Article

Shrub invasion alters the soil CO_2 efflux in tropical dry deciduous forests of Madhya Pradesh, Central India

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Abstract
Soil CO_2 efflux was measured in uninvaded (UI; *Lantana* cover absent) and *Lantana*-invaded (LI; *Lantana* cover > 50%) sites in tropical forests of Central India. Significantly ($P < 0.05$) higher mean monthly CO_2 efflux was recorded in LI (396.6 ± 42.8 mg CO_2 m^{-2} h^{-1}) than UI (342.1 ± 37.6 mg CO_2 m^{-2} h^{-1}) sites and ranged from 157.6 - 736.7 mg CO_2 m^{-2} h^{-1} in LI and 125.8 - 614.5 mg CO_2 m^{-2} h^{-1} in UI sites in January and August respectively. The efflux peaked during the rainy season (mean 553.5 CO_2 m^{-2} h^{-1}) followed by summer (377.1 mg CO_2 m^{-2} h^{-1}) and the lowest in winter (259.2 mg CO_2 m^{-2} h^{-1}) season in LI sites. Significantly ($P < 0.05$) lower soil temperature (T_S) and higher soil moisture (M_S) content were observed in LI sites, whereas the higher T_S and lower M_S were found in UI sites. The cumulative annual soil CO_2 efflux was 4105.3 and 4759.2 mg CO_2 m^{-2} h^{-1} for UI and LI sites respectively. Soil CO_2 efflux was significantly positively correlated with *Lantana* density (r=0.76), *Lantana* basal area (r = 0.79), standing crop litter (r = 0.92), T_S (r = 0.49), M_S (r = 0.59), SOC stock (r = 0.66), pH (r = 0.56) and with mean annual precipitation (MAP) (r = 0.94). The present study concludes that plant invasions could alter the CO_2 efflux in tropical forests, which would lead to changes in both atmospheric and soil C. Therefore, a proper management strategy and long-term monitoring are necessary to contain Lantana's expansion and its impacts.

Keywords soil respiration; *Lantana camara*; soil temperature; tropical dry deciduous; Central India.

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1 Introduction

Soil respiration, also known as soil carbon dioxide (CO_2) efflux, is a major pathway of CO_2 release to the atmosphere from organic matter decomposition (Schlesinger and Andrews, 2000). It is a vital functional process in terrestrial carbon (C) cycling that releases about 80-98 Pg C every year (Raich et al., 2002;

Bilandzija et al., 2016; Zhao et al., 2017). Soil respiration occurs in two ways: auto and heterotrophic (Pandey and Singh, 2018). It constitutes the totality of all soil metabolic processes (Yang and Wang, 2006).

Several factors of both abiotic as well as biotic such as soil temperature (T_S), soil moisture (M_S), plant photosynthetic activity, soil organismal activity, organic matter (SOM), soil organic carbon (SOC), etc. influence soil CO_2 efflux (Meena et al., 2020). Among all these, T_S is a critical factor that rises with global warming and affects soil respiration rates (Prasad and Baishya, 2019). However, soil respiration is also dependent on M_S, in particular, in dry forest soils (Li et al., 2017). The interacting effects of these two major factors, together with the other above-said factors on soil CO_2 efflux is still uncertain.

Biological invasion is the second major driver of global change (Drake et al., 2003; Zhang and Chen, 2011; Sardans et al., 2017). Invasive species such as *Lantana* could significantly impact soil CO_2 efflux by causing changes in net primary productivity, substrate quality and quantity, microclimatic conditions, root biomass and microbial populations. The effect of plant invasions on soil CO_2 efflux has been found to be mixed (positive, negative and negligible) owing to variation in site conditions and different factors (Fang and Moncrieff, 2001; Metcalfe et al., 2011). A slight difference in soil respiration as a result of plant invasion can affect both the SOC stock as well as the atmospheric CO_2 concentration (Lone et al., 2019).

