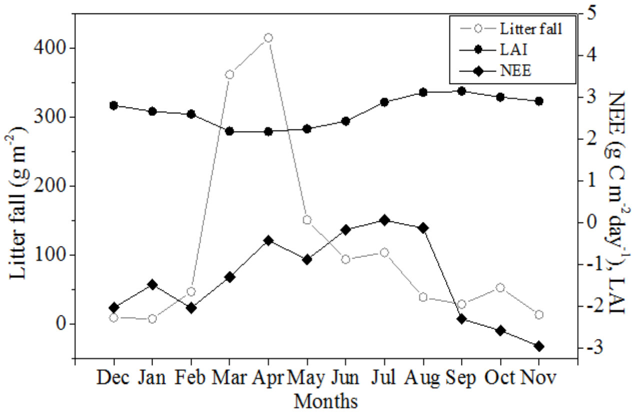

Fig. 4. Monthly averaged daily net CO_2 ecosystem exchange (NEE), with leaf area index (LAI) and litter fall (g m^{-2} $month^{-1}$).

explained by rainfall. In month of September, Dinghushan flux site recorded rain was 305.70 mm (Yan *et al.* 2009) whereas BFS received only 22.86 mm rain *i.e.* more Rg for photosynthesis in BFS during September.

Lesser NEE during April–June was due to two reasons: (i) lower LAI (Fig. 4), and (ii) high VPD. High VPD causes plants to reduce stomatal opening, which in turn reduces CO_2 uptake for photosynthesis (Cunningham 2005; Farquhar & Sharkey 1982). Positive or very less NEE during July-August was due to rain events. Rain events affected NEE in two ways: (i) increase in R*e*, and (ii) interception of Rg by clouds. Rain aggravates soil respiration and reduces plant photosynthesis (Davidson *et al.* 1998; Wright *et al.* 2006). Lower Rg value during July (185.06 Wm^{-2}) and August (190.65 Wm^{-2}) compared to September (218.31 Wm^{-2}) explains interception of Rg by cloud during this months. Highest NEE in November month was due to lower R*e* caused by drop in temperature. In November, site T_a and T_s reduced by 4.5 °C and 4.7 °C, respectively as compared to previous month (Table 2).

Annual NEE found in BFS (−507.89 g C m^{-2} yr^{-1}) was little higher than NEE (−428.8 g C m^{-2} yr^{-1}) reported by Jia *et al.* (2015) and much lesser than NEE (−900 g C m^{-2} yr^{-1}) reported by Tan *et al.* (2011). Yu *et al.* (2013) found decrease in GPP, NEE and R*e* with increase in latitude. They reported mean NEE of −510.88 g C m^{-2} yr^{-1}, −592.36 ± 343.59 g C m^{-2} yr^{-1}, 395.95 g C m^{-2} yr^{-1} for China's northern, central and southern subtropical forests, respectively. Also, they reported NEE of two forest sites in ~ 30 °N to be ~ 500 g C m^{-2} $year^{-1}$, in which case the NEE value of BFS (30°6'44.391"N) is in sync with their results. During this study, it was not possible to compare BFS obtained NEE with NEE reported from Indian forests due to absence of other site information.

Higher GPP and R*e* of BFS must be due to its warm-humid nature. Warmer-humid climate favour tree development compared to drier and cooler weather (UXL 2009). Kosugi *et al.* (2008) reported GPP and R*e* of 3243 and 3119 g C m^{-2} yr^{-1}, respectively for Malaysian evergreen broad-leaved forest site with annual mean temperature of 26.3 °C. The accounted GPP and R*e* in BFS was 2916.19 and 2408.32 g C m^{-2} yr^{-1}, respectively, meaning that the R*e* contributed approximately 82% of the total GPP, slightly lower than 86% reported by Jassal *et al.* (2007).

