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Net carbon-dioxide exchange in green manuring ecosystem,*sesbaniaaculeata*: assessment through eddy covariance approach

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ABSTRACT

Fluxes of CO_2 froma green manuring crop,dhaincha(*Sesbaniaaculeata*) grown on a marginal (shallow basaltic) soil were quantified using the open path eddy covariance technique and the characteristics were related to various environmental parameters. Flux data was screened for various factors like wind from the tower, its frictional velocity, data monitored during rain events etc. and validated using the principle of energy balance closure. During the 82 days study period (9-August to 29-October, 2013), the net ecosystem exchange (NEE) averaged on a half-hourly basis ranged between +18.2 and -43.1 μmolm^{-2}s^{-1}.The maximum daytime capture occurred during 9-20 September when the crop was at its phase transfer from vegetative to flowering and abundant soil water was available. Daytime NEE was strongly controlled by soil moisture, soil temperature, net radiation and insolation.The dhaincha ecosystem had an average CO_2 sink value of -1.52 μmol m^{-2} s^{-1} as computed from the net daily exchange rates.

Key words : CO_2-Flux, NEE, dhaincha, marginal soil,energy balance closure

Quantifying greenhouse gas (GHG) exchange between various ecosystems and the atmosphere is the key for assessing the global budget of greenhouse gases, hence also important from climate change investigation perspectives.Eddy covariance (EC) technique is widely employed as the standard micrometeorological method to monitor energy and mass exchanges between vegetation and the atmosphere (Aubinet*et al.,* 2000). Systematic observations of CO_2 flux using eddy covariance technique have mostly been carried out in natural forest ecosystems under regional flux-networks of the world such as AmeriFlux, AsiaFlux,CarboAfrica, Fluxnet-Canada and Oz-Flux (Bhattacharyya *et al.,* 2013). With respect to agro-ecosystems, a few studies on CO_2 fluxes from various crops or cropping systems, tillage and water management and its intra- or inter-seasonal variability on account of environmental factors have been reported in literature (Suyker*et al.,* 2004; Anthoni*et al.,* 2005; Baker and Griffis, 2005; Hollinger *et al.*, 2005; Verma*et al.,* 2005; Bhattacharyya *et al.,* 2013).

Dhaincha (*Sesbaniaaculeata*) is one of the green manuring crops that are known to have good potential for quick fertility build up.To keep pace with the ever growing food requirement of the country and the world, agriculture is expanding into areas that have unfavourable plant growth environment from a variety of considerations. Keeping in view the agricultural trend that it could be, this study was initiated to generate quantitative information, for the first time, on the net ecosystem exchange (NEE) of $CO_2$from dhaincha grown on an abiotically stressed basaltic soil of shallow depth and marginal productivity.The study also analyzed the role of some important environmental factors in controlling the CO_2 exchange process from the above type of dhaincha ecosystem.

MATERIALS AND METHODS

Site description

The study was conducted at the experimental farm of the National Institute of Abiotic Stress Management (NIASM), Baramati (Latitude: 18°09' N, Longitude: 74°30' E and height about 560m above the mean sea level) which falls under the agro-climatic region, Western Maharashtra Scarcity Zone (MH-6) in Maharashtra, India. Long-term average (LTA, 1986-2011) rainfall during the growing-season (Aug-Oct) is 334.4 mm.Averages of daily maximum,minimum and mean temperature during growing season are 31.2°C,21.5°C and 26.4°C respectively and wind mostly blow from a 45° sector centeredon west.The site was almost flat (with a very gentle slope from west to east side) and had adequate footprint area for reliable flux measurement.

Crop establishment

The study was conducted during the monsoon season, 2013 (August to October) in dhaincha crop grown in about 2.25 ha of land area of shallow basaltic soil. All the plots were first tilled with a rotavator followed by application of organic manure (FYM) at the rate of about 5tha^{-1}. Afterwards the plots wereploughed with single reversible plough followed by harrowing with tractor driven cultivator. All these various field operations and sowing in different plots had been commenced on25th June and went on till 2nd July. Sowing was done manually through seed broadcasting method wherein a seed rate of about 40 kgha^{-1}was used.During the first week of September, agro-chemicals (imidachlorpid) were applied in the footprint area @ 1ml/L to control insect pests. No manual weeding operation was needed as the seed rate of dhaincha was high enough to suppress weed growth and very low top soil depth, poor fertility and gravelly condition of the soil did not support much weed growth.