Of the total forest cover in India, 39.3% of it is covered by tropical dry deciduous forests (ISFR, 2021). The state Madhya Pradesh, located in Central India has the largest forest cover of the country and tropical dry forests comprise roughly about 83% of the state's forest cover (ISFR, 2021). *Lantana camara* (hereafter *Lantana*) is a highly invasive plant with 650 varieties and occurs in over 60 countries (Lüi, 2011; Global Invasive Species Database, 2020). It covers over 13 million hectares and threatens 44% of the forest cover in India, and has invaded almost all the dry deciduous forests of India (Sharma et al., 2005; Sharma and Raghubanshi, 2006; Goyal et al., 2018; Mungi et al., 2020). However, the impacts of *Lantana* on the soil CO_2 efflux in tropical dry deciduous forests are seldom quantified. To fill this gap, this study has been undertaken: (1) to investigate the impact of *Lantana* invasion on soil CO_2 efflux in three tropical dry deciduous forest types, and (2) to know the relationship between soil respiration with other environmental variables.

2 Study area and Methodology

2.1 Study area

The present research was conducted in three forest study sites in Sagar, Madhya Pradesh, Central India (21° 17' – 26° 52′ N and 78° 08′ – 82° 49′ E; Table 1; Fig. 1). The study area is located in north-central Madhya Pradesh and surrounded by Vindhyachal mountain range. According to Champion and Seth's (1968) classification, the forest in the study region belongs to group 4b. A subtropical climate with hot summer from March to mid-June, followed by rainy season from mid-June to September and cool winter from October to February prevails in the area. The mean annual minimum and maximum temperatures in the area are 11.6 and 40.7˚C, whereas the mean annual rainfall is 1197.6 mm. Clay to sandy loam comprise the soil of the study area which is dominated by tropical dry deciduous forests. *Butea monosperma*, *Diospyros melanoxylon*, *Lagerstroemia parviflora* and *Tectona grandis* are the most prevalent species in this forest which has now been invaded by *Lantana* (Dar et al., 2019).

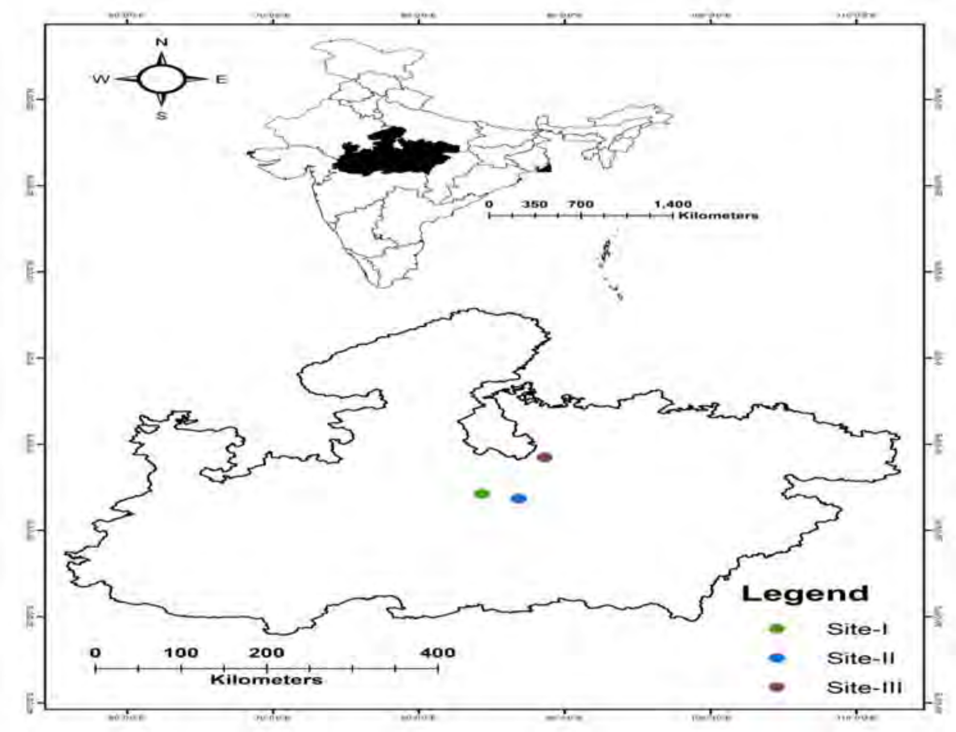

Fig. 1 Study area.

