MEASUREMENT AND SCALING OF CARBON DIOXIDE (CO2) EXCHANGE IN WHEAT USING FLUX-TOWER AND REMOTE SENSING

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ABSTRACT:

The present study investigates the characteristics of CO_2 exchange (photosynthesis and respiration) over agricultural site dominated by wheat crop and their relationship with ecosystem parameters from MODIS. Eddy covariance measurements of CO_2 and H_2O exchanges was carried out at 10Hz interval and fluxes of CO_2 were computed at half-hourly time steps. The net ecosystem exchange (NEE) was partitioned into gross primary productivity (GPP) and ecosystem respiration (Re) and integrated daily to derive seasonal course of CO_2 exchange over wheat. Diurnal pattern in Net ecosystem exchange (NEE) reveals negative NEE during day-time representing CO_2 uptake and positive during night as release of CO_2. The amplitude of the diurnal variation in NEE increased with growth of wheat and reached its peak around the anthesis stage. The mid-day uptake during this stage was around 1.15 mg CO2 m^{-2} s^{-1} and night-time release was around 0.15 mg CO_2 m^{-2} s^{-1}. Large daily GPP above 30 g CO_2 m^{-2} d^{-1} continued until mid of anthesis stage (15 march) and decline rapidly during maturity stage. Linear and non-linear least square regression procedures were employed to develop phenomenological models and empirical fits between flux tower based GPP and NEE with satellite derived variables and environmental parameters. Enhanced vegetation index was found significantly related to both GPP and NEE. However, NDVI showed little less significant relationship with both GPP and NEE. Furthemore, temperature-greenness model combining scaled EVI and LST was parameterized to estimate daily GPP over dominantly wheat crop site. ($R^2 = 0.77$). Multi-variate analysis shows that inclusion of LST or air temperature with EVI improved variance explained in daily NEE and GPP.

1. INTRODUCTION

In the past few decades, remote sensing has received much attention in the study of biogeochemical cycles such as carbon, water, and energy exchange between ecosystems and the atmosphere in the context of global climate change. Many remote sensing based models of CO_2 and water vapour exchanges are developed but they still require considerable input from ground based meteorological measurements and look up tables based on vegetation type. Simple photosynthetic efficiency based models even needs assignment of correct LUE and spatially representative meteorological data for estimating carbon storage over large areas. The MODIS product termed MOD17 (Running *et al*., 2004) is one of the primary sources of remote sensing based gross primary productivity (GPP) estimates at the global scale.

Flux towers are now-a-days become a promising tool to measure net exchange of carbon dioxide and water vapor at land-scape (0.5 – 1 km^2) scale. Flux towers are mostly operating worldwide as FLUXNET (http://daac.ornl.gov/FLUXNET/); Valentini, 2003; Baldocchi *et al*. 2001; Falge *et al*.,2002). At present, over 400 tower are operating on a long-term and continuous basis but mostly located in forest and grassland ecosystems. Agroecosystems are equally important and contributes to regional carbon budget where croplands are dominant. Croplands in India covers almost 60 percent of land mass and contributes approximately 50% of terrestrial productivity on a national scale (Nayak *et al*. 2009).

Furthermore, flux measurements of photosynthesis and respiration over crops and their response to environmental variables is indispensable for understanding physiological behaviour of agroecosystem under current condition and predicting in future climate change.

In past one decades, the use of time series of MODIS data to monitor changes in physical surface characteristics governing biospheric processes over large geographical areas have received a greater attention by scientific community. MODIS based vegetation indices and land surface temperature information have been proved effective for quantifying vegetation greenness, water stress and net primary productivity (Patel *et al*, 2010).

Recently, relationship between times-series of satellite derived vegetation indices from MODIS and tower based flux data have been emerged as promising alternative to LUE models in a number of studies on ecosystem carbon exchange (Sims *et al*., 2006; Huete *et al*., 2009). Vegetation indices e.g normalized difference vegetation index (NDVI), Enhanced vegetation index (EVI) and Photochemical reflectance index (PRI) have shown potential to upscale carbon assimilation fluxes (GPP, NEE_{CO2} and R_e) from eddy covariance tower to large geographical areas (Nakaji *et al*., 2007; Glenn *et al*. 2008).

