Article

Dynamics of soil CO_2 efflux in three tropical dry deciduous forests of Central Indian landscape

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Abstract
Dynamics of soil CO_2 efflux in tropical dry deciduous forests is imperative to know their contribution in regulating the regional and global carbon (C) cycles. In this study, three forest types: dry deciduous teak (DDTF), dry deciduous mixed (DDMF) and *Boswellia* (BF) forests were selected to measure the dynamics of soil CO_2 efflux and its driving factors. Significantly ($p < 0.001$) higher mean monthly CO_2 efflux was recorded in DDMF (626.1 ± 9.1 mg $CO_2/m^2/h$) while it was lowest in BF (122.3 ± 5.0 mg $CO_2/m^2/h$) and DDTF (142.8 ± 6.9 mg $CO_2/m^2/h$) forest types, respectively. The CO_2 efflux peaked during the rainy season (mean 551.1 ± 63.5 mg $CO_2/m^2/h$, DDMF) followed by summer (363.7 ± 68.6 mg $CO_2/m^2/h$, DDTF) and the lowest in winter (181.8 ± 36.3 mg $CO_2/m^2/h$, BF) season. Significantly ($p < 0.05$) lower soil temperature (T_S) and higher soil moisture (M_S) content were observed in BF and DDMF forest types, respectively. The cumulative annual soil CO_2 efflux was highest in DDMF (4625.2 mg $CO_2/m^2/yr$) and lowest in BF (3536.7 mg $CO_2/m^2/yr$). Soil CO_2 efflux was significantly positively correlated with TS (R^2 = 0.49), MS (R^2 = 0.59). This study will provide an understanding of the dynamics of soil CO_2 efflux among tropical dry deciduous forest types in the Central Indian landscape and identify the roles of different drivers in soil CO_2 efflux.

Keywords soil CO_2 efflux; seasonal dynamics; soil moisture; tropical dry deciduous forests; Central India.

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1 Introduction

The carbon (C) cycle is a biogeochemical process that exchanges fluxes of C between different reservoirs, such as the atmosphere, geosphere, hydrosphere and pedosphere (Riebeek, 2011). Soil respiration plays a significant role in global C cycle, releasing 98 Pg C per year into the atmosphere (Bilandžija et al., 2016; Zhao et al., 2017). Globally, carbon dioxide (CO_2) efflux is estimated to be 98 ± 12 Pg C/yr or 85 Pg C/yr if agricultural areas are excluded and is increasing at a rate of 0.1 Pg C/yr (Bond-Lamborty and Thomson, 2010). It is considered as the second largest C flux between the terrestrial ecosystems and the atmosphere (Hanson et al., 2000). Soil CO_2 flux consists of two major C fluxes, i.e., autotrophic respiration of plant roots and heterotrophic respiration through the soil microbial activities and is affected by a multitude of environmental factors (Chen et al., 2017; Zhou et al., 2013). It is estimated that about 90% of the soil CO_2 emissions is performed by the soil microflora via decomposition of organic matter (Reichle et al., 1975). Root respiration can also contribute to about 50% of the total respiration in soil (Pregitzer et al., 2007). It is therefore important to understand the dynamics of soil respiration in any ecosystem to mitigate climate change.

Tropical forests play a significant role in global C cycling as it comprises about 40% of all global terrestrial biomass C stocks and adds up to 67% of the overall soil CO_2 flux (Field et al., 1998; Phillips et al., 1998; Bond-Lamberty and Thomson, 2010b). Thereby, estimations of soil respiration from tropical forests are very useful in understanding total metabolic activities that occur in the soil, concentrations of carbon fluxes via soil, and interrelations among soil and air. Howard and Howard (1993) have examined the relationships that exist among soil CO_2 evolution, moisture content and temperature for various soil types. Various abiotic and biotic factors such as soil temperature, soil moisture (Arroyo and Wood, 2021; Bao et al., 2016), soil pH (Andersson and Nilsson, 2011), availability of C substrates for microorganisms (Okello et al., 2023), soil microbial activity (Tang et al., 2018), soil fertility (Butnor et al. 2003), plant photosynthetic activity (Zhang et al., 2013a, 2013b), and soil organisms (Rai and Srivastava 1981) affect the rate of soil CO_2 efflux.

Even small changes in soil CO_2 fluxes across vast areas can have a considerable impact on atmospheric CO_2 concentration and provide potential positive feedback to global warming (Schlesinger and Andrews, 2000). Comprehensive data on soil CO_2 efflux and its control variables are therefore crucial to frame the ecosystem C budget and identify the response of soil to global warming and climate change in different ecosystems (Buchmann, 2000; Han et al., 2007). With this backdrop, the present study aimed: i) to assess the seasonal and monthly variations in soil CO_2 efflux, ii) to understand the impacts of soil temperature and soil moisture on soil CO_2 efflux, and iii) to analyze the relationships between CO_2 efflux with soil temperature (Ts) and soil moisture (Ms) in three different tropical dry deciduous forest types of Sagar, Madhya Pradesh.

2 Study area and Methodology

2.1 Study area

The present study was undertaken in three tropical dry deciduous forest types viz., dry deciduous teak forest (DDTF, Site I), dry deciduous mixed forest (DDMF, Site II) and *Boswellia* forest (BF, Site III) in Sagar, Madhya Pradesh (Table 1, Fig. 1) which are a part of lower Vindhyan range of Central India, and is situated at an average height of 420 m a.s.l. The area has a hot dry summer from April to June, followed by a monsoon season from July to September and a cool and relatively dry winter from October to March. The area receives an annual average rainfall of 1187.6 mm of which the rainy months contribute approximately 90%. The mean annual minimum and maximum temperatures vary between 10°C (January) and 42.7°C (May) respectively (WorldClim, 2020). As per Champion and Seth's Classification (Champion and Seth, 1968), the forest in the area belongs to group 4b. Vegetation and soil CO_2 efflux were done in three forest ranges of Sagar district, viz. Shahgarh, Nanakpur and Heerapur by laying 14 plots of 60 m × 20 m in each study site/forest type following standard methods (Misra, 1968). In each plot, the diameter of all the tree individuals (≥ 10 cm diameter at breast height of 1.37 m (DBH)) were recorded. The predominant tree species in the study sites of the three different forest types are *Tectona grandis*, *Butea monosperma* and *Lagerstroemia parviflora* in DDTF, *Tectona grandis*, *Terminalia tomentosa* and *Lagerstroemia parviflora* in DDMF, and *Boswellia serrata*, *Tectona grandis* and *Lagerstroemia parviflora* in BF. A total of 25 tree species (24 genera, 14 families) were recorded from the above-said three forest types. Diversity indices (Shannon’s diversity and Simpson’s dominance) were calculated using PAleontological STatistics software (PAST; Hammer et al., 2001; Natural History Museum, University of Oslo).