Response of carbon exchange to environmental factors

Effect of temperature and moisture on ecosystem respiration

In EC studies, R*e* is most often scaled as a temperature-dependent variable for the entire growing season (Goulden *et al.* 1997). Yet, studies have shown that R*e* may be limited by either temperature or moisture, depending on Phenological stage (Reichstein *et al.* 2002). To reduce the effect of moisture and phenology, R*e* was calculated using temperature coefficient (Q_{10}) developed on 8-day scale. The Q_{10} value ranged between 1.174 and 1.83, with annual mean Q_{10} of 1.39 ± 0.16. Fig. 5 shows the relationship between night-time R*e* with T_a.

Table 2. Monthly average climatic condition in study site.

Month	Rg (Wm^{-2})	T_a (°C)	T_s (°C)	VPD (hPa)	Rainy days	Rainfall (mm)
DEC	138.66	16.18	13.85	7.51	NA	NA
JAN	134.89	12.49	12.33	6.96	NA	NA
FEB	164.83	11.75	17.05	12.18	NA	NA
MAR	208.89	15.46	20.25	16.57	NA	NA
APR	257.35	19.26	22.27	22.24	NA	NA
MAY	280.83	22.68	27.65	35.79	NA	NA
JUN	227.13	28.28	28.91	26.76	6	135.2
JUL	185.06	28.16	27.21	14.37	19	303.53
AUG	190.65	26.78	26.79	13.31	20	517.398
SEP	218.31	26.44	25.76	18.14	5	22.86
OCT	190.33	25.36	21.60	17.18	2	39.116
NOV	160.92	20.86	16.96	14.43	2	3.556
Mean	196.54	21.19	21.74	17.12		

*NA - Not Available.

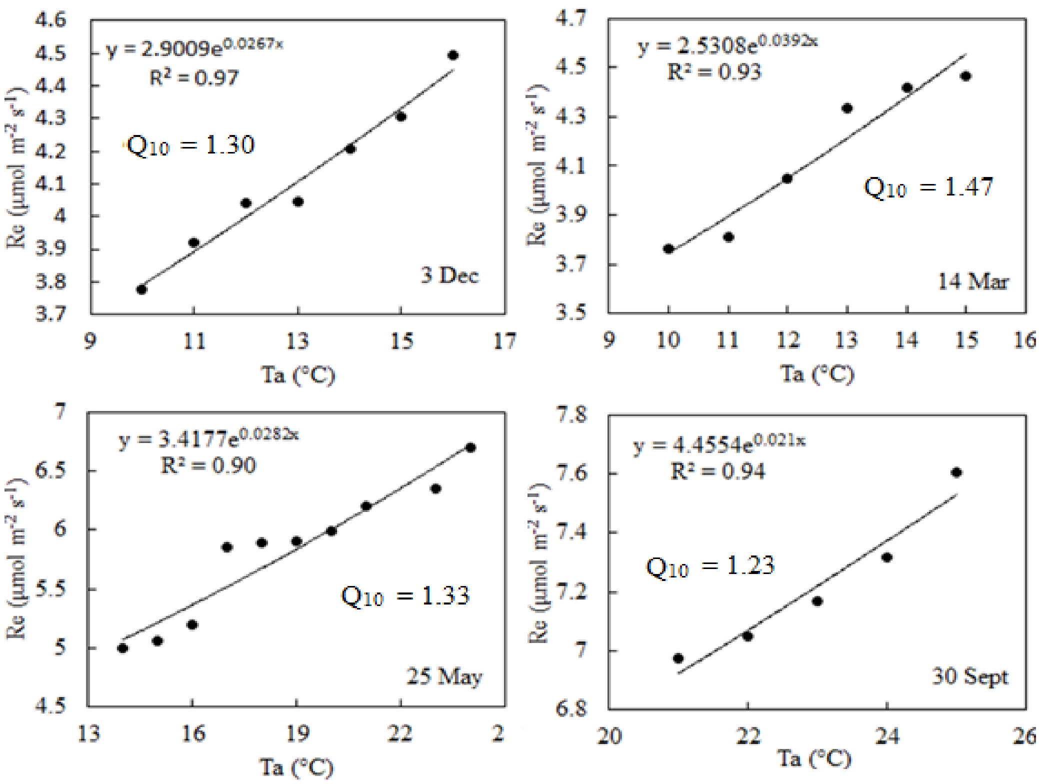

Fig. 5. Relationship between night-time ecosystem respiration (R*e*) and air temperature (T_a).

