Gross primary production, ecosystem respiration and net ecosystem exchange in Asian rice paddy: an eddy covariance-based approach

P. Bhattacharyya*, S. Neogi, K. S. Roy and K. S. Rao

Division of Crop Production, Central Rice Research Institute, Cuttack 753 006, India

Carbon dioxide (CO_2) exchange between the terrestrial ecosystems and the atmosphere is one of the major processes affecting atmospheric CO_2 concentration. In various ecosystems in the world long-term observations of CO_2 exchange have been made for assessing the role of terrestrial ecosystems in the present-day global CO_2 budget and to predict its changes in the future climatic scenario. The eddy covariance (EC) system can provide a measure of net ecosystem exchange (NEE), which can be partitioned into gross primary production (GPP) and ecosystem respiration (RE) using mathematical modelling approach helpful for characterization of ecosystem carbon budgets. The EC technique for measuring CO_2, water vapour and energy fluxes between the biosphere and the atmosphere is widely used in various regional networks. Presently, more than 400 EC sites are operational worldwide measuring carbon exchange in different biomes and climatic conditions at high temporal resolution. Rice paddy fields are widespread in monsoon Asia and the carbon exchange between paddy fields and the atmosphere is greatly influenced by cultivation and field management practices. In this review, an attempt has been made to summarize NEE, GPP and RE with the help of EC system in Asian rice paddies focusing on CO_2 exchange between the biosphere and the atmosphere.

Keywords: Ecosystem respiration, eddy covariance, gross primary production, net ecosystem exchange, rice paddy.

GLOBAL budgeting of the greenhouse gas (GHG) exchanges between ecosystems (terrestrial, aquatic) and the atmosphere is one of the key issues of climate change research. There is a need to monitor and quantify GHG exchanges in the various ecosystems prevalent in the world. There has been a drastic increase in the atmospheric concentration of GHGs, viz. carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), etc. since the industrial revolution because of fossil-fuel combustion, land-use change, deforestation and intensification of agriculture. Agriculture accounted for an estimated emission of 5.1 to 6.1 $GtCO_2$-eq yr^{-1} GHGs in 2005 (10–12% of total global anthropogenic emissions of GHGs)[1]. Global atmospheric concentration of CO_2 has increased markedly as a result of human activities[1] since 1750 (pre-industrial era) from 280 to 379 ppmv in 2005 and is currently increasing at the rate of 1.9 ppmv yr^{-1}. Despite large annual exchanges of CO_2 between the atmosphere and agricultural lands, the net flux is approximately balanced, with CO_2 emissions only around 0.04 Gt CO_2 yr^{-1}. Agriculture releases to the atmosphere[1,2] a significant amount of CO_2 along with CH_4 and N_2O. Carbon dioxide is released largely from microbial decay or burning of plant litter and soil organic matter[3,4]. According to the US-EPA estimation[5], net CO_2 emission from the soil is less than 1% of global anthropogenic CO_2 emissions. Half of the anthropogenically released CO_2 may be absorbed in the terrestrial biosphere, the soil or the ocean, or some combination of all three[1]. Agro-ecosystems are equally important and contribute to regional carbon budget where crops are dominant[6] and, therefore, proper methodology is required for the upscaling and budgeting of carbon exchange components in crop lands. Carbon dioxide flux measurements of agro-ecosystems in relation to photosynthesis and respiration over crops and their response to environmental variables are vital for understanding the physiological behaviour of agro-ecosystems and predicting future climate change[6].

Rice is the major crop in Asia and the area of rice paddies in this region is about 87% of the world's total rice cultivated area[7] and about 80% of it is grown under flooded conditions[8]. Rice is grown in different environments, in varied climatic (tropical to temperate), edaphic and biological conditions and different agricultural management practices (viz. ploughing, manure amendment, seeding, transplanting, water management, harvest), which affect the rates of CO_2 and CH_4 emissions[9]. Therefore, it is important to quantify CO_2 exchange in paddy fields in Asia, where the highest number of such fields in the world exists. The eddy covariance (EC) technique has been widely employed for CO_2, water vapour and heat

*For correspondence. (e-mail: pratap162001@yahoo.co.in)

flux measurement in various parts of the world, especially in forests, savannah and grasslands, but there are few studies on the rice ecologies. In India, no such studies in rice fields have been reported so far. The Central Rice Research Institute (CRRI) has an EC flux tower over lowland flooded rice paddy ecosystem. For the first time in India CRRI installed the flux tower in submerged rice ecosystem in October 2009. Since then continuous monitoring of CO_2 concentration as well as its fluxes, flux pattern and dynamics leading to quantification of net CO_2-C on diurnal, seasonal and annual scales is going on during rice cultivation and fallow periods as well. This study helps to assess the source and/or strength capacity of this agro-ecosystem, which ultimately determines the emission and/or sequestration potential of flooded rice paddies (with regard to CO_2) under the background of global warming and climate change. Carbon dioxide exchange and energy balance of rice paddies have been studied intensively during 1950s and 1960s employing conventional micrometeorological techniques, viz. the aerodynamic and Bowen ratio methods[10]. Since 1980s, with the development of fast-response CO_2 analysers, CO_2 fluxes over rice canopy are measured by the EC method as this is a powerful tool for characterizing the gaseous carbon budget of rice paddy ecosystem[8]. But, most of the conducted studies involved short-term measurements lasting for a few days to a few weeks.

Micrometeorological methods like EC do not interfere with the processes of gas exchange between the surface source and the atmosphere, and are suited for continuous flux measurements[11]. In Asia, notable work with EC flux measurements has been done in western Japan[8], China[12], central Japan[13], Bangladesh[14,15], the Philippines[16] and Taiwan[9] to monitor seasonal, annual and inter-annual variations in CO_2 flux in irrigated, submerged (flooded) and aerobic rice fields. Rice paddies in Asia have an important role in the global budget of GHGs[1] such as CO_2 and CH_4, yet there is considerable uncertainty in the magnitude of the net fluxes of CO_2 from these ecosystems. Globally, the rice-growing areas are predicted to increase by 4.5% at the end of 2030 (ref. 17). Therefore, field-level studies to measure net CO_2 fluxes and to improve understanding of the factors controlling them are needed in changed climatic scenarios.