Eddy covariance flux measurement and data quality control

An open path eddy covariance system was installed in the middle of a 2.25 ha field area sown with dhaincha (Fig. 1). Three-dimensional (3-D) wind speed and virtual temperature were measured using a 3-Dsonic anemometer (CSAT3, Campbell Scientific. Corp., Canada). Actual temperature was measured using fine wire thermocouple. An open path infrared gas analyser (EC-150, Campbell Scientific. Corp., Canada) was used to measure the fluctuations in CO_2 and water vapour densities.CSAT3 and EC-150 Sensors were installed at 3.0 mheight on a tower and kept west alignedas that was the prevalent wind directionduring the season. The above two sensors had a physical separation (mid-axis distance) of only 2 cm.

The CO_2fluxes measured by the eddy covariance system represented the net CO_2 exchange rate between the crop surface and the overlying atmosphere. As dhaincha comes under the category of short height crop (height < 3 m), CO_2storage within the plant canopy was considered negligible. Eddy covariance measurements with fast response sensors were complemented with a set of slow response sensors for recording data on important meteorological parametersand computation of energy balance components (net radiation and soil heat flux). The system measured all the parameters diurnally *i.e.* for the entire 24-hours period and continued without any break throughout the season. The mean vertical flux density of CO_2(Fz) obtained as covariance between vertical wind fluctuations (w) and the CO_2 mixing ratio (c)was averaged at 30 minutes interval (Baldocchi, 2003).

$$Fz = \overline{a} * \overline{w'c'}$$

Where, "a" refers to air density, the over bars denote time averaging and the primes represent fluctuations from average value. A positive covariance between vertical wind and CO_2 mixing ratio indicates net CO_2 transfer into the atmosphere and a negative value indicates net CO_2flow towards the vegetation and soil surface, asign convention that is followed by the atmospheric physicists and micrometeorologists who consider the atmosphere as the source of CO_2. Diurnal data points of all measured parameters were divided into two equal halves- representing daytime (6AM to 6 PM of any given calendar date) and nighttime (6 PM to 6 AM of the next calendar date) conditions and statistics were worked out corresponding to those time periods. Footprint analysis was done using eddypro software (V. 4.2.1) on different time periods of the diurnal cycle to know the cumulative normalized contribution to the surface flux from the upwind location.The software by default uses footprint models of Kljun*et al.* (2004) and Kormann&Meixner(2001) depending on the datasets, and analysis revealed that during both day and night time majority of the contribution could be traced well within the fetch area. The raw data for eddy flux computations was sampled at 10 Hz frequency using a programme in-built in the data logger that performed all the processing online and in real time. It also applied density corrections on the measured CO_2 fluxes by following the WPL (Webb-Pearman-Leuning)-procedure(Webb *et al.,* 1980). WPL-term correction is used to compensate for the fluctuations of temperature and water vapour that affect the measured fluctuations in CO_2.

All the statistics from half-hourly flux data were derived using Microsoft Excel software. Quality control of eddy covariance flux data were done by eliminating unreliable data that had been suspected to be badly affected by precipitation events, poor signal strength during data acquisition,wind flown from the back of the EC-150 and CSAT-3 sensors, atmospheric stability, noise and spikes. Wind that flew into the aforesaid sensors from a 52.5° to 127.5°sector (clockwise) was influenced by the hardware infrastructure of the tower,hence corresponding eddy fluxes (4.8 % of total data points) were kept out of the ambit of computation. The friction velocity (u*) threshold for

Table 1: Daytime and nighttime averages of CO_2 flux (Net Ecosystem Exchange, NEE) during various phenophases and stress conditions in the Dhaincha ecosystem

Time Period	Description of the ecosystem condition	Night time NEE (micromole m^{-2} s^{-1})	Day time NEE (micromole m^{-2} s^{-1})
09-Aug to 08-Sep	Vegetative phase with moderate soil moisture stress (I)	4.15	-7.60
09-Sep to 20-Sep	Vegetative to flowering phase without soil moisture stress (II)	5.54	-11.93
21-Sep to 29-Oct	Rapid phase transition to Senescence with soil moisture stress (III)	4.48	-6.17
27-Sep to 29-Oct	Senescence phase with soil moisture stress (IV)	3.99	-4.04
09-Aug to 29-Oct	Seasonal Pool (V)	4.50	-7.56