Table 1 Study site characteristics of the three different forest types (DDTF - dry deciduous teak forest, DDMF - dry deciduous mixed forest and BF - *Boswellia* forest) of Sagar, Madhya Pradesh.

Parameter	**Forest type**		
	DDTF	**DDMF**	**BF**
Latitude (^{o})	24.212 - 24.226	24.130 - 24.241	24.240 - 24.243
Longitude (^{o})	79.111 - 79.113	79.144 - 79.145	79.121 - 79.133
Altitude (m a.s.l.)	401.6	371.8	486.2
Slope (°)	0.26 - 1.25	0.27 - 0.84	0.40 - 1.06
Aspect (°)	262.2 - 354.3	105.3 - 187.3	213.8 - 245.7
No. of plots	14	14	14
Species richness	14	23	15
Genera	14	22	15
Families	9	13	10
Shannon’s index (H)	1.14	2.08	1.76
Dominance index (D)	0.46	0.19	0.27
Evenness index	0.22	0.34	0.39
Total tree density	8192	12032	7272
Density (No./ha)	585.1 ± 35.7	859.4 ± 93.1	519.4 ± 35.9
Total tree basal area	287.9	287.1	413.3
Basal area (m^2/ha)	20.6 ± 1.7	20.5 ± 1.4	29.5 ± 1.6
Maximum tree DBH (cm)	60.8	54.1	62.9
Mean tree DBH (cm)	18.9	15.7	24.3

DBH: Diameter at breast height.

2.2 Estimation of soil respiration

Soil CO_2 efflux was measured by alkali absorption method (Gupta and Singh, 1977), at three different forest types, using plastic jars, inserted 10 cm into the ground. Three replicate sub-plots in each forest type were selected for the measurement of soil CO_2 efflux. Five replicates of the plastic jars were set up in each sub-plot, and one set of three control plastic jars with airtight lids in each sub-plot. Before each plastic jar was fixed, the vegetation falling within the plastic jar was clipped at the base with the help of scissor. A 50 ml beaker containing 20 ml 0.5 N NaOH was placed in a thin wire tripod stand that holds the jar off the ground by about 2 cm. The alkali was titrated against 1N HCL after 24 hours of absorption period to avoid diurnal variations (Joshi et al., 1991; Harris and van Bavel, 1957). The jars were placed randomly, and on each sampling date the soil moisture was measured by gravimetric method up to 10 cm soil depth. The CO_2 evolved during the experiment was calculated by following the formula of Joshi et al. (1991).

$$\text{mg } CO_2 = V \times N \times 22$$

where V represents titration of the blank minus the sample titration and N is the normal acid value.

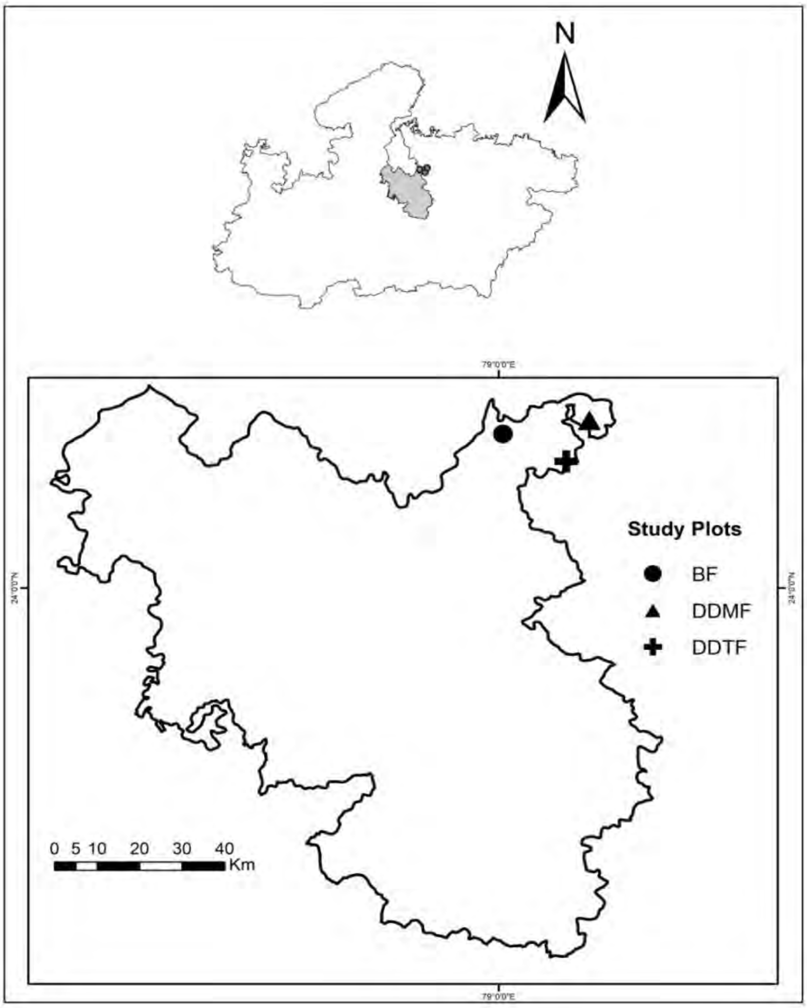

Fig. 1 Location of the study sites in Sagar, Madhya Pradesh.

2.3 Soil temperature (Ts) and soil moisture (Ms)

Soil temperature was measured using a digital soil thermometer at a depth of 0 - 10 cm adjacent to each soil CO_2 efflux beaker. Soil moisture was measured by gravimetric method at 0 to 10 cm depth adjacent to each CO_2 efflux beaker.

2.4 Statistical analyses

One-way ANOVA was used to test the differences between mean soil CO_2 efflux, soil temperature, and soil moisture among the three forest types, and Turkey's HSD test was applied whenever the ANOVA was significant. The level of significance for the analyses was set at $p < 0.05$ (Zhang, 2022). Linear correlation/regression analyses were used to examine the relationship of soil CO_2 efflux with soil temperature and soil moisture. SPSS 20.0 software was used for all statistical analyses.

3 Results

3.1 Monthly and seasonal variations in the soil CO_2 efflux

Soil CO_2 efflux varied significantly among all the forest types ($p < 0.001$). The monthly soil CO_2 efflux ranged from 116.3 to 626.0 mg $CO_2/m^2/h$, with an average value of 338.6 ± 132 mg $CO_2/m^2/h$. Soil CO2 efflux varied significantly ($p < 0.001$) among the months. The mean monthly soil CO_2 efflux was measured to be 335.5, 385.4 and 294.7 mg $CO_2/m^2/h$ in site I, site II and site III respectively. The highest monthly soil CO_2 efflux was observed in July (626.0 mg $CO_2/m^2/h$), compared to all other months in all the forest sites. Among the three study sites, site II showed a higher rate of soil CO_2 efflux compared to the other two study sites (Table 2).