Table 1 Study site characteristics of uninvaded (UI) and *Lantana*-invaded (LI) sites of tropical dry deciduous forest of Sagar, Madhya Pradesh.

Parameter	Uninvaded (UI)			*Lantana*-invaded (LI)		
	Site-I	Site-II	Site-III	Site-I	Site-II	Site-III
Latitude (°)	23.46 - 23.47	23.19 - 23.20	24.39 - 24.39	23.46 - 23.47	23.19 - 23.20	24.39 - 24.39
Longitude (°)	78.77 - 78.78	79.03 - 9.04	79.23 - 79.23	78.77 - 78.78	79.03 - 79.04	79.23 - 79.23
Altitude (m)	536 - 568	428 - 476	386 - 397	535 - 588	435 - 460	378 - 393
No. of plots	10	10	10	10	10	10
Tree density (no. ha^{-1})	528	443	400	343	354	300
Tree basal area (m^2 ha^{-1})	22.5	18.2	18.3	15.2	12.3	16.5
Mean tree DBH	20.96	19.8	22.2	21.4	19.3	23.3
Max. tree DBH	128.2	113.5	75.1	71.8	57.5	124.8
Bulk density g cm^{-3} (0 - 10 cm)	1.06	1.12	1.17	0.89	0.98	1.1

2.2 Field sampling and measurements of soil CO_2 efflux

Three study sites were chosen after a reconnaissance survey and each site was divided into uninvaded (UI; *Lantana* cover absent) and *Lantana*-invaded (LI; *Lantana* cover >50%) subsites. Soil respiration was measured by alkali absorption method using plastic jars with 30 cm height and 15 cm diameter (Gupta and Singh, 1977). These jars {5 control (airtight) and 5 experimental (open-ended)} were inserted into the ground surface up to a soil depth of 5 cm for 24 h (to avoid diurnal variations) in each subsite. The understorey vegetation is clipped prior to insertion of the jars into soil. A 100 ml beaker was held 2.5 cm above the ground with 20 ml of 0.25 N

NaOH to collect the evolved CO_2. The amount of CO_2 was estimated by following Harris and van Bavel (1957) and Dar et al. (2015). The evolved CO_2 was calculated following Anderson and Ingram (1993):

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

Soil parameters such as T_S and M_S were measured adjacent to each CO_2 efflux beaker. T_S was measured next to the soil CO_2 efflux beaker using a digital soil thermometer (at 0 - 10 cm depth). Soil samples were taken next to the soil CO_2 efflux beaker to estimate M_S (at 0 - 10 cm depth). The soil samples were dried in a hot-oven (107 ± 5 °C) and M_S was estimated by gravimetric method. The soil total nitrogen and SOC were estimated following Kirk (1950) and Walkley and Black (1934). The pH of the soil was measured with the help of a digital pH meter. For each forest, triplicate samples were tested (30 per subsite).

2.3 Statistical analyses

Statistical analyses in soil CO_2 flux in different months and seasons of the year were done by analysis of variance (one-way ANOVA). Tukey's HSD test ($P \leq 0.05$) was used to test differences in means. Linear correlations were performed to understand how *Lantana* cover is related to soil and vegetation parameters. All the statistical analyses were done using the SPSS 20.0 (2012).

3 Results

3.1 Impact of *Lantana* on monthly and seasonal variations in soil CO_2 efflux

Soil respiration varied significantly between and within the sites ($P < 0.05$). The monthly soil CO_2 efflux ranged from 125.8 mg CO_2 m^{-2} h^{-1} in January in Site-III to 614.5 mg CO_2 m^{-2} h^{-1} in August in Site-I, with an average value of 342.1 ± 37.6 mg CO_2 m^{-2} h^{-1} among UI sites. The monthly soil respiration ranged from 157.6 mg CO_2 m^{-2} h^{-1} in January in Site-III to 736.7 mg CO_2 m^{-2} h^{-1} in August in Site-I, with an average value of 396.6 ± 42.8 mg CO_2 m^{-2} h^{-1} among LI sites. The mean monthly soil respiration values among UI sites were 365.3, 352 and 309.1 mg CO_2 m^{-2} h^{-1}, and among LI sites were 426.1, 403.9 and 359.9 mg CO_2 m^{-2} h^{-1} in Sites I, II and III respectively (Table 2).