Table 2: Coefficient of determination (R^2) for daytime NEE in Dhaincha with respect to various environmental parameters

Environmental Parameters	09-Aug to 08-Sept (n = 31)	09-Sept to 20-Sept (n = 12)	21-Sept to 29-Oct (n = 39)	27-Sept to 29-Oct (n = 33)	09-Aug to 29-Oct (n = 82)
Net Radiation	NS	0.47*	0.34**	0.35**	0.25**
Insolation	NS	0.45*	0.22**	0.28**	0.15**
Soil Moisture	NS	NS	0.92**	0.90**	0.44**
Soil Temperature	0.14*	NS	0.75**	0.59**	0.54**
Ambient Temperature	NS	0.45*	NS	NS	NS

* and ** indicate relationship between the variables and NEE are statistically significant at 95 % and 99 % confidence intervals respectively; 'NS' stands for statistically non-significant at 95 % confidence interval; 'n' stands for no. of sample points or days.

rejecting calm period CO_2-flux data was taken as 0.1 ms^{-1} which amounted to about 15.9 % of the total data points.

RESULTS AND DISCUSSION

Net ecosystem exchange (NEE) dynamics

Peak rates of half-hourly averaged NEE of CO_2 during the study period (45-126 days after sowing) of the crop season varied between +18.2 $\mu molm^{-2}s^{-1}$ and -43.1 $\mu molm^{-2}s^{-1}$ while that of daily averages lied between +3.1 and -7.2 $\mu molm^{-2}s^{-1}$ and the mean -1.5 $\mu molm^{-2}s^{-1}$ *i.e.* -1.6 g C m^{-2} d^{-1}. Net assimilation fluxes between -9 and –13 g C $m^{-2}d^{-1}$ were observed for winter wheat (Baldocchi, 2003; Soegaard *et al.,* 2003; Anthoni *et al.,* 2004; Moureaux *et al.,* 2008; Béziat *et al.,* 2009). Similar values were reported for soybean (Hollinger *et al.,* 2005), rapeseed (Béziat *et al.,* 2009) and sugar beet (Moureaux *et al.,* 2008).

To investigate the effect of crop phenophases, canopy growth and abiotic stress conditions on daytime NEE, the entire study period was divided into five phases that represent distinctly different conditions of the ecosystem. Daytime average values of NEE during the above phases were found to vary between -4.0 and -11.9 $\mu molm^{-2}s^{-1}$ and the seasonal average stood at -7.6 $\mu molm^{-2}s^{-1}$ (Table 1). Corresponding variations of the nighttime fluxes (NEE) ranged between 4.0 and 5.5 $\mu molm^{-2}s^{-1}$ with a mean seasonal value of 4.5 $\mu molm^{-2}s^{-1}$. It was observed that both the daytime and nighttime fluxes showed highest magnitude during the vegetative/flowering phase with no moisture

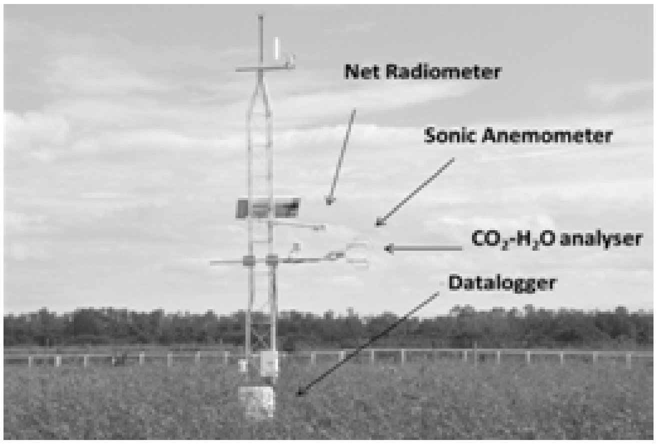


Fig. 1: Eddy covariance system for CO_2 flux measurement installed in the dhaincha field atNIASM, Baramati

