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Net ecosystem CO_2 exchange from jute crop (*Corchorus olitorius* L.) and its environmental drivers in tropical Indo-Gangetic plain using open-path eddy covariance technique

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Abstract Present study is a maiden attempt to assess net ecosystem exchange (NEE) of carbon dioxide (CO_2) flux from jute crop (*Corchorus olitorius L.*) in the Indo-Gangetic plain by using open-path eddy covariance (EC) technique. Diurnal variations of NEE were strongly influenced by growth stages of jute crop. Daytime peak NEE varied from − 5 μmol m^{-2} s^{-1} (in germination stage) to − 23 μmol m^{-2} s^{-1} (in fibre development stage). The ecosystem was net CO_2 source during nighttime with an average NEE value of 5–8 μmol m^{-2} s^{-1}. Combining both daytime and nighttime CO_2 fluxes, jute ecosystem was found to be a net CO_2 sink on a daily basis except the initial 9 days from date of sowing. Seasonal and growth stage-wise NEEs were computed, and the seasonal total NEE over the jute season was found to be − 268.5 gC m^{-2} (i.e. 10.3 t CO_2 ha^{-1}). In different jute growth stages, diurnal variations of NEE were strongly correlated ($R^2 > 0.9$) with photosynthetic photon flux density (PPFD). Ecosystem level photosynthetic efficiency parameters were estimated at each growth stage of jute crop using the Michaelis–Menten equation. The maximum values of photosynthetic capacity (P_{max}, 63.3 ± 1.15 μmol CO_2 m^{-2} s^{-1}) and apparent quantum yield (α, 0.072 ± 0.0045 μmol CO_2 μmol $photon^{-1}$) were observed during the active vegetative stage, and the fibre development stage, respectively. Results of the present study would significantly contribute to understanding of the carbon flux from the Indian agro-ecosystems, which otherwise are very sparse.

Highlights

- Diurnal, daily, and seasonal variations of net ecosystem exchange of CO_2 from jute fibre crop were assessed by using open-path eddy covariance technique.
- Daytime peak net CO_2 influx reached − 23 μmol m^{-2} s^{-1} during fibre development stage of jute crop.
- Jute ecosystem was a net CO_2 sink with seasonal net ecosystem CO_2 exchange of − 268.5 gC m^{-2} (i.e. 10.3 t CO_2 ha^{-1}).
- Maximum photosynthetic capacity of jute crop was 63.3 μmol CO_2 m^{-2} s^{-1} in the active vegetative stage and maximum apparent quantum yield was 0.072 μmol CO_2 μmol $photon^{-1}$ in the fibre development stage.

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Introduction

Steady increases in concentrations of greenhouse gases notably CO_2 in the atmosphere, particularly during the time frame of post-industrial revolution period, are considered to be the major drivers of global warming and climate change (Datta et al., 2011; Field et al., 2014). Assessment of various sources and sinks of atmospheric CO_2 and its dynamics is essential to mitigate the menace of climate change. Terrestrial ecosystem has been considered as a large sink of atmospheric CO_2 (3.1 ± 0.9 Gt C year^{-1}), but disturbed heavily by land use change and unsustainable agricultural practices (Le Quere et al., 2016). Long-term monitoring of ecosystem-atmosphere carbon exchanges by eddy covariance (EC) flux towers is routinely being used for accurate quantification of the carbon budget of any ecosystem (Baldocchi et al., 2001). A global network of more than eight-hundred active EC stations, called FLUXNET, exists across the North, Central, and South America, Europe, Asia, Africa, and Australia (http://fluxnet.fluxdata.org). The Indian subcontinent is under-represented in this network and thus has a lot of uncertainty in carbon budgeting (Chakraborty et al., 2021; Deb Burman et al., 2020; Patra et al., 2013). India has diverse agro-ecosystems with nearly 198 M ha of gross cropped area (Agricultural Statistics at a Glance, 2018). Hence, the Indian agricultural systems play a very vital role in ecosystem-atmosphere carbon exchanges and global carbon budget as a whole. However, such EC measurements over agricultural ecosystems are still limited in number and also insufficient for representing the diverse agricultural landscapes of the country (Bhattacharyya et al., 2013a, b; Chakraborty et al., 2021; Chatterjee et al., 2020; Deb Burman et al., 2020; Patel et al., 2011, 2021). Hence, there is an urgent need for measurements and reporting of carbon fluxes data of various agricultural ecosystems including the jute ecosystem.

Jute crop (*Corchorus* spp.) provides an eco-friendly (Hoque et al., 2018) natural 'bast fibre' (Summerscales et al., 2010; Kundu et al., 2012) popularly known as 'golden fibre'. The fibres are long, lustrous, strong, and also economical, and therefore used to make diversified household goods and various industrial products (Shahinur et al., 2015). The worldwide menace of plastics especially of single use plastics can be prevented by replacing them with jute fibre products. Jute holds second position after cotton as the textile fibre production in the world. Globally, jute crop is mainly grown in India, Bangladesh, China, Uzbekistan, Nepal, Myanmar, and Thailand (FAOSTAT, 2018). The crop is cultivated over an area of 1.54 M ha with production of 3.6 M tonnes across the globe (FAOSTAT, 2018). India has the highest jute growing area of 0.76 M ha with average fibre yield of 2.55 tonnes per ha and total production of 1.9 M tonnes. Among the major jute producing countries, India ranks first and followed by Bangladesh and China (FAOSTAT., 2018). India and Bangladesh together contribute more than 95% of the global jute fibre production, and therefore jute plays an important role in the economies of India (Mahapatra et al., 2009) and Bangladesh (Islam & Ali, 2017). In India, it is predominantly grown over the Gangetic delta in the eastern part of the country covering the states of West Bengal, Assam, Bihar, and Odisha (Mahapatra et al., 2009).

Being a high biomass producing crop, jute has the potential to be a good carbon sink by absorbing a substantial amount of CO_2 from the atmosphere during its growing season. Further, jute fibres and its by-products remain in use for years before naturally degrading into the ecosystem (Banerjee & Mathew, 1985; Mohanty et al., 2000; Chander et al., 2002; Saha et al., 2012). Hence, jute crop plays an important role in carbon sequestration by removing carbon from the atmosphere as well as by longer residency in the ecosystem as fibre products. The eddy covariance (EC) measurement of carbon flux during jute production can give a clear picture about carbon sequestration in the jute ecosystem. However, EC measurements of fluxes of CO_2 and/or water vapour have mainly been done either in grain producing agricultural crops viz., paddy rice (Alberto et al., 2009; Bhattacharyya et al., 2013a; Saito et al., 2005; Zheng et al., 2008), wheat (Moureaux et al., 2008; Zheng et al., 2008; Aubinet et al., 2009), barley (Lohila et al., 2004), grain sorghum (Wagle et al., 2018), maize (Dold et al., 2019; Suyker & Verma, 2010; Wagle et al., 2018), pulse and oil seed (Chakraborty et al., 2021; Dold et al., 2019; Suyker & Verma, 2010; Wagle et al., 2017) or in pasture (Wagle et al., 2014), and forest ecosystems (Babst et al., 2013; Jha et al., 2013; Rodda et al., 2016). EC-based measurements of CO_2 and moisture fluxes from fibre crops like cotton were also reported (Alferi et al., 2012; Fong et al., 2020). However, to the best of our knowledge, such high-frequency precise EC-based measurement of carbon flux for ‘bast fibre’ crop of jute had not been reported till date.

To address the knowledge gap as mentioned above, present study was carried out to quantify the net ecosystem exchange (NEE) of CO_2 fluxes from irrigated jute crop along with related meteorological variables using an open-path eddy covariance system. This is the first EC-based study on assessment of NEE from jute crop at diurnal, daily, phenological, and seasonal scales along with its relationship with environmental drivers in tropical climate. The response of CO_2 flux to PPFD at different growth stages of the jute crop was also quantified and ecosystem level photosynthetic parameters were retrieved.

Materials and methods

Study site

The study site (22°45′30.64″ N, 88°25′40.83″ E; 9 m above msl) is located in the experimental farm of Indian Council of Agricultural Research-Central Research Institute for Jute & Allied Fibres (ICAR-CRIJAF), Barrackpore, Kolkata, India. EC flux tower along with biometeorological sensors was installed in the centre of the experimental field in such a way that its fetch covers only jute crop (Fig. 1). The climate is tropical hot and moist sub-humid (NBSS & LUP, 1990). The average annual rainfall is 1552 mm of which about 73.3% is received during monsoon season (June to September) and 14.3% during pre-monsoon season (March to May), and the mean annual maximum and minimum temperatures are 31.1 °C and 20.8 °C, respectively (Barman et al., 2017). Soil temperature regime of the study site is classified as hyperthermic, which means that the mean annual soil temperature remained more than 22 °C (NBSS&LUP, 1994). Soil type is well drained, moderately deep, sandy clay loam (Anthropic Irragic Anthrosols (Stagnic, Dystic)) (Mazumdar et al., 2018).