Table 2 Mean soil respiration (mg $CO_2/m^2/h$) under three different dry deciduous forest types in Sagar, Madhya Pradesh, India.

	Soil CO_2 efflux (mg $CO_2/m^2/h$)			
Months	**DDTF**	**DDMF**	**BF**	**P-value**
January	$142.8^a \pm 6.9$	$162.8^b \pm 10.9$	$122.3^c \pm 5.0$	0.001
February	$238.4^a \pm 10.8$	$267.1^b \pm 8.5$	$190.9^c \pm 4.1$	0.001
March	$250.1^a \pm 4.5$	$277.1^b \pm 16.8$	$226.4^c \pm 8.5$	0.001
April	$335.7^a \pm 9.4$	$370.9^b \pm 15.9$	$270.5^c \pm 3.2$	0.001
May	$337.1^a \pm 6.9$	$339.5^b \pm 13.8$	$281.7^b \pm 3.0$	0.001
June	$418.5^a \pm 7.9$	$467.1^b \pm 7.4$	$373.4^c \pm 11.3$	0.001
July	$563.5^a \pm 4.8$	$614.1^b \pm 9.1$	$489.5^c \pm 9.7$	0.001
August	$529.8^a \pm 5.2$	$603.5^b \pm 6.7$	$478.3^c \pm 32.7$	0.001
September	$431.9^a \pm 20.6$	$530.6^b \pm 18.3$	$371.9^c \pm 9.1$	0.001
October	$337.1^a \pm 7.0$	$456.3^a \pm 25.2$	$317.6^b \pm 7.7$	0.001
November	$231.1^a \pm 9.8$	$303.3^a \pm 9.3$	$220.5^b \pm 9.0$	0.001
December	$210.1^a \pm 7.6$	$232.9^b \pm 3.2$	$193.6^c \pm 7.1$	0.001

Soil CO_2 efflux showed a strong seasonal pattern across all the forest sites peaking during monsoon season (mean 477 ± 57.3 mg CO2/m2/h; range: 396.4 - 559.2 mg $CO_2/m^2/h$), followed by summer (mean 329 ± 31.5 mg $CO_2/m^2/h$; range: 286.2 - 377.1 mg $CO_2/m^2/h$). The lowest values were observed during winter (mean 209.6 ± 24.9 mg $CO_2/m^2/h$; range: 172.9 - 246.4 mg $CO_2/m^2/h$, Table 3).

Table 3 Seasonal variation in soil respiration (RS), soil temperature (TS) and soil moisture (SM) under three different dry deciduous forest types in Sagar, Madhya Pradesh, India.

Forest	Season	Soil respiration (mg CO_2 m^2/h)	P-value	Soil temperature (°C)	P-value	Soil moisture (%)	P-value
DDTF	Monsoon	465.6^b ± 88.5	0.001	29.4^b ± 3.2	0.001	16.6^b ± 2.0	0.001
	Winter	205.6^c ± 37.7		21.0^c ± 2.8		9.9^b ± 0.4	
	Summer	363.7^a ± 68.6		32.7^a ± 4.1		11.4^a ± 1.8	
DDMF	Monsoon	551.1^b ± 63.5	0.001	29.2^b ± 3.6	0.001	17.8^b ± 0.9	0.001
	Winter	241.5^c ± 51.8		20.0^b ± 3.0		10.9^c ± 0.4	
	Summer	288.0^a ± 53.4		32.2^a ± 4.4		9.6^a ± 2.1	
BF	Monsoon	414.4^b ± 72.3	0.001	27.5^a ± 3.3	0.001	16.1^a ± 1.6	0.001
	Winter	181.8^c ± 36.3		19.8^b ± 3.1		9.7^b ± 0.6	
	Summer	335.4^a ± 59.6		33.0^a ± 3.7		11.5^a ± 1.7	

Table 4 Mean soil moisture (%) under three different dry deciduous forest types in Sagar, Madhya Pradesh, India.

Soil moisture (%)				
Months	**DDTF**	**DDMF**	**BF**	**P-value**
January	9.5^a ±0.2	10.6^b ± 0.3	8.9^c ±0.1	0.001
February	10.6^a ± 0.3	10.6^b ± 0.2	9.5^b ± 0.2	0.001
March	9.9^a ±0.2	9.8^b ± 0.2	8.8^b ± 0.2	0.001
April	11.1^a ±0.2	11.2^b ±0.3	9.2^b ± 0.3	0.001
May	10.5^a ± 0.2	10.2^b ±0.3	7.5^b ± 1.5	0.001
June	14.4^a ±0.3	14.3^b ± 0.3	13.0^b ± 0.4	0.001
July	18.4^a ± 0.2	18.9^b ± 0.1	17.8^c ± 0.2	0.001
August	17.8^a ± 0.3	18.4^b ± 0.3	16.8^c ± 0.2	0.001
September	16.8^a ± 0.2	17.5^a ± 0.6	16.6^b ± 0.3	0.001
October	13.2^a ± 0.2	16.5^a ± 0.3	13.4^b ± 0.3	0.001
November	9.9^a ± 0.2	11.6^b ± 0.3	10.5^c ± 0.2	0.001
December	9.7^a ± 0.2	10.8^a ± 0.2	10.0^b ± 0.2	0.001

Mean value ± standard error (SE). Different letter (s) in the same row indicates significant differences at $p < 0.05$.

3.2 Soil temperature (T_S) and soil moisture content (M_S)

Mean monthly T_S and M_S showed significant differences among the forest sites ($p < 0.001$) (Tables 4 and 7.4). The average monthly T_S was 27.2°C. The maximum T_S was recorded in site I (37.2°C) during June, whereas, the minimum temperature was recorded under site II (15.3°C) during the month of January. The average monthly M_S was 12.6%. The highest monthly M_S was observed in site II (19.1%) in July, whereas the lowest M_S was measured in site III (6.1%) in May over the study period (Table 4).

Soil temperature showed a strong seasonal pattern across all the forest sites with the maximum during summer (25.7 - 37.2°C, Table 5) followed by monsoon and winter seasons, whereas soil moisture (%) showed a different trend. The highest M_S value was generally observed during monsoon when compared to other seasons (Table 5).

Table 5 Mean soil temperature (°C) under three different dry deciduous forest types in Sagar, Madhya Pradesh, India.

