# SOIL $CO_2$ FLUX MEASUREMENTS FROM A MATURE NATURAL RUBBER PLANTATION

**Joshua Abraham and M.D. Jessy**

Rubber Research Institute of India, Kottayam-686 009, Kerala, India

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Soil $CO_2$ flux, also often referred as soil respiration is defined as the emission of $CO_2$ generated in the soil as a result of microbial and root activities. Soil $CO_2$ flux was measured and related to soil temperature and moisture in a 21 year old rubber plantation in central Kerala for a period of two years (June, 2010 to May, 2012). Measurements were made on an hourly basis for 272 days in the first year and 308 days in the second year. Soil respiration varied between the two years as well as between seasons in a given year due to variations in soil temperature and moisture. Total amount of $CO_2$ emitted was more in 2010-11 (26.1 tonnes $ha^{-1}$) than in 2011-12 (20.7 tonnes $ha^{-1}$) which was apparently related to more rainfall and number of rainy days in 2010-11 than in 2011-12. Soil respiration was slightly more in the night than in the day indicating that the cooler temperature of the night favoured more soil respiration. Soil respiration was higher during monsoon and summer seasons than during post monsoon and winter seasons in both the years. During monsoon, post monsoon, winter and summer seasons, the soil $CO_2$ fluxes were 2.21, 1.45, 1.47 and 2.19 µmol $m^{-2}$ $s^{-1}$, respectively in 2010-11. In 2011-12, the soil $CO_2$ fluxes were 1.78, 1.15, 0.98 and 1.75 µmol $m^{-2}$ $s^{-1}$ during monsoon, post monsoon, winter and summer seasons, respectively. In general, warmer temperatures favoured more soil respiration when sufficient moisture was available in the soil. When soil moisture status remained continuously high for longer periods, soil $CO_2$ fluxes were impaired. Sudden and intense rainfall during an otherwise relatively dry period led to voluminous eruption of $CO_2$ from soil as observed during many instances in winter and summer seasons in both the years. This may be due to burst of entrapped $CO_2$ in soil pores by rain water. Availability of moisture in soil was more critical than the soil temperature for soil respiration during summer whereas during wet periods, the soil temperature was more important. Rising temperature and changes in the amount and pattern of rainfall as a consequent effect of climate change may affect soil respiration rates which can have profound impact on global carbon cycle and also on soil organic matter, a key component that determines soil fertility.

**Key words**: *Hevea brasiliensis,* Climate change, Soil $CO_2$ flux, Soil respiration, Soil moisture, Soil temperature

## INTRODUCTION

Soil respiration is a process by which the $CO_2$ generated by micro-organisms and roots in the soil is released to the atmosphere. Soils are the largest C pool in terrestrial ecosystems containing more than 1500 Pg C (Raich and Schlesinger, 1992; Eswaran *et al.*, 1993). Soil respiration exceeds all other terrestrial-atmospheric carbon exchange processes with the exception of photosynthesis (Xu and Shang, 2016; IPCC, 2001; Raich and Schlesinger, 1992). Carbon dioxide is a major greenhouse gas released from soil to atmosphere and it is a crucial component

Correspondence: Joshua Abraham (Email: joshua@rubberboard.org.in)

of the global C cycle (Jones *et al.*, 2003; Rustad *et al.*, 2000). Even a small change in this flux can bring about drastic effects on the atmospheric $CO_2$ concentration (Bohn, 1982; Eswaran *et al.*, 1993; Eswaran *et al.*, 1995), which in turn will have a bearing on global warming. Hence, it is important to have accurate estimation of soil $CO_2$ efflux or soil respiration from different terrestrial ecosystems (Liang *et al.*, 2004; Schlesinger and Andrews, 2000).

Soil $CO_2$ flux at a given site is largely dependent on soil temperature and moisture (Raich and Schlesinger, 1992; Raich and Potter, 1995; Davidson *et al.*, 1998). Variations in soil $CO_2$ flux in different seasons in an agrarian system may largely be associated with seasonal changes in soil temperature and moisture (Raich and Potter, 1995). Diurnal variations in soil respiration rates also occur mainly due to the diurnal variations in soil temperature and moisture. Soil respiration also varies in different vegetation types. Factors affecting microbial activity such as quality and quantity of soil organic matter, root densities, microbial populations, soil physical and chemical properties, soil drainage *etc.* can also influence the soil respiration rates in different soil ecosystems (Raich and Tufekcioglu, 2000).

