Impact of ecosystem respiration on carbon balance in a semi-evergreen forest of Northeast India

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We have estimated in this study the annual net ecosystem productivity (NEP) of Kaziranga National Park by using real-time eddy covariance data. We partitioned the net CO_2 flux into gross primary productivity and ecosystem respiration (R_e) using standardized method. Estimated annual NEP of the ecosystem 92.93 ± 1.7 g C m^{-2} $year^{-1}$ indicated that the forest is a moderate sink of CO_2 and is reported for the first time from a forest of Northeast India.

Keywords: Eddy covariance, gross primary productivity, net ecosystem productivity.

THE concentration of carbon dioxide (CO_2) in the atmosphere is increasing from the last several decades which has affected the radiative characteristics of the atmosphere. The exchange of CO_2 between forest and atmosphere is believed to have a profound impact on the regulation of atmospheric CO_2 concentration[1]. The role of forest in the regulation of the global carbon cycle is important[2]. Gross primary productivity (GPP) of terrestrial ecosystem is considered as the largest global CO_2 flux and is estimated as 123 ± 8 Pg C per year[3]. GPP of a forest is primarily a function of photosynthetically active radiation (PAR) and leaf area index (LAI) of forest canopy[4]. Ecosystem respiration of forest is reported to be modulated by variation of soil and air temperature[5]. Eddy covariance (EC) is an efficient method for high frequency measurement of trace gas fluxes between atmosphere and biosphere[1]. It is essential to partition the net CO_2 flux of any ecosystem into its components for mechanistic interpretation of the processes in the ecosystems[6].

Ecosystem respiration is the major determinant of net ecosystem carbon exchange[6]. Soil respiration (plant root respiration and microbial respiration) contributes about 65% to total ecosystem respiration[5]. The rate of increase of soil organic matter (SOM) decomposition may change an ecosystem from sink to source[7]. Decomposition of SOM in forest ecosystem may rise along with increase of microbial activity due to an increase in temperature, moisture and litter input[8].

The Kaziranga National Park (KNP) falls within the Asian monsoon zone which receives large amount of rainfall during the pre-monsoon, monsoon and the transition phase of summer to autumn in October. As a result, the park encounters frequent flood events[9]. We have earlier reported monthly variations of turbulent CO_2 flux[10] from this site and GPP was estimated using a calibrated model[11]. There are only a few tropical forest sites in the Indian subcontinent from which internal carbon dynamics has been reported[12]. In this study, we have made an effort to partition net CO_2 flux into its component fluxes from the semi-evergreen forest of KNP located in this unique climatic zone.

Materials and methods

Site description

The forest site under study (26°34′48″N, 93°6′28″E) is inside KNP which is located on the border of the Eastern Himalaya partly in Nagaon and Golaghat districts of Assam, India. The forest is considered as a biodiversity hotspot which hosts a variety of plant and animal species. The experimental site inside the forest is a part of ‘Metflux India’ project carried across the Indian subcontinent by the Indian Institute of Tropical Meteorology (IITM), Pune. The EC set-up and other meteorological sensors installed in the site are being monitored and maintained by the Tezpur Central University which is about 60 km away from the experimental site. Figure 1 shows the location and photograph of the flux tower. The average canopy height around the tower is 20 m. Dominant plant species around the flux tower are listed in Table 1.

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Table 1. Dominant plant species around the tower

Scientific name	Family	Canopy/height
Gmelina arborea Roxb.	Lamiaceae	Medium
Mallotus repandus (Willd.) Müll. Arg.	Euphorbiaceae	High
Tetrameles nudiflora R. Br.	Tetramelaceae	High
Psidium guajava L.	Myrtaceae	Small
Dalbergia sissoo DC.	Papilionaceae	High
Lagerstroemia speciosa (L.) Pers.	Lythraceae	High
Derris indica (Lam.) Bennet	Papilionaceae	High
Syzygium cumini (L.) Skeels	Myrtaceae	High
Dysoxylum mollissimum Blume	Meliaceae	High
Albizia lebbeck (L.) Benth.	Mimosaceae	Moderate
Bridelia retusa (L.) A.Juss.	Phyllanthaceae	Moderate
Erythrina indica Lam.	Papilionaceae	Moderate
Pennisetum purpureum Schumach.	Poaceae	Low
Chrysopogon zizanioides (L.) Roberty	Poaceae	Low