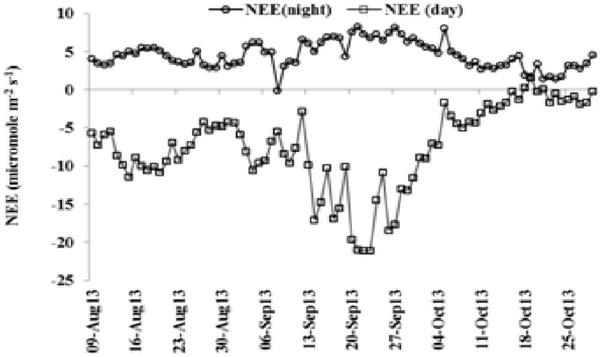


Fig. 2: Seasonal dynamics of daytime and nighttime CO_2 fluxes (NEE) from dhaincha

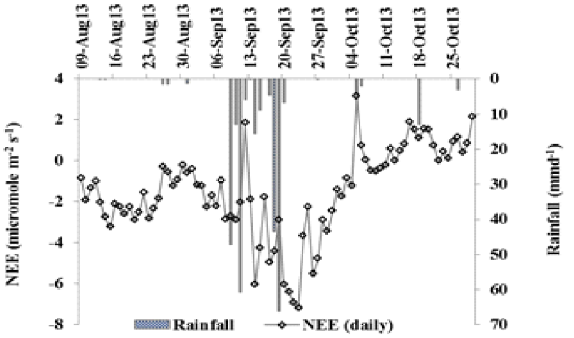


Fig.3: Seasonal course of rainfall events and daily CO_2 fluxes (NEE)