NEE, RE and GPP

The net ecosystem exchange (NEE) of CO_2 between the biosphere and the atmosphere is the balance between the fluxes associated with photosynthetic assimilation by the foliage (gross primary production, GPP) and respiratory effluxes (RE) from autotrophs and heterotrophs (microbial and soil fauna)[18].

NEE = RE – GPP (ref. 19).

NEE provides information about the length of the active season and the strength of the component processes, photosynthesis and respiration[20]. The EC system has become popular for estimating NEE between the atmosphere and rice paddy ecosystem for characterizing the carbon balance during the period of interest[21,22]. The two most vital environmental factors affecting RE are temperature and soil moisture[23]. It is important to separate or partition NEE into GPP and RE, as it provides a better understanding of assimilatory or respiratory processes[20,24] (Figure 1). Figure 1 depicts the typical diurnal variation of NEE, GPP and RE during the course of a particular 24 h day when continuous flux observation study was going on in CRRI, during the 2010–11 dry (rabi) season in a lowland (flooded) rice paddy ecology at heading to flowering stage of the crop. However, the EC technique provides a measure of NEE only; so to partition NEE into GPP and RE, ancillary measurements are required.

Eddy covariance system for CO_2 flux measurement

The EC technique is widely employed as the standard micrometeorological method to monitor fluxes of CO_2, water vapour and heat, which are necessary to determine CO_2 and heat balances of land surfaces[25]. The EC technique has become the most important method for measuring trace gas exchange between terrestrial ecosystems and the atmosphere[22,26]. It can represent a large area of land at the ecosystem scale than the typical plot area[27–31] for a short period or even for several years. It has become the backbone for bottom-up estimates of continental carbon balance from hourly to inter-annual timescales[32–35]. The EC technique is based on high frequency (10–20 Hz) measurements of wind speed and direction as well as CO_2 and H_2O concentrations at a point over the canopy using a three-axis sonic anemometer and a fast-response infrared gas analyser[25,36,37] (Figure 2). The two sensors, three-

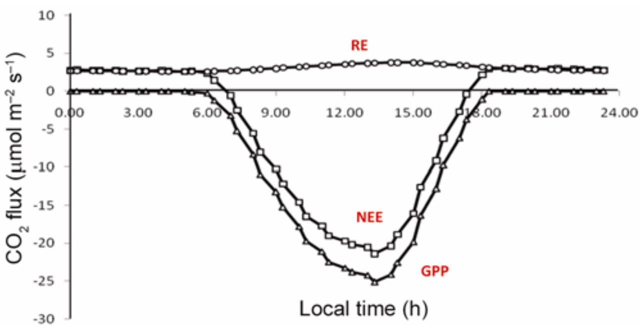

Figure 1. Diurnal course of CO_2 fluxes derived from eddy covariance showing partitioning of net ecosystem exchange (NEE) into gross primary production (GPP) and ecosystem respiration (RE) during rabi (dry) season 2010–11, observed on 3 April 2011, at heading to flowering stage of rice in the experimental farm of the Central Rice Research Institute, Cuttack.

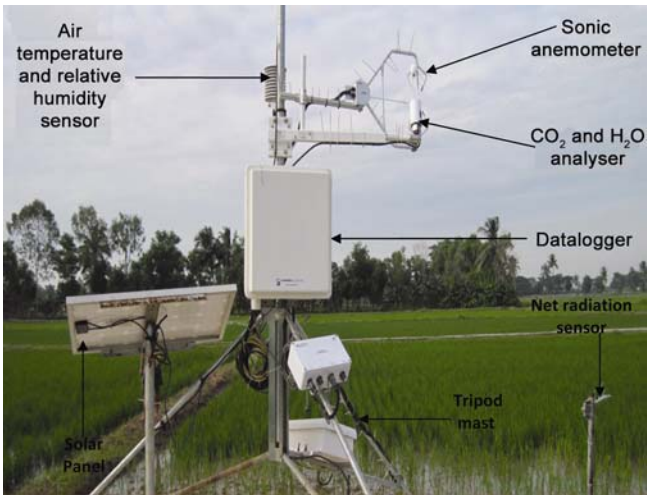

Figure 2. Eddy covariance system for CO_2 flux measurement installed in the rice field of CRRI, Cuttack.

axis sonic anemometer and fast-response infrared gas analyser, are normally installed at 2–3 m height (depending on the rice crop canopy height) on a tripod mast with a sensor separation of 15–20 cm. Data obtained from the three-axis sonic anemometer and CO_2/H_2O infrared gas analyser, are sampled at 10 and/or 20 Hz using a fast-response datalogger[18,38,39]. The mean vertical flux density of CO_2 is obtained as the 30 min covariance between vertical fluctuations (ω') and CO_2 mixing ratio (c')[26]

$$F_z = \overline{\rho_a} \cdot \overline{\omega' c'}. \tag{1}$$

In eq. (1), ρ_a represents air density, the overbars denote time-averaging and primes represent fluctuations about average value. A positive covariance between ω' and c' indicates net CO_2 transfer into the atmosphere and a negative value indicates net CO_2 absorption by the vegetation. NEE is calculated as the sum of CO_2 storage change (F_s) within the air space below flux measuring height and the eddy CO_2 flux (F_z). But, for the purpose of NEE calculation, F_s is neglected when canopy height is less than 1 m. EC flux data are usually subject to varying degrees of quality checks because the data may be affected by precipitation, improper functioning of the instrument (and/or) inappropriate meteorological conditions for flux studies. For proper EC flux measurement studies integral turbulent characteristics test and stationarity test of the half-hourly flux data are conducted. The datasets which pass these two tests are then processed for further calculation and other data are rejected. The EC system is set-up at the centre of a flat, homogeneous similar rice ecology having enough fetch for micrometeorological flux measurement depending upon the prevalent wind direction. The partitioning of NEE into GPP and RE is done using the conventional mathematical modelling approach, wherein GPP and RE are expressed as empirical functions of meteorological variables[40]. GPP is CO_2 uptake by the photosynthesis of vegetation and RE represents CO_2 release through respiration of soil, roots, stems and leaves of plants. Night-time RE (RE(N)) is determined using the EC system from night-time NEE, as at night-time NEE is equal to night-time ecosystem respiration (RE(N)), since GPP = 0. NEE in night-time hours is expressed as an exponential function of air temperature (T) and the relationship is then applied to the daytime for estimating RE in daytime (RE(D)).