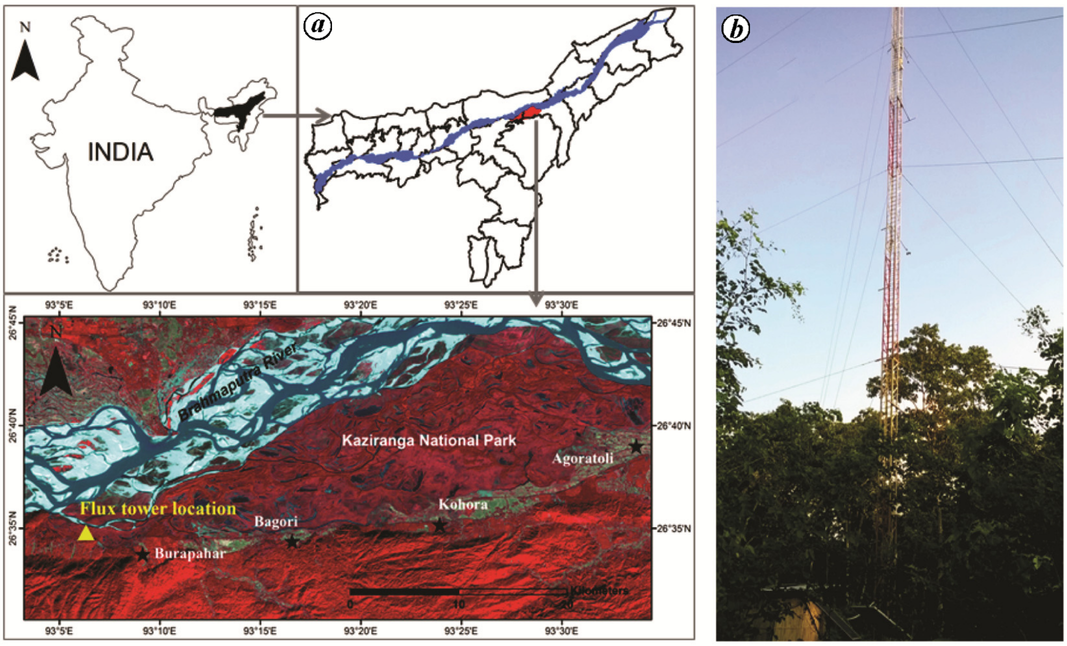

Figure 1. ***a***, The location of the experimental site in map. ***b***, Photograph of the tower.

EC system

CO_2 flux above the canopy (at 37 m height) was measured with the help of EC system which includes a sonic anemometer (Wind Master Pro, Gill Instruments, UK) and a CO_2–H_2O closed path analyser (LI-7200, LI-COR, USA)[10].

Measurement of meteorological and soil parameters

The soil temperature was measured by using soil temperature sensor (model: Therm-SS, ICT International, Australia) at 5 cm depth. Temperature of air and rainfall was measured using a multicomponent weather sensor (WXT520, Vaisala Oyj, Finland) at the height of 37 m on the tower. Radiation components were measured at 24 m height using a four-component net radiometer (NR01, Hukseflux, The Netherlands). The PAR sensor (SQ-100 and 300 series, Apogee Instruments, USA) was also installed at the height of 24 m on the tower for measurement of incoming PAR. Data from all the above slow sensors were recorded together at 30 min average in a data logger (CR3000, Campbell Scientific, USA).