Natural rubber plantations are unique agriculture systems and are considered as environmentally acceptable closed ecosystems with a regular cycle of uptake and return of soil nutrients (Jacob, 2000; Delabarre and Serier, 2000) besides acting as a large sink of carbon (Jacob, 2000). Numerous studies and reports are available on $CO_2$ uptake and photosynthesis in many agricultural systems, including natural rubber (Akinola, 2014; Murchie *et al.*, 2009; Kositsup *et al.*, 2009) but reports are sparse on soil $CO_2$ flux (soil respiration), especially from natural rubber plantations.

Main objective of this study was to quantify soil $CO_2$ efflux from a typical rubber plantation during different seasons of the year in Kerala, India. Variations in soil $CO_2$ flux in different seasons with respect to the variations in soil temperature and moisture were also studied.

## MATERIALS AND METHODS

The study was carried out in the farm of Rubber Research Institute of India at Kottayam, Kerala (9°32′N, 76°36′E). The rubber trees were 21 years old and the area was in the second planting cycle. Soil samples (0-15 cm) were collected from the the observation sites and it was found to be high in organic carbon (3.01 %) and total nitrogen (0.22 %) and was acidic (pH, 4.57). Four permanent sites, two between the trees in a row and two between tree rows were randomly selected to record the observations which were about 40 to 70 m apart. Daily rainfall data recorded in the weather station situated adjacent to the field was utilized for interpretations.

Observations were recorded from the permanent sites in the field for a period of two years from June 2010 to May 2012, covering all the four seasons *viz.* monsoon (June to September), post monsoon (October to December), winter (January to February) and summer (March to May) continuously. Prior to the measurements, soil collars (PVC, inner diameter 20 cm) were fixed at all the four sites covered with leaf litter with minimum soil disturbance. Using an iron ring with exact diameter of the PVC collar and having sharp edges on one side, a circular incision was made on the soil surface. The PVC collar was inserted about 1.5 cm deep on the incision made by the iron ring without disturbing the soil. Measurements commenced two weeks after fixing the soil collars. Soil $CO_2$ flux was recorded using chambers (LI-8100-104) fixed at the four sites in the field connected to an automated soil $CO_2$ flux measurement system (LI-8100) through a multiplexer (LI-8150). A temperature probe (LI-8150-202) and moisture probe (LI-8150-203) were connected to each chamber. Measurements of soil $CO_2$ flux, soil temperature and soil moisture from each site were made on an hourly basis round the clock while daily rainfall data was collected from the meteorological station in the farm. Observations were made on 272 and 308 days covering all seasons during 2011-12 and 2011-12, respectively. Due to instrument / power associated technical snags and thunderstorms / lightening associated problems, data recording could not be made on rest of the days.

The hourly data recorded for soil $CO_2$ flux, temperature and moisture from the four sites were averaged to represent the field. Whole day (24 hours), day time (9.00 – 20.00 hrs) and night time (21.00 – 8.00 hrs) means of soil $CO_2$ flux, temperature and moisture were worked out for every day. The entire data for 2010-11 and 2011-12 were classified into four seasons, *viz.* monsoon, post monsoon, winter and summer. Variations in soil $CO_2$ flux, temperature and moisture between the respective seasons in 2010-11 and 2011-12 were compared using independent t test. The variations in soil $CO_2$ flux, temperature and moisture between day time and night time were analysed using independent t test in every season during 2010-11 and 2011-12. Soil $CO_2$ emissions for the whole day (24 hrs) and day time and night time for every day of observation were computed using the respective means of whole day, day time and night time. Total emission and range of soil $CO_2$ were computed for every season based on which the total annual soil $CO_2$ emissions were calculated for 2010-11 and 2011-12. To find out the influence of soil temperature and moisture on soil $CO_2$ flux, multiple linear regression analyses were carried out for each season and the significance was evaluated using the F-statistics (Snedecor and Cochran, 1967).

## RESULTS AND DISCUSSION

### Variations in soil $CO_2$ flux, temperature, moisture and rainfall

Whole day (24 hrs) mean of soil $CO_2$ flux, temperature and moisture during 2010-11 and 2011-12 are shown in Figures 1 and 2, respectively. Mean soil $CO_2$ flux in 2010-11 was higher (1.88 $\mu$mol m$^{-2}$ s$^{-1}$) and ranged from 0.85 to 4.67 $\mu$mol m$^{-2}$ s$^{-1}$ than in 2011-12 (1.49 $\mu$mol m$^{-2}$ s$^{-1}$) which ranged from 0.72 to 2.76 $\mu$mol m$^{-2}$ s$^{-1}$. The mean soil temperature (25.0 $^oC$) was also higher in 2010-11 which ranged from 22.5 to 27.9 $^oC$ than in 2011-12 (23.3 $^oC$) which ranged from 20.8 to 25.7 $^oC$. The mean soil moisture was higher (24.1%) in 2010-11, ranging from 9.6 to 31.3 per cent than in 2011-2012 (22.9%) which ranged from 12.9 to 33.6 per cent.