$$\mathrm{RE(N)} = R_0\, Q_{10}^{[(T - T_0)/10]}, \tag{2}$$

where R_0 and Q_{10} are empirical constants determined by running regression analysis between RE(N) and temperature $(T - T_0)/10$; T can either be air or soil temperature[41] and T_0 is the reference temperature. Based on the assumption that the daytime temperature response of RE is the same as that of the RE(N), eq. (2) is applied to the daytime data to estimate daytime half-hourly RE (RE(D)) and GPP (F_{GPP}) is calculated as

$$F_{GPP} = -F_{NEE} + \mathrm{RE(D)}, \tag{3}$$

where F_{NEE} denotes NEE[42,43]. GPP is generally expressed as a rectangular hyperbolic function of incident photosynthetically active radiation (Q_P),

$$F_{GPP} = P_{max}\, \alpha\, Q_P/(P_{max} + \alpha Q_P), \tag{4}$$

where P_{max} and α are empirical constants to be determined by regression between GPP and PAR. P_{max} represents the hypothetical maximum of GPP or the closeness to the linear response coefficient[44] and α denotes the initial slope of the function or ecosystem quantum yield. There is a need to gap-fill those missing values of eddy flux data (in order to estimate seasonal NEE) which are rejected by quality control tests or due to instrument malfunctioning. For CO_2 flux nonlinear regression analysis is performed for gap-filling missing data of few hours or more and missing values are estimated from meteorological variables. For gap-filling of night-time NEE data, eq. (2) is used. To gap-fill daytime NEE data, RE(D) and GPP are first gap-filled. RE (D) is gap-filled using eq. (2) and GPP is gap-filled using eq. (4).

Quantification of NEE, GPP and RE employing EC technique in Asian rice paddies

Carbon dioxide fluxes from different Asian rice paddy ecologies at different spatio-temporal scales revealed that NEE, GPP and RE differ in different regions depending on the cropping pattern, duration, sequence of crop cycle, irrigation, drainage pattern, soil type, tillage practices and

Table 1. Experimental details of net ecosystem exchange (NEE) studies by eddy covariance techniques in some rice ecologies in Asia

Location	Temperature (°C)	Rainfall (mm)	Soil type	Fertilization	Drainage status	NEE*	Cropping pattern	Period of observation	Stage of crop
Bangladesh Agricultural University (BAU), Bangladesh (24.75°N lat., 90.5°E long. and 18 m amsl)[14]	–	2175	Sandy loam texture	–	Irrigated	Integrated NEE approximately –105 g C m^{-2}	Rice–fallow–rice	From 70 to 79 days after transplanting in Boro (dry season) rice-growing season 2006	Full heading stage of rice
BAU (24.73°N lat., 90.42°E long. and 18 m amsl)[15]	25.4	2055	Sandy loam texture	Chemical	Irrigated and rainfed	Summer fallow +22 g C m^{-2} Winter fallow +40 g C m^{-2} Boro season NEE –299 g C m^{-2} Aman season –290 g C m^{-2} Whole year NEE –527 g C m^{-2}	Rice–fallow–rice	Whole year of 2007, including two cropping seasons and two fallow periods	Vegetative to harvesting period of two crop-growing seasons plus fallow periods
International Rice Research Institute (IRRI), The Philippines (14°09′53″N, 120°15′14″E, 21 m amsl)[16]	27	1971	Silty clay loam	Chemical	Irrigated	Flooded rice fields integrated season-long NEE is –258 g C m^{-2}, whereas in aerobic rice fields integrated season-long NEE is –85 g C m^{-2}	Rice–rice	From 6 to 118 days after transplanting (flooded rice) and/or days after sowing (aerobic rice), dry season 2008	Vegetative to harvesting stage
Taiwan (23°58′13.3″N lat. and 120°39′27.2″E long. having an elevation of 100 m amsl)[9]	–	–	–	Chemical	Drained	Integrated NEE approximately +22.1 g C m^{-2} for one month	Rice–rice	One month, 24 October – 23 November 2006 (2 cropping season)	Heading to maturity stage of the crop
Mase paddy flux site, Japan (36°03′N lat., 140°01′E long. and 15 m amsl)[13]	13.5	1235.6	Clay loam	Chemical	Irrigated	Integrated NEE approximately –397.64 g C m^{-2}	Rice	Primary crop period, from 2 May–18 September 2002	Transplanting to harvesting
Okayama University, Japan (34°32′N lat., 133°56′E long. and 2 m amsl)[8]	–	–	Clay	Chemical	Irrigated and drained	Integrated NEE approximately –47.62 g C m^{-2}	Rice–rice	Almost one week, 6–13 August 1996	A month before heading stage of crop
Central Rice Research Institute, India (20°27.113′N lat., 85°56.416′E long. and 24 m amsl)	27.7	1500	Clay loam	Chemical	Irrigated	Integrated NEE: –341g C m^{-2}, rabi (dry) season, 2010–11 (unpublished data)	Rice–fallow–rice	Ten days after transplanting to maturity during rabi (dry) season, 2010–11	Vegetative to maturity stage
China (28°55′N lat., 111°27′E long.)[12]	16.5	1448	Red clay	–	–	Annual cumulative total soil respiration is about 425.45, 616.36 and 621.82 g C m^{-2}	Rice–rice–fallow	Annual observations of soil respiration of the years 2003, 2004 and 2005 respectively	Total rice-growing seasons along with fallow periods

*Negative NEE represents CO_2 fluxes from atmosphere towards the rice field (CO_2 absorption or uptake by rice), whereas positive NEE represents CO_2 fluxes from rice fields towards the atmosphere (CO_2 emission from the rice field).

climate parameters (Table 1). The CO_2 fluxes quantified by the EC technique were used to study the inter-relationship of NEE in some selected Asian rice paddies.

At an agricultural farm in Bangladesh[14], rice paddies exhibited a clear diurnal pattern in CO_2 fluxes. NEE ranged from –38 to 10 μmol CO_2 m^{-2} s^{-1} during heading stage (70–79 DAT) in boro rice (dry season rice), 2006. It showed a daytime uptake (negative NEE, i.e. uptake of CO_2 due to photosynthetic assimilation) and night-time release of CO_2 (positive NEE, i.e. emission of CO_2 due to respiration in the absence of photosynthesis) from the canopy leading to net cumulative NEE of –105 g C m^{-2} (Table 1).