Calculation of net ecosystem exchange of CO_2

Net ecosystem exchange (NEE) was calculated using the flux estimated by EC method (F_e) and storage flux (S_t)

$$\mathrm{NEE} = F_e + S_t.$$

F_e was calculated with the help of eddy–pro (6.2.0, LI-COR, USA) software and by following spike removal and filtering methods applied in our previous analysis[10].

CO_2 storage was estimated using the half hourly changes in CO_2 concentration at 37 m. Only one point concentration was used for storage flux calculation because of unavailability of vertical profile data during the period of study.

$$S_t = \frac{P}{RT}\frac{\partial c(h)}{\partial t}h,$$

where P is the atmospheric pressure, T the temperature of air, R the molar gas constant, c the concentration of CO_2 and h is the height where concentration of CO_2 is measured.

Partitioning of NEE

NEE was partitioned using the online tool of Max Planck Institute for Biogeochemistry (https://www.bgc-jena.mpg.de/REddyproc/brew/REddyproc.rhtml) in which we selected day time-based algorithm[13].

In the day time based approach of the partitioning tool, NEE was modelled using the rectangular hyperbolic light response function[14]

$$\mathrm{NEE} = \frac{xyR}{xR + y} + r_e,$$

where x indicates light utilization efficiency of canopy (μmol C J^{-1}), y denotes maximum CO_2 uptake rate of canopy at saturated condition of light (μmol C m^{-2} s^{-1}), r_e denotes total ecosystem respiration (μmol C m^{-2} s^{-1}) and R indicates global solar radiation (W m^{-2}). In the algorithm of the tool r is replaced by respiration model according to Lloyd and Taylor[15].

$$\mathrm{NEE} = \frac{xyR}{xR + y} + r\exp\left(E_0\left(\frac{1}{T_{rf} - T_0} - \frac{1}{T_a - T_0}\right)\right),$$

T_0 and T_{rf} were fixed at –46.02°C and 15°C respectively, similar to night time-based approach[16]. Night-time data ($R < 4$ Wm^{-2}) was used for estimation of E_0 (activation energy parameter), after that E_0 was fixed and r, x and y were estimated using day-time data.

At high vapour pressure deficit (VPD), y in the above equation was modified by an exponential decreasing function following Korner[17] to avoid limitation of VPD on GPP

$$y = y_0 \exp(-k(\mathrm{VPD} - \mathrm{VPD}_0)),\ \mathrm{VPD} > \mathrm{VPD}_0,$$

$$y = y_0,\ \mathrm{VPD} < \mathrm{VPD}_0.$$

For estimation of the parameter k, data window of each 4 day was used which quantifies maximum carbon uptake to VPD, VPD_0 threshold was fixed at 10 hPa following Korner[17].

Analysis of soil organic carbon

Soil samples were collected using an iron core from two depths (0–15 cm and 15–30 cm) and from four different sites during four seasons of the year: (i) winter (December, January and February), (ii) pre-monsoon (March, April and May), (iii) monsoon (June, July, August and September) and (iv) post-monsoon (October and November). The soil organic carbon (SOC) content of the samples was determined using TOC analyzer (Multi NC 2100S, Analytic Zena, Germany).

Results and discussion

Diurnal variation of soil temperature (monthly mean) is depicted in Figure 2 *a*. Highest average soil temperature of 30.29°C was recorded in August 2016 which decreased to 14.37°C in January 2017. Variation of soil and air temperature closely followed each other. Diurnal variation (monthly average) of incoming short wave radiation is shown in Figure 2 *b*. Incoming radiation attained a peak of 754.225 W m^{-2} in August 2016 during noon hours. Annual total rainfall received by the site (Figure 2 *c*) during the period of study was 1884 mm. LAI of the forest canopy increased from February 2016 and attained a peak in the first half of June (3.25) and decreased slowly thereafter up to January 2017. Monthly average of day-time VPD in the study area during monsoon season is presented in Figure 2 *d*. Out of the four monsoon months (June, July, August and September), the highest average VPD of 1.74 kPa was recorded in August 2016.