Crop growth and input management

The field experiment was conducted for irrigated jute crop during April to August of 2018. The jute crop was sown on 17th April, 2018 and harvested after 111 days on 5th August, 2018. Standard agronomic practices were followed to raise the crop (Mitra et al., 2006). Sowing was done by maintaining row to row spacing of 25 cm and plant to plant spacing of 5 to 7 cm. Recommended doses of nitrogen (N), phosphorus (P), and potassium (K) fertilisers (per ha 80 kg N, 40 kg P and 40 kg K) were applied. The total amount of P and K, and one-third of N dose were applied as basal dose at the time of land preparation. First top dressing of N (1/3rd of N dose) was applied 30 days after sowing and after weeding operation. The second top dressing of N (1/3rd of N dose) was applied 60 days after sowing. Each top dressing was followed by irrigation. The harvested jute crop was bundled

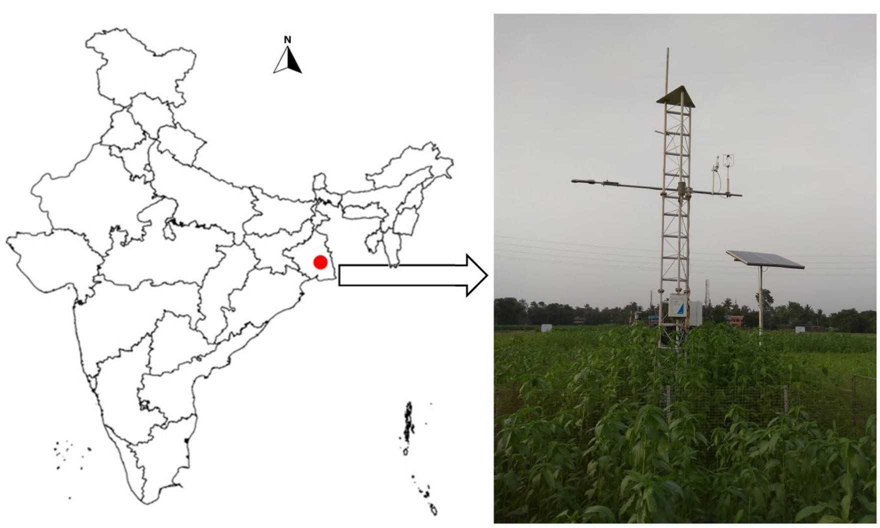

Fig. 1 Open-path eddy covariance flux tower over jute crop at Indian Council of Agricultural Research-Central Research Institute for Jute & Allied Fibres (ICAR-CRIJAF), Barrackpore, West Bengal, India

and kept in the field for 2 to 3 days to shed the leaves, later taken for retting and then extraction of fibres.

The crop biophysical parameters such as plant height, basal diameter, leaf area index (LAI), and total chlorophyll content of leaf were measured at different jute growth stages. Plant height and basal diameter were measured using a measuring scale, and a vernier calliper, respectively. Leaf area index (LAI) was measured using a canopy analyser (LI 2200, LICOR Inc., USA). Total leaf chlorophyll content was measured using the dimethyl sulfoxide (DMSO) method (Lichtenthaler, 1987). In this method, 50 mg fresh leaf tissue was taken in a test tube containing 10 ml of DMSO and incubated at 60 °C for 4 h, and then the absorbances were recorded at 663 and 645 nm. Total chlorophyll was calculated using the formula, total chlorophyll (mg g^{-1} fresh weight) = [20.2 × A645 + 8.02 × A663] × (*V*/*W*) × 1000; where, A645 and A663 are absorbance at 645 at 663 nm, respectively, *V* is volume of extract, *W* is weight of fresh leaf tissue.

Flux data and meteorological measurements

The eddy covariance (EC) technique has extensively been employed as the state-of-the-art micrometeorological method for monitoring fluxes of CO_2, water vapour, and heat, which are necessary to determine carbon and energy balances of the land surfaces (Foken, 2008; Aubinet et al., 1999, 2012; Burba, 2013). The exchanges of trace gases between terrestrial ecosystems and the atmosphere are measured by the widely adapted EC technique because of its large coverage of the extent of an ecosystem along with short- and long-term data collection (Baldocchi et al., 2003). By this technique, continental level of carbon balance is estimated through a 'bottom-up' approach using sub-hourly to inter-annual timescales data (Takata et al., 2017). The EC technique is fundamentally based on high-frequency (10 Hz) measurements of wind speed and direction using a three-axis sonic anemometer as well as the CO_2 and H_2O concentrations by a fast-response infrared gas analyser (IRGA) at a certain height above the crop canopy (Foken, 2008; Aubinet et al., 2012; Burba, 2013). In the present study, the CO_2 and H_2O fluxes over the canopy were measured using an open-path IRGA (LI-7500A, LICOR Inc., USA). Three-dimensional wind speeds and sonic temperature were measured using a 3-D sonic anemometer (GILL WINDMASTER-PRO). Both the sensors were installed at 4.8-m height above the ground considering the maximum height of the full-grown jute crop to be nearly 3 m. Generally, it is recommended to maintain minimum of 1.5- to 2-m distance between the top of the canopy and the sensors. These two sensors were separated by a distance of 20 cm and such separation was adjusted statistically during data processing. The LI-7500A set back to sonic anemometer considering the predominant wind direction to minimise flow distortion. The head of the LI-7500A sensor was tilted about 10° from the vertical line for minimising accumulation of precipitation in the window. Data were collected by the Sutron (Xlite 9210) data logger.

Concurrent measurements of different meteorological variables were also carried out continuously with a suite of sensors placed with the flux tower. Downward/upward short- and long-wave radiation components were measured using four components net radiometer (CNR4, Kipp & Zonen) whereas photosynthetic photon flux density (PPFD) was measured using LICOR (LI-190R) quantum sensor. Air temperature (T_a) and relative humidity (RH) were measured using temperature and humidity sensors (HMP155, Vaisala, Helsinki, Finland). Soil temperature (T_s) and soil water content (SWC) were measured at 5-cm depth by temperature and moisture sensors (Hydra Probe II, Stevens, Portland, Oregon), and soil heat flux (SHF) was also measured at 5-cm depth by self-calibrating soil heat flux plate (HFP01SC-15, Hukseflux Thermal Sensors B.V., Delft-The Netherlands). Rainfall was recorded using tipping and bucket type rain gauge (Texas Electronic). These micrometeorological observations and air pressure were recorded in 1 Hz, and averaged over a 30-min time interval.

Flux calculation and correction

The EC system recorded CO_2 fluxes and other meteorological variables as (.ghg) raw data file format. These raw data files (.ghg) were processed by using the EddyPro® 6.2 software (LI-COR, Inc., 2016), and the CO_2 fluxes were obtained as half-hourly data. The eddy flux of CO_2 (F_c) is computed as the mean covariance between deviations in instantaneous vertical wind speed (w') and density of CO_2 in air (c') using the following equation given by Baldocchi et al. (1988).

$$F_c = \overline{w'c'} \tag{1}$$

The standard flux correction measures (Mauder et al., 2013) were applied for the flux data. It is important to note that the height of the jute crop increased very fast and attained 2.75 m within 111 days. The increase of height causes changes in the displacement height and roughness length that are crucial for canopy level mass and energy exchanges (Jacob & Boxel, 1988). Height of the jute crop, therefore, was adjusted by processing the raw data in weekly time windows as per the field condition using the dynamic metadata file in the EddyPro® software. The primary processing includes different statistical corrections such as angle of attack correction (Nakai & Shimoyama, 2012), tilt correction (Wilczak et al., 2001), time lag compensation by covariance maximisation and frequency response correction (Moncrieff et al., 1997, 2004), and Web-Pearson-Leuing (WPL) correction for density fluctuations of CO_2/water vapour due to thermal expansion and dilution (Webb et al., 1980). Further, the secondary processing includes spike removal (Thomas et al., 2011), frictional velocity correction (Zhu et al., 2006), and uncertainty analysis. The inherent gaps or low-quality EC data were corrected by gap filling method as employed by the CarboEurope (http://www.bgc-jena.mpg.de/bgc-mdi/html/eddyproc/, Reichstein et al., 2005), which is an improved technique of the look up table method (Falge et al., 2001). It considers both the covariations of fluxes with meteorological variables and the temporal autocorrelation of the fluxes. These gap-filled data were used to derive seamless half-hourly time series data of NEE.

Correlation analysis between NEE and environmental factors

Correlation analysis was done between NEE (μmol CO_2 m^{-2} s^{-1}) and related environmental variables such as net radiation (R_n, W m^{-2}), photosynthetic photon flux density (PPFD, μmol CO_2 m^{-2} s^{-1}), relative humidity (RH, %), vapour pressure deficit (VPD, kPa), air temperature (T_a, °C), and soil heat flux (SHF, W m^{-2}) and soil water content (SWC, %) at 5-cm depth. The correlations were statistically tested with 1% ($p < 0.01$) and 5% ($p < 0.05$) levels of significance. Further, responses of NEE to the light intensity (PPFD) at different growth stages were assessed by regression analysis.

Estimation of photosynthetic parameters for jute ecosystem

The Michaelis–Menten equation as described by Ruimy et al. (1995) was used in the current study to estimate the ecosystem level photosynthetic efficiency parameters and the equation is given below:

$$NEE = \frac{\alpha \times \mathrm{PPFD} \times \mathrm{P}_{\max}}{\alpha \times \mathrm{PPFD} + \mathrm{P}_{\max}} - R_e \quad (2)$$

where α (μmol CO_2 μmol $photon^{-1}$) denotes apparent quantum yield of the ecosystem, PPFD (μmol m^{-2} s^{-1}) denotes photosynthetic photon flux density, P_{max} (μmol CO_2 m^{-2} s^{-1}) denotes maximum photosynthetic capacity, and R_e (μmol CO_2 m^{-2} s^{-1}) denotes ecosystem respiration in daytime.