Soil temperature (°C)				
Forest type	**DDTF**	**DDMF**	**BF**	**P-value**
January	$17.9^a \pm 0.5$	$15.8^b \pm 0.3$	$16.6^c \pm 13.3$	0.001
February	$25.2^a \pm 0.2$	$24.0^a \pm 0.5$	$24.5^b \pm 0.3$	0.001
March	$27.9^a \pm 0.5$	$26.1^a \pm 0.2$	$26.4^b \pm 0.2$	0.001
April	$31.0^a \pm 0.4$	$32.8^b \pm 0.6$	$29.3^c \pm 0.3$	0.001
May	$36.1^a \pm 0.4$	$35.3^b \pm 0.3$	$36.4^b \pm 0.3$	0.001
June	$37.0^a \pm 0.1$	$36.7^a \pm 0.3$	$36.5^b \pm 0.3$	0.003
July	$34.1^a \pm 0.4$	$33.9^b \pm 0.4$	$32.4^b \pm 0.3$	0.001
August	$30.6^a \pm 0.7$	$30.7^b \pm 0.8$	$28.2^b \pm 0.2$	0.001
September	$27.0^a \pm 0.4$	$27.9^b \pm 0.5$	$25.5^c \pm 0.4$	0.001
October	$26.0^a \pm 0.9$	$24.2^a \pm 0.2$	$23.7^b \pm 0.4$	0.001
November	$21.7^a \pm 0.4$	$20.9^a \pm 0.5$	$20.4^b \pm 0.2$	0.001
December	$19.1^a \pm 0.5$	$19.4^b \pm 0.2$	$17.5^b \pm 0.3$	0.001

Mean value ± standard error (SE). Different letter(s) in the same row indicates significant differences at $p < 0.05$.

3.3 Annual soil CO_2 efflux

The cumulative annual soil CO_2 efflux from April to December for each forest type was calculated as the sum of values of all the months and it ranged between 3536.8 and 4625.2 mg CO_2/m^2/yr, with an overall mean value of 4062.7 mg CO_2/m^2/yr across all the studied sites. The highest cumulative CO2 efflux was observed in site II (4625.2 mg CO_2/m^2/yr), followed by site I (4026.2 mg CO_2/m^2/yr) and site III (3536.8 mg CO_2/m^2/yr, Fig. 2).

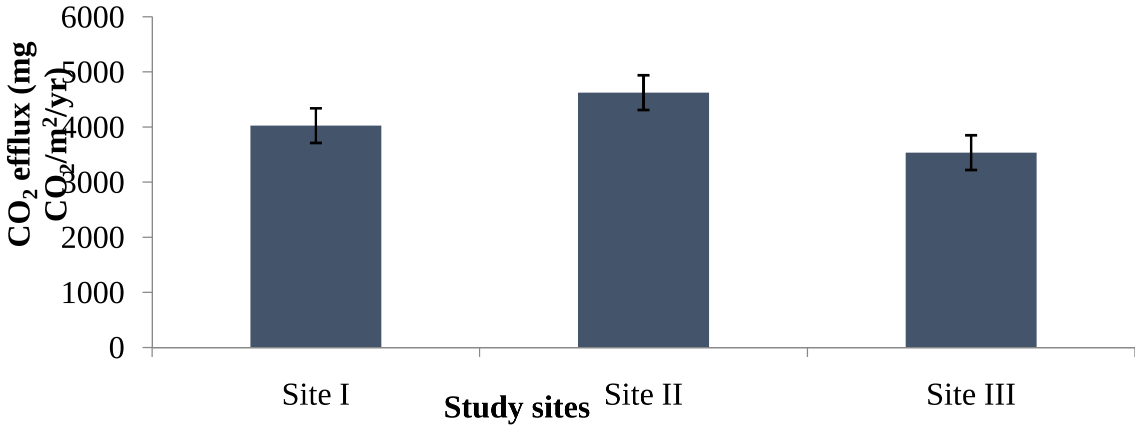

Fig. 2 Cumulative annual soil CO_2 efflux (mg CO_2/m^2/yr).

3.4 Relationship between soil CO_2 efflux and environmental variables

Significant positive correlations were observed between soil CO_2 efflux and soil moisture in study site I (R^2 = 0.88, $p < 0.001$), study site II (R^2 = 0.85, $p < 0.001$) and study site III (R^2 = 0.75, $p < 0.001$, fig 3). Positive correlation was also observed between soil CO_2 efflux and soil temperature in study site I (R^2 = 0.53, $p < 0.001$), study site II (R^2 = 0.44, $p < 0.001$) and study site III (R^2 = 0.39, $p < 0.001$, Fig 4).