Daily average and 7-day moving average of GPP and R_e are presented in Figure 3 *a* and *b*. During the whole period of study annual GPP of the forest was 2660.07 g C m^{-2} $year^{-1}$. Estimated GPP in this study is close to the model estimated GPP of 2.11 kg C m^{-2} $year^{-1}$ in the same ecosystem from July 2015 to June 2016 (ref. 11). Daily average of GPP showed a peak of 15.86 g C m^{-2} day^{-1} in the last part of April, whereas a minimum GPP of 1.58 g C m^{-2} day^{-1} was recorded in January 2017 (Figure 3 *a*). Most of the high values of GPP were observed from May to June 2016 which is attributed to the occurrence of favourable conditions for photosynthesis in the forest with high values of PAR coupled with high LAI. Reduction of daily average GPP to 1.58 g C m^{-2} day^{-1} in January signifies leafless condition of the forest canopy which was caused by leaf senescence and abscission along with dry soil conditions. Estimated GPP was low in July due to low radiation received by the site and is in agreement with Thomas *et al.*[18]. GPP values were

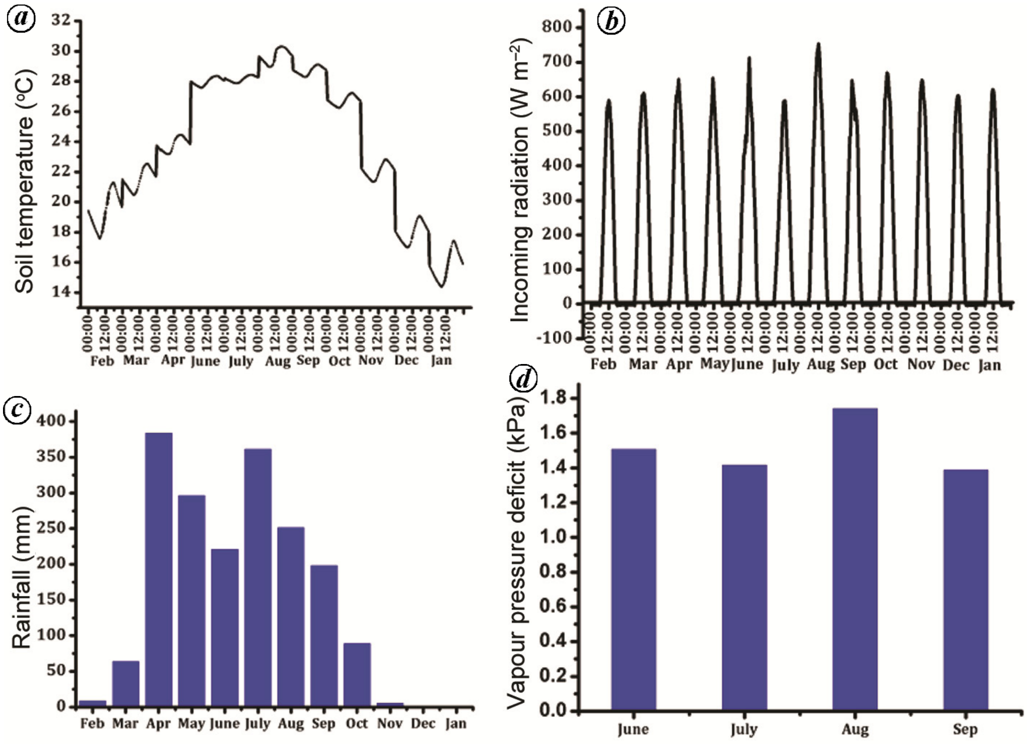

Figure 2. ***a***, Diurnal variations (monthly mean) of soil temperature; ***b***, Diurnal variations (monthly mean) of incoming solar radiation; ***c***, Monthly total rainfall recorded in the site; ***d***, Day-time average of VPD during monsoon season.