Results and discussions

Meteorological condition

Diurnal variations of the seasonal average meteorological conditions of the present study site during jute growing season are presented in Fig. 2. The diurnal mean net radiation (R_n) ranged from − 29.09 (19.00 h) to + 505.17 W m^{-2} (12.30 h) with mean value of 134.63 W m^{-2} (Fig. 2a). The R_n remained positive from sunrise to sunset (daytime), and it became negative during nighttime due to absence of incoming solar radiation. During the diurnal period, R_n became positive at 6.00 h in the morning immediately after sunrise and it gradually increased with the increasing sun elevation and reached its peak at 12.30 h. Further, it gradually declined due to inclined radiation (Bhattacharyya et al., 2013a) and started to become negative at 18.00 h and reached its lowest negative value at 19.00 h. The PPFD is an inherent part of incoming solar radiation, which is utilised for photosynthetic activities. Hence, it followed a similar diurnal pattern as that of R_n. The PPFD was zero during nighttime and reached its peak of 1200 μmol m^{-2} s^{-1} in mid-day. The seasonal average air temperature (T_a) was 26 to 27 °C during nighttime, whereas it ranged from 32 to 33 °C in mid-day. At 5-cm depth, diurnal mean soil temperature mainly varied from 30 to 31 °C during the crop season. Soil

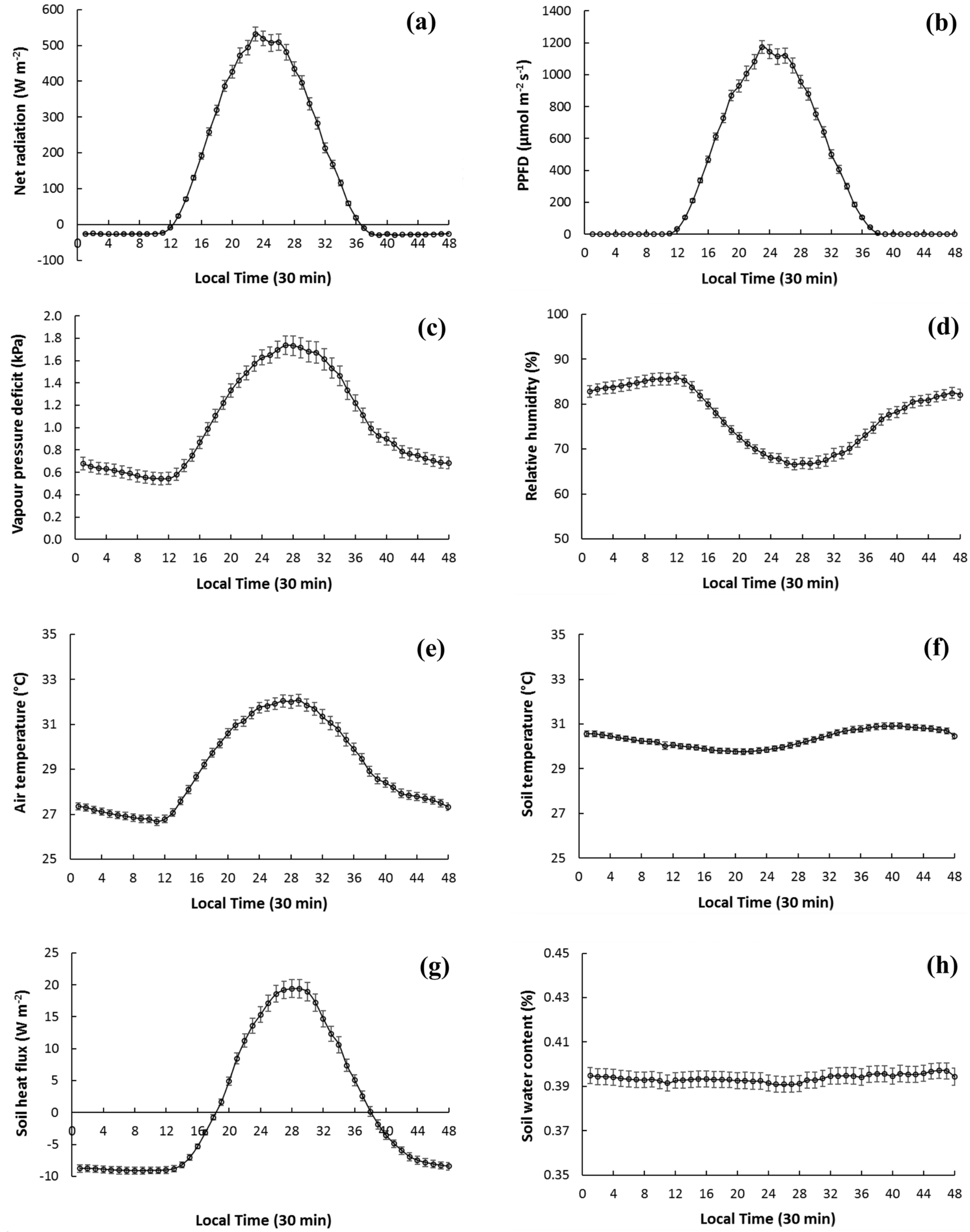

Fig. 2 Diurnal pattern of half-hourly seasonal mean of (**a**) Net radiation, (**b**) Photosynthetic Photon Flux Density (PPFD), (**c**) Vapour Pressure Deficit, (**d**) Relative Humidity, (**e**) Air temperature, (**f**) Soil temperature at 5 cm depth , (**g**) Soil heat flux, and (**h**) soil water content over the jute growth period (17th April to 5th August, 2018)

heat flux at 5-cm depth ranged from − 5 to − 10 W m^{-2} during nighttime, and reached up to 20 W m^{-2} during mid-day. Soil moisture at 5-cm depth remained nearly constant with little variations between 38 and 42% that is well within the available range to the jute crop. Relative humidity varied between 80 to 90% during nighttime and from 65 to 70% during daytime. Similarly, vapour pressure deficit ranged from 0.5 to 0.7 kPa during nighttime and reached up to 1.8 kPa during mid-day. In nutshell, weather condition during the jute growing season was hot and humid with bright sunshine, which is typically ideal and favourable for crop growth.

Crop growth, biomass, and fibre yield

The germination of jute seeds started 3 days after sowing (DAS), i.e. 109 days of the year (DOY) and completed by 6 DAS i.e. 112 DOY. Growth of the jute plants was initially slow. It took 46 days (153 DOY) to attain 42.4-cm height but thereafter it gained another 92.6-cm height in only 14 days (167 DOY). Plant height in the fetch area increased continuously and reached an average height of 275 cm at harvest by 111 DAS i.e. 217 DOY (Fig. 3). Average basal diameter of the jute plants was 0.92 cm at 46 DAS, 1.27 cm at 60 DAS, and 2.10 cm at harvest (111 DAS). Diameter of the plants reduced from the base towards its tip and formed cylindrical stem slightly tapering towards tip. Leaf Area Index (LAI) of the crop was found to be nearly 1.0, 2.0, 3.0, 4.0, and 4.6 m^2 m^{-2} at 30 (137 DOY), 50 (157 DOY), 65 (172 DOY), 85 (192 DOY), and 111 (217 DOY) DAS, respectively (Fig. 3). Chlorophyll content of leaf varied between 1.5 and 2.5 mg g^{-1} on fresh weight basis.

Diurnal variations of NEE at different growth stages of jute crop

Jute crop season was divided into different growth stages based on different phenological/developmental phases viz. germination stage [1 to 6 DAS i.e. 107 to 112 DOY], seedling stage (7 to 36 DAS i.e. 113 to 143 DOY), active vegetative stage (37 to 66 DAS i.e.

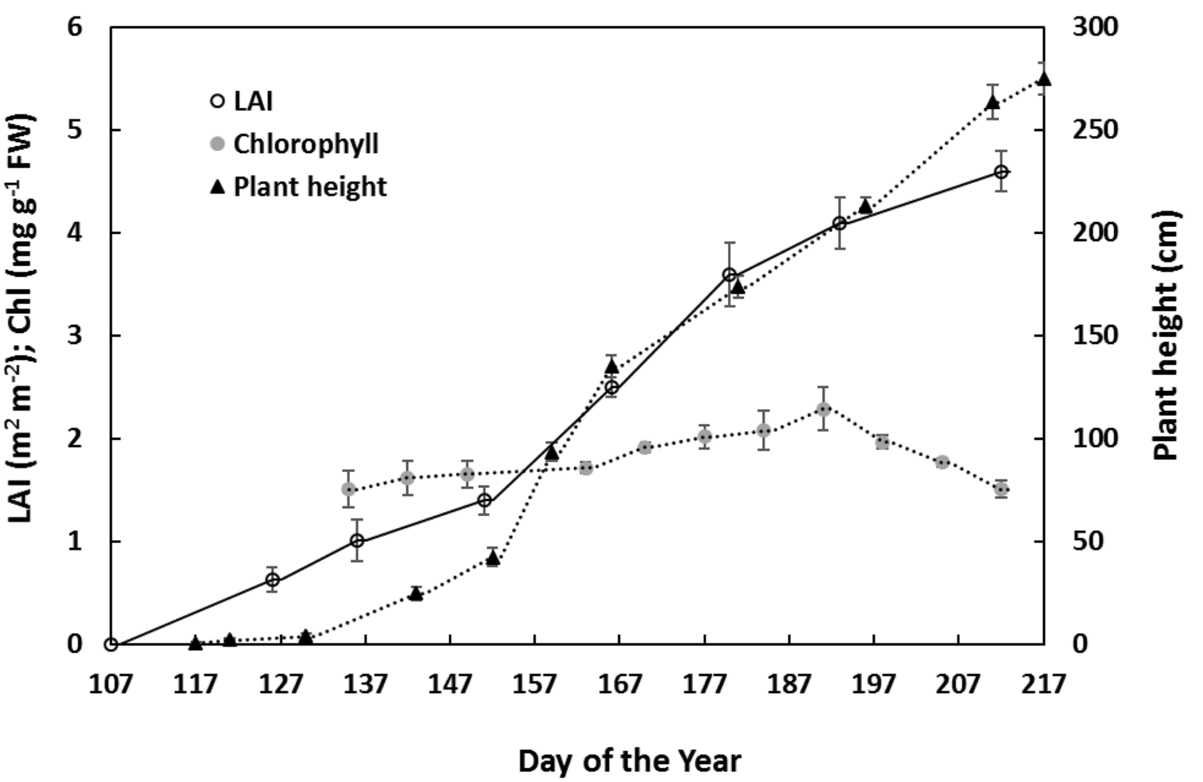

Fig. 3 Leaf area index (LAI), leaf chlorophyll content and plant height of jute crop during its growth period

144 to 173 DOY), fibre development stage (67 to 96 DAS i.e. 174 to 203 DOY), and maturity (97 to 111 DAS i.e. 204 to 218 DOY). Diurnal patterns of the mean NEE of different growth stages of the jute crop are presented in Fig. 4.