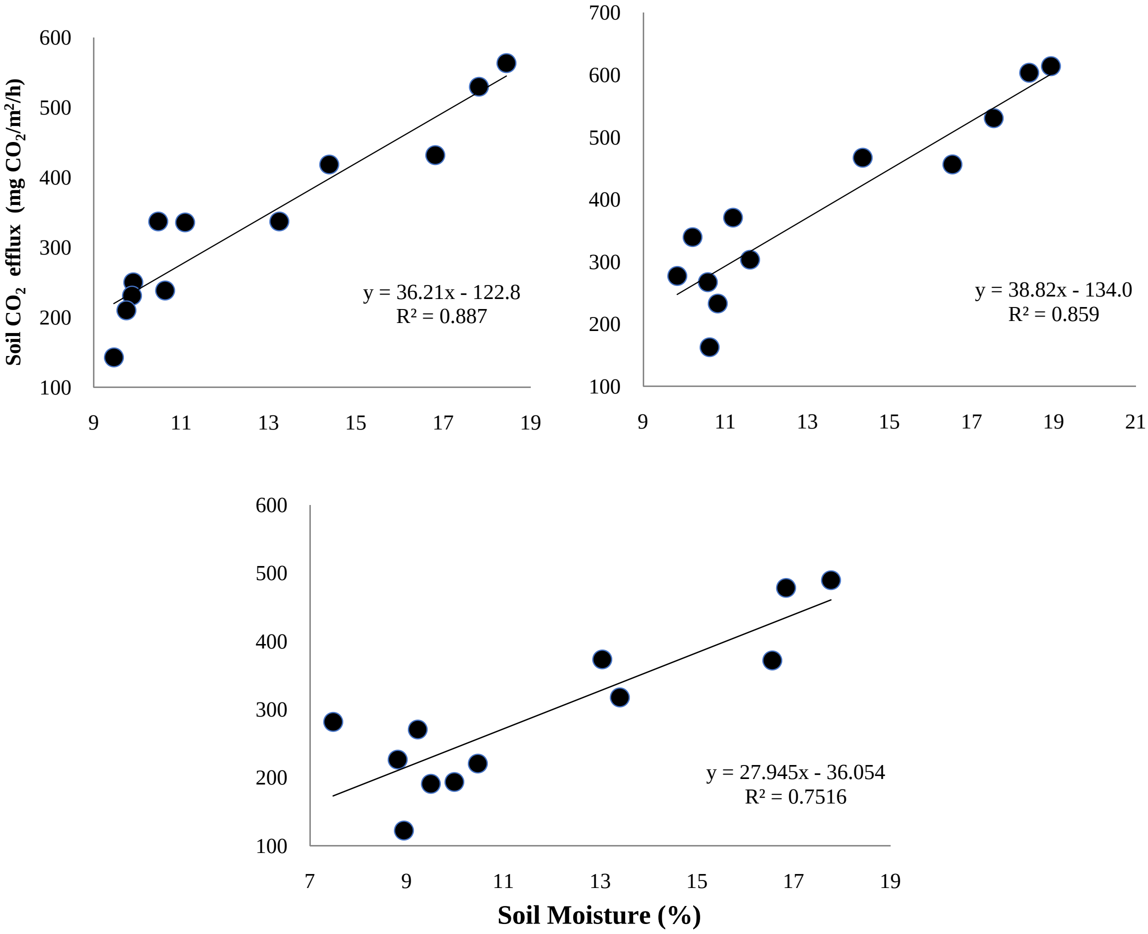

Fig. 3 Relationship between soil CO_2 efflux (month wise) and soil moisture in three studied sites.

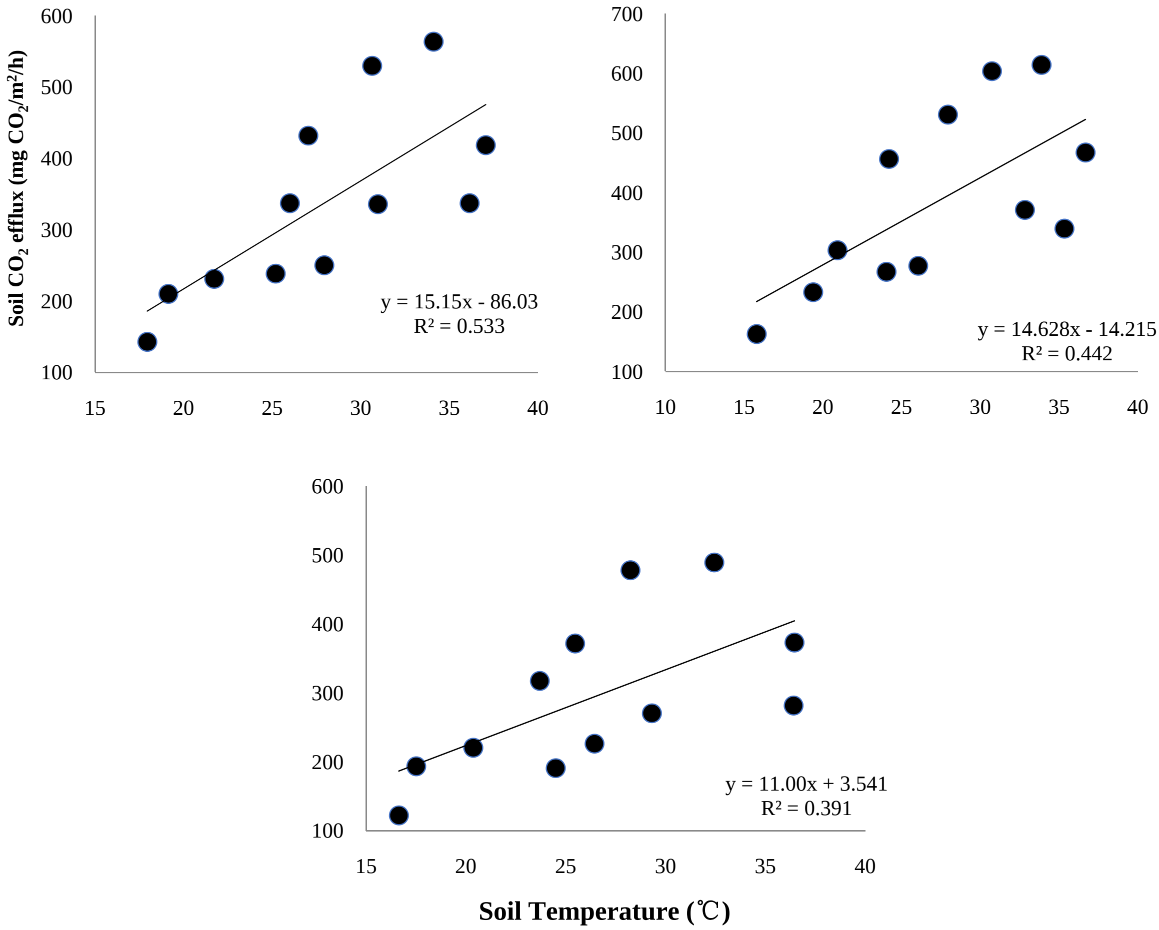

Fig. 4 Relationship between soil CO_2 efflux (month wise) and soil temperature in three studied sites.

4 Discussion

In this study, both monthly and seasonal variations in soil CO_2 efflux were observed in all the three tropical dry deciduous forest sites. The soil CO_2 efflux reached its peak during July and attained its minimum during January in all the study sites, which may be because of the similar climatic conditions in all the three sites. A strong seasonal variation in soil respiration has been observed across all the three study sites, with higher efflux rate during the monsoon season (July-October). The reason for the high rates of soil CO_2 efflux in the study sites during monsoon season could be the displacement of air rich in CO_2 from within the soil due to soil microbial activity which oxidizes the C dissolved in water. Soil contains small pores, which are usually filled with CO_2-rich air, when the soil is saturated; the small pores with air are substituted by water, producing a CO_2 efflux from the soil. The soil CO_2 efflux can therefore enhance rapidly during heavy rainfall (Lee et al., 2002; Luo et al., 2006). Increase in organic matter decomposition along with the proliferation in soil microbial (fungal, bacterial and actinomycetes) activity during the monsoon season which has frequent spells of rainfall with short periods of drying is regarded as an important reason for increased rates of soil respiration during rainy months (Jha and Mohapatra, 2011; Pandey et al., 2010). In all the three study sites, the minimum rate of soil CO_2 efflux during the winter season (November-February) may be attributed due to variations in the incoming solar radiation, temperature and day-length which result in low soil temperature and slow microbial activities (Dar et al., 2015; Han et al., 2012; Lloyd and Taylor, 1994; Pandey et al., 2010).