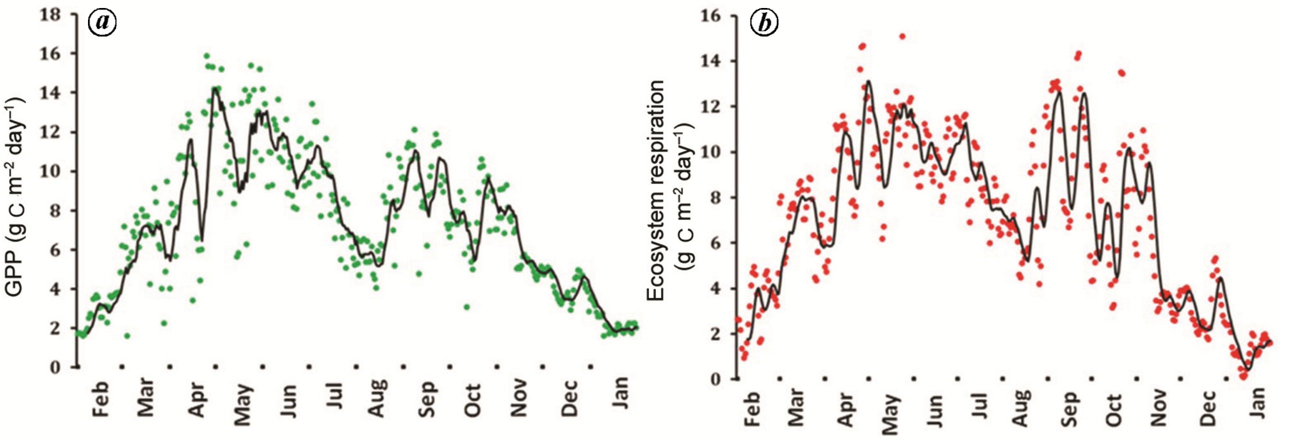

Figure 3. Daily averages of (***a***) GPP and (***b***) ecosystem respiration; daily averages in the figures are indicated by dots and bold line indicates 7 days moving average.

also low during August which was caused by partial stomatal closure of forest canopy as a result of high VPD in August. Similar relationship between VPD and stomatal closure was also reported by Pita *et al.*[4] in their study over four forest sites of Belgium and France. Decrease of GPP in the mid monsoon period is also attributed to the limitation of photosynthetic activity of understorey vegetation owing to waterlogged condition of the site.

Daily and weekly averages of ecosystem respiration are plotted in Figure 3 *b*. Over the annual cycle of study the estimated R_e was 2567.13 g C m^{-2} year^{-1}. Daily average respiration of this semi-evergreen forest ranged between 0.06 g C m^{-2} day^{-1} and 15.06 g C m^{-2} day^{-1}. R_e increased continuously from February to May 2016 due to increase in temperature and soil moisture[16]; similar findings were also reported by Heinemeyer *et al.*[19]. During this period a significant change in matric potential of soil can make heterotrophic microbiota more active[20]. Remarkable decrement in ecosystem respiration was observed from the beginning of the monsoon season (June) to August 2016 which was perhaps caused by water stagnation in the site, resulting in decreased