Season-long measurement of CO_2 flux employing the EC method to study the CO_2 budget in single rice-cropping paddy field was made at the Mase paddy flux site, in central Japan[13] (Table 1). During the mid-vegetative stage the paddy field became the net CO_2 sink and diurnal variation of NEE became prominent. NEE reached its peak in heading stage with the midday uptake of –29.55 μmol CO_2 m^{-2} s^{-1} and night-time release of +6.82 μmol CO_2 m^{-2} s^{-1} (Figure 3 *a*).

In the International Rice Research Institute (IRRI), the Philippines during dry season 2008, NEE was monitored in both flooded and aerobic rice fields[16]. NEE was about –10 μmol CO_2 m^{-2} s^{-1} from active tillering to panicle initiation stage, and it reached a lowest value of –22 μmol CO_2 m^{-2} s^{-1} (Figure 3 *b*) during heading to flowering stage in flooded rice fields. From tillering to ripening stage, the flooded rice fields behaved as net CO_2 sink on daily basis. On the other hand, aerobic rice fields behaved as net CO_2 sink from reproductive to harvesting stage with the mean value of –2.23 μmol CO_2 m^{-2} s^{-1}.

In central Taiwan (Table 1), CO_2 fluxes showed a clear diurnal pattern during rice maturity period (from 24 October to 23 November 2006)[9]. The fluxes and concentration of CO_2 were measured by the EC system mounted at 27.5 m above ground level. During the study period the daily values of CO_2 exchange ranged from –17.03 to 12.85 μmol CO_2 m^{-2} s^{-1} having a standard deviation of 4.7 μmol m^{-2} s^{-1}. But the diurnal mean hourly composite of CO_2 flux ranged between –7 and +7 μmol CO_2 m^{-2} s^{-1} (Figure 3 *c*). As a whole, during the measurement period, the rice paddy ecosystem behaved as a potential CO_2 source with a daily average flux of 0.71 μmol CO_2 m^{-2} s^{-1} and contributed to atmosphere 22.1 g C m^{-2} (Table 1).

In the experimental farm of CRRI, diurnal variations in mean NEE during the rabi (dry) season of 2010–11 were monitored with the help of the EC system, and the values of NEE varied between +3.87 and –19.22 μmol CO_2 m^{-2} s^{-1} depending upon the crop phenology (Figure 3 *d*). Maximum NEE and GPP by rice crop was found between 12.00 and 14.00 h, whereas maximum RE was found between 12.00 and 15.00 h over the cropping season (Figure 3 *d*). The average daily CO_2 concentration in the atmosphere varied between 360 and 385 μmol mol^{-1} during the entire course of study (Figure 4). Plant photosynthesis during the daytime led to the uptake of CO_2 from the atmosphere whereas respiration at night contributed to an efflux of CO_2 to the atmosphere in the absence of photosynthesis. Rice crop behaved as a net CO_2 sink almost over the entire crop season, except a few days during the maturity period when it became a net CO_2 emitter.

In Bangladesh, one year continuous monitoring of CO_2 fluxes was done by a tower-based EC system in a double-cropping paddy field (Table 1) for evaluating seasonal variation of RE[15]. Boro rice is cultivated in the dry season, from late winter (February) to mid-summer (May), under irrigated condition, whereas aman rice (wet-season rice) is cultivated mostly in the rainy season, from August to early winter (December) in rainfed condition. The seasonal variation in daily RE in the rice field was characterized by two annual peaks (Figure 5 *a*), one in the late-boro season (mid-May) and another in the mid-aman season (late September). The peak in the boro season was larger. During the summer fallow period considerable large RE was observed, which was caused by respiration of the ratoon crop. RE during the summer fallow period was almost balanced by active photosynthetic CO_2 assimilation with a resultant NEE of 22 g C m^{-2} (Figure 5 *b*). The integrated cumulative RE values for the boro season, summer fallow period, aman season, winter fallow period and for total annual scale were 412, 257, 311, 68 and 1047 g C m^{-2} respectively. The integrated GPP and NEE values were in the order of 711, 235, 601, 28 and 1574 g C m^{-2} and –299, 22, –290, 40 and –527 g C m^{-2} respectively, for boro season, summer fallow period, aman season, winter fallow period and for total annual scale in 2007 (Figure 5 *b*).

The total C budget integrated over the rice cropping period showed that the NEE in flooded rice fields (–258 g C m^{-2}) was about three times higher than that of aerobic rice fields (–85 g C m^{-2} in IRRI)[16] (Table 1; Figure 5 *c*). The integrated seasonal GPP and RE values for flooded and aerobic rice fields were 778 and 521 g C m^{-2}, and 515 and 430 g C m^{-2} respectively (Figure 5 *c*).

In the Mase paddy flux site in central Japan, the rice plant biomass over the season exhibited seasonal changes which affected ecosystem respiration[13]. The mid-season and pre-harvest drainages also affected ecosystem respiration because removal of standing water enhanced direct CO_2 diffusion from the soil. It was found that the ecosystem respiration in the late growing period was dominated by rice plant respiration as a result of large above-ground biomass. In a nutshell, the daily net ecosystem CO_2 exchange showed a seasonal variation and the maximum uptake rate in a day was –10.64 g C m^{-2} when the leaf area index of rice reached its peak. On a seasonal scale the integrated GPP, RE and NEE values of the primary crop period were 1143.55, 745.91 and –397.64 g C m^{-2} respectively (Figure 5 *d*).