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Present study, therefore, investigates diurnal and seasonal variation in CO2 flux over wheat and its relationship with satellite derived measures for scaling over large areas.

2. MATERIALS AND METHODS

2.1 Study Site

The site is pre-dominantly under agriculture and located near Modipurum about 10 km northwest from Meerut in western UttarPradesh, India (29°05'N, 77°42'E; 237 m above mean sea level). The site is basically a Practical Crop Production (PCP) Farm for graduate student training and falls within Sardar Vallabhbhai Patel University of Agriculture and Technology (SVBPAUT) Campus, Modipurum. The western Uttar Pradesh represents Upper Gangetic Plains and frequently referred as "Food Bawl" of Uttar Pradesh. This is an intensively cultivated transect with 150% cropping intensity. The climate of Meerut is semiarid subtropical, with dry, hot summers and cold winters. The average annual rainfall is 810 mm, 75% of which is received during July–September. Mean maximum and minimum 26.9 and 10.1°C during the wheat (Nov. to Apr.) growing season.

2.2 Flux and Meteorological Data

An eddy covariance (EC) system (29°05′33″N, 77°41′53″E) has been operated continuously by Indian Institute of Remote Sensing (ISRO), at the agriculture site dominated by wheat crop since January 2009 (fig. 1). Wheat crop was emerged on 16th December, 2009 and harvested by third week of April, 2009.

Figure 1. Eddy Covariance Measurements at Meerut Site

The EC system consists of a three-dimensional sonic anemometer (model CSAT3, Campbell Sci., Logan, UT) and an open-path infrared gas analyzer (IRGA, Li-7500, Li-Cor Inc., Lincoln, Nebraska, USA). Components of the turbulent wind vector were measured using a sonic anemometer. Open-path IRGA was used to measure CO_2 and water vapor concentrations. Signals from both sensors were recorded at 10 Hz interval with a data logger (model CR3000, Campbell Scientific Inc.). Half-hourly fluxes of CO_2 and H_2O were calculated online using the open-path eddy flux technique after making corrections to latent heat and CO2 fluxes for the effects of density fluctuations arising from sensible and latent heat fluxes (Webb *et al.*, 1980). Meteorological data such as air temperature and humidity was also measured at 30 minute interval using shielded and aspirated sensor (HMP-35 A, Vaisala, Helsinki, Finland).

2.3 Satellite Data

MODIS is a versatile payload on-board the NASA's Terra and Aqua satellites. The Terra (MODIS) and Aqua (MODIS) captures earth observations over entire globe every 1–2 days in 36 spectral bands with the spatial resolution of 250 m, 500 m and 1 km.. The MODIS Land Science Team provides a suite of standard data products to the users (http://modis-land.gsfc.nasa.gov/) which comprises daily, 8-day, 16-day and some other long-term products. Products from Terra (MOD) and Aqua (MYD) satellite platforms were downloaded from the EOS Data Gateway. We obtained daily surface reflectance (MOD09GA & MYD09GA) and land surface temperature (MOD11A1 & MYD11A1) for Jan- Apr, 2009. Surface reflectance values from these four spectral bands (Blue, Red, NIR (841–875 nm) and SWIR (1628–1652 nm)) were used to calculate the vegetation indices (NDVI, EVI).