NEE was found to be positive in nighttime as photosynthesis process ceased to exist and respiration produced CO_2 from the ecosystem. The nighttime NEE varied between 5 and 8 µmol m^{-2} s^{-1} across different growth stages. The photosynthesis process kicks in after the sunrise and resulted in high influx of CO_2 into the ecosystem, superseding the CO_2 efflux due to ecosystem respiration. Thus, NEE became negative during daytime. Substantial differences were noticed in diurnal variations of NEE across the growth stages. NEE was found to be proportional to the accumulated above-ground biomass except in maturity (Figs. 3 and 4). During the germination stage, photosynthetic activity was minimal but the ecosystem respiration (soil respiration in particular) was high and therefore the NEE was positive. In this stage, the peak influx of CO_2 was − 5 µmol m^{-2} s^{-1}

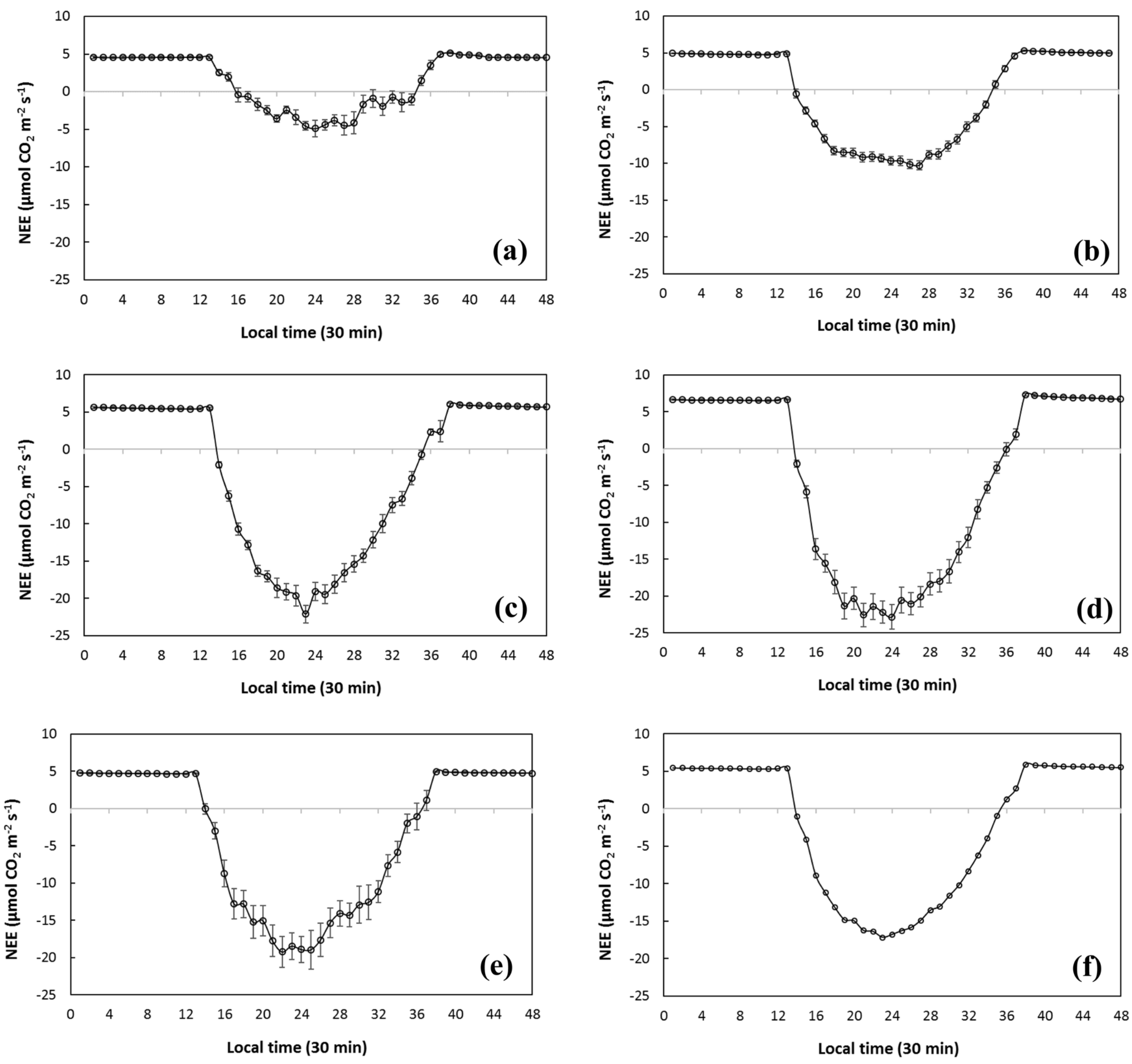

Fig. 4 Net ecosystem exchange of CO_2 (NEE) at different growth stages of jute: (**a**) germination stage, (**b**) seedling stage, (**c**) active vegetative stage, (**d**) fibre development stage, (**e**) maturity stage, (**f**) entire growth period

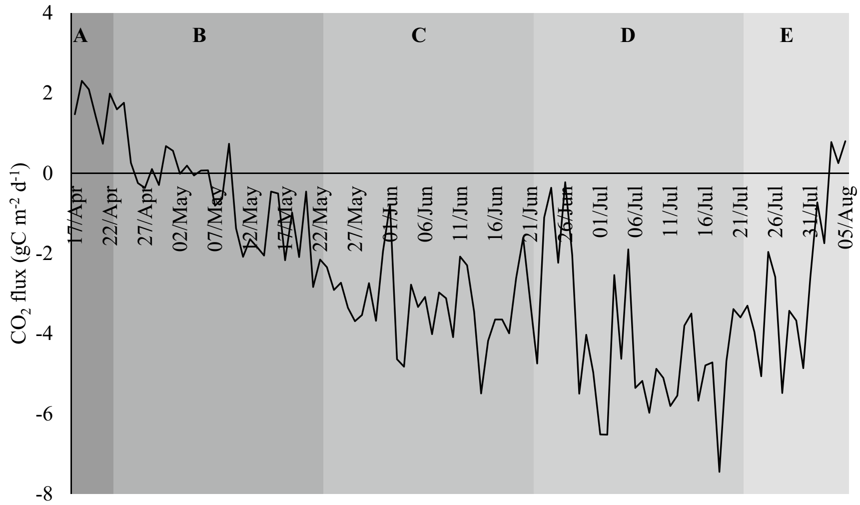

Fig. 5 Daily net ecosystem CO_2 exchange (NEE) of jute crop during different crop stages. **A**, Germination stage: **B**, Seedling stage: **C**, Active vegetative stage: **D**, Fibre development stage: **E** Maturity stage

during mid-day (Fig. 4a). With progress of the crop season, the ecosystem acted significantly as a net CO_2 sink and the peak CO_2 influx reached − 10, − 20, − 23, and − 20 μmol m^{-2} s^{-1} in seedling, active vegetative, fibre development, and maturity stages, respectively (Fig. 4). It is important to note here that the jute crop was harvested before it produced flowers. Hence, the typical senescence phase was absent and the peak CO_2 influx remained almost the same between active vegetative stage and maturity stage.

Dynamics of daily NEE over the jute growing season

The half-hourly NEEs (including daytime and nighttime observations) were converted to daily time scale for the entire jute season and presented in Fig. 5. Growth stage-wise accounts of mean and cumulative NEE are presented in Table 1. Jute crop acted daily as a net CO_2 sink almost during the entire growing season except initial 9 days from date of sowing to until 25th April, 2018 (115 DOY). In germination stage, the mean NEE was 1.66 gC m^{-2} day^{-1} with the cumulative NEE of 9.98 gC m^{-2} and the positive values depict that the jute ecosystem acted as a net CO_2 source in this stage. This is because of more soil respiration than photosynthesis due to the much lower value of LAI (< 0.3 m^2 m^{-2}) in this stage. The subsequent negative values of daily NEE signify that the ecosystem acted as a net CO_2 sink until the harvesting of the jute crop. In seedling stage, photosynthetic activities increased as the LAI increased from 0.3 to 1.0 m^2 m^{-2} along with crop height of 30 cm, and the mean NEE reached − 0.57 gC m^{-2} day^{-1} with the cumulative value of − 17.12 gC m^{-2}. In the active vegetative stage, crop height and LAI increased rapidly from 30 to 150 cm and 1.0 to 2.6 m^2 m^{-2}, respectively. In this stage, the mean and cumulative NEEs were − 3.23 gC m^{-2} day^{-1} and − 96.87 gC m^{-2}, respectively. The rapid crop growth was also observed in fibre development stage where the crop

Table 1 Net ecosystem CO_2 exchange (NEE) at different growth stages of jute crop and seasonal as a whole