R*e*, when regressed against available daily T_s and soil moisture (*SW*), showed a stronger relationship with T_s ($R^2 = 0.66$) compared to *SW* ($R^2 = 0.53$). Fig. 6 shows the relationship between daily averaged R*e* with T_s. Combined influence of *SW* and T_s on R*e* was tested using the equation $Re = a\exp(bTs) \times SW^C$ (Burton *et al.* 2004; Xu & Qi 2001). The observed value of a, b, and c were 7.80, 0.02 and 0.27 with R^2 value of 0.79 ($P < 0.005$). Improvement with respect to variance explained in R*e* ($R^2 = 0.79$) signifies the synergic control of R*e* by these variables. Dependency of R*e* on *SW* and T_s is well depicted through three-dimensional plot (Fig. 7).

Effect of environmental factors on GPP

For this study, half hourly GPP was averaged

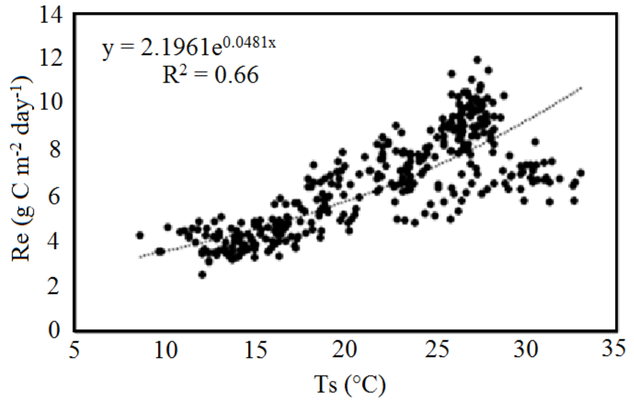

Fig. 6. Relationship between ecosystem respiration (R*e*) and soil temperature (T_s) at 5 cm depth.

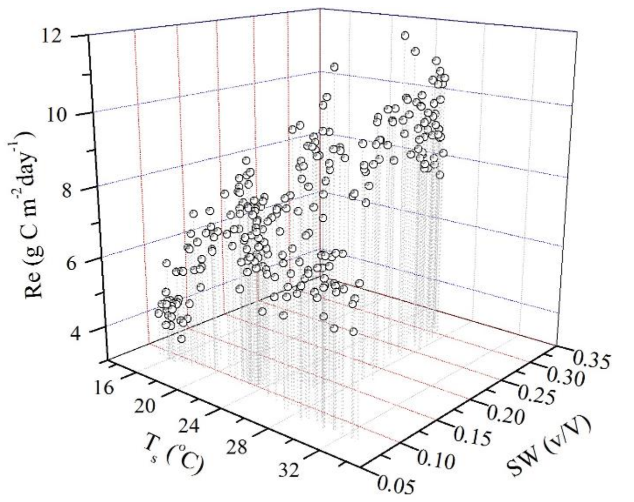

Fig. 7. 3-D plot of ecosystem respiration (R*e*) and soil temperature (T_s) and soil moisture (*SW*).