Several peaks and large fluctuations in soil $CO_2$ flux were observed from January to May *viz.* during winter and summer seasons in 2011 and also in 2012 (Fig. 1 and 2). These spikes were likely due to the sudden displacement of $CO_2$ entrapped in the soil pores during dry spells by water due to intermittent rains during this period. Soil moisture also fluctuated and several dry spells were observed during this period compared to other seasons. However, fluctuations in soil temperature were minimal unlike in the case of $CO_2$ flux or moisture. Such observations were reported earlier in different types of vegetation when summer rains were received during dry seasons

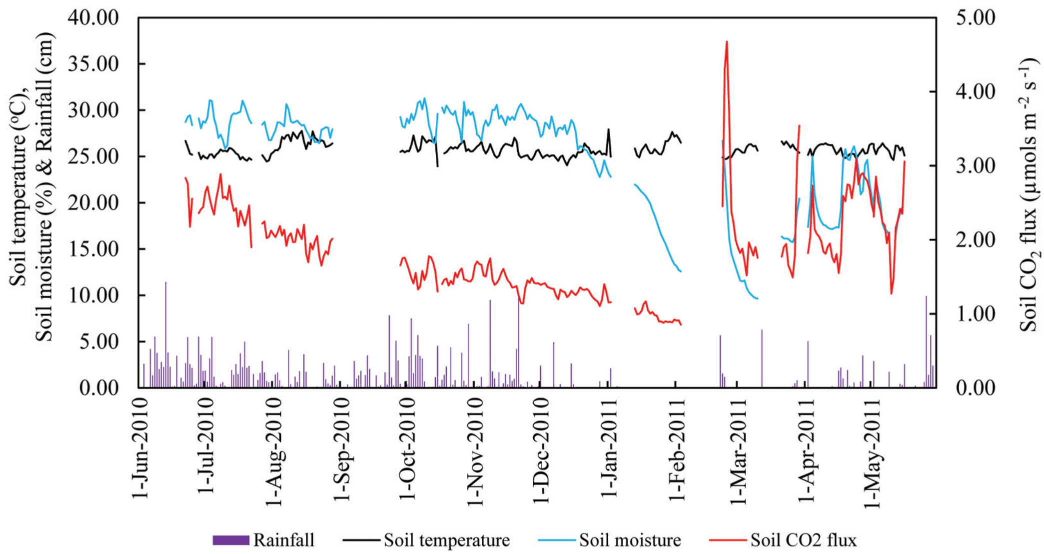


Fig. 1. Whole day means of soil $CO_2$ flux (μmol $m^{-2}$ $s^{-1}$), soil temperature ($^{\circ}C$), soil moisture (%) and daily rainfall (cm) during 2010-2011