Growth stages	Date	Days after sowing (DAS)	Cumulative NEE (gC m^{-2})	Mean NEE (gC m^{-2} day^{-1})	LAI (m^2 m^{-2})
Sowing to germination	17–22 Apr	1–6	+ 9.98	+ 1.66	0.1
Seedling stage	23 Apr–22 May	7–36	− 17.12	− 0.57	0.8
Active vegetative stage	23 May–21 Jun	37–66	− 96.87	− 3.23	2.3
Fibre development	22 Jun–21 Jul	67–96	− 126.86	− 4.23	4.5
Maturity	22 Jul–5 Aug	97–111	− 37.63	− 2.51	4.9
Total		111 days	− 268.49		

height and LAI increased from 150 to 220 cm and from 2.6 to 4.1 m^2 m^{-2}, respectively, and the mean and cumulative NEEs were − 4.23 gC m^{-2} day^{-1} and − 126.86 gC m^{-2}, respectively. Among all growth stages, the maximum NEE was observed in the fibre development stage, which might be due to the highest increase in LAI that led to more photosynthetic activities than soil respiration. During maturity stage, crop height and LAI further increased from 220 to 275 cm and 4.1 to 4.6 m^2 m^{-2}, respectively, and the mean and cumulative NEEs were − 2.51 gC m^{-2} day^{-1} and − 37.63 gC m^{-2} day^{-1}, respectively. Shedding of lower matured leaves is common during this stage, which might have led to a lower rate of increase of LAI. The seasonal cumulative NEE was found to be − 268.49 gC m^{-2} (i.e. 10.3 t CO_2 ha^{-1}) during 111 days of jute growing season.

Correlation between NEE and major environmental variables

The NEE of the jute agro-ecosystem is governed by multiple environmental variables that mainly influence the biological and physical processes. Therefore, correlation analysis was done between NEE and the related environmental variables such as net radiation (R_n), photosynthetic photon flux density (PPFD), vapour pressure deficit (VPD), air temperature (T_a), soil heat flux (SHF), and soil water content (SWC) and presented in Table 2.

The environmental drivers were found to have collinearity between them. PPFD being a part of R_n was found to be highly correlated. Further, VPD was also highly correlated with T_a and RH. As discussed in the "Meteorological condition" section, the environmental condition was congenial for growth and development of the jute crop. There were no major biotic or abiotic stresses during the growing season. Hence, the crop growth was mainly driven by the available solar radiation. NEE was statistically highly correlated with both PPFD ($r = -0.79$) and R_n ($r = -0.78$). Similar results were reported for the rice ecosystem by Bhattacharyya et al. (2013a); Alberto et al. (2009); and Saito et al. (2005). NEE was also statistically significantly correlated with Ta ($r = -0.51$), SHF ($r = -0.44$), VPD ($r = -0.42$), and RH ($r = -0.41$). Among these correlations, the magnitude of correlation coefficient between NEE and PPFD was found the highest ($r = -0.79$) which indicates that NEE is highly driven by PPFD.

Multiple regression analysis was done by taking half-hourly time series data of the season to develop empirical equation to estimate NEE of jute agro-ecosystem using related environmental drivers and the derived regression model is given below:

$$NEE = 50.01 - 0.02\ PPFD + 5.34\ VPD - 1.02 \times Ta - 56.71 \times SWC \tag{3}$$

The multiple regression equation between NEE and the environmental predictors explained the variance of the model. The derived model (Eq. 3) can explain the reasons of about 56% variations ($R^2 = 0.56$) of NEE of CO_2 in tropical jute agro-ecosystem using the environmental predictors such as PPFD, VPD, T_a, and SWC.

Table 2 Correlation matrix between net ecosystem CO_2 exchange (NEE) and related meteorological variables ($n = 3038$)

	NEE	PPFD	R_n	RH	SHF	T_a	VPD
NEE	1.00						
PPFD	− 0.79**	1.00					
R_n	− 0.78**	0.99**	1.00				
RH	− 0.41**	− 0.66**	− 0.65**	1.00			
SHF	− 0.44**	0.68**	0.68**	− 0.73**	1.00		
T_a	− 0.51**	0.67**	− 0.66**	− 0.79**	0.81**	1.00	
VPD	− 0.42**	0.69**	0.68**	− 0.98**	0.76**	0.87**	1.00

NEE net ecosystem CO_2 exchange (μmol m^{-2} s^{-1}), *PPFD* photosynthetic photon flux density (μmol m^{-2} s^{-1}), R_n net radiation (W m^{-2}), *RH* relative humidity (%), *SHF* soil heat flux at 5-cm depth (W m^{-2}), T_a air temperature (°C), *VPD* vapour pressure deficit (kPa), *ns* non-significant

** 1% level of significance ($p < 0.01$)

* 5% level of significance ($p < 0.05$)

Relationship of NEE vs PPFD at different growth stages of jute crop

As the photosynthetic activities of jute crop is mainly driven by the radiation factor (availability of photon) with significant correlation between NEE and PPFD, an effort was made to assess the relationship at every growth stages of the crop. The daytime NEE and PPFD were correlated over the different jute growth stages and the season as a whole. For each growth stages, the best-fit logarithmic models and their R^2 values along with corresponding LAI values are presented in Fig. 6. The scatter plot of NEE and PPFD for the entire jute growing season was found to be wide spread with R^2 value of 0.56 (Fig. 6f). The biophysical parameters (LAI/biomass) of jute crop changed very rapidly during the growing season (Fig. 3) and significantly altered the light interception as well as the ecosystem level photosynthetic parameters. Hence, a single fitted equation relating NEE to PPFD ($R^2 = 0.54$) for the entire growing season could not accommodate the differential light response of jute crop over the season. However, for each of the growth stages, the correlations

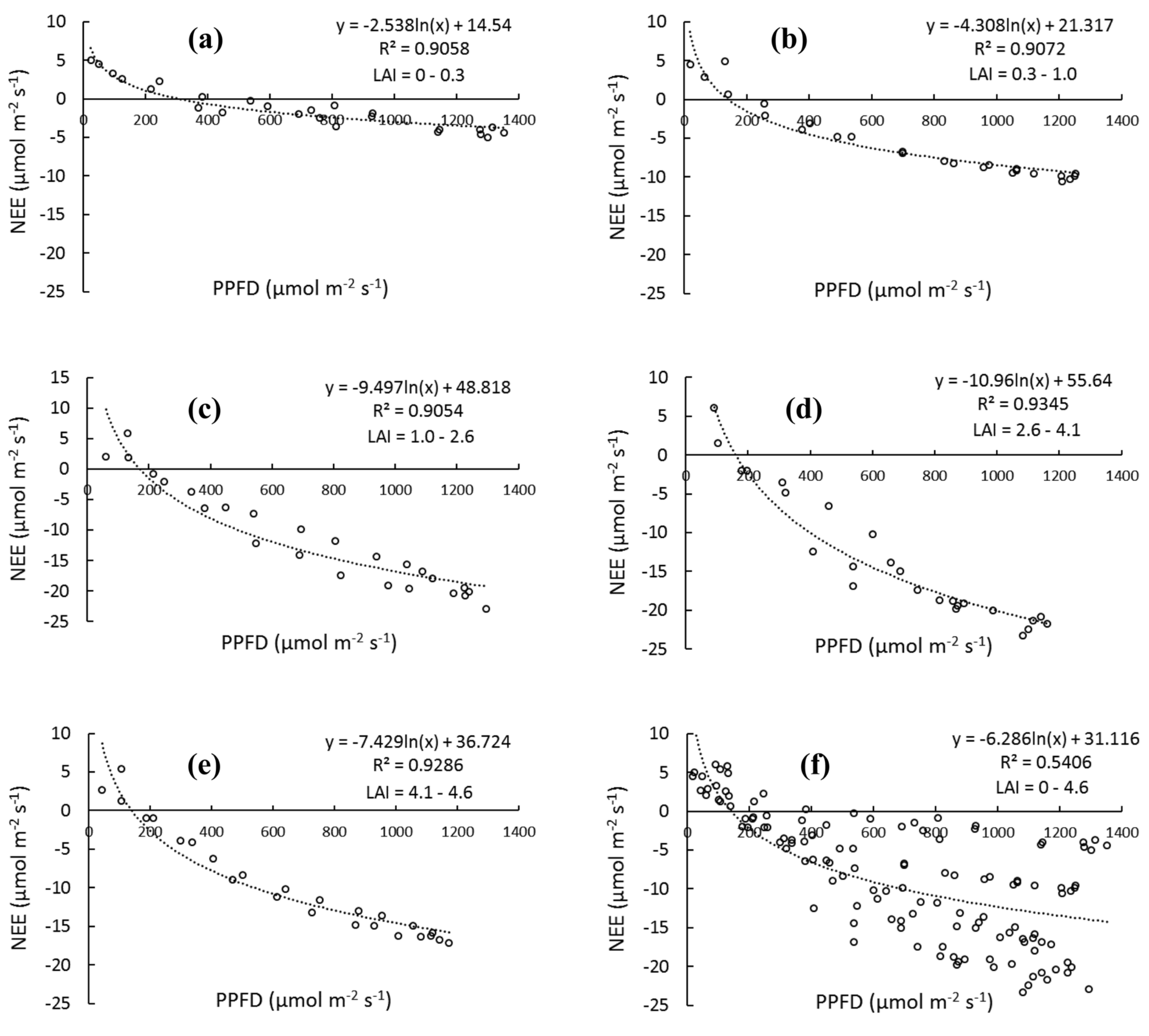

Fig. 6 Relationship between daytime photosynthetic photon flux density (PPFD) and net ecosystem CO_2 exchange (NEE) over jute ecosystem during (**a**) germination stage, (**b**) seedling stage, (**c**) active vegetative stage, (**d**) fibre development stage, (**e**) maturity stage, and (**f**) entire jute growth period (17th April to 5th Aug, 2018)