A strong seasonal pattern of soil respiration was observed in all the three study sites (Table 3). The soil respiration peaked during the rainy season (mean 480.0 ± 23.5 mg CO_2 m^{-2} h^{-1}, range: 438.6 - 519.8 mg CO_2 m^{-2} h^{-1} in UI sites; mean 553.5 ± 27.8 mg CO_2 m^{-2} h^{-1}, range: 506.2 - 602.2 mg CO_2 m^{-2} h^{-1} in LI sites), followed by summer (mean 328.6 ± 15.2 mg CO_2 m^{-2} h^{-1}, range: 300.6 - 352.8 mg CO_2 m^{-2} h^{-1} in UI sites; mean 377.1 ± 16.6 mg CO_2 m^{-2} h^{-1}, range: 346.7 - 403.6 mg CO_2 m^{-2} h^{-1} in LI sites). The lowest values of soil CO_2 efflux were recorded in the winter (mean 217.7 ± 16.2 mg CO_2 m^{-2} h^{-1}, range: 187.9 - 243.6 mg CO_2 m^{-2} h^{-1} in UI sites; mean 259.2 ± 19.8 mg CO_2 m^{-2} h^{-1}, range: 226.7 - 295.1 mg CO_2 m^{-2} h^{-1} in LI sites). Site-III had the lowest soil respiration in all the seasons for both UI and LI sites, whereas Site-I had the highest soil respiration during rainy and winter seasons. Site-II had the maximum soil respiration during the summer in both UI and LI sites.

3.2 Impact of Lantana on soil temperature (T_S) and soil moisture (M_S)

Significant differences ($P < 0.05$) were observed in the mean monthly T_S and M_S in both UI and LI sites (Tables 4 and 5). The average monthly T_S values were 28.5 ± 1.7°C in UI sites and 27.9 ± 1.7°C in LI sites. The maximum T_S was recorded in the month of June in Site-I (38.1°C in UI and 37.3°C in LI), whereas the minimum T_S was recorded under Site-II (17.2°C in UI and 16.7°C in LI) during the month of January.

The average monthly M_S values were 11.4 ± 1.3% in UI sites and 12.4 ± 1.5% in LI sites. The maximum M_S was recorded in the month of August in Site-II (24.2% in UI and 25.4% in LI), whereas the minimum M_S was recorded under Site-I (4.8% in UI and 5.5% in LI) during the month of May.

Both T_S and M_S showed a strong seasonal pattern in both UI and LI sites (Table 4 and 5). In both UI and LI sites, the highest T_S was observed during summer (mean 34.1°C and 33.4°C respectively) followed by rainy season (mean 29.4°C and 28.8°C respectively) and winter (mean 22°C and 21.4°C respectively). The highest

M_S was recorded during the rainy season (mean: 17.4% in UI and 18.5% in LI) followed by winter (mean: 9.7% in UI and 10.3% in LI) and summer (mean: 7.4% in UI and 8.2% in LI).

Table 2 Mean soil CO_2 efflux (mg m^{-2} h^{-1}) in uninvaded (UI) and *Lantana*-invaded (LI) sites of tropical dry deciduous forest of Sagar, Madhya Pradesh.