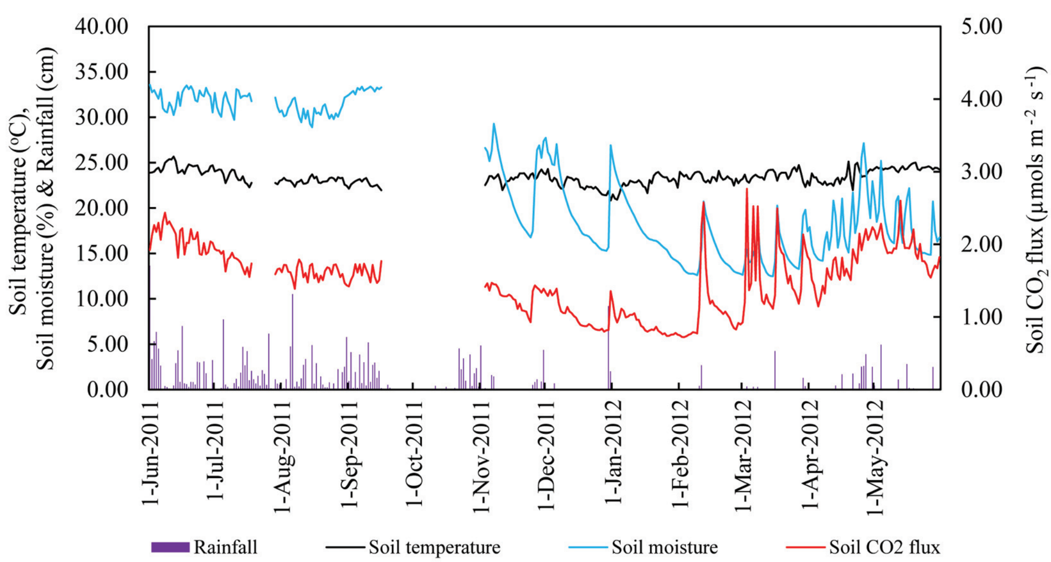


Fig. 2. Whole day means of soil $CO_2$ flux (μmol $m^{-2}$ $s^{-1}$), soil temperature ($^{\circ}C$), soil moisture (%) and daily rainfall (cm), during 2011-2012

Table 1. **Amount of rainfall, number of rainy days, soil $CO_2$ emissions in different seasons during 2010-2011 and 2011-2012**

| Seasons | Rainfall (mm) | Number of rainy days | Soil $CO_2$ emissions (tonnes $ha^{-1}$ $season^{-1}$) | | |
|---|---|---|---|---|---|
| | | | Day time | Night time | Total |
| Monsoon 2010 | 1827 | 86 | 5.02 | 5.22 | 10.22 |
| Post Monsoon 2010 | 1067 | 48 | 2.44 | 2.52 | 4.97 |
| Winter 2011 | 110 | 4 | 1.47 | 1.81 | 3.25 |
| Summer 2011 | 536 | 23 | 3.35 | 4.17 | 7.64 |
| Annual (2010-2011) | 3540 | 161 | 12.29 | 13.72 | 26.08 |
| Monsoon 2011 | 1974 | 87 | 4.10 | 4.19 | 8.30 |
| Post Monsoon 2011 | 490 | 21 | 1.99 | 2.04 | 4.02 |
| Winter 2012 | 31 | 3 | 1.03 | 1.18 | 2.21 |
| Summer 2012 | 360 | 19 | 2.90 | 3.22 | 6.11 |
| Annual (2011-2012) | 2855 | 130 | 10.02 | 10.62 | 20.65 |

(Xu *et al.*, 2004; Shi *et al.*, 2011; Jiang *et al.*, 2013). Rainfall in winter and summer seasons in 2011 was higher than in 2012 while the number of rainy days was similar (Table 1). A gradual declining trend in soil $CO_2$ flux was observed from June to September (monsoon season) in both the years (Fig. 1 and 2).

Frequent rains occurred during the monsoon period in the two years. Though the number of rainy days was similar, rainfall was higher in 2010 than in 2011 (Table 1).

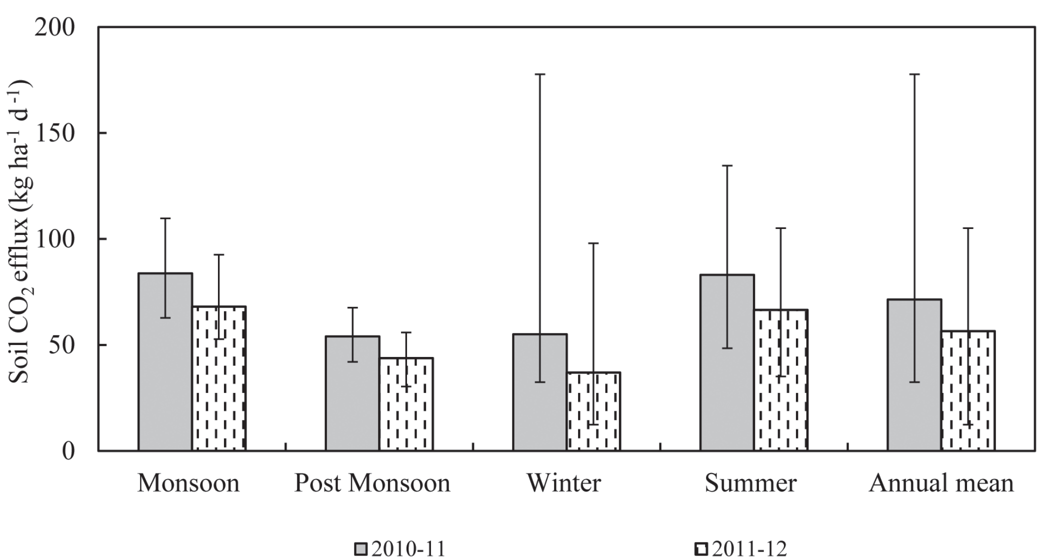


Fig. 3. Mean daily soil $CO_2$ emission in different seasons in 2010-2011 and 2011-2012. (Vertical bars represent the range of daily $CO_2$ emissions)

However, during 2010 post monsoon season the amount of rainfall and number of rainy days were almost double compared to 2011 (Table 1). During winter and summer seasons also, the amount of rainfall was more in 2011 than in 2012 (Table 1). Thus the total amount of rainfall and its distribution were higher in 2010-11 than in 2011-12. This could be the reason for higher mean soil moisture in 2010-11 than in 2011-12 (Table 1). However, the rainfall or number of rainy days did not influence the mean soil temperature as it was higher in 2010-11 than in 2011-12.