2.4 Estimation of GPP and Ecosystem Respiration (R_e)

The measured net ecosystem CO_2 exchange on half-hourly basis was calculated after applying gapfilling and various corrections with respect to air density fluctuation effects and insufficient turbulence. We rejected NEE data that are spurious and outside logical bounds. Small gaps (< 2 h) were filled by simple linear interpolation from adjacent data. Longer gaps were filled using mean diurnal variation method. We also screen out night-times CO_2 flux data that appeared with below friction velocity (u_*) threshold ($u_* < 0.1$). Gaps and screen out NEE during night hours were filled by applying the relationship between night-time R_e and air temperature developed from valid nocturnal CO_2 flux. Daytime respiration (Re, day)) was estimated by extrapolating the relationship between nigh-time respiration and air temperature to daytime air temperature. A rectangular hyperbolic function (Michaelis–Menten, 1983) was applied to parameterize quantam yield (α) and hypothetical maximum GPP saturation (P_{max}) at infinite PAR. Parameters of hyperbolic function were also used to fill gaps in NEE during day hours.

Finally, the gross primary productivity was quantified as residual of NEE and ecosystem respiration:

$$GPP = -NEE + R_e$$

2.5 Satellite Data Processing

We acquired daily surface reflectance of Blue, Red, Near-infrared (NIR) and shortwave-infrared (SWIR) to derive time-evolution of vegetation indices (NDVI and EVI). Vegetation indices were calculated as :

$$NDVI = (\rho_{NIR} - \rho_{Red}) / (\rho_{NIR} + \rho_{Red})$$

$$EVI = 2.6 *[(\rho_{NIR} - \rho_{Red}) / (\rho_{NIR} + 6*\rho_{Red} - 7.5*\rho_{Blue} + 1.0)]$$

Time-series of NDVI so calculated was corrected for cloud interference. We used three-point time filter to replace vegetation index values of cloudy pixels identified in quality-flag layer of MODIS products. Many studies have explored earlier the simple relationship between vegetation index and tower flux data for developing predictive equation. Such type of relationship could not be able to estimate GPP accurately during drought or water stress conditions. So we used temperature-greenness model (Sims et al., 2008) that takes into account both greenness index and land surface temperature for improving flux estimates. T-G model is simple multiplicative formula:

$$GPP = m \times EVI* \times scaled\ LST$$

Where, m is a scalar (mol C m^{-2} d^{-1}), EVI* is scaled EVI as recommended by Sims et al. 2006:

$$EVI* = EVI - 0.1$$

The scaled LST in T-G model is defined as:

$$ScaledLST = \min\left[\left(\frac{LST}{30}\right); (2.5 - (0.05 \times LST))\right]$$

This scaled LST represents maximum value of scaledLST = 0 when LST is 30°C and minimum values of scaledLST=0 when LST declines to 0 or increases to 50 °C (Sims et a 2008). This equation also fits to GPP data of our flux site and shows that GPP reaches optimum around 30 °C and declines to zero if LST decreases to 0 °C or increases to 50 °C. For developing a predictive model, we used time series of EVI* and scaled LST values extracted surrounding flux tower by using geographical coordinates. A 3 × 3 pixel window was used to extract the values of vegetation indices and corresponding to time series of CO2 flux data

Furthermore, we also employed multi-variate analysis to develop phenomenological models for estimating major CO2 exchange components (GPP, NEE) in wheat from remotely sensed (EVI, NDVI, LST) and other environmental parameters.

3. RESULTS AND DISCUSSION

3.1 Diurnal NEE Patterns

Seasonal changes in diurnal pattern of net ecosystem exchange of CO_2 can provide how crop phenology and growth dynamics controls the rate of photosynthesis and respiration. To examine such behaviour, diurnal pattern of measured CO_2 exchanges after gap filling and filtering is illustrated for different four growth periods in Fig. 2. Throughout the period, NEE was negative during the daytime and positive during the nighttime. Day-time NEE