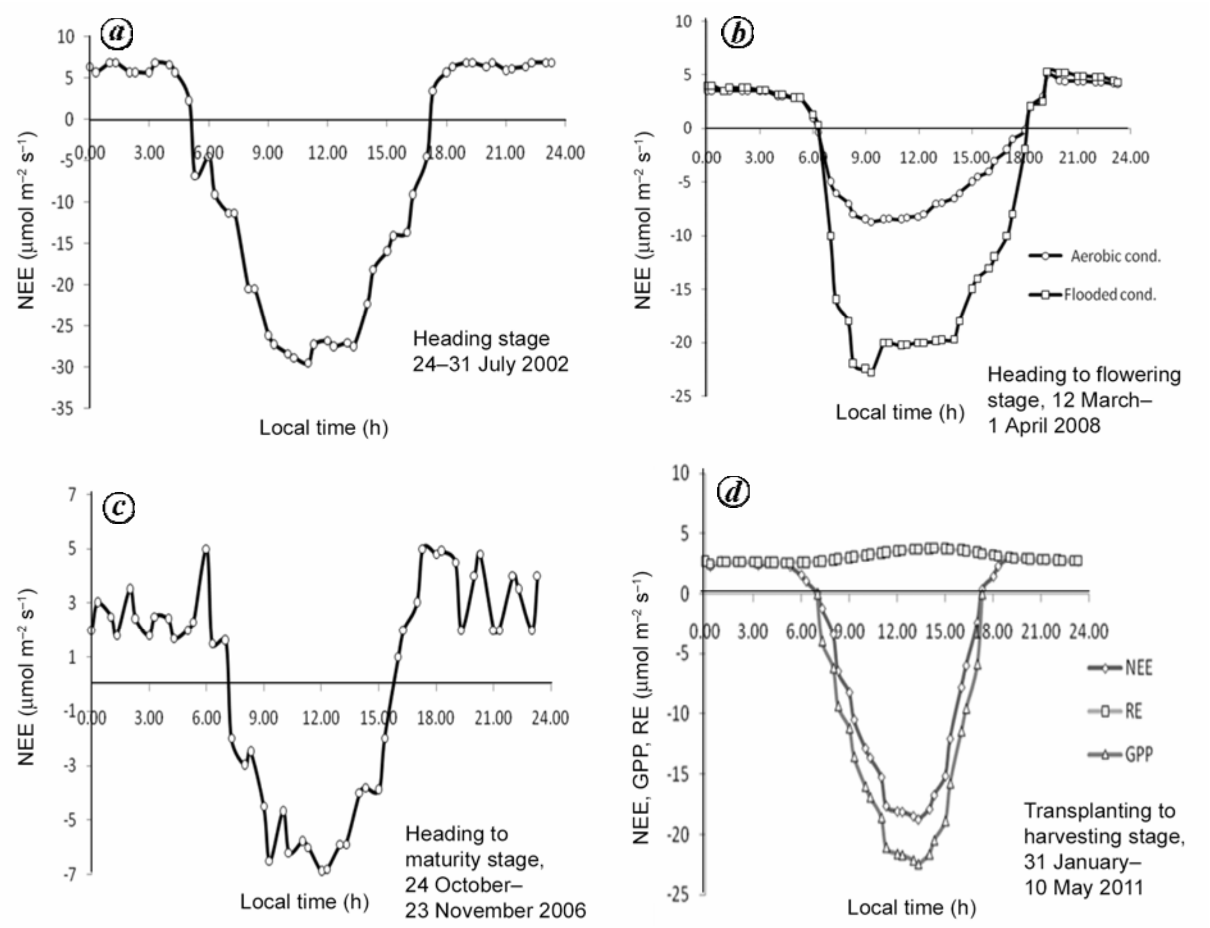

Figure 3. Diurnal variations in half-hourly NEE in a rice growing season in (***a***) Japan in heading stage of rice (24–31 July 2002), (***b***) in heading to flowering stage of rice (12 March–1 April 2008) in International Rice Research Institute, the Philippines, (***c***) in heading to maturity stage of rice in Taiwan (24 October–23 November 2006) and (***d***) in CRRI, Cuttack along with the diurnal variations in half-hourly GPP and RE observed during rabi (dry) season of 2010–11 from transplanting to harvesting stage (31 January–10 May 2011).

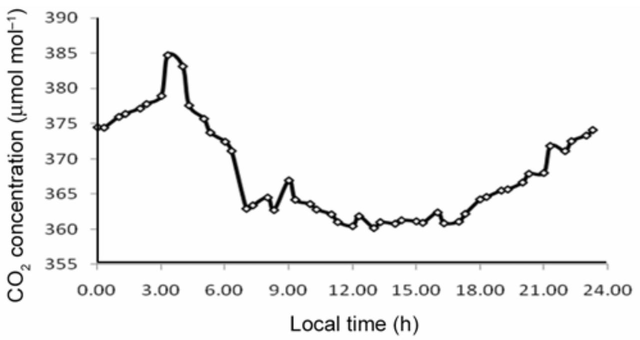

Figure 4. Diurnal changes in mean CO_2 concentration observed during the rabi season 2010–11 at CRRI, Cuttack.

The measurement of CO_2 fluxes over the rice canopy was made for eight days, about a month before heading of the rice plants at the experimental farm of Okayama University, Japan[8] (Table 1). It was noticed that the daily net uptake of CO_2 from the atmosphere by the paddy field was 50% lower when the paddy was drained than when it was flooded. Enhanced fluxes of CO_2 from the drained soil due to removal of flood water acted as a barrier to gas transport from soil to air. The average CO_2 flux (NEE) during drained and flooded conditions was –3.81 and –7.63 μmol CO_2 m^{-2} s^{-1} respectively, and the total integrated NEE over those eight days was estimated to be –47.62 g C m^{-2} (Table 1).

The annual and seasonal variation of soil respiration was also noticed in rice field of China[12]. The total cumulative annual soil respiration of paddy soil in the subtropical region of China was 425.45, 616.36 and 621.82 g C m^{-2} in 2003, 2004 and 2005 respectively (Figure 5 *e*).

In CRRI, the seasonal cumulative NEE, GPP and RE were –341, 636 and 295 g C m^{-2} respectively, in lowland rice field (Table 1; Figure 5 *f*). It is evident from the findings that the lowland rice fields sequestered carbon from the atmosphere, which is attributed to higher photosynthetic capacity of lowland rice to convert atmospheric carbon into organic compounds and to slow down organic matter decomposition in flooded soils. Similar results were reported from Taiwan, Japan, the Philippines and Bangladesh under lowland rice field[9,13,14,16].