Table 3 Growth stage-wise ecosystem photosynthetic parameters of jute crop with standard error (95% confidence)

Growth stage	P_{max} (µmol CO_2 m^{-2} s^{-1})	α (µmol CO_2 µmol photon^{-1})	R_e (µmol CO_2 m^{-2} s^{-1})	R^2
Germination stage	14.15 ± (0.45)	0.021 ± (0.0015)	5.18 ± (0.19)	0.93
Seedling stage	24.51 ± (0.78)	0.036 ± (0.0025)	5.75 ± (0.21)	0.97
Active vegetative stage	63.30 ± (1.15)	0.039 ± (0.0031)	6.72 ± (0.24)	0.95
Fibre development stage	52.36 ± (1.12)	0.072 ± (0.0045)	9.76 ± (0.28)	0.94
Maturity	41.34 ± (1.04)	0.045 ± (0.0028)	6.45 ± (0.22)	0.97

P_{max} maximum photosynthetic capacity, α apparent quantum yield, R_e ecosystem respiration, R^2 coefficient of determination; values in parentheses are standard errors

were found statistically significant with high R^2 values (> 0.9). But the sensitivity of NEE to PPFD was found to be very low during the germination stage due to low LAI (Fig. 6a). It improved as the jute crop season progressed through the seedling stage (LAI 0.3 to 1.0 m^2 m^{-2}), active vegetative stage (LAI 1.0 to 2.6 m^2 m^{-2}), and fibre development stage (LAI 2.6 to 4.1 m^2 m^{-2}). Sensitivity slightly decreased in the maturity stage (LAI 4.1 to 4.6 m^2 m^{-2}) perhaps due to the reduction of the leaf chlorophyll content (Palit & Meshram, 2004), and yellowing and shedding of lower leaves (Kumar et al., 2016).

Such growth stage-wise relations are also very important to assess the apparent quantum yield (α) of an ecosystem to improve parameterisation for carbon cycle models (Zhang et al., 2006). The apparent quantum yield is described as the fixation of quanta of CO_2 molecules per unit of photon irradiated (Ruimy et al., 1995). It has a key role in understanding the photosynthetic responses of a crop, and also estimating α, which provides important information for large-scale ecosystem models e.g. CASA (Potter et al., 1993), Biome-BGC (Running & Coughlan, 1988), TEM (Raich et al., 1991), TURC (Ruimy et al., 1996), and BIOME3 (Haxeltine & Prentice, 1996). The α is generally computed by fitting a rectangular hyperbolic function between NEE and PPFD (Ruimy et al., 1995; Saito et al., 2005). This function responds to two different light conditions: there is near-linear response during low light conditions, and saturation to maximum productivity response in higher light conditions (Ruimy et al., 1995). Using Eq. (3), growth stage-wise estimated coefficients of photosynthetic efficiency of the jute ecosystem are presented in Table 3.

Substantial differences in photosynthetic efficiency parameters were observed across the jute growth stages. The maximum photosynthetic capacity (P_{max}) was very low (14.15 µmol CO_2 m^{-2} s^{-1}) in the germination stage due to minimal green biomass. It gradually increased with increase in the above-ground green biomass of the crop and reached 24.51, and 63.3 µmol CO_2 m^{-2} s^{-1} in seedling stage and active vegetative stage, respectively, but subsequently reduced to 52.36 and 41.34 µmol CO_2 m^{-2} s^{-1} in fibre development stage and maturity stage, respectively. The low value of P_{max} in the maturity stage might be due to cessation of crop growth and shedding of lowers leaves. The apparent quantum yield (α) also followed the similar trend as that of P_{max}. The α-value was found to be maximum in the fibre development stage (0.072 µmol CO_2 µmol photon^{-1}). Rapid increase in plant height together with fibre development during this stage necessitates more energy supply and thus well coincided with the maximum value of α. The maximum R_e-value (9.76 µmol CO_2 m^{-2} s^{-1}) was estimated in this stage might be due to high physiological activities in plants. It is apt to note here that jute is a C3 crop and all values of the parameters were well within the ranges of the C3 crops as reported by Ruimy et al. (1995) and Ehleringer and Björkman (1977).

Conclusion

India has very diverse and dynamic agro-ecosystems which play a vital role in ecosystem-atmospheric carbon exchanges and global carbon budget as a whole. The present study could characterise CO_2 fluxes from jute ecosystem using high-frequency measurements by eddy covariance system along with bio-meteorological observations in a hot and sub-humid Indo-Gangetic plain. The study could capture the diurnal, daily, growth stage-wise variations of NEE over the jute crop. It was observed that the diurnal variations of NEE are highly influenced by the different growth stages of the crop and incoming solar radiation (PPFD or R_n). The daytime peak NEE was lowest in the germination stage (−5 μmol CO_2 m^{-2} s^{-1}) and highest in the fibre development stage (−23 μmol CO_2 m^{-2} s^{-1}). At nighttime, the jute ecosystem acted as a net CO_2 source (5 to 8 μmol CO_2 m^{-2} s^{-1}) throughout the jute season. The daily NEE was found to increase (influx) with the progression of crop growth due to accumulation of above-ground biomass or LAI. The daily mean NEEs in germination, seedling, active vegetative, fibre development, and maturity stages of the jute crop were found to be 1.66, −0.57, −3.23, −4.23, and −2.51 gC m^{-2} day^{-1}, respectively. The seasonal cumulative NEE was found to be −268.5 gC m^{-2} (i.e. 10.3 t CO_2 ha^{-1}) signifying the jute ecosystem as a significant net CO_2 sink. The study has also reported the ecosystem level photosynthetic parameters over the different growth stages of jute crop. Maximum photosynthetic capacity was observed during the active vegetative stage (63.3 ± 1.15 μmol CO_2 m^{-2} s^{-1}), whereas peak value of apparent quantum yield was recorded during fibre development stage (0.072 ± 0.0045 μmol CO_2 μmol $photon^{-1}$). To the best of our knowledge, such dataset of ecosystem level CO_2 fluxes along with photosynthetic parameters of jute crop is the first report and can be used as a primary data source to develop/validate different jute-specific ecosystem models, crop growth models, satellite-based production estimates, light use efficiency-based productivity models, etc. These models can further be used to upscale the ecosystem CO_2 exchanges at regional level and to assess the response of the jute ecosystem at different climatic scenarios.

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Data availability The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Conflict of interest The authors declare no competing interests.

References

Agricultural Statistics at a Glance. (2018). Directorate of Economics and Statistics, Department of Agriculture Cooperation & Farmers Welfare, Ministry of Agriculture & Farmers Welfare, Government of India. http://agricoop.gov.in/sites/default/files/agristatglance2018.pdf [Accessed dated 25th February 2022]

Alberto, R. C. M., Wassmann, R., Hirano, T., Miyata, A., Kumar, A., Padre, A., & Amante, M. (2009). CO_2/heat fluxes in rice fields: Comparative assessment of flooded and non-flooded fields in the Phillippines. *Agricultural and Forest Meteorology, 149*, 1737–1750.

Alfieri, J. G., Kustas, W. P., Prueger, J. H., Hipps, L. E., Evett, S. R., Basara, J. B., Neale, C. M., French, A. N., Colaizzi, P., Agam, N., & Cosh, M. H. (2012). On the discrepancy between eddy covariance and lysimetry-based surface flux measurements under strongly advective conditions. *Advances in Water Resources, 50*, 62–78. https://doi.org/10.1016/j.advwatres.2012.07.008

Aubinet, M., Grelle, A., Ibrom, A., Rannik, Ü., Moncrieff, J., Foken, T., Kowalski, A.S., Martin, P. H., Berbigier, P., Bernhofer, C., Clement, R., Elbers, J., Granier, A., Grünwald, T., Morgenstern, K., Pilegaard, K., Rebmann, C., Snijders, W., Valentini, R., & Vesala, T. (1999). Estimates of the annual net carbon and water exchange of forests: the EUROFLUX methodology. *Adv Ecol Res, 30,* 113–175. https://doi.org/10.1016/S0065-2504(08)60018-5

Aubinet, M., Moureaux, C., Bodsonb, B., Dufrannea, D., Heinesch, B., Suleaua, M., Vancutsemb, F., & Vilret, A. (2009). Carbon sequestration by a crop over a 4-year sugar beet/winter wheat/seed potato/winter wheat rotation cycle. *Agricultural and Forest Meteorology, 149*, 407–418.

Aubinet, M., Vesala, T., & Papale, D. (Eds.). (2012). Eddy covariance: a practical guide to measurement and data analysis. Springer-Verlag.

Babst, F., Bouriaud, O., Papale, D., Gielen, B., Janssens, I. A., Nikinmaa, E., Ibrom, A., Wu, J., Bernhofer, C., Köstner, B., Grünwald, T., Seufert, G., Ciais, P., & Frank, D. (2013). Above-ground woody carbon sequestration measured from tree rings is coherent with net ecosystem productivity at five eddy-covariance sites. *New Phytologist, 201*, 1289–1303. https://doi.org/10.1111/nph.12589

Baldocchi, D. D. (2003). Assessing the eddy covariance technique for evaluating carbon dioxide exchange rates of ecosystems: Past, present and future. *Global Change Biology, 9*(4), 479–492. https://doi.org/10.1046/j.1365-2486.2003.00629.x

Baldocchi, D. D., Falge, E., Gu, L., Olson, R., Hollinger, D. Y., Running, S. W., Anthoni, P., Bernhofer, Ch., Davis, K. J., Evans, R., Fuentes, J., Goldstein, A., Katul, G., Law, B. E., Lee, X., Malhi, Y., Meyers, T. P., Munger, J. W., Oechel, W. C., … Wofsy, S. C. (2001). FLUXNET: A new tool to study the temporal and spatial variability of ecosystemscale carbon dioxide, water vapor, and energy flux densities. *Bulletin of the American Meteorological Society, 82*, 2415–2434. https://doi.org/10.1175/1520-0477(2001)082%3c2415:FANTTS%3e2.3.CO;2

Baldocchi, D. D., Hincks, B. B., & Meyers, T. P. (1988). Measuring biosphere-atmosphere exchanges of biologically related gases with micrometeorological methods. *Ecology, 69*, 1331–1340.