Parameter	Uninvaded (UI)				*Lantana*-invaded (LI)			
	Site-I	Site-II	Site-III	Mean	Site-I	Site-II	Site-III	Mean
Sept. 2018	473.4 ± 16.4[bc]	414.8 ± 10.1[ab]	393.0 ± 19.3[a]	427.1± 11.9	520.8 ± 21.3[c]	471.7 ± 8.1[bc]	441.5 ± 17.1[ab]	478.0 ±14.1
Oct. 2018	397.3 ± 6.7[b]	335.2 ± 5.9[a]	323.4 ± 6.0[a]	352.0 ± 11.8	458.4 ± 16.8[c]	404.3 ± 12.3[b]	341.8 ± 13.1[a]	401.5 ±18.3
Nov. 2018	293.7 ± 24.1[ab]	276.8 ± 20.5[ab]	224.8 ± 6.9[a]	265.1± 14.9	353.2 ±15.5[b]	303.9 ± 17.7[ab]	273.4 ± 9.7[ab]	310.2 ±13.7
Dec. 2018	250.6 ± 5.8[ab]	242.8 ± 19.9[ab]	195.6 ± 4.1[a]	229.7 ± 10.5	337.8 ± 14.6[c]	281.1 ± 12.5[bc]	250.2 ± 14[ab]	289.7 ±14.6
Jan. 2019	184.7 ± 9.8[bc]	145.7 ±14.2[ab]	125.8 ± 3.5[a]	152.1 ± 10.0	219.6 ± 18.1[c]	195.7 ± 6.4[bc]	157.6 ± 6.0[ab]	190.9 ± 10.9
Feb. 2019	245.5 ± 9.2[bc]	220.7 ± 13.1[ab]	205.5 ± 2.8[a]	223.9 ± 6.4	269.8 ± 4.7[c]	242.8 ± 13.5[abc]	225.7 ± 4.8[ab]	246.1 ± 7.7
Mar. 2019	297.6 ± 3.9[b]	270.4 ± 23.0[ab]	233.5 ± 5.6[a]	267.2 ± 11.5	370.8 ± 11.2[c]	326.7 ± 15.5[bc]	316.3 ± 8.4[bc]	337.9 ± 10.1
Apr. 2019	348.8 ±11.1[ab]	392.2 ± 14.7[bc]	317.8 ± 4.4[a]	352.9 ± 12.1	397.4 ± 11.1[bc]	421.8 ± 2.5[c]	365.1 ± 13.8[ab]	394.8 ± 10.2
May 2019	327.1 ± 8.4[a]	343.5 ± 15.6[a]	320.1 ± 6.2[a]	330.2 ± 6.4	353.7 ± 10.1[ab]	406.8 ± 20.7[b]	337.5 ± 9.6[a]	366.0 ± 8.6
Jun. 2019	356.6 ± 10.2[ab]	405.0 ± 9.7[bc]	331.2 ± 7.2[a]	364.2 ± 11.7	401.7 ± 19.4[abc]	459.2 ± 14.5[c]	367.8 ± 22.9[ab]	409.6 ± 16.4
Jul. 2019	593.9 ± 20.0[bc]	585.7 ± 12.6[ab]	518.7 ± 7.07[a]	566.1 ± 13.9	692.8 ±11.3[d]	660.6 ± 21.6[cd]	611.4 ± 14.7[bc]	654.9 ± 14.4
Aug. 2019	614.5 ± 26.1[ab]	590.7± 21.0[ab]	519.3 ± 7.1[a]	574.8 ± 17.4	736.7 ± 13.5[c]	671.8 ± 25.8[bc]	630.1 ± 26.1[b]	679.6 ± 19.3

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

Table 3 Seasonal variation in soil CO_2 efflux (Rs, mg CO_2 m^{-2} h^{-1})), soil temperature (Ts, °C), and soil moisture (Ms, %) in uninvaded (UI) and Lantana-invaded (LI) sites of tropical dry deciduous forest of Sagar, Madhya Pradesh.