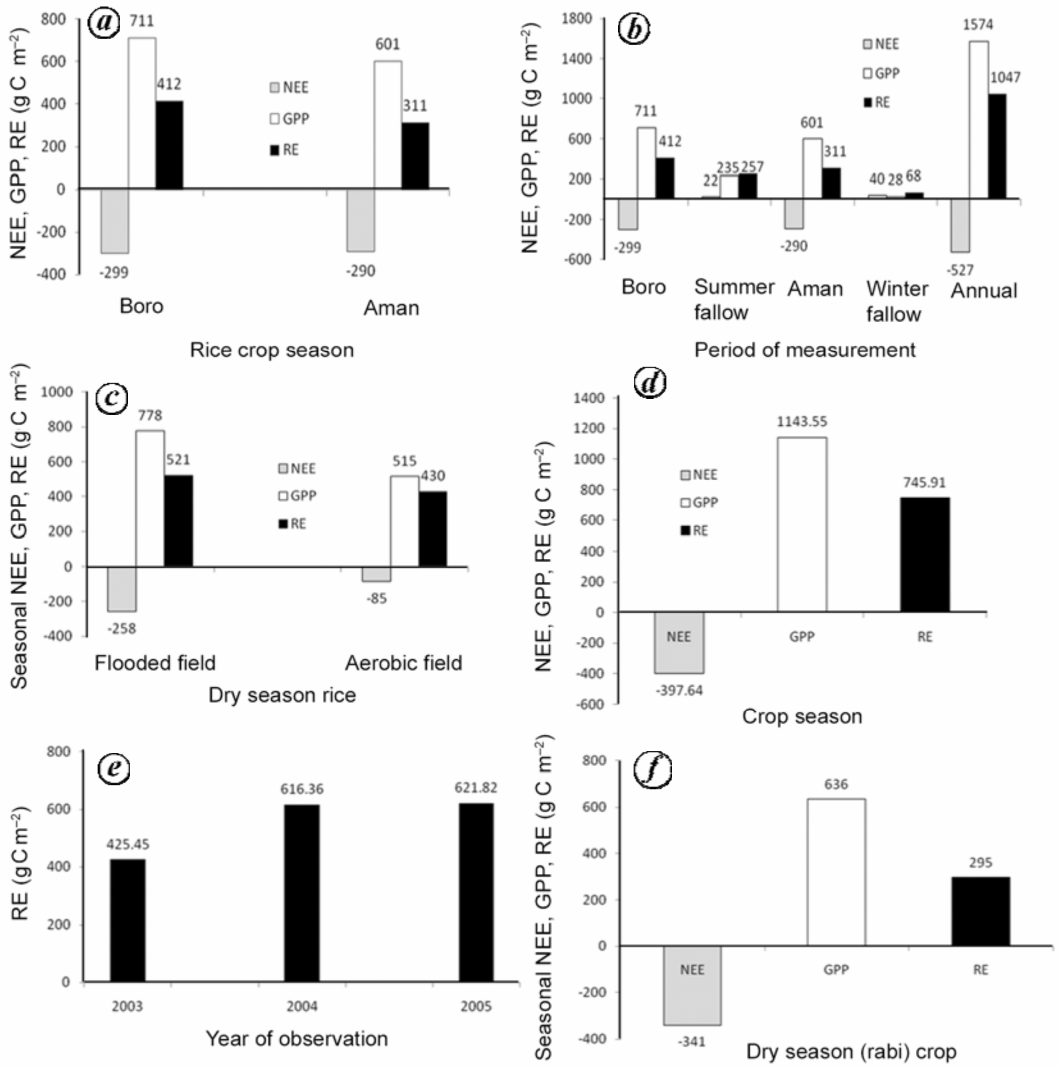

Figure 5. Integrated NEE, GPP and RE from transplanting to harvesting stages in two rice-growing seasons, i.e. Boro (29 January–26 May 2007) and Aman (20 August–2 December 2007) in Bangladesh (***a***) in two rice-growing seasons, i.e. Boro (29 January–26 May 2007) and Aman (20 August–2 December 2007) along with two fallow periods, namely summer (27 May–19 August 2007) and winter (3 December 2007–28/29 January 2008) and round-the-year (2007) annual observation in Bangladesh (***b***), in a single cropping season (11 January–15 May 2008) in IRRI, the Philippines (***c***), in a single cropping season in Mase paddy flux site in Japan (2 May–18 September 2002) (***d***), cumulative annual (whole round-the-year observations of 2003, 2004 and 2005) soil respiration in China (***e***) and integrated NEE, GPP and RE from transplanting to harvesting (31 January–10 May 2011) in a single cropping season in CRRI, Cuttack (***f***).

Important factors affecting NEE

Factors controlling gas exchange between rice paddies and the atmosphere are of varying nature because they are cultivated under submerged condition. Flooding and drainage affect CO_2 exchange in paddy fields[8]. The changes of micrometeorological environment with flooding influence root activity, photosynthesis and respiration of rice plants. The activity of aquatic plants such as algae in the floodwater may also affect CO_2 exchange between rice paddies and the atmosphere[8]. The characteristics of CO_2 exchange over rice canopy have a relationship with several ecosystem parameters and environmental variables (latent heat, air temperature, vapour pressure deficit, canopy irradiance, heat stress, stomatal response, high evaporative demand, circadian rhythm, growth stages of rice crop, leaf area index, biomass, etc.)[6,45]. The amplitude of the diurnal variation in NEE increases as leaf area index at different crop growth stages advances and reaches its peak around the anthesis/heading to flowering stage[6]. The diurnal pattern of CO_2 flux and carbon uptake is dependent on sunlight. This is due to leaf gas exchange and pattern of light interception by the canopy[45–47]. The CO_2 flux pattern is also dependent on physical environmental conditions and is particularly sensitive to climate change.

Summary and discussion

NEE between rice paddies and the atmosphere is controlled by several biological and physical processes. During the daytime, plant photosynthesis leads to the uptake of CO_2 from the atmosphere and respiration at night leads to an efflux of CO_2 to the atmosphere in the absence of photosynthesis. During the harvesting or maturity stage when the rice fields remain drained, the rice paddies along with the soil system behave as a net CO_2 source, but most of the times during the crop season rice paddies act as CO_2 sink. The carbon dynamics in terrestrial vegetation follows complex pathways and shows variability at different timescales starting from diurnal, seasonal, annual and inter-annual. The EC technique and measures directly the net ecosystem CO_2 exchange, which is a powerful micrometeorological technique for characterization of carbon budget in terrestrial ecosystems. This method can account for all the components of carbon fluxes required for accurate quantification of carbon exchange at the landscape level with regard to a particular vegetation.