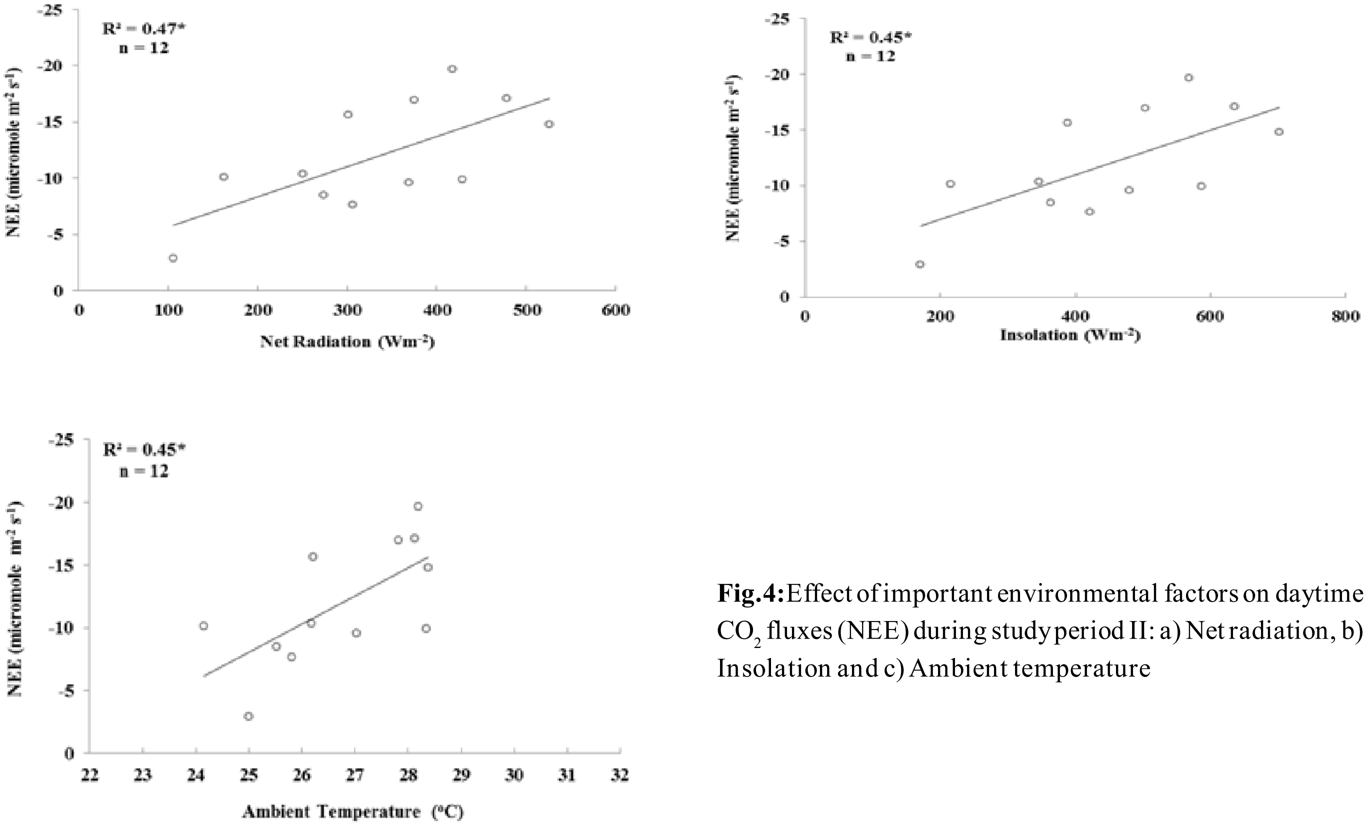


Fig.4: Effect of important environmental factors on daytime CO_2 fluxes (NEE) during study period II: a) Net radiation, b) Insolation and c) Ambient temperature

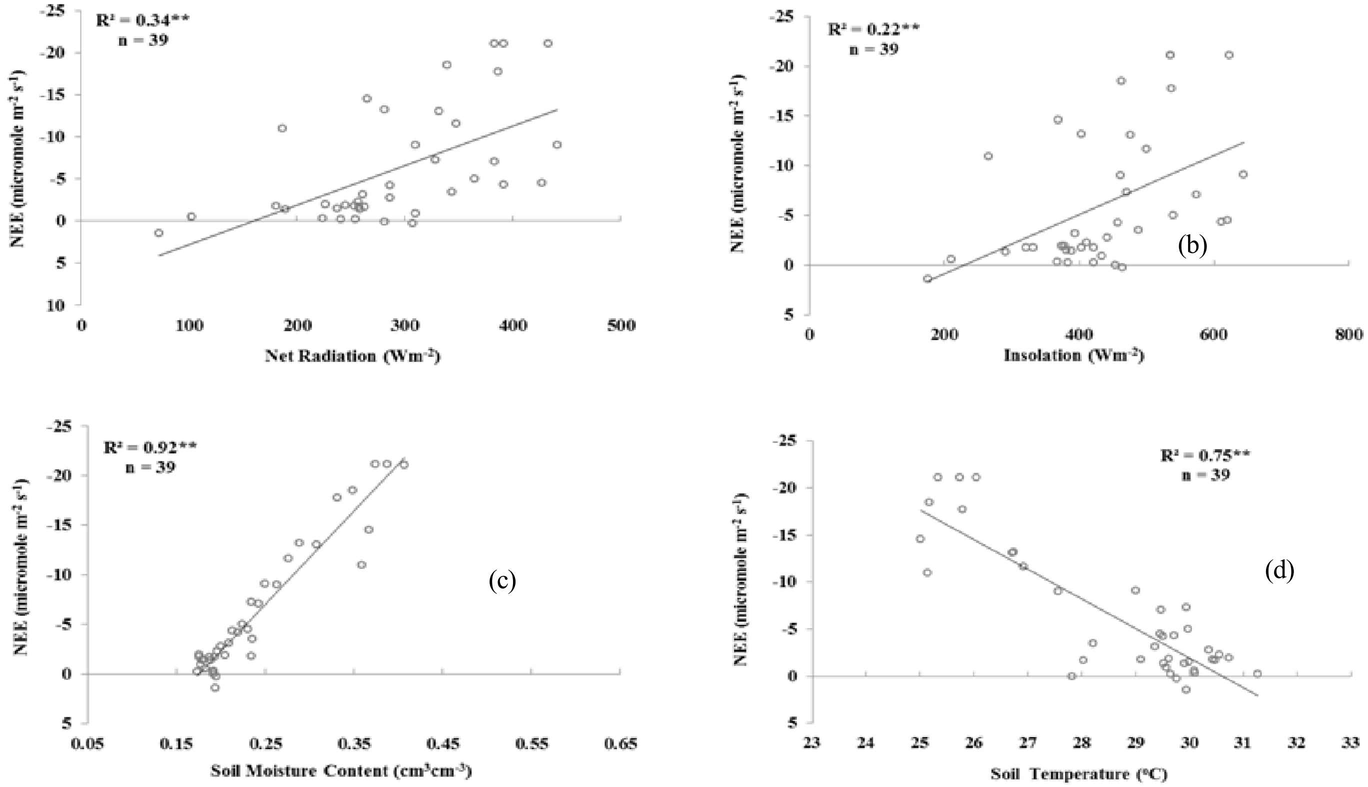


Fig.5: Effect of important environmental factors on daytime CO_2 fluxes (NEE) during the study period III: a) Net radiation, b)Insolation, c) Soil moisture content and d) Soil temperature