In this study, site II (DDMF) showed the highest rate of soil CO_2 efflux when compared with other two study sites. Higher soil CO_2 efflux in the study site II (DDMF) could be due to the higher tree density and floristic diversity. Floristic diversity and composition can influence the rate of soil CO_2 efflux by affecting soil microclimate and composition, the quantity and quality of detritus material, and the overall rate of root respiration (Raich and Tufekcioglu, 2000; Lee et al., 2010; Dias et al., 2010). Variations in soil CO_2 efflux due to differences in floristic diversity and vegetation attributes have been documented by several researchers (Dias et al., 2010; Han et al., 2012; Houghton et al., 2012; Raich and Tufekcioglu, 2000; Yan et al., 2011). Vegetation composition and stand structure are known to influence soil ecological properties such as soil temperature (Savva et al., 2010), soil moisture (Buytaert et al., 2006; Nosetto et al., 2005; Wang et al., 2012), and quality and quantity of soil organic matter (Smith et al., 2014).

In general, the upper soil layer is the zone with maximum root concentration and soil biological activity (Tripathi and Singh, 1992; Tripathi et al., 1999), so the results obtained in the present study were found to be fairly comparable with other studies. The range of soil CO_2 efflux recorded in the present study (116.3 to 626.0 mg $CO_2/m^2/h$) is similar with other reports from different forests Devi and Singh, 2016 (195.71 - 345.98 mg $CO_2/m^2/h$); Devi and Yadava, 2009 (138.49–250.94 mg $CO_2/m^2/h$); Fernandes et al., 2002 (216 - 510 mg $CO_2/m^2/h$); Gupta and Singh, 1981 (44 - 448 mg $CO_2/m^2/h$); Joshi et al., 1991 (62.4 - 362 and 37.6 - 282 mg $CO_2/m^2/h$); Laishram et al., 2002 (368–634.23 mg $CO_2/m^2/h$); Lamotte, 1975 (330 mg $CO_2/m^2/h$); Leith and Quellette, 1962 (251 mg $CO_2/m^2/h$); Medina and Zelwar, 1972 (234 - 511 mg $CO_2/m^2/h$); Monteith et al., 1964 (312 - 500 mg $CO_2/m^2/h$); Pandey et al., 2010 (102 - 320 and 99 - 543 mg $CO_2/m^2/h$); Redmann, 1978 (0 - 433 mg $CO_2/m^2/h$); Schwendenmann et al., 2003 (430–675 mg $CO_2/m^2/h$); Sundarapandian and Dar, 2013 (126 - 427 and 182 - 646 mg $CO_2/m^2/h$); Tewari et al., 1982 (101.3 - 270 mg $CO_2/m^2/h$); Thokchom and Yadava, 2014 (124.33 - 586.03 mg $CO_2/m^2/h$).

Climatic factors, in particular, soil temperature and moisture are known to be the principal governing factors of soil CO_2 efflux (Rodtassana et al., 2021; Sundarapandian and Kirthiga, 2011). In the present study, soil temperature showed a significant positive correlation with soil CO_2 efflux in all the three study sites. A similar trend has been reported by several researchers (Cao et al., 2004; Fang and Moncrieff, 2001; Jha and Mohapatra, 2011; Peri et al., 2015; Rubio and Detto, 2017). Soil temperature influences soil CO_2 efflux rates by increasing the metabolic activity of soil microbes upto an optimal threshold, after which the soil microbial activity and rate of soil CO_2 efflux begin to decline (Conant et al., 2004; Meena et al., 2020). Higher soil temperatures lead to more rapid decay of soil organic matter, lesser C accumulation in the slow and passive pools, and a larger loss of C via respiration, provided there is adequate moisture (Okello et al., 2023; Canadell et al., 2007). Hence, soil temperature is often considered as a major factor that drives seasonal variations in soil CO_2 efflux in forest ecosystems (Rodtassana et al., 2021, Arroyo and Wood, 2021; Reichstein et al., 2003; Bahn et al., 2008).

Besides soil temperature, soil moisture is another main factor that greatly regulates soil CO_2 efflux (Akburak and Makineci, 2013; Dar et al., 2015). In the present study, soil CO_2 efflux was found to be significantly positively correlated with soil moisture in all the three study sites. Similar results were obtained in other studies as well (A'Bear et al., 2014; Dar et al., 2015; Devi and Yadav, 2008; Jangra et al., 2011; Londo et al., 1999; Morén and Lindroth, 2000; Ohashi et al., 1999; Soe and Buchmann 2005; Steinweg et al., 2013; Sundarapandian and Dar, 2013). In this study, soil CO_2 efflux was found to be highest during the monsoon season, when soil moisture was also at its peak. Soil moisture acts as a medium for solubilization of the organic substrates and microbial activity (Koizumi et al., 1999). Hence, soil moisture influences different processes like soil organic matter decomposition, soil C mineralization, microbial activity, etc. which in turn, influence soil respiration (Bao et al., 2016; Meena et al., 2020; Zhang et al., 2019). Although many studies indicated a strong correlation between soil CO_2 efflux and soil organic carbon (Dube et al., 2009; Iqbal et al., 2010; Wang et al., 2013), a non-significant, yet positive relationship between the two variables was observed in this study. This is so because soil CO_2 efflux is mainly determined by living plant roots, and organic matter mineralization by soil microbial activity (Buchmann, 2000).

5 Conclusions

The present study revealed the monthly and seasonal variations in soil CO_2 efflux in the three tropical dry deciduous forest types in Madhya Pradesh. It is also evident that the soil CO_2 effluxes in the three study sites are mainly controlled by soil temperature and soil moisture. Changes in temperature and precipitation regimes as a result of climate change could affect the rates of soil CO_2 efflux in tropical dry forests and alter the global C balance.

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References

A’Bear et al. 2014. Interactive effects of temperature and soil moisture on fungal-mediated wood decomposition and extracellular enzyme activity. Soil Biology and Biochemistry, 70: 151-158

Akburak S, Makineci E. 2013. Temporal changes of soil respiration under different tree species. Environmental Monitoring and Assessment, 185: 3349-3358

Andersson S, Nilsson SI. 2001. Influence of pH and temperature on microbial activity, substrate availability of soil-solution bacteria and leaching of dissolved organic carbon in a mor humus. Soil Biology and Biochemistry, 33: 1181-1191

Arroyo OG, Wood TE. 2021. Large seasonal variation of soil respiration in a secondary tropical moist forest in Puerto Rico. Ecology and Evolution, 11:263-272

Bahn M, et al. 2008. Soil respiration in European grasslands in relation to climate and assimilate supply. Ecosystems 11: 1352-1367

Bao et al. 2016. Effects of soil temperature and moisture on soil respiration on the Tibetan plateau. PLoS One, 11(10): e0165212