Season	Parameter	Uninvaded (UI)				*Lantana*-invaded (LI)			
		Site-I	Site-II	Site-III	Mean	Site-I	Site-II	Site-III	Mean
Winter	CO_2 efflux	243.6 ± 13.1[abc]	221.5 ± 16.2[ab]	187.9 ± 21.5[a]	217.7 ± 16.2	295.1 ± 17.3[c]	255.9 ± 13.6[bc]	226.7 ± 13.8[ab]	259.2 ± 19.8
	Ts	23.0 ± 1.4[a]	20.8 ± 1.4[a]	22.2 ± 1.7[a]	22.0 ± 0.6	22.4 ± 1.4[a]	20.4 ± 1.5[a]	21.5 ± 1.9[a]	21.4 ± 0.6
	Ms	8.6 ± 0.2[a]	11.0 ± 0.3[bc]	9.4 ± 0.2[a]	9.7 ± 0.71	9.2 ± 0.2[a]	12.0 ± 0.3[c]	9.8 ± 0.3[ab]	10.3 ± 0.8
Summer	CO_2 efflux	332.5 ± 7.8[ab]	352.8 ± 17.4[bc]	300.6 ± 12.1[a]	328.6 ± 15.2	380.9 ± 8.2[bc]	403.6 ± 16.0[c]	346.7 ± 9.1[ab]	377.1 ± 16.6
	Ts	35.0 ± 1.6[a]	33.0 ± 1.8[a]	34.2 ± 1.7[a]	34.1 ± 0.6	34.2 ± 1.5[a]	32.5 ± 1.7[a]	33.5 ± 1.6[a]	33.4 ± 0.5
	Ms	6.6 ± 0.6[a]	8.2 ± 0.7[ab]	7.5 ± 0.6[a]	7.4 ± 0.5	7.1 ± 0.6[a]	9.4 ± 0.8[b]	8.2 ± 0.8[ab]	8.2 ± 0.7
Rainy	CO_2 efflux	519.8 ± 27.9[ab]	481.6 ± 33.7[ab]	438.6 ± 25.7[a]	480.0 ± 23.5	602.2 ± 35.6[b]	552.1 ± 36.1[ab]	506.2 ± 37.1[ab]	553.5 ± 27.8
	Ts	30.4 ± 1.6[a]	28.4 ± 1.7[a]	29.4 ± 1.5[a]	29.4 ± 0.6	29.7 ± 1.5[a]	27.9 ± 1.8[a]	28.9 ± 1.6[a]	28.8 ± 0.5
	Ms	16.8 ± 1.3[a]	19.1 ± 1.8[ab]	16.4 ± 1.7[a]	17.4 ± 0.8	17.6 ± 1.5[ab]	20.9 ± 1.7[b]	17.1 ±1 .7[ab]	18.5 ± 1.2

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

Table 4 Mean soil temperature (°C) in uninvaded (UI) and Lantana-invaded (LI) sites of tropical dry deciduous forest of Sagar, Madhya Pradesh.

Parameter	Uninvaded (UI)				*Lantana*-invaded (LI)			
	Site-I	Site-II	Site-III	Mean	Site-I	Site-II	Site-III	Mean
Sept. 2018	29.4 ± 0.3^{c}	27.1 ± 0.2^{ab}	28.2 ± 0.4^{bc}	28.2±1.1	28.4 ± 0.5^{bc}	26.1 ± 0.3^{a}	27.8 ± 0.3^{b}	27.4±1.1
Oct. 2018	26.6 ± 0.5^{d}	24.6 ± 0.1^{ab}	25.8 ± 0.1^{bcd}	25.7±0.9	26.2 ± 0.2^{cd}	24.2 ± 0.2^{a}	25.1 ± 0.1^{abc}	25.2±0.9
Nov. 2018	24.2 ± 0.3^{c}	22.4 ± 0.2^{ab}	23.1 ± 0.1^{bc}	23.2±0.8	23.3 ± 0.4^{bc}	21.1 ± 0.5^{a}	22.4 ± 0.2^{ab}	22.2±1.1
Dec. 2018	22.4 ± 0.4^{c}	20.2 ± 0.2^{ab}	21.2 ± 0.3^{bc}	21.2±1.0	22.4 ± 0.2^{c}	19.8 ± 0.2^{a}	20.5 ± 0.3^{ab}	20.9±1.2
Jan. 2019	19.4 ± 0.3^{d}	17.2 ± 0.2^{abc}	18.2 ± 0.2^{bcd}	18.3±0.9	18.5 ± 0.2^{cd}	16.7 ± 0.4^{a}	17.0 ± 0.3^{ab}	17.4±1.0
Feb. 2019	26.2 ± 0.5^{c}	23.6 ± 0.4^{a}	26.5 ± 0.2^{c}	25.4±1.5	25.4 ± 0.1^{bc}	24.0 ± 0.6^{ab}	26.0 ± 0.3^{c}	25.1±1.0
Mar. 2019	30.5 ± 0.1^{d}	28.3 ± 0.2^{ab}	29.6 ± 0.4^{cd}	29.4±1.0	30.2 ± 0.2^{cd}	27.9 ± 0.4^{a}	29.2 ± 0.1^{bc}	29.1±1.1
Apr. 2019	34.8 ± 0.4^{c}	32.2 ± 0.3^{a}	33.7 ± 0.3^{bc}	33.6±1.2	33.8 ± 0.5^{bc}	32.1 ± 0.2^{a}	33.2 ± 0.1^{ab}	33.1±0.9
May 2019	36.6 ± 0.1^{d}	34.9 ± 0.4^{ab}	36.2 ± 0.2^{cd}	35.9±0.9	35.5 ± 0.2^{bc}	34.3 ± 0.1^{a}	35.1 ± 0.2^{ab}	35.0±0.6
Jun. 2019	38.1 ± 0.2^{c}	36.6 ± 0.3^{ab}	37.5 ± 0.1^{bc}	37.4±0.7	37.3 ± 0.1^{bc}	35.8 ± 0.2^{a}	36.7 ± 0.3^{ab}	36.6±0.7
Jul. 2019	34.1 ± 0.3^{b}	32.7 ± 0.1^{a}	32.8 ± 0.4^{a}	33.2±0.8	33.1 ± 0.3^{ab}	32.2 ± 0.2^{a}	32.6 ± 0.1^{a}	32.6±0.5
Aug. 2019	31.7 ± 0.5^{b}	29.2 ± 0.3^{a}	30.8 ± 0.3^{ab}	30.5±1.3	31.1 ± 0.4^{b}	29.3 ± 0.1^{a}	30.3 ± 0.5^{ab}	30.2±0.9