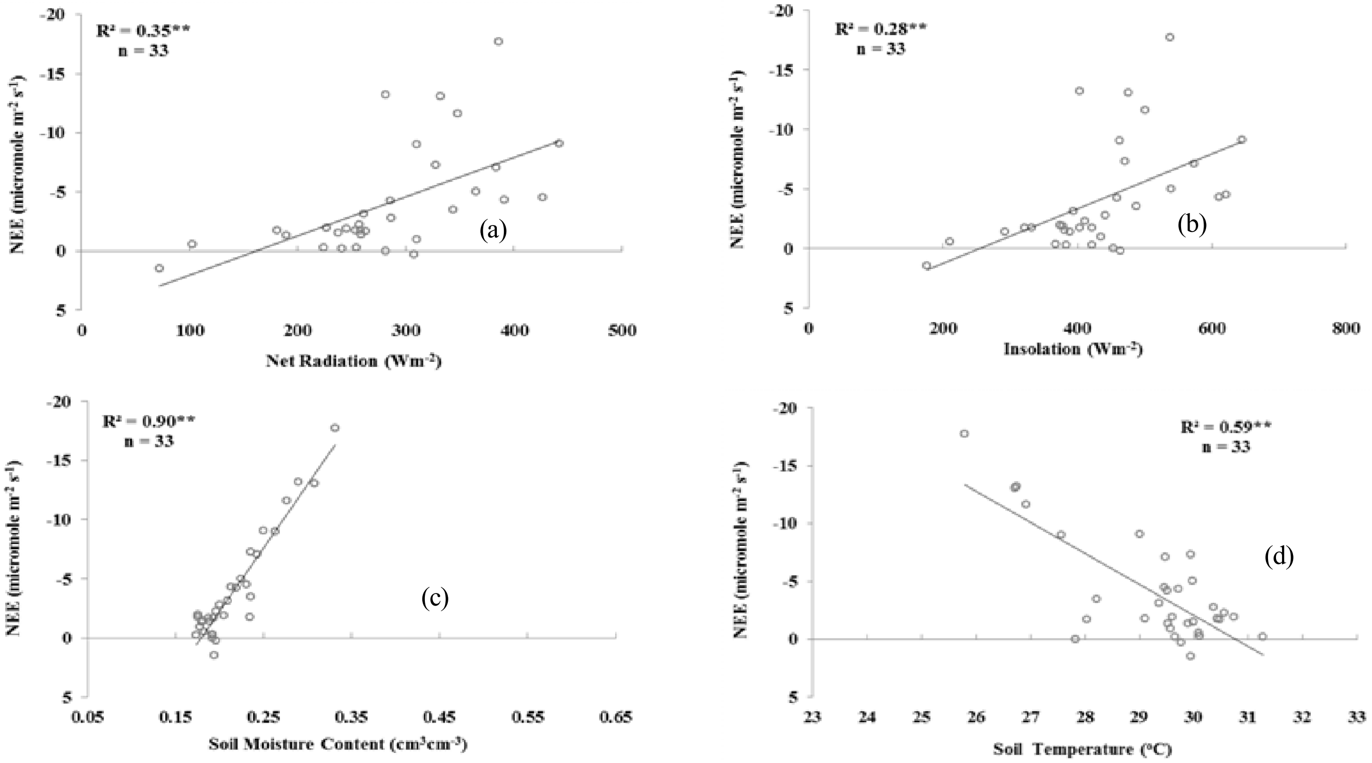
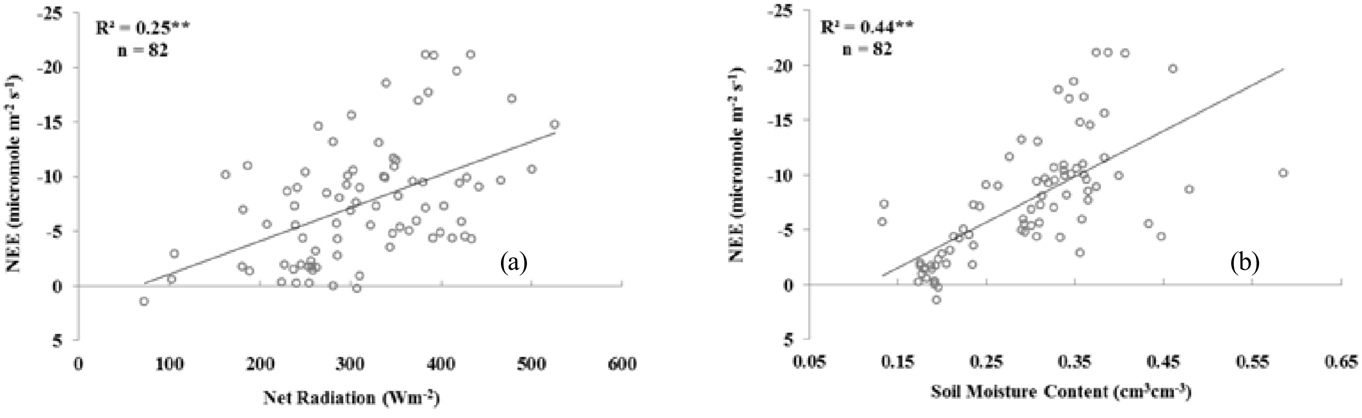