Bilandžija, D., Zgorelec, Ž. and Kisić, I. 2016. Influence of tillage practices and crop type on soil CO2 emissions. Sustainability, 8(1): 1-10

Bond-Lamberty B and Thomson A. 2010a. Temperature-associated increases in the global soil respiration record. Nature, 464: 579582

Bond-Lamberty B, Thomson, A. 2010b. A global database of soil respiration data. Biogeosciences. 7(6): 1915-1926

Buchmann N. 2000. Biotic and abiotic factors controlling soil respiration rates in Picea abies stands. Soil Biology and Biochemistry, 32: 1625-1635

Butnor et al. 2003. Reduction of forest floor respiration by fertilization on both carbon dioxide enriched and reference 17-year-old loblolly pine stands. Global Change Biology, 9(6): 849-861

Buytaert et al. 2006. Human impact on the hydrology of the Andean páramos. Earth Science Reviews, 79: 53-72

Canadell JG, Le Quéré C, Raupach MR, Field CB, Buitenhuis ET, et al. 2007. Contributions to accelerating atmospheric CO2 growth from economic activity, carbon intensity, and efficiency of natural sinks. Proceedings of the National Academy of Sciences, 104: 18866-18870

Cao et al. 2004. Grazing intensity alters soil respiration in an alpine meadow on the Tibetan plateau. Soil Biology and Biochemistry 36(2): 237-243

Chen Z, Xu Y, Fan J, Yu H, Ding W. 2017. Soil autotrophic and heterotrophic respiration in response to different N fertilization and environmental conditions from a cropland in Northeast China. Soil Biology and Biochemistry, 110: 113-115

Conant et al. 2004. Controls on soil respiration in semiarid soils. Soil Biology & Biochemistry, 36: 945-951

Cusack DF, Dietterich LH, Sulman BN. 2023. Soil respiration responses to throughfall exclusion are decoupled from changes in soil moisture for four tropical forests, suggesting processes for ecosystem models. Global Biogeochemical Cycles, 37: e2022GB007473

Dar et al. 2015b. Soil CO_2 efflux among four coniferous forest types of Kashmir Himalaya, India. Environmental monitoring and assessment, 187(11): 715

Devi BN, P Yadav. 2008. Emissions of CO_2 from soil in a subtropical miced forest of Manipur, Northeastern India. International Journal of Ecology and Environmental Science, 34: 293-297

Devi NB, Yadava PS. 2009. Emission of CO_2 from the soil and immobilization of carbon in microbes in a sub-tropical mixed oak forest ecosystem, Manipur, NE India. Current Science, 96: 1627- 1630

Devi NL, Singh EJ. 2016. Soil respiration and microbial population in a subtropical mixed oak forest of Manipur, North-eastern India. International Journal of Scientific and Research Publications. 6(7)

Dias et al. 2010. Plant species richness regulates soil respiration through changes in productivity. Oecologia, 163: 805-813

Dube F, Zagal E, Stolpe N, Espinosa M. 2009. The influence of land-use change on the organic carbon distribution and microbial respiration in a volcanic soil of the Chilean Patagonia. Forest Ecology and Management, 257: 1695-1704

Fang C, Moncrieff JB. 2001. The dependence of soil CO_2 efflux on temperature. Soil Biology and Biochemistry, 33: 155-165

Fernandes et al. 2002. Seasonal variation of soil chemical properties and CO_2 and CH4 flux in unfertilized and P-fertilized pasture in an ultisol of the Brazilian Amazon. Geodermatalogy, 107: 227-241

Field, C.B. et al. 1998. Primary production of the biosphere: integrating terrestrial and oceanic components. Science, 281: 237-240

Gupta SR, Singh JS. 1977. Effect of alkali concentration, volume and absorption area on the measurement of soil respiration in a tropical sward. Pedobiologia, 17: 233-239

Gupta SR, Singh JS. 1981. Soil respiration in a tropical grassland. Soil Biology and Biochemistry, 13: 261-268

Han et al. 2007. Biotic and abiotic factors controlling the spatial and temporal variation of soil respiration in an agricultural ecosystem. Soil Biology and Biochemistry, 39: 418-425

Han et al. 2012. Winter soil respiration from different vegetation patches in the yellow river delta, China. Environmental Management, 50: 39-49

Hanson PJ, Edwards NT, Garten CT, Andrews JA. 2000. Separating root and soil microbial contributions to soil respiration: a review of methods and observations. Biogeochemistry, 48(1): 115-146

Harris DG, van Bavel GHM. 1957. Root respiration in tobacco, cotton, corn and cotton plants. Agronomy Journal, 49: 182-184

Houghton et al. 2012. Carbon emissions from land use and land-cover change. Biogeosciences 9: 5125-5142

Howard DM, Howard PJA. 1993. Relationships between co2 evolution, moisture content and temperature for a range of soil types. Soil Biology and Biochemistry, 25(11): 1537-1546

Iqbal J, Hu R, Feng M, Lin S, Malghani S, Ali IM. 2010. Microbial biomass, and dissolved organic carbon and nitrogen strongly affect soil respiration in different land uses: a case study at Three Gorges Reservoir Area, South China. Agriculture, Ecosystems and Environment, 137: 294-307

Jangra et al. 2011. Soil respiration, microbial biomass and mycorrhizal diversity in sodic grassland ecosystems in Northwestern India. American-Eurasian Journal of Agricultural and Environmental Science 10: 863-875.

Jha P, Mohaptra KP. 2011. Soil respiration under different forest species in the riparian buffer of the semi-arid region of northwest India. Current Science 100: 1412-1420

Joshi et al. 1991. Seasonal pattern of total soil respiration in undisturbed and disturbed ecosystems of central Himalaya. Biology and Fertility of Soils, 11: 267-272

Laishram et al. 2002. Soil respiration in a mixed oak forest ecosystem at Shiroy hills, Manipur in North-Eastern India. International Journal of Ecology and Environmental Science, 28: 133-137

Lamotte M. 1975. The structure and function of a tropical savannah ecosystem. In: Tropical Ecological Systems (Golley FB, Medina E, eds). Ecological Studies Vol. 11. 179-222, Springer-Verlag, New York, USA

Lee et al. 2002. Effects of rainfall events on soil CO2 flux in a cool temperate deciduous broad-leaved forest. Ecological Research, 17(3): 401-409

Lee et al. 2010. Seasonal variation in soil Co2 efflux in evergreen coniferous and broad-leaved deciduous forests in a cool temperate forest, central Korea. Ecological Research 25: 609-617

Leith H, Quellette R. 1962. Studies on the vegetation of the Gaspe peninsula: II. The soil respiration of some plant communities. Canadian Journal of Botany, 40: 127-140

Lloyd J, Taylor JA. 1994. On the temperature dependence of soil respiration. Functional Ecology, 8(3): 315-323