during tillering stage was fluctuated within 0.25 to 0.90 mg CO_2 m^{-2} s^{-1}. At this stage, the NEE was low but CO2 uptake during mid day was quite clear even at low LAI (1 -2). The midday peak value of NEE increased with increasing LAI and decreased rapidly during maturity period. The photosynthetic rate was much lower during the maturity stage than during the tillering stage, with similar values of green LAI. The amplitude of the diurnal variation in NEE increased with growth of wheat and reached its peak around the anthesis stage. The mid-day uptake during this stage was around 1.15 mg CO_2 m^{-2} s^{-1} and night-time release was around 0.15 mg CO_2 m^{-2} s^{-1}. As crop advances to post anthesis stage, peak NEE decreases to 0.8 mg CO2 m^{-2} s^{-1} due to crop senescence as reflected from reduced LAI. However night-time respiration remain at same magnitude as in previous stage. During maturity, the mid-day uptake of CO2 declined drastically to below 0.50 mg CO2 m^{-2} s^{-1}. There was also reduction in number of hours during which daytime NEE was negative
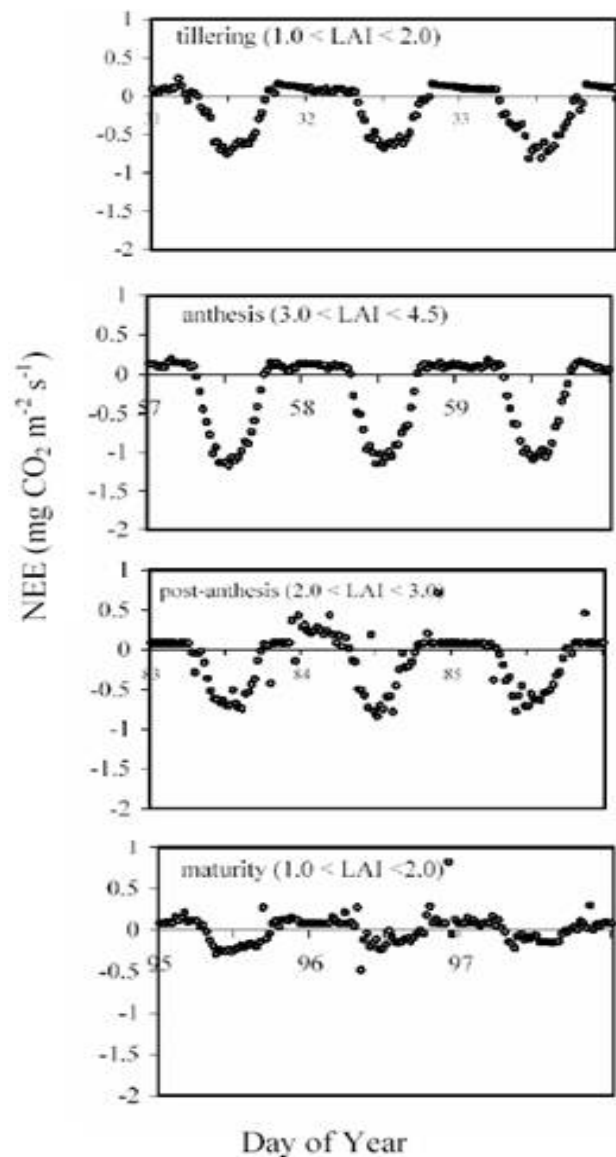

Figure 2. Diurnal Variation in Net Ecosystem CO2 Exchange from Four Growth Stages. Negative NEE Indicates Flux from Atmosphere to Ecosystem

3.2 Respiration-Temperature Response Function

Ecosystem respiration consists of both growth and soil respiration and largely influenced by environmental parameters such as temperature and moisture. Temperature response functions were evaluated for different growth periods to check dependence of Re on biomass. For a each growth periods, the night Re was separated into 1 °C wide temperature bins and averaged. We tried exponential relationship between night-time Re sorted for U* > 0.1 m/s-1 and bin averaged air temperature for different periods. We found strong exponential relationships with variance explained in night Re were 70, 42 and 62% during anthesis, maturity and after-harvest periods. The temperature sensitivity coefficient (Q_{10}) observed during anthesis and harvest period were 2.1 and 1.95 which is close to a value (2.0) often used in respiration models (Arora and Gajri, 1998). Very low Q_{10} of 1.06 at maturity stage was mainly due to curtailed need of respiration for growth and maintenance. Night Re was high when crop had more active green biomass and decline drastically during maturity stage.