Further studies are required to continuously monitor and estimate diurnal, seasonal, annual, inter-annual and even long-term variations in CO_2 exchange and carbon budget, including the fallow periods in different rice-production systems under different agro-climatic zones. Moreover, the studies should focus on how they are affected by microclimate and/or climatic variables and land-surface characteristics prevalent in each location in double-cropping rice paddy fields in monsoonal South and Southeast Asian countries, where rice is grown as a staple food. As many of the factors controlling gas exchange between rice paddies and the atmosphere are different from other ecosystems, field studies should be designed to measure net fluxes and to improve understanding of the factors, including detailed mechanisms controlling the fluxes. Moreover, accurate quantification of carbon exchange in the tropical flooded rice paddy ecosystem is extremely important to determine carbon stock in that ecosystem. EC studies for CO_2, water vapour and energy fluxes in the ecosystem if coupled with other important components may be employed to estimate net ecosystem production or for assessing net ecosystem carbon budget. EC measurements using tunable diode laser absorption spectroscopy and quantum cascade laser absorption spectroscopy are now becoming available among the FLUXNET communities worldwide for improved trace gas (NH_3, N_2O, NO_2, CH_4 and CO_2) analysis. This tool could be helpful for monitoring and estimation of GHGs and their budgeting via ecosystem modelling approach. These high-resolution process-based models can be applied to upscale and validate GHG emissions from any point-scale cropland to local, regional, national level to help in predicting future anticipated climate changes.

1. IPCC, Climate change–synthesis report. In An Assessment of the Intergovernmental Panel on Climate Change. Plenary XXVII, Valencia, Spain, 12–17 November 2007, p. 52.
2. Paustian, K. *et al.*, Mitigation of greenhouse gases: science and policy options. Council on Agricultural Science and Technology Report, R 141 2004, RSBN 1-887383-26-3, 2004, p. 120.
3. Smith, P., Engineered biological sinks on land. In *The Global Carbon Cycle. Integrating Humans, Climate and the Natural World* (eds Field, C. B. and Raupach, M. R.), SCOPE 62, Island Press, Washington DC, USA, 2004, pp. 479–491.
4. Janzen, H. H., Carbon cycling in earth systems – a soil science perspective. *Agric., Ecosyst. Environ.*, 2004, **104**, 399–417.
5. US-EPA, Global mitigation of non-CO_2 greenhouse gases. United States Environmental Protection Agency, EPA 430-R-06-005, Washington DC, USA; http://www.epa.gov/nonco2/econ-inv/downloads/GlobalMitigationFullReport.pdf (accessed on 26 March 2007).
6. Patel, N. R., Dadhwal, V. K. and Saha, S. K., Measurement and scaling of carbon dioxide (CO_2) exchanges in wheat using flux-tower and remote sensing. *J. Ind. Soc. Remote Sensing*, 2011; doi: 10.1007/s12524-011-0107-1.
7. Food and Agricultural Organization of the United Nations (FAO), 2004; http://www.fao.org/ag/agp/agpc/doc/riceinfo/asia/ascont.htm (accessed in March 2009).
8. Miyata, A., Leuning, R., Denmead, O. W., Kim, J. and Harazano, Y., Carbon dioxide and methane fluxes from an intermittently flooded paddy field. *Agric. For. Meteorol.*, 2000, **102**, 287–303.
9. Tseng, K. H., Tsai, J. L., Alagesan, A., Tsuang, B. J., Yao, M. H. and Kuo, P. H., Determination of methane and carbon dioxide fluxes during the rice maturity period in Taiwan by combining profile and eddy covariance measurements. *Agric. For. Meteorol.*, 2010, **150**, 852–859.
10. Uchijima, Z., Maize and rice. In *Vegetation and the Atmosphere* (ed. Monteith, J. L.), Academic Press, London, 1976, vol. 2, pp. 33–64.
11. Denmead, O. T., Novel meteorological methods for measuring trace gas fluxes. *Philos. Trans. R. Soc. Phys. Eng. Sci.*, 1995, **351**, 383–396.
12. Xiu, E. R. *et al.*, Estimation of soil respiration in a paddy ecosystem in the subtropical region of China. *Chin. Sci. Bull.*, 2007, **52**, 2722–2730.
13. Saito, M., Miyata, A., Nagai, H. and Yamada, T., Seasonal variation of carbon dioxide exchange in rice paddy field in Japan. *Agric. For. Meteorol.*, 2005, **135**, 93–109.
14. Hossen, M. S., Baten, M. A., Khatun, R., Khan, M. B., Mano, M., Ono, K. and Miyata, A., Establishment of a flux study site in Bangladesh with its preliminary observation result. *AsiaFlux Newsl.* (*Special Issue*), 26 January 2007, pp. 3–6.
15. Hossen, M. S., Mano, M., Miyata, A., Baten, M. A. and Hiyama, T., Seasonality of ecosystem respiration in a double-cropping paddy field in Bangladesh. *Biogeosci. Discuss.*, 2011, **8**, 8693–8721; doi: 10.5194/bgd-8-8693-2011.
16. Alberto, Ma *et al.*, CO_2/heat fluxes in rice fields: comparative assessment of flooded and non-flooded fields in the Philippines. *Agric. For. Meteorol.*, 2009, **149**, 1737–1750.
17. FAO, World Agriculture: towards 2015/2030. An FAO perspective. FAO, Rome, 2003, p. 97.
18. Kaimal, J. C. and Finnigan, J. J., *Atmospheric Boundary Layer Flows*, Oxford University Press, 1994, p. 289.
19. Moffat, A. M. *et al.*, Comprehensive comparison of gap filling techniques for eddy covariance net carbon fluxes. *Agric. For. Meteorol.*, 2007, **147**, 209–232.
20. Falge, E. *et al.*, Phase and amplitude of ecosystem carbon release and uptake potentials as derived from FLUXNET measurements. *Agric. For. Meteorol.*, 2002, **113**, 75–95.