Luo Y, Zhou X. 2006. Soil Respiration and the Environment. Amsterdam: Elsevier

Medina E, Zelwer M. 1972. Soil respiration in tropical plant communi-ties. In: Papers from A Symposium On Tropical Ecology With An Emphasis On Organic Productivity (Golley PM, Golley FB). 245-269. University of Georgia, Athens, USA

Meena et al. 2020. Soil moisture controls the spatio-temporal pattern of soil respiration under different land use systems in a semi-arid ecosystem of Delhi, India. Ecological Processes, 9(1): 1-13

Monteith et al. 1964. Crop photosynthesis and the flux of carbon dioxide below the canopy. Journal of Applied Ecology, 1: 321-337

Nosetto et al. 2005. Land-use change and water losses: the case of grassland afforestation across a soil textural gradient in central Argentina. Global Change Biology, 11: 1101-1117

Okello J, Bauters M et al. 2023. Temperature sensitivity of soil organic carbon respiration along a forested elevation gradient in the Rwenzori Mountains, Uganda. Biogeosciences, 20: 719-735

Pandey et al. 2010. Factors influencing soil CO_2 efflux in a north-eastern Indian oak forest and plantation. African Journal of Plant Science, 4: 280-289

Peri et al. 2015. Soil respiration in Patagonian semiarid grasslands under contrasting environmental and use conditions. Journal of Arid Environment, 119: 1-8

Phillips OL, et al. 1998. Changes in the carbon balance of tropical forests: evidence from long-term plot data. Science, 282: 439-442

Pregitzer KS, Zak DR, Loya WM, Karberg NJ, King JS, Burton AJ. 2007. The contribution of root - rhizosphere interactions to biogeochemical cycles in a Changing World. The Rhizosphere (Cardon ZG, Whitbeck JL, eds). 155-178, Academic Press, USA

Rai B, Srivastava AK. 1981. Studies on microbial population of a tropical dry deciduous forest soil in relation to soil respiration. Pedobiologia, 22(3): 185-190

Raich JW, Tufekcioglu A. 2000. Vegetation and soil respiration: Correlation and controls. Biogeochemistry, 48: 71-90

Redmann RE. 1978. Soil respiration in a mixed grassland ecosystem. Canadian Journal of Soil Science, 58(2): 119-124

Reichle DE, McBrayer JF, Ausmus BS. 1975. Progress in soil zoology. 283-292, Academic Publishing, Prague, Hungary

Reichstein et al. 2003. Modeling temporal and large-scale spatial variability of soil respiration from soil water availability, temperature and vegetation productivity indices. Global Biogeochemical Cycles, 17

Riebeek, H. 2011. The carbon cycle: Feature articles

Rodtassana C, Unawong W, Yaemphum S, Chanthorn W, Chawchai S, Nathalang A, Brockelman WY, Tor-Ngern P. 2021. Different responses of soil respiration to environmental factors across forest stages in a Southeast Asian forest. Ecology and Evolution, 11(21): 15430-15443

Rubio VE, Detto M. 2017. Spatiotemporal variability of soil respiration in a seasonal tropical forest. Ecology and Evolution, 7(17): 7104-7116

Savva et al. 2010. Effects of land use and vegetation cover on soil temperature in an urban ecosystem. Soil Science Society of America, 73: 469-480

Schlesinger WH, Andrews JA. 2000. Soil respiration and the global carbon cycle. Biogeochemistry, 48: 7-20

Schwendenmann et al. 2003. Spatial and temporal variation in soil CO_2 efflux in an old-growth neotropical rain forest, La Selva, Costa Rica. Biogeochemistry, 64(1): 111-128

Smith et al. 2014. Microbial community structure varies across soil organic matter aggregate pools during tropical land cover change. Soil Biology and Biogeochemistry, 77: 292-303

Steinweg et al. 2013. Microbial responses to multifactor climate change: effects on soil enzymes. Frontiers in Microbiology, 4: 1-11

Sundarapandian S, Dar J. 2013. Variation in Soil CO_2 Efflux in Pinus Wallichiana and Abies Pindrow Temperate Forests of Western Himalayas. India. Forestry Research, 3(116): 2

Sundarapandian SM, Kirthiga J. 2011. Soil respiration in different land use systems in Puducherry, India. Journal of Theoretical and Experimental Biology, 8: 17-28

Tang et al. 2018. Effects of temperature, soil substrate, and microbial community on carbon mineralization across three climatically contrasting forest sites. Ecology and Evolution, 8(2): 879-881

Tewari et al. 1982. Soil litter respiration rates in different micro-habitats of mixed oak-conifer forest and their control by edaphic conditions and substrate quality. Plant and Soil, 65: 233-238

Thokchom A, Yadava PS. 2014. Soil CO_2 flux in the different ecosystems of North East India. Current Science, 99-105

Tripathi et al. 1999. Temporal changes in spatial pattern of fine root mass and nutrient concentrations in Indian bamboo savanna. Applied Vegetation Science, 2: 229-238

Tripathi SK, Singh KP. 1992. Nutrient immobilization and release pattern during plant decomposition in a dry tropical bamboo savanna, India. Biology and Fertility of Soil, 14: 191-199

Wang et al. 2012. Soil moisture and evapotranspiration of different land cover types in the Loess Plateau, China. Hydrology and Earth System Sciences, 16: 2883-2892

Wang Q, Xiao F, He T, Wang S. 2013. Responses of labile soil organic carbon and enzyme activity in mineral soils to forest conversion in the subtropics. Annals of Forest Science, 70: 579-587

Yan et al. 2011. Temporal and spatial variation in soil respiration of poplar plantations at different developmental stages in Xinjiang, China. Journal of Arid Environments, 75: 51-57

Zhang WJ. 2022. *p*-value based statistical significance tests: Concepts, misuses, critiques, solutions and beyond. Computational Ecology and Software, 12(3): 80-122

Zhang et al. 2013a. How do environmental factors and different fertilizer strategies affect soil CO_2 emission and carbon sequestration in the upland soils of southern China? Applied Soil Ecology, 72(2): 109-118

Zhang et al. 2013b. Variations of carbon stock with forest types in subalpine region of southwestern China. Forest Ecology and Management, 300: 88-95

Zhao J, Li R, Li X, Tian L. 2017. Environmental controls on soil respiration in alpine meadow along a large altitudinal gradient on the central Tibetan Plateau. Catena, 159: 84-92

Zhou Z, Zhang Z, Zha T, Luo Z, Zheng J, Sun OJ. 2013. Predicting soil respiration using carbon stock in roots, litter and soil organic matter in forests of Loess Plateau in China. Soil Biology and Biochemistry, 57: 135-143