3.3 Photosynthesis-Light Response Curve

Gross primary productivity is mainly influenced by canopy characteristics (e.g. leaf area index, chlorophyll content etc) and intensity of radiation. Considering absorbed light as source of energy for gross photosynthesis, we examine relationship between gross primary productivity and absorbed photosynthetically active radiation at four critical growth periods of wheat growing season. The GPP data are half-hourly diurnal averages during a week of respective periods. of weekly measured PAR of different growth stages.

A hyperbolic Michaelis–Menton relationship (e.g. Falge *et a*l., 2001) was fitted to the data by the least square regression. Parameters obtained for this function such as ecosystem quantum yield (α) and GPP saturation (P_{max}) are listed in table 1. Results reveals that quantum yield decreased from 0.14 mol CO_2 mol photons-1 during tillering growth stage to merely 0.021 mol CO_2 mol photons-1. Although LAI was less at tillering, high value of α was mainly resulted from reduced light levels caused by foggy weather condition. However, GPP maxima showed trend that matches with LAI. Peak GPP in wheat was 2.6 mg CO_2 m^{-2} s^{-1} and occurred at anthesis stage.

Growth Stage	α (mol CO_2 mol photon^{-1})	P_{maz} (mg CO_2 m^{-2} s^{-1})	R^2	N
Tillering	0.14	1.47	0.64	17
Anthesis	0.052	2.60	0.76	39
Post-anthesis	0.054	1.60	0.85	27
maturity	0.02	0.33	0.51	22

Table 1: Ecosystem Quantum Yield (α), the Hypothetical Maximums of GPP (P_{max}) for Different Growth Stages of Wheat

3.4 Relationship Between CO2 Exchange Components and MODIS Derived Ecosystem Variables

Correlation analysis results as shown in table 2 indicates that components (NEE, Re, GPP and NEE$_{satpass}$) of CO_2 exchange over wheat ecosystem were strongly related to MODIS derived ecosystem variable (EVI, NDVI,LST etc).

Variables	NDVI	EVI	LST	T_{air}	VPD
GPP	0.73**	0.76**	-0.68**	-0.64**	-0.66**
NEE	0.74**	0.76**	-0.74**	-0.70**	-0.71**
NEE$_{satpass}$	0.75**	0.76**	-0.73**	-0.67**	-0.66**
Re	0.67**	0.61**	-0.47**	-0.44**	-0.47**

Table 2: Correlation Between Flux Components and Ecosystem Variables

Results as shown in table 2 reveals that GPP and NEE over agro-ecosystem dominated by wheat was found significantly and positively related to vegetation indices. Whereas, environmental variables such as LST, air temperature and vapor pressure deficit were negatively correlated with GPP, carbon exchange components (GPP, NEE, Re and NEEsatpass). The significant correlation allowed us to evaluate combined effect of both greenness and temperature on GPP by parameterization of T-G model. The combined effect of greenness and temperature as discussed in T-G model could better explained variance in GPP (R2 = 0.77). The fit is significant based on t-test (p = 0.012). The scalar parameter (m) was parameterized for wheat site (Meerut) is 4.32 mol C m-2 d-1 (fig. 3). The T-G model demonstrates that GPP can be estimated with a high degree of accuracy using only satellite remote sensing data, if scalar parameter is parameterized for diverse ecosystems and climate regimes. The applicability over a regional scale requires testing of model across varied agro-ecosystems and multiple years.
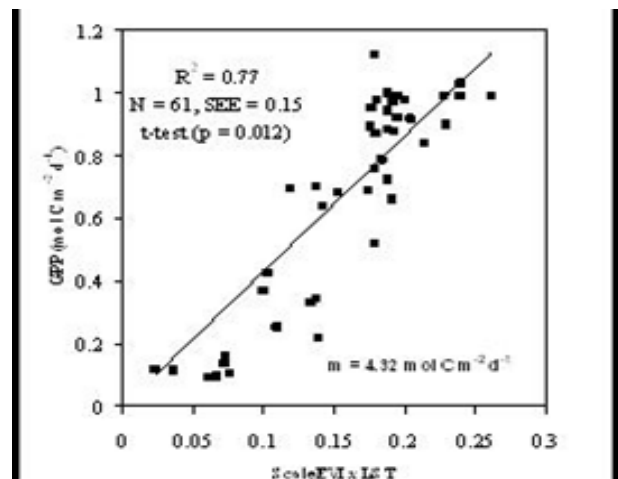