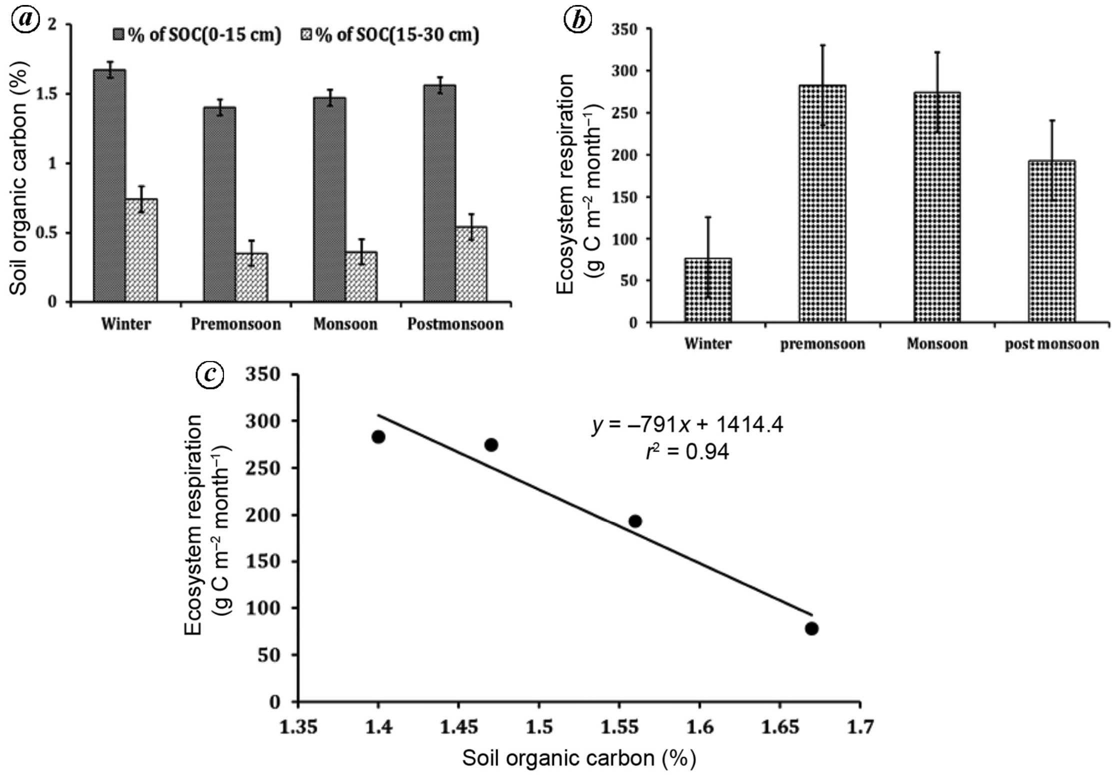

Figure 4. ***a***, Variation of SOC (average) in four seasons; ***b***, Seasonal average of ecosystem respiration; ***c***, Negative correlation between seasonal average of SOC and seasonal average of ecosystem respiration.

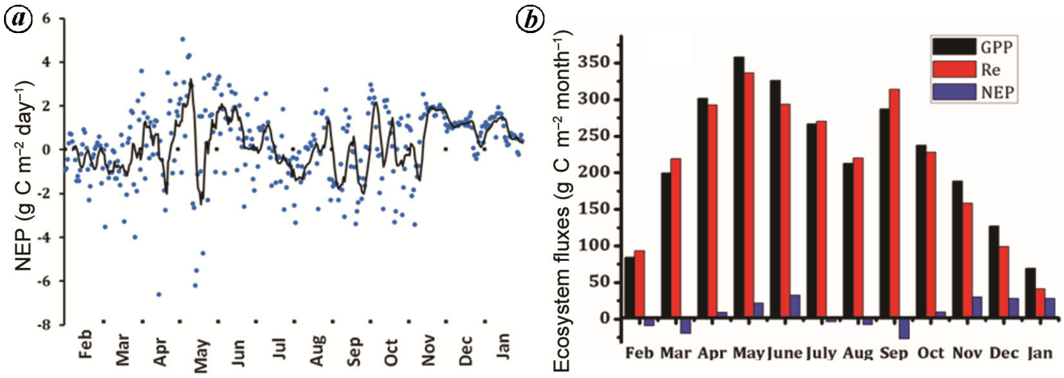

Figure 5. ***a***, Daily averages of NEP, daily averages in the figure are indicated by dots and the bold line indicates 7 days moving average; ***b***, Monthly total of GPP, ecosystem respiration and NEP.