Fig.6: Effect of important environmental factors on daytime CO_2 fluxes (NEE) during study period IV: a) Net radiation, b) Insolation, c) Soil moisture content and d) Soil temperature



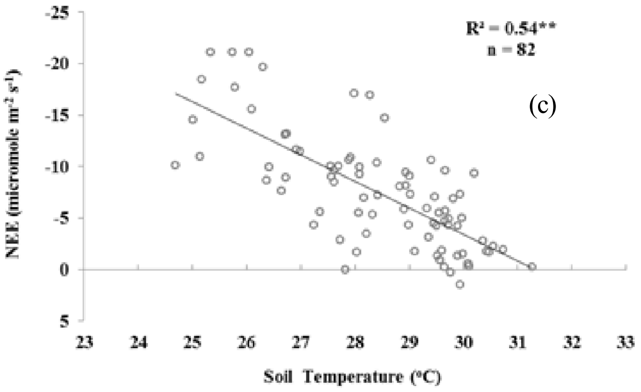


Fig.7: Effect of important environmental factors on daytime CO_2 fluxes (NEE) during study period- V: a) Net radiation, b) Soil moisture content and c) Soil temperature

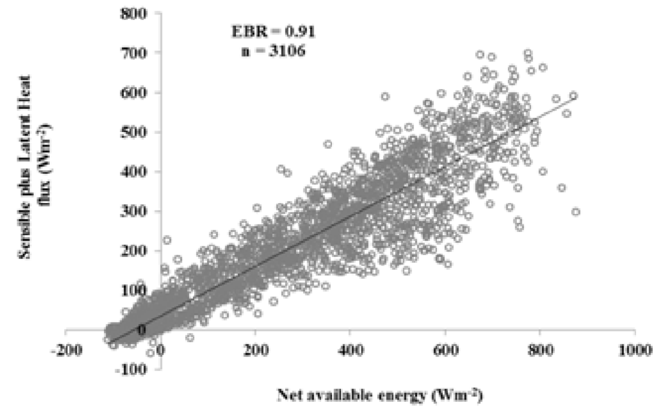


Fig.8: Validation of CO_2 flux (NEE) from Dhaincha through energy balance closure (Aug-Oct, 2013)

stress and that of lowest during the vegetation senescence coupled with severe soil moisture stress.

The crop was grown under rainfed condition. From the time of field preparation to 16th August *i.e.* 52 days after sowing, the crop received a total of about 120.1 mm of rainfall. Continuous vegetative growth helped by regular occurences of rain events during this period lead to an increasing trend in the daytime fluxes till that time. Afterwards, due to lack of any significant rainfall the crop continue to lose its vigour and a consequent decrease in carbon uptake was observed till the end of August. Most of the major rainfall events totaling 274.3 mm of rain occurred during the period 9th Sep to 19th Sep (Fig.3). Consequently, the crop revived and attained its maximum vigour with a footprint averaged crop height of about 87.5 cm during the third week of September. As a result, net carbon capture by the vegetation canopy continued to increase during the above period. However, the crop again lost its vigour as senescence phase was approaching and the few rain events in the month of October could not revive the ecosystem's carbon assimilation capability till the end of crop harvest.