Figure 3. Daily GPP Measured at Flux Tower as a Function of Scaled EVI × Scaled LST for Year 2009

It was also observed that GPP verses scaled EVI × LST is not truly linear. We therefore fitted sigmoidal function to see existence of

non-linearity (Fig. 4). It was found that the use of a sigmoid function in place of the linear function improved amount of variance explained in GPP ($R^2 = 0.81$).
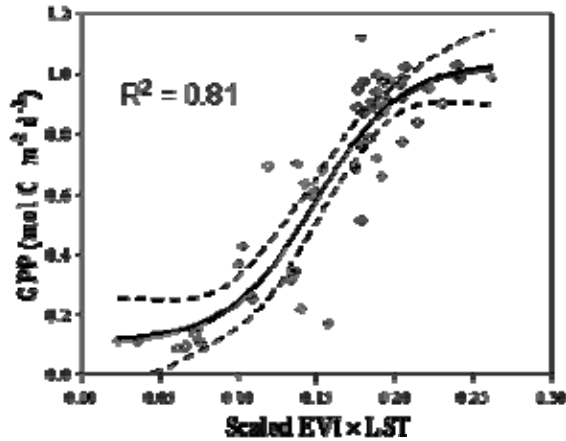

Figure 4. Sigmoid Curve of GPP from a Flux Tower (Merrut site) as a Function of Scaled EVI × LST

3.5 Phenomenological Models for GPP and NEE

Multi-variate regression analysis revealed significant relationship between the major CO_2 exchange components (NEE_{CO2}, GPP) and various combination of vegetation indices and environmental variables (LST, T_{air}). We found that inclusion of either LST or T_{air} with either of vegetation index led to slight improvement in statistical model (Table 3). Most of these combinations had explained variance in GPP or NEE_{CO2} within range of 55 to 65 percent. Although significant relationship, we did not find any improvement performance of model fit as compared to T-G model.

Carbon Exchange Components	Predictor Variables	R^2	N	SEE
NEE_{CO2}	EVI, T_{air}	0.64	75	5.26
	EVI, LST	0.61	57	5.51
	NDVI, Tair	0.61	75	5.49
	NDVI, LST	0.54	57	5.98
GPP	EVI, T_{air}	0.60	75	8.81
	EVI, LST	0.57	57	9.12
	NDVI, T_{air}	0.61	75	8.72
	NDVI, LST	0.63	57	8.44

Table 3: Functional Characteristics of Phenomenological models

CONCLUSION

The study explores utility of eddy covariance measurements for better understanding of diurnal and seasonal behavior of CO_2 exchange in agro-ecosystem dominated by wheat crop. Negative NEE found during day-time represents photosynthesis and positive NEE during night-time as respiration. At a given growth stage, the daytime NEE (net ecosystem CO_2 exchange) and incident PAR were closely linked through a hyperbolic relationship. High quantum yield of 0.14 was observed during early stage due to foggy weather. Light-saturation limits however found closely related to leaf area index. Temperature sensitivity coefficient (Q_{10})

of respiration was found much close to reported values. Peaks in GPP were observed approximately 72 days after emergence and coincides with the seasonally maximum LAI. When examine relationship of major CO_2 exchange components with remotely sensed signatures, we found that temperature-greenness model involving enhanced vegetation index and land surface temperature might provides accurate estimation of gross primary productivity. Overall, this study provides basis for better physiological characterization of wheat and improvement of crop models.

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