respiration rates from the soil (autotrophic and heterotrophic) and other herbaceous plants accompanied by reduced root respiration. Similar observation of reduction of CO_2 efflux from soil during the wet period was reported[21] from an oak plantation ecosystem in northeastern Himalayan region. Ecosystem respiration started to increase from September as a result of withdrawal of stagnated water and due to decomposition of leaf litter in soil[18] as evident from the decrease in LAI in September[10]. With the progress of the dry season (October 2016 to January 2017), respiration of the ecosystem decreased slowly and became almost negligible in January as a result of low soil temperature. Results of SOC in both the depths during four seasons are presented in Figure 4*a*. SOC content was highest in winter season and lowest in pre-monsoon season. Average ecosystem respirations for each season is presented in Figure 4*b*. The regression analysis between seasonal average of ecosystem respiration and seasonal average of SOC (Figure 4*c*) showed negative correlation (adj $r^2 = 0.92$, $P < 0.05$). Highest SOC content in soil during the winter season might have been caused by high litter fall and low respiratory loss of CO_2 from soil due to dry and cold condition. The estimated SOC values were slightly lower during pre-monsoon

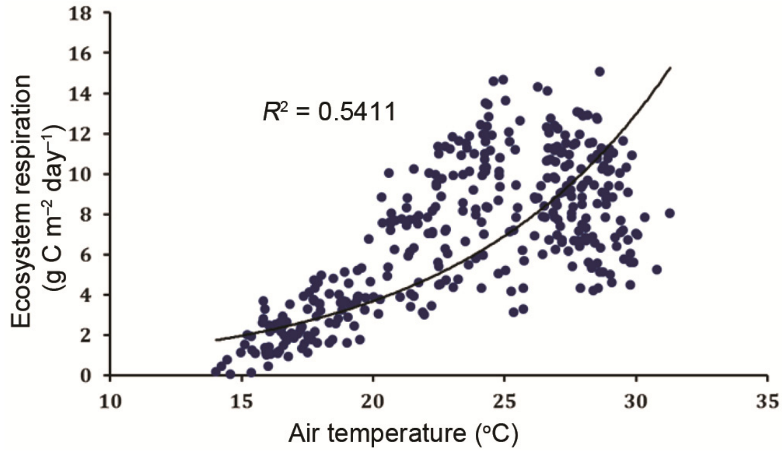

Figure 6. Relationship between temperature of air and ecosystem respiration during the study period ($P < 0.01$).