**Seasonal and annual soil $CO_2$ emissions**

Mean soil $CO_2$ emissions (daily) in different seasons in 2010-11 and 2011-12 are given in Figure 3. Mean daily soil $CO_2$ emission in 2010-11 was 71.4 kg $ha^{-1}$ $d^{-1}$ and ranged from 32.5 to 177.7 kg $ha^{-1}$ $d^{-1}$ while in 2011-2012 this was 56.5 kg $ha^{-1}d^{-1}$ with a range of 12.4 to 105.1 kg $ha^{-1}$ $d^{-1}$ (Fig. 3). The total annual soil $CO_2$ emissions in 2010-11 and 2011-12, were estimated to be 26.1 and 20.7 tonnes $ha^{-1}$, respectively (Table 1). From similar studies in Thailand during 2009 to 2011, it was reported that from 15 year old rubber plantations, the average annual $CO_2$ emission was 18.8 tonnes $ha^{-1}$ (Satakhun *et al.*, 2013) while Hassler *et al.* (2015) reported that the annual soil $CO_2$ emission from rubber plantations (14 -17 year old) in Indonesia was approximately 16.5 tonnes $ha^{-1}$. Soil $CO_2$ emission during day and night in different seasons in 2010-11 and 2011-12 are given in Table 1. Invariably in all the seasons in both the years, soil $CO_2$ emissions were slightly higher during night time than during day time. This difference was marginal during monsoon and post monsoon seasons and was prominent during winter and summer seasons.

The mean daily soil $CO_2$ emission in monsoon (83.8 kg $ha^{-1}$ $d^{-1}$) and summer (83.1 kg $ha^{-1}$ $d^{-1}$) seasons in 2010-2011 were similar. Also the mean soil $CO_2$ emissions were similar in post monsoon (55.0 kg $ha^{-1}$ $d^{-1}$) and winter (54.0 kg $ha^{-1}$ $d^{-1}$) seasons (Fig. 3). However, the ranges during monsoon (62.8 to 109.7 kg $ha^{-1}$ $d^{-1}$) and post monsoon (42.0 to 67.6 kg $ha^{-1}$ $d^{-1}$) seasons were narrower than during summer (48.4 to 134.6 kg $ha^{-1}$) and winter (32.5 to 177.7 kg $ha^{-1}$ $d^{-1}$) seasons

Table 2. **Mean soil $CO_2$ flux, temperature and moisture during different seasons in 2010-2011 and 2011-2012**

| Means | Parameters | Monsoon | | Post monsoon | | Winter | | Summer | |
|---|---|---|---|---|---|---|---|---|---|
| | | 2010 | 2011 | 2010 | 2011 | 2011 | 2012 | 2011 | 2012 |
| Whole day | Soil $CO_2$ flux *($\mu mol\ m^{-2}\ s^{-1}$)* | 2.2 ** | 1.8 | 1.4 ** | 1.2 | 1.5 ** | 1.0 | 2.2 ** | 1.8 |
| | Soil temperature *($^oC$)* | 23.9 ** | 23.5 | 25.6 ** | 22.9 | 25.9 ** | 23.0 | 25.8 * | 23.8 |
| | Soil moisture *(%)* | 28.4 | 31.7 ** | 28.3 ** | 21.3 | 18.1 | 16.4 | 18.3 | 17.1 |
| Day time | Soil $CO_2$ flux *($\mu mol\ m^{-2}\ s^{-1}$)* | 2.2 ** | 1.8 | 1.4 ** | 1.1 | 1.3 * | 0.910 | 1.9 ** | 1.7 |
| | Soil temperature *($^oC$)* | 24.3 ** | 23.7 | 26.5 ** | 23.5 | 26.6 ** | 23.8 | 26.3 * | 24.4 |
| | Soil moisture *(%)* | 28.4 | 31.7 ** | 28.1 * | 21.2 | 18.2 | 16.3 | 18.2 | 17.0 |
| Night time | Soil $CO_2$ flux *($\mu mol\ m^{-2}\ s^{-1}$)* | 2.3 ** | 1.8 | 1.4 ** | 1.2 | 1.6 ** | 1.0 | 2.4 ** | 1.8 |
| | Soil temperature *($^oC$)* | 23.3 | 23.1 | 24.8 ** | 22.6 | 24.7 ** | 22.7 | 25.2 * | 23.7 |
| | Soil moisture *(%)* | 28.4 | 31.7 ** | 28.4 ** | 21.3 | 18.0 | 16.5 | 18.3 | 17.1 |