Banerjee, S. K., & Mathew, M. D. (1985). Carbonisation of jute stick, an agricultural waste. *Agricultural Wastes, 13*(3), 217–227.
Barman, D., Kundu, D. K., Pal, S., Pal, S., Chakraborty, A. K., Jha, A. K., Mazumdar, S. P., Saha, R., & Bhattacharyya, P. (2017). Soil temperature prediction from air temperature for alluvial soils in lower Indo-Gangetic plain. *International Agrophysics, 31*, 9–22.
Bhattacharyya, P., Neogi, S., Roy, K. S., & Rao, K. S. (2013a). Gross primary production, ecosystem respiration and net ecosystem exchange in Asian rice paddy: An eddy covariance-based approach. *Current Science, 104*(1), 67–75.
Bhattacharyya, P., Neogi, S., Roy, K. S., Dash, P. K., Tripathi, R., & Rao, K. S. (2013b). Net ecosystem CO2 exchange and carbon cycling in tropical lowland flooded rice ecosystem. *Nutrient Cycling in Agroecosystems, 95*, 133–144.
Burba, G. (2013). Eddy covariance method for scientific, industrial, agricultural and regulatory applications. *LI-COR Biosciences*.
Chakraborty, A., Choudhary, K. K., Srikanth, P., Ramana, K. V., Seshasai, M. V. R., Narayanarao, K., Amaregouda, A., Yadav, Y., & Annapurna, G. (2021). CO_2, H_2O and energy fluxes from chickpea crop grown under residual soil moisture condition in rainfed peninsular India using eddy covariance techniques. *Field Crops Research, 273*, 108307. https://doi.org/10.1016/j.fcr.2021.108307
Chander, K., Mohanty, A. K., & Joergensen, R. G. (2002). Decomposition of biodegradable packing materials jute, Biopol, BAK and their composites in soil. *Biology and Fertility of Soils, 36*, 344–349. https://doi.org/10.1007/s00374-002-0548-3
Chatterjee, S., Swain, C. K., Nayak, A. K., Chatterjee, D., Bhattacharyya, P., Mahapatra, S. S., Debnath, M., Tripathi, R., Guru, P. K., & Dhal, B. (2020). Partitioning of eddy covariance-measured net ecosystem exchange of CO_2 in tropical lowland paddy. *Paddy and Water Environment, 18*, 623–636. https://doi.org/10.1007/s10333-020-00806-7
Datta, A., Rao, K. S., Santra, S. C., Mandal, T. K., & Adhya, T. K. (2011). Greenhouse gas emissions from rice based cropping systems: economic and technologic challenges and opportunities. *Mitigation and Adaptation Strategies for Global Change*, 16(5), 597–615, ISSN 1381–2386.
Deb Burman, P. K., Shurpali, N. J., Chowdhuri, S., Karipot, A., Chakraborty, S., Lind, S. E., Martikainen, P. J., Chellappan, S., Arola, A., Tiwari, Y. K., & Murugavel, P. (2020). Eddy covariance measurements of CO_2 exchange from agro-ecosystems located in subtropical (India) and boreal (Finland) climatic conditions. *Journal of Earth System Science, 129*(43), 1–18. https://doi.org/10.1007/s12040-019-1305-4
Dold, C., Hatfield, L. J., Prueger, H. J., Sauer, J. T., Moorman, B. T., & Wacha, M. K. (2019). Impact of management practices on carbon and water fluxes in corn–soybean rotations. *Agrosystems, Geosciences and Environment, 2*, 180032. https://doi.org/10.2134/age2018.08.0032
Ehleringer, J., & Björkman, O. (1977). Quantum yields for CO_2 uptake in C_3 and C_4 plants dependence on temperature, CO_2, and O_2 concentration. *Plant Physiology, 59*, 86–90.
Falge, E., Baldocchi, D. D., Olson, R. J., Anthoni, P., Aubinet, M., Bernhofer, C., Burba, G., Ceulemans, R., Clement, R., Dolman, H., Granier, A., Gross, P., Grünwald, T., Hollinger, D., Jensen, N.-O., Katul, G., Keronen, P., Kowalski, A., Ta Lai, C., … Wofsy, S. (2001). Gap filling strategies for defensible annual sums of net ecosystem exchange. *Agricultural and Forest Meteorology, 107*, 43–69.
FAOSTAT. (2018). FAOSTAT statistical database. Available at: http://www.fao.org/faostat/en/#data/QC (Accessed on 19 November 2020).
Field, C. B., Barros, V. R., Dokken, D. J., Mach, K. J., Mastrandrea, M. D, Bilir, T. E., Chatterjee, M., Ebi, K. L., Estrada, Y. O., Genova, R. C., Girma, B., Kissel, E. S., Levy, A. N., MacCracken, S., Mastrandrea, P. R., & White, L. L. (2014). Climate change impacts, adaptation and vulnerability: Part A: Global and sectoral aspects: Working group II contribution to the fifth assessment report of the intergovernmental panel on climate change. https://doi.org/10.1017/CBO9781107415379.
Foken, T. (2008). *2008*. Springer-Verlag.
Fong, B. N., Reba, M. L., Teague, T. G., Runkle, B. R., & Suvočarev, K. (2020). Eddy covariance measurements of carbon dioxide and water fluxes in US mid-south cotton production. *Agriculture, Ecosystems & Environment*, *292*, 106813.https://doi.org/10.1016/j.agee.2019.106813
Haxeltine, A., & Prentice, I. C. (1996). BIOME3: An equilibrium terrestrial biosphere model based on ecophysiological constraints, resource availability, and competition among plant functional types. *Global Biogeochemical Cycles, 10*(4), 693–709. https://doi.org/10.1029/96GB02344
Hoque M. B., Solaiman, A. B. M., Alam, H., Mahmud, H., & Nobi, A. (2018). Mechanical, degradation and water uptake properties of fabric reinforced polypropylene based composites: effect of alkali on composites. *Fibers, 6*, 94. https://doi.org/10.3390/fib6040094
Islam, M. M., & Ali, M. S. (2017). Economic importance of jute in Bangladesh: Production, research achievements and diversification. *International Journal of Economic Theory and Application, 4*(6), 45–57.
Jacobs, A. F. G., & Van Boxel, J. H. (1988). Changes of the displacement height and roughness length of maize during a growing season. *Agricultural and Forest Meteorology, 42*, 53–62. https://doi.org/10.1016/0168-1923(88)90066-4
Jha, C. S., Thumaty, K. C., Rodda, S. R., Sonakia, A., & Dadhwal, V. K. (2013). Analysis of carbon di oxide and energy fluxes over an India teak mixed deciduous forest for winter and summer months using eddy covariance technique. *Journal of Earth System Sciences, 122*(5), 1259–12368.
Kumar, M., Mitra, S., Majumdar, B., & Kundu, D. K. (2016). Quantification of leaf fall and nutrient recycled in jute cultivation. *Jaf News, 14*(1), 16.
Kundu, A., Sarkar, D., Mandal, N. A., Sinha, M. K., & Mahapatra, B. S. (2012). A secondary phloic (bast) fibre-shy (bfs) mutant of dark jute (*Corchorus olitorius* L.) develops lignified fibre cells but is defective in cambial activity. *Plant Growth Regulation, 67*, 45–55. https://doi.org/10.1007/s10725-012-9660-z
Le Quere, C., Andrew, R. M., Canadell, J. G., Sitch, S., Ivar Korsbakken, J., Peters, G. P., Manning, A. C., Boden, T. A., Tans, P. P., Houghton, R. A., Keeling, R. F., Alin, S., Andrews, O. D., Anthoni, P., Barbero, L., Bopp, L., Chevallier, F., Chini, L. P., Ciais, P., … Zaehle, S. (2016). Global Carbon Budget 2016. *Earth System Science Data, 8*, 605–649. https://doi.org/10.5194/essd-8-605-2016

Lichtenthaler, H. K. (1987). Chlorophylls and carotenoids: Pigments of photosynthetic biomembranes. *Methods in Enzymology, 148*, 350–382.

LICOR, Inc. (2016). EddyPro® Software (Version 6.2) [Computer software]. Infrastructure for Measurements of the European Carbon Cycle consortium. Lincoln, NE. LI-COR, Inc.

Lohila, A., Aurela, M., Tuovinen, J. P., & Laurila, T. (2004). Annual CO_2 exchange of a peat field growing spring barley or perennial forage grass. *Journal of Geophysical Research, 109*, D18116. https://doi.org/10.1029/2004JD004715

Mahapatra, B. S., Mitra, S., Sinha, M. K., & Ghorai, A. K. (2009). Research and development in jute (*Corchorus sp*.) and allied fibres in India-A review. *Indian Journal of Agronomy*, *54*(4), 361–373.

Mauder, M., Cuntz, M., Drüe, C., Graf, A., Rebmann, C., Schmid, H. P., Schmidt, M., & Steinbrecher, R. (2013). A strategy for quality and uncertainty assessment of long-term eddy-covariance measurements. *Agricultural and Forest Meteorology*, *169*, 122–135, ISSN 0168–1923.