21. Chapin, F. S. *et al.*, Reconciling carbon-cycle concepts, terminology and methods. *Ecosystems*, 2006, **9**, 1041–1050.
22. Smith, P. *et al.*, Measurements necessary for assessing the net ecosystem carbon budget of croplands. *Agric. Ecosyst. Environ*., 2010, **139**, 302–315; doi: 10.1016/j.agee.2010.04.004.
23. Buchmann, N., Biotic and abiotic factors controlling soil respiration rates in *Picea abies* strands. *Soil Biol. Biochem*., 2000, **32**, 1625–1635.
24. Reichstein, M., Tenhunen, J. and Ourcival, J. M., Severe drought effects on ecosystem CO_2 and H_2O fluxes at three Mediterranean sites: revision of current hypothesis? *Global Change Biol*., 2002, **8**, 999–1017.
25. Aubinet, M. *et al.*, Estimates of the annual net carbon and water exchange of forests: the EUROFLUX Methodology. *Adv. Ecol. Res.*, 2000, **30**, 113–175.
26. Baldocchi, D. D., Assessing the eddy covariance technique for evaluating carbon dioxide exchange rates of ecosystem: past, present and future. *Global Change Biol*., 2003, **9**, 479–492.
27. Papale, D. *et al.*, Towards a standardized processing of net ecosystem exchange measured with eddy covariance technique: algorithms and uncertainty estimation. *Biogeosciences*, 2006, **3**, 571–583.
28. Desai, A. R. *et al.*, Cross-site evaluation of eddy covariance GPP and RE decomposition techniques. *Agric. For. Meteorol*., 2008, **148**, 821–838.
29. Lalrammawia, C. and Paliwal, K., Seasonal changes in net ecosystem exchange of CO_2 and respiration of *Cenchrus ciliaris* L. grassland ecosystem in semi-arid tropics: an eddy covariance measurement. *Curr. Sci*., 2010, **98**, 1211–1218.
30. Baldocchi, D. D. and Meyers, T. P., On using eco-physiological, micrometeorological and biogeochemical theory to evaluate carbon dioxide, water vapor and gaseous deposition fluxes over vegetation. *Agric. For. Meteorol*., 1998, **9**, 1–26.
31. Foken, T. and Wichura, B., Tools for quality assessment of surface based flux measurements. *Agric. For. Meteorol*., 1996, **78**, 83–105.
32. Baldocchi, D. *et al.*, FLUXNET, a new tool to study the temporal and spatial variability of ecosystem-scale carbon dioxide, water vapor and energy flux densities. *Bull. Am. Meteorol. Soc.*, 2001, **82**, 2415–2434.
33. Papale, D. and Valentini, R., A new assessment of European forests carbon exchanges by eddy fluxes and artificial neural network spatializaion. *Global Change Biol.*, 2003, **9**, 525–535.
34. Reichstein, M., Dinh, N. and Running, S., Towards improved European carbon balance estimates through assimilation of MODIS remote sensing data and CARBOEUROPE eddy covariance observations into an advanced ecosystem and statistical modeling system. In Proceedings of the International Geosciences and Remote Sensing Symposium (IGARSS'03), Toulouse, France, 2003, pp. 21–25.
35. Reichstein, M. *et al.*, On the separation of net ecosystem exchange into assimilation and ecosystem respiration: review and improved algorithm. *Global Change Biol*., 2005, **11**, 1424–1439.
36. Aubinet, M. *et al.*, Methodology for data acquisition, storage and treatment. In *Fluxes of Carbon, Water and Energy of European Forests* (ed. Valentini, R.), Springer-Verlag, Berlin, 2003.
37. Goulden, M. L., Munger, J. W., Fan, S. M., Daube, B. C. and Wofsy, S., Measurements of carbon sequestration by long-term eddy covariance: methods and a critical evaluation of accuracy. *Global Change Biol*., 1996, **2**, 169–182.
38. Tanner, C. B. and Thurtell, G. W., Anemoclinometer measurements of Reynolds stress and heat transport in the atmospheric surface layer. University of Wisconsin Technical Report, ECOM-66-G22-F, 1969, p. 82.
39. Webb, E. K., Pearman, G. I. and Leuning, R., Correction of flux measurements for density effects due to heat and water vapour transfer. *Q. J. R. Meteorol. Soc.*, 1980, **106**, 85–100.
40. Falge, E. *et al.*, Gap filling strategies for defensible annual sums of net ecosystem exchange. *Agric. For. Meteorol*., 2001, **107**, 43–69.
41. Greco, S. and Baldocchi, D. D., Seasonal variations of CO_2 and water vapour exchange rates over a temperate deciduous forest. *Global Change Biol*., 1996, **2**, 183–198.
42. Davis, K. J., Bakwin, P. S., Yi, C., Berger, B. W., Zhaos, C., Teclaw, R. M. and Isebrands, J. G., The annual cycles of CO_2 and H_2O exchange over a northern mixed forest as observed from a very tall tower. *Global Change Biol*., 2003, **9**, 1278–1293.
43. Falge, E. *et al.*, Seasonality of ecosystem respiration and gross primary production as derived from FLUXNET measurements. *Agric. For. Meteorol*., 2002, **78**, 83–105.
44. Gu, L., Baldocchi, D., Verma, S. B., Black, T. A., Vesala, T., Falge, E. M. and Dowty, P. R., Advantages of diffuse radiation for terrestrial ecosystem productivity. *J. Geophys. Res.*, 2002, **107**, 1–23; doi: 10.1029/2001JD001242.
45. Nair, R., Juwarkar, A. A., Wanjari, T., Singh, S. K. and Chakrabarti, T., Study of terrestrial carbon flux by eddy covariance method in revegetated manganese mine spoil dump at Gumgaon, India. *Climatic Change*, 2011, **106**, 609–619.
46. Jarvis, P. G. and Leverenz, J. M., Productivity of temperate, deciduous and evergreen forests. In *Physiological Plant Ecology, Ecosystem Processes: Mineral Cycling, Productivity and Man's Influence*, Springer, Berlin, 1983, pp. 233–261.
47. Ruimy, A., Jarvis, P. G., Baldocchi, D. D. and Sauiger, B., CO_2 fluxes over plant canopies and solar radiation: a review. *Adv. Ecol. Res*., 1995, **26**, 1–81.

ACKNOWLEDGEMENTS. We thank the NAIP subproject 'Soil organic carbon dynamics vis-a-vis anticipatory climatic changes and crop adaptation strategies' Component-4 (2031), NICRA for funding and Dr T. K. Adhya, former Director, Central Rice Research Institute, for helping in conceptualizing the content of the topic.

Received 3 November 2011; re-revised accepted 22 October 2012