*(*, ** - Significance at $P \leq 0.01$ and $P \leq 0.05$, respectively)*

(Fig. 3). In general, daily means of soil $CO_2$ emissions were lower in 2011 in all seasons than in 2010 (Fig. 3). However, the trends were similar as in 2010-2011. Daily mean soil $CO_2$ emissions in monsoon and summer seasons were 68.0 and 66.5 kg ha$^{-1}$ d$^{-1}$, respectively. During post monsoon and winter seasons, mean soil $CO_2$ emissions were 43.7 and 36.9 kg ha$^{-1}$ d$^{-1}$, respectively. The ranges were 52.8 to 92.6, and 30.4 to 55.9 kg ha$^{-1}$ d$^{-1}$ in monsoon and post monsoon seasons, respectively. The ranges were 35.2 to 105.1 and 12.4 to 98 kg ha$^{-1}$ d$^{-1}$ in summer and winter seasons, respectively (Fig. 3).

Higher rainfall and more number of rainy days in 2010-11 might be the reason for higher soil $CO_2$ emission in 2010-11 than in 2011-12. In all the seasons amount of rainfall was higher in 2010-11 than in 2011-12 (Table 1) and this reflected in the corresponding daily mean soil $CO_2$ emissions. For more clarity on variations in soil $CO_2$ emissions during different seasons, the role of soil temperature and moisture on soil $CO_2$ flux was examined.

## Seasonal soil $CO_2$ fluxes with respect to soil temperature and moisture

### *Monsoon season*

Whole day (24 hours), day time and night time means of soil $CO_2$ flux, temperature and moisture during monsoon season in 2010 and 2011 are shown in Table 2. Whole day mean soil $CO_2$ flux was significantly higher in 2010 than in 2011. The mean soil temperature was also higher in 2010 while mean soil moisture was significantly lower in 2010 than in 2011. Multiple linear regression (MLR) analysis indicated that soil $CO_2$ flux was positively influenced by soil temperature during the monsoon season in 2010 and 2011 (Table 3). However, soil moisture did not influence $CO_2$ flux (Table 3) in 2010 and 2011. During the monsoon season, soil moisture status was very high, 28.4 and 31.7 per cent in 2010 and 2011, respectively (Table 2). Amount of rainfall in 2011 was higher than in 2010 with similar number of rainy days (Table 1), resulting in higher soil moisture status in 2011 (Table 2). The higher soil moisture status in 2011 (monsoon season) might be the reason for the lower soil $CO_2$ flux than in 2010. When the soil moisture is high, it may limit gas exchange between soil and atmosphere and may lead to lower soil oxygen concentration and can restrict aerobic respiration of soil biota (Yu *et al.*, 2011). Raich (2017) reported a negative relationship between soil moisture and soil respiration in wet seasons. In maize based systems in China when soil moisture exceeded 20 per cent a decline in soil $CO_2$ flux rate was observed (Gao *et al.*, 2012). During wet season, soil temperature can influence $CO_2$ flux more than soil moisture (Jiang *et al.*, 2013). Xu *et al.* (2004) observed that when soil moisture exceeded 15 per cent, it was not a limiting factor in soil $CO_2$ flux process, but soil temperature was the deciding factor in certain tree systems in California.

In general, during monsoon season, with high rainfall and more number of rainy days soil moisture will maintain at sufficiently higher levels and may not be a constraint for increased microbial or root activity. At times in monsoon season soil moisture status may exceed certain levels and can adversely influence soil $CO_2$ flux. However, temperature may become a constraining factor for microbial activity during the monsoon season and can positively influence the microbial activity, thereby increase soil $CO_2$ flux as evidenced by the higher $CO_2$ flux and higher soil temperature in 2010 than in 2011 (Table 2). Mean soil $CO_2$ flux and temperature during day and night also followed a similar trend in 2010 and 2011 (Table 2). In both the years mean soil $CO_2$ flux and moisture during day and night did not significantly vary. However, soil temperature during night was lower than during day.