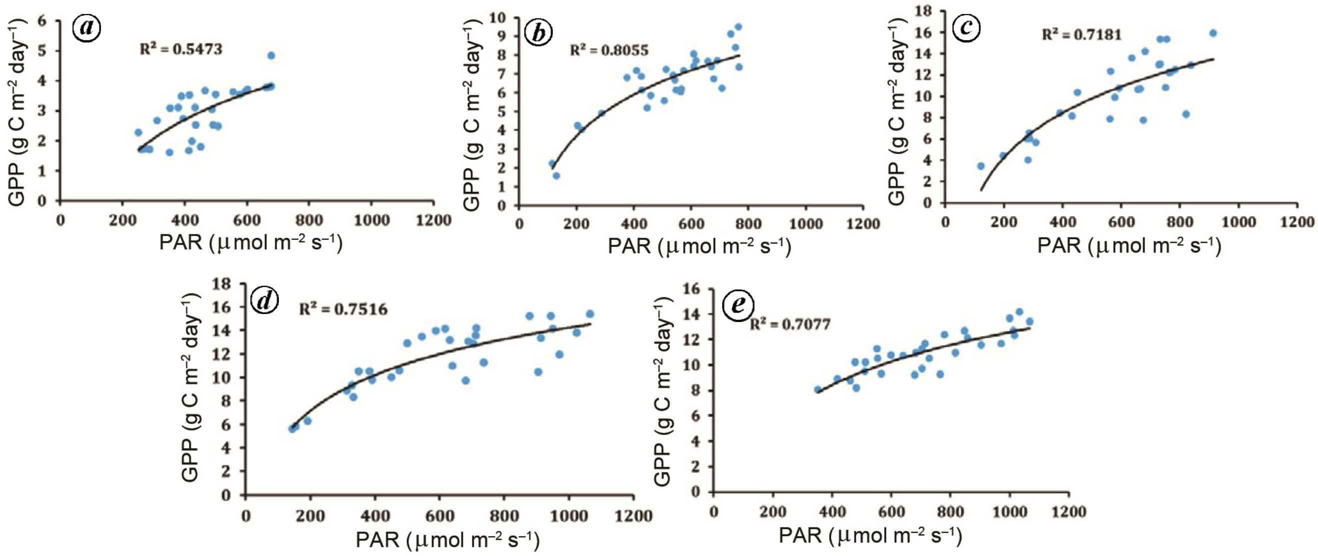

Figure 7. PAR versus GPP in different months: ***a***, February; ***b***, March; ***c***, April; ***d***, May; ***e***, June, $P < 0.001$ (in all the cases).

season due to high soil respiration as a result of increased microbial activity (Figure 4 *a*). Similar seasonal variation of SOC was reported by Sheikh *et al.*[22] in their study on SOC variation over different forest ecosystems in Garhwal Himalaya, India. The estimated annual ecosystem respiration of KNP is higher compared to the reports from other sites[6] owing to the complex structure of northeastern forest ecosystem and unique climatic conditions[9].

Although high fluctuation in daily average NEP was observed (Figure 5 *a*), the weekly mean followed a distinct pattern. Daily average NEP showed a peak of 5.03 g C m^{-2} day^{-1} at the beginning of May. In Figure 5 *a*, positive and negative values of NEP represent net uptake and release of carbon respectively. Estimated annual NEP of 92.93 ± 1.7 g C m^{-2} $year^{-1}$ indicates that KNP is a small sink of carbon. The annual NEP of KNP is lower compared to other similar ecosystems which might be because of higher ecosystem respiration and lower LAI of the forest[6].

Monthly sums of GPP, ecosystem respiration and NEP are shown in Figure 5 *b*, the highest monthly total of GPP and ecosystem respiration was observed in May 2016 just before the arrival of Indian summer monsoon in the region. In February and March the forest acted as net carbon source. Monthly total GPP dominated the respiration from April to June causing the ecosystem to act as a carbon sink. From the middle to end of monsoon season (July–September), the ecosystem released carbon (source) to the atmosphere as a result of dominance of R_e over GPP, a similar role of R_e in controlling the variation of NEP was also reported from European forests[6]. From October to January the ecosystem acted as a sink of carbon.

We have made an attempt to find a co-relationship between air temperature and ecosystem respiration

(Figure 6) during the whole study period and observed a fairly good correlation $r^2 = 0.54$ ($P < 0.01$) between the two parameters. Impact of PAR on GPP was analysed month-wise and the results are presented in Figure 7 *a–e*. Good correlation between PAR and GPP was observed from March to June ($P < 0.001$). From July to January the correlation between PAR and GPP remained insignificant.

Conclusion

Remarkable seasonal variation of ecosystem respiration has been observed in this study which has a significant role over annual NEP of KNP. Stagnated water during monsoon showed significant influence over the monthly variation of ecosystem respiration during that period. The forest ecosystem of KNP acted as a moderate carbon sink with annual NEP of 92.93 g C m^{-2} $year^{-1}$. Estimated annual GPP and ecosystem respiration of the forest are 2660.07 g C m^{-2} $year^{-1}$ and 2567.13 g C m^{-2} $year^{-1}$ respectively. Monthly variation of NEP indicated the highest carbon fixation potential of KNP forest in June.

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