Mazumdar, S. P., Kundu, D. K., Saha, A. R., Majumdar, B., Saha, R., Singh, A. K., Barman, D., Ghosh, D., Dey, R., Behera, M. S., Mitra, S., & Bhattacharyya, P. (2018). Carbon and nutrient dynamics under long-term nutrient management in tropical rice-wheat-jute system. *Archives of Agronomy and Soil Science, 64*, 1595–1607. https://doi.org/10.1080/03650340.2018.1446521

Mitra, S., Sinha, M. K., Maiti, S. N., & Sarkar, S. (2006). Recommendations for jute and allied fibres crops – an endeavor of All India Network Project. Technical Bulletin Series No. 3/2006. ICAR-All India Network Project on Jute and Allied Fibres, Kolkata – 700120, 28.

Mohanty, A. K., Khan, M., & A, & Hinrichsen, G. (2000). Surface modification of jute and its influence on performance of biodegradable jute-fabric/Biopol composites. *Comp Sci Technol, 60*, 1115–1124.

Moncrieff, J., Clement, R., Finnigan, J., & Meyers, T. (2004). Averaging, detrending, and filtering of eddy covariance time series. In Handbook of Micrometeorology; Lee, X., Massman, W., Law, B., Eds.; Kluwer Academic: Dordrecht, Netherlands, 7–31.

Moncrieff, J. B., Massheder, J. M., de Bruin, H., Elbers, J., Friborg, T., Heusinkveld, B., Kabat, P., Scott, S., Soegaard, H., & Verhoef, A. (1997). A system to measure surface fluxes of momentum, sensible heat, water vapour and carbon dioxide. *Journal of Hydrology, 188–189*, 589–611.

Moureaux, C., Debacq, A., Hoyaux, J., Suleau, M., Tourneur, D., Bodson, B., & Aubinet, A. (2008). Carbon balance assessment of a Belgian winter wheat crop (*Triticum aestivum* L.). *Global Change Biology*, *14*(6), 1353–1366.

Nakai, T., & Shimoyama, K. (2012). Ultrasonic anemometer angle of attack errors under turbulent conditions. *Agricultural and Forest Meteorology, 18*, 162–163.

NBSS & LUP. (1990). Agro-ecological regions of India (2nd ed.). *NBSS Publisher, 24*, 130. ISBN:81–85460–15–9.

NBSS & LUP. (1994). Soil Temperature Regimes of India. *NBSS Publisher, 41*, 4. ISBN:81–85460–23-X.

Palit, P., & Meshram, J. H. (2004). Physiological characterization of a phenotypically distinct jute (*Corchorus olitorius*) genotype. *Plant Genetic Resources, 2*(3), 175–180. https://doi.org/10.1079/PGR200449

Patel, N. R., Dadhwal, V. K., & Saha, S. K. (2011). Measurement and scaling of carbon dioxide (CO2) exchanges in wheat using flux-tower and remote sensing. *Journal of the Indian Society of Remote Sensing, 39*, 383. https://doi.org/10.1007/s12524-011-0107-1

Patel, N. R., Pokhariyal, S., Chauhan, P., & Dadhwal, V. K. (2021). Dynamics of CO_2 fluxes and controlling environmental factors in sugarcane (C4)–wheat (C3) ecosystem of dry sub-humid region in India. *International Journal of Biometeorology, 65*(7), 1069–1084. https://doi.org/10.1007/s00484-021-02088-y

Patra, P. K., Canadell, J. G., Houghton, R. A., Piao, S. L., Oh, N. H., Ciais, P., Manjunath, K. R., Chhabra, A., Wang, T., Bhattacharya, T., Bousquet, P., Hartman, J., Ito, A., Mayorga, E., Niwa, Y., Raymond, P. A., Sarma, V. V. S., & Lasco, R. (2013). The carbon budget of South Asia. *Biogeoscience, 10*, 513–527. https://doi.org/10.5194/bg-10-513-2013

Potter, C. S., Randerson, J. T., Field, C. B., Matson, P. A., Vitousek, P. M., Mooney, H. A., & Klooster, S. A. (1993). Terrestrial ecosystem production: A process model based on global satellite and surface data. *Global Biogeochemical Cycles, 7*(4), 811–841. https://doi.org/10.1029/93GB02725

Raich, J. W., Rastetter, E. B., Melillo, J. M., Kicklighter, D. W., Steudler, P. A., Peterson, B. J., Grace, A. L., Moore, B., III., & Vorosmarty, C. J. (1991). Potential net primary productivity in South America: Application of a global model. *Ecological Applications, 1*(4), 399–429. https://doi.org/10.2307/1941899\

Reichstein, M., et al. (2005). On the separation of net ecosystem exchange into assimilation and ecosystem respiration: Review and improved algorithm. *Global Change Biology, 11*(9), 1424–1439.

Rodda, S. R., Thumaty, K. C., Jha, C. S., & Dadhwal, V. K. (2016). Seasonal Variation of carbon di oxide, water vapour and energy fluxes in tropical Indian Mangroves. *Forest, 7*(2), 35.

Ruimy, A., Dedieu, G., & Saugier, B. (1996). TURC: A diagnostic model of continental gross primary productivity and net primary productivity. *Global Biogeochemical Cycles, 10*(2), 269–285. https://doi.org/10.1029/96GB00349

Ruimy, A., Jarvis, P. G., Baldocchi, D. D., & Saugier, B. (1995). CO_2 fluxes over plant canopies and solar radiation: A review. *Advances in Ecological Research, 26*, 1–68. https://doi.org/10.1016/S0065-2504(08)60063-X

Running, S. W., & Coughlan, J. C. (1988). A general model of forest ecosystem processes for regional applications I. Hydrologic balance, canopy gas exchange and primary production processes. *Ecological Modelling*, *42*(2), 125–154, http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.554.2161&rep=rep1&type=pdf [Accessed dated 25th February 2022]

Saha, P., Roy, D., Manna, S., Adhikari, B., Sen, R., & Roy, S. (2012). Durability of transesterified jute geotextiles. *Geotext. Geomembranes, 35*, 69–75. https://doi.org/10.1016/j.geotexmem.2012.07.003

Saito, M., Miyata, A., Nagai, H., & Yamada, T. (2005). Seasonal variation of carbon dioxide exchange in rice paddy field in Japan. *Agricultural and Forest Meteorology, 135*, 93–109.

Shahinur, S., Hasan, M., Ahsan, Q., Saha, D. K., & Islam, M. (2015). Characterization on the properties of jute fiber atdifferent portions. *International Journal of Polymer Science*. Article ID 262348. https://doi.org/10.1155/2015/262348

Summerscales, J., Dissanayake, N. P. J., Virk, A. S., & Hall, W. (2010). A review of bast fibres and their composites. Part 1 - Fibres as reinforcements. *Composites Part A, 41,* 1329–1335.

Suyker, A. E., & Verma, S. B. (2010). Coupling of carbon dioxide and water vapor exchanges of irrigated and rainfed maize–soybean cropping systems and water productivity. *Papers in Natural Resources, 565*.

Takata K., et al. (2017). Reconciliation of top-down and bottom-up CO2 fluxes in Siberian larch forest. *Environmental Research Letter, 12*, 125012

Thomas, M. V., Malhi, Y., Fenn, K. M., Fisher, J. B., Morecroft, M. D., Lloyd, C. R., Taylor, M. E., & McNeil, D. D. (2011). Carbon dioxide fluxes over an ancient broadleaved deciduous woodland in southern England. *Biogeosciences, 8*, 1595–1613.

Wagle, P., & Kakani, V. G. (2014). Seasonal variability in net ecosystem carbon dioxide exchange over a young Switchgrass stand. *GCB Bioenergy, 6*(4), 339–350.

Wagle, P., Gowda, H. P., Moorhead, E. J., Marek, W. G., & Brauer, K. D. (2018). Net ecosystem exchange of CO_2 and H_2O fluxes from irrigated grain sorghum and maize in the Texas High Plains. *Science of the Total Environment, 637–638*, 163–173.

Wagle, P., Gowda, P. H., Anapalli, S. S., Reddy, K. N., & Northup, B. K. (2017). Growing season variability in carbon dioxide exchange of irrigated and rainfed soybean in the southern United States. *Science of the Total Environment, 593*, 263–273.

Webb, E. K., Pearman, G. I., & Leuning, R. (1980). Correction of flux measurements for density effects due to heat and water vapour transfer. *Quarterly Journal of the Royal Meteorological Society, 106*, 85–100.

Wilczak, J. M., Oncley, S. P., & Stage, S. A. (2001). Sonic anemometer tilt correction algorithms. *Boundary Layer Meteorology, 99*, 127–150.

Zhang, L. M., Yu, G. R., Sun, X. M., Wen, X. F., Ren, C. U., Fu, Y. L., Li, Q. K., Li, Z. Q., Liu, Y. F., Guan, D. X., & Yan, J. H. (2006). Seasonal variations of ecosystem apparent quantum yield (a) and maximum photosynthesis rate (Pmax) of different forest ecosystems in China. *Agricultural and Forest Meteorology, 137*, 176–187. https://doi.org/10.1016/j.agrformet.2006.02.006

Zheng, X., et al. (2008). Quantifying net ecosystem carbon dioxide exchange of a short-plant cropland with intermittent chamber measurements. *Global Biogeochemical Cycles, 22*, GB3031, https://doi.org/10.1029/2007GB003104.

Zhu, Z., Sun, X., Wen, X., Zhou, Y., Tian, J., & Yuan, G. (2006). Study on the processing method of nighttime CO_2 eddy covariance flux data in China FLUX. *Science in China Series d: Earth Sciences, 49*, 36–46.