***Post-monsoon season***

Mean soil $CO_2$ flux, temperature and moisture during post-monsoon season in 2010 and 2011 are shown in Table 2. Soil $CO_2$ flux was significantly and positively influenced by soil temperature and moisture during post-monsoon season in 2010 and 2011 (Table 3). The higher soil $CO_2$ flux in 2010 than in 2011 can be attributed to the correspondingly higher soil temperature and moisture (Table 2). The amount of rainfall and number of rainy days (Table 1) were almost double in 2010 than in 2011 and this had a clear effect on the higher soil moisture status in 2010 (Table 2). However, soil $CO_2$ flux exhibited lower rates during the post-monsoon season than the preceding monsoon season in both the years. While soil temperature was higher in post monsoon season in 2010 than in the preceding monsoon season, soil moisture was more or less similar in both the seasons (Table 2). Apparently, the soil moisture remained at a higher level (> 25 %) continuously for about seven months in monsoon and post monsoon seasons in 2010 and could be a possible reason for the reduction in soil $CO_2$ flux during the post monsoon season as discussed earlier.

In 2011, soil moisture status during the post monsoon season declined by about ten per cent compared to the preceding monsoon season (Table 2), which was obviously due to the lower amount of rain fall coupled with a lesser number of rainy days (Table 1). Though soil moisture declined considerably in the post monsoon season, soil temperature remained more or less similar to the monsoon season (Table 2). Wider variations in soil moisture status with less number of rainy days and low rainfall may result in more dry spells with lower moisture status. Between post-monsoon seasons in 2010 and 2011, wider variations in soil moisture, less rainfall and number of rainy days with more dry spells were noticed in 2011 (Fig. 1, 2 and Table 1 and 2). This might be a reason for the lower $CO_2$ flux in the post-monsoon season in 2011. The negative effect of higher soil moisture status (> field capacity) on soil $CO_2$ flux will not be changed with a reduction in moisture status alone but only with an improvement in soil temperature to the optimum level (Jiang *et al*., 2013).

Though the $CO_2$ flux rates were lower in post-monsoon season in 2010 and 2011 than the monsoon seasons in the respective years, due to the soil temperature and moisture effects as explained earlier, the soil temperature and moisture *per se,* had a significant and positive effect on soil $CO_2$ flux rate in the post-monsoon season in 2010 and 2011 as indicated by the MLR analysis of the daily mean data. The influence of soil temperature was much higher than soil moisture on soil $CO_2$ flux (Table 3).

Mean soil $CO_2$ flux, temperature and moisture during day and night also followed a similar trend in post-monsoon seasons of 2010 and 2011 as in the case of whole day mean (Table 2). In both years mean soil $CO_2$ flux and soil moisture status did not vary significantly between day and night while mean soil temperature was significantly higher during day than night hours.

***Winter season***

Whole day, day time and night time means of soil $CO_2$ flux, temperature and moisture during winter season in 2011 and 2012 are

Table 3. **Influence of daily means of soil temperature and moisture on soil $CO_2$ flux in different seasons**

| Seasons | Constant | Coefficient of soil temperature | Coefficient of soil moisture | $R^2$ |
|---|---|---|---|---|
| Monsoon 2010 | -5.64 | 0.32 ** | - | 0.86 |
| Monsoon 2011 | -5.41 | 0.27 ** | - | 0.79 |
| Post-monsoon 2010 | -2.19 | 0.12 * | 0.02 ** | 0.39 |
| Post-monsoon 2011 | -1.27 | 0.07 ** | 0.04 ** | 0.85 |
| Winter 2011 | 16.61 | -0.58 * | - | 0.26 |
| Winter 2012 | -4.30 | 0.18 * | 0.06 * | 0.21 |
| Summer 2011 | 2.21 | - | 0.08 ** | 0.51 |
| Summer 2012 | -1.82 | 0.09 * | 0.08 ** | 0.45 |

*(*, ** - Significance at $P \leq 0.01$ and $P \leq 0.05$, respectively)*

shown in Table 2. Mean soil $CO_2$ flux was significantly higher by about 50 per cent in 2011 than in 2012 (Table 2). In 2011, soil temperature was higher while soil moisture did not vary compared to 2012 (Table 2). Soil $CO_2$ flux was not influenced by soil moisture in 2011, while it significantly and positively influenced in 2012. However, soil $CO_2$ flux was negatively influenced by soil temperature in 2011 and positively in 2012 (Table 3).