Effect of environmental factors on NEE

Analysis revealed thatwith about 3-fold variations in the diurnal difference of temperature extremes, 4.7 °C in that of daily mean temperature, a fluctuation in daily mean relative humidity of about 31 % (between 57.5 and 88.5 %), about four-fold variation in daily average wind speed, about 3 times variation in daily total insolation, about five-fold variations in reference evapotranspiration (Penmann-Monteith) and daytime average albedo of the soil-crop surface ranging between 0.11 and 0.28, half-hourly average

NEE during the season showed a variability (Coefficient of Variation) of about 400%. Diurnally averaged NEE for the same time period ranged between +3.1 and -7.2 μmolm^{-2} s^{-1} *i.e.* a difference of about 10.3 μmolm^{-2} s^{-1} (~140 % change).

To elucidate the role of environment in controlling NEE, statistical relations between daytime averageNEE and five environmental factors were worked out (Table 2& Figs. 4-7). It was observed that during study period I when the crop was still growing and canopy vigour was reduced due to intermittent stress developed due to low rain and very poor water holding capacity of the soil, no single environmental variable could adequately explain the variations in daytime NEE. During study period II when the crop had already attained its maximum canopy growth and there was optimum soil moisture on account of good rain, net radiation, insolation *i.e.* solar radiation and ambient temperature, all of these factors alone could explain 45-47 % of variations in NEE. It was also observed that daytime ambient temperature upto about 29° C had favoured higher carbon assimilation during the aforesaid period. During study period III when the crop was rapidly shifting to senescence phase due to its age and onset of moisture stress, soil moisture and soil temperature alone could explain 92 % and 75 % of variability in NEE, respectively.During the study period IV, when most of the dhaincha plants in the footprint area were into senescence and the soil mostly dry with a few rain events, soil moisture and soil temperature again played important roles as theseregulated the soil respiration process which assumed higher importance than photosynthesis and explained about 90 % and 59 % variations in NEE, respectively. When data corresponding to the entire flux observation period *i.e.* between 45-126 days after sowing (study period V) were pooled together, it was found that soil moisture, soil temperature, net radiation and insolation showed significant correlations with the daytime NEE. Hernandez-Ramirez *et al.* (2011) observed that under non-limiting soil water availability conditions seasonal variations of CO_2 fluxes were mostly controlled by ambient temperature and available light in corn and soybean. In contrast, with full-developed canopies, available light was the main driver of daytime CO_2 uptake. Similar observation on therelationship between daytime NEE and incident light in maize have been reported by Suyker *et al.* (2004). Guo *et al.* (2013)found good correlations between daily CO_2 flux and crop growth stage, soil temperature and rainfall.

Flux validation

To validate measured fluxes, energy balance closure study was undertaken. Energy balance ratio (EBR) was computed from the slopes of regression lines (with and without intercept) between net available energy and summation of sensible and latent heat fluxes (Fig.8). For computation of net available energy, only soil heat flux was deducted from net radiation and the other energy sink term *i.e.* canopy heat storage was not considered as the latter was negligible compared to the soil heat flux. A value of EBR close to one enhances our confidence about the reliability of measured fluxes. However, for various practical reasons a full energy balance closure never happens to be the case in any of flux sites. EBR for the present study was found to be 0.91 which is fairly good and consistent with several findings from fluxnet sites all over the world (Li, Z. *et al.,* 2005).

CONCLUSION

Dhaincha grown on shallow basaltic soil with marginal productivity, acted as a net sink of atmospheric $CO_2$with seasonal average rate of daily carbon gain about -1.6g C m^{-2}d^{-1}.Rate of carbon capture by the ecosystem took place at its highestrate when the crop was in the vegetative to flowering phase with maximum vigour and non-limiting soil moisture condition. Soil moisture, soil temperature,net radiation and insolation emerged out as important environmental controlling factors for CO_2 gain and release from the dhaincha ecosystem. However, on the whole, the relationship between ambient air temperature and NEE found to be insignificant.From the results obtained, it could be concluded further that 25-26° C was the most favourable range of soil temperature for maximum carbon assimilation by the dhaincha crop grown on the shallow basaltic soil. Similarly, ambient temperature upto about 28-29° C and volumetric soil moisture content uptoabout 0.40 cm^{3}cm^{-3}found to befavourable for ecosystem carbon gain when other resources were not limiting.Measured fluxes by the eddy covariance system were quite reliable given a very high degree of energy balance closure.

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