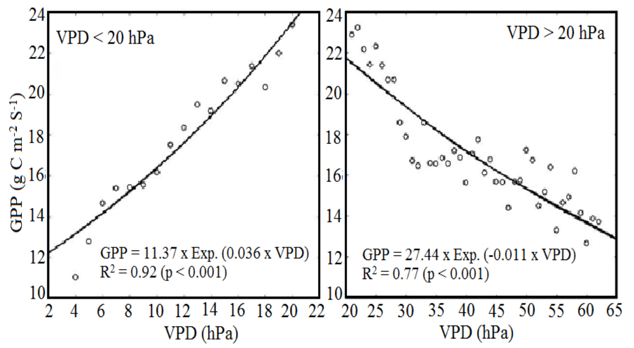

Fig. 8. Relationship between gross primary productivity (GPP) and vapour pressure deficit (VPD).

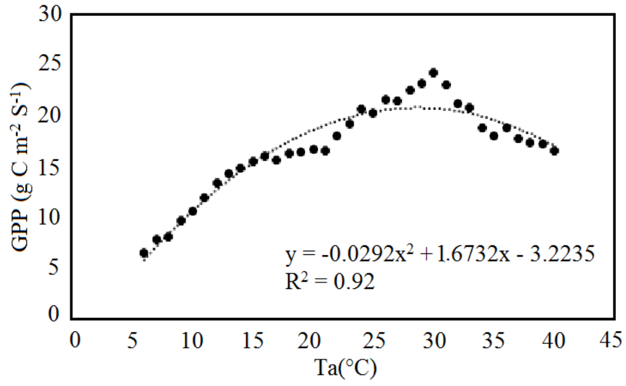

Fig. 9. Relationship between gross primary productivity (GPP) and air temperature (T_a).

using 1 °C and 1 hPa bin size for T_a and VPD, respectively. Fig. 8 showed increase in GPP with increasing VPD till 20 hPa, then declined rapidly till 30 hPa, and slow decline when VPD > 30 hPa. VPD had a strong linear relationship with GPP when VPD was < 20 hPa (R^2 = 0.92), whereas a logarithmic relation was observed when VPD > 20 hPa (R^2 = 0.77). High and low temperature acted as limiting factor on GPP (Fig. 9). GPP increased with increase in T_a and touches peak when temperature was ≈ 30 °C, T_a > 30 °C had negative feedback on GPP. The relationship between GPP and T_a descried using 2rd polynomial order fit had an R^2 value of 0.92.

Combined effect of environmental factors on GPP

To study the interaction of GPP with meteorological factors, GPP and meteorological variables were averaged on 8-day and monthly scale. The 8-day average of the entire study period when regressed against meteorological variables using multi-linear regression model had an R^2 of 0.69 (P < 0.005), whereas monthly regression models R^2 ranged between 0.90 to 0.99. Lower R^2 on 8-day scale proves the influence of LAI/phenology on GPP. In BFS, the overall influence of LAI on the NEE was poorly reflected as monthly LAI and NEE had a low R^2 of 0.12. The low R^2 was due to cloud in June, July and August months. During these months the LAI increased however the NEE remained low (due to high VPD in June, rain effect during July–August). Relationship between NEE and LAI when re-examined after removing these months had a R^2 of 0.76, indicating significant relation between LAI and NEE.

Conclusions

This study examined the carbon balance of a northern Indian moist sal forest. Sal forest occupies approx. 16% of total Indian forest and a very important component of Indian carbon budget. With the use of EC technique we were able to account the CO_2 flux pattern and study how climatic variables influences carbon fluxes. High VPD and low LAI caused reduction in NEE during pre-monsoon season. During rainy month (July–August) clouds interception of Rg and aggravated R*e* resulted to very less sequestration and release of carbon. Clear-sky, higher LAI and sufficient water availability during post monsoon (September–March) resulted to more carbon sequestration rate. Our study highlights the sink nature of BFS with NEE of −507.89 g C m^{-2} yr^{-1}. More EC based research in other various Indian forest types are needed for deeper understanding of Indian forest ecosystems and its processes. The results obtained during this study can be used for parameterizing LUE model and validation of various ecosystems models.

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