The higher soil $CO_2$ flux in 2011 may be due to the higher rainfall intensity in 2011 than in 2012. Rainfall was about three times more in 2011 than in 2012 while the number of rainy days was almost similar (Table 1 and 2). Intense and occasional rainfalls in dry spells can result in sudden and voluminous eruption of entrapped $CO_2$ from soil causing sharp variations in flux and also in soil moisture status (Fig. 1, 2 and Table 2). This resulted in higher average values in soil $CO_2$ flux in 2011 than in 2012. However, the higher amount of rainfall in 2011 did not significantly increase the soil moisture status in 2011 than in 2012. Higher soil temperature in 2011 coupled with less frequent rainfall might have resulted in higher evaporation and subsequent depletion in soil moisture. Mean soil $CO_2$ flux, temperature and moisture during day and night also followed a similar trend in winter seasons of 2010 and 2011 as in the case of whole day mean (Table 2).

Compared to the preceding post monsoon season, the mean soil $CO_2$ flux and temperature did not vary in winter season, while soil moisture declined considerably, due to less rainfall in both the years. In spite of such low soil moisture status in winter, mean soil $CO_2$ flux remained similar to that during the post monsoon season due to the intermittent rains in dry spells causing spiked fluctuations in $CO_2$ flux. In both the years, soil moisture status did not vary significantly between day and night, while soil temperature was significantly higher during day than during night. In both the years soil $CO_2$ flux was higher during night than during day.

***Summer season***

Mean soil $CO_2$ flux, temperature and moisture during summer season in 2011 and 2012 are shown in Table 2. Soil $CO_2$ flux and temperature were higher in 2011 than in 2012, but soil moisture did not vary between the two years (Table 2). Soil $CO_2$ flux was influenced by soil moisture positively in both the years while soil temperature had its positive effect only in 2012 (Table 3). The amount of rainfall was higher in 2011 than in 2012 and the number of rainy days was almost similar in both the years (Table 1 and 2). This might have resulted in more intense rainfall incidents and outbursts of $CO_2$ from soil in 2011 (Fig. 1 and 2). This was the major reason for higher mean soil $CO_2$ flux in 2011 than in 2012. Such observations were reported by Xu *et al.* (2004), Shi *et al.* (2011) and Jiang *et al.* (2013) for different types of soils in summer seasons. However, the higher rainfall or number of rainy days in 2011 than in 2012 did not improve the soil moisture status to a significant level.

Soil $CO_2$ flux was lower during day time than night time and the trend was reverse in the case of soil temperature in 2010 and 2011. The higher soil temperature during day time was as expected and experienced usually in hot summer season with hot and bright sunshine during the day hours. Soil moisture did not vary significantly between day and night hours in summer season in both years (Table 2). Soil $CO_2$ flux in summer was much higher than in the preceding winter season in spite of the comparable soil moisture and temperature between the two seasons in 2011 and 2012. This could be due to the much higher number of intense rainfall incidents in the summer than in the preceding winter (Fig. 1 and 2). This resulted in more number of soil $CO_2$ outbursts in summer than in winter (Fig. 1 and 2) and elevated the mean $CO_2$ flux (Table 2).

## CONCLUSION

Mean annual soil $CO_2$ emissions from a typical mature natural rubber plantation ranged from 20.65 to 26.08 tonnes $ha^{-1}$. Soil temperature and moisture influenced soil $CO_2$ flux from the mature rubber plantation to various degrees in different seasons. In general, soil moisture levels were high and less fluctuating during monsoon. If high soil moisture status prevailed for longer periods, soil $CO_2$ flux was impaired. Such situations arose when frequent rains in the monsoon season is extended to the post monsoon season. When soil moisture was not a constraint, soil temperature became more influential in determining the soil $CO_2$ flux positively and such situations usually prevailed during the monsoon and post monsoon seasons. Soil temperature was maintained at higher levels with lower moisture status (dry spells) during summer season and in such situations, soil moisture determined the rate of soil $CO_2$ flux. Longer dry spells and intermittent rains were common during winter and summer seasons which caused sudden outbursts of $CO_2$ from soils.

Soil temperature and moisture are two important factors that influence soil respiration rates. The amount of rainfall and its pattern determine the soil moisture and temperature status. Hence, any drastic changes in the rainfall amount or pattern would result in substantial changes in soil $CO_2$ emissions as evidenced from the present work. In the context of global climate change, the predicted rise in temperature may alter the soil C dynamics in agrarian ecosystems in tropical regions and may result in higher $CO_2$ emissions from soil, especially during monsoon season when the soil moisture status is likely to remain at sufficiently higher levels. This may further increase atmospheric $CO_2$ levels and deplete the soil organic matter status, a key component that determines soil fertility.

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