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

Table 5 Mean soil moisture (%) in uninvaded (UI) and Lantana-invaded (LI) sites of tropical dry deciduous forest of Sagar, Madhya Pradesh.

Parameter	Uninvaded (UI)				*Lantana*-invaded (LI)			
	Site-I	Site-II	Site-III	Mean	Site-I	Site-II	Site-III	Mean
Sept. 2018	17.4 ± 0.4^{ab}	19.1 ± 0.3^{bc}	15.8 ± 0.3^{a}	17.4 ± 0.5	17.9± 0.2^{abc}	20.0 ± 0.8^{c}	16.1 ± 0.6^{a}	18.0 ± 0.6
Oct. 2018	14.9 ± 0.3^{abc}	16.1 ± 0.7^{bc}	13.2 ± 0.2^{a}	14.7 ± 0.5	15.0 ± 0.6^{abc}	17.4 ± 0.6^{c}	14.2 ± 0.7^{ab}	15.5 ± 0.5
Nov. 2018	9.7 ± 0.2^{a}	12.5 ± 0.8^{bc}	10.2 ± 0.2^{ab}	10.8 ± 0.5	10.5 ± 0.3^{ab}	13.1 ± 0.7^{c}	10.8 ± 0.3^{abc}	11.4 ± 0.5
Dec. 2018	8.4 ± 0.2^{a}	10.6 ± 0.3^{bc}	9.2 ± 0.3^{ab}	9.4 ± 0.4	9.2 ± 0.3^{ab}	11.6 ± 0.5^{c}	9.3 ± 0.4^{ab}	10.0 ± 0.4
Jan. 2019	7.8 ± 0.3^{a}	9.8 ± 0.2^{ab}	8.1 ± 0.5^{a}	8.6 ± 0.3	8.2 ± 0.6^{a}	10.3 ± 0.5^{b}	8.3 ± 0.4^{ab}	8.9 ± 0.4
Feb. 2019	8.4 ± 0.4^{a}	11.2 ± 0.3^{ab}	10.1 ± 0.4^{a}	9.9 ± 0.4	9.0 ± 0.6^{a}	13.2 ± 0.8^{b}	10.8 ± 0.9^{ab}	11.0 ± 0.7
Mar. 2019	7.2 ± 0.3^{a}	9.1 ± 0.4^{bc}	8.8 ± 0.3^{ab}	8.4 ± 0.3	7.8 ± 0.1^{ab}	10.5 ± 0.5^{c}	9.2 ± 0.3^{bc}	9.1 ± 0.5
Apr. 2019	6.6 ± 0.3^{a}	8.3 ± 0.4^{ab}	7.1 ± 0.4^{a}	7.3 ± 0.3	6.7 ± 0.4^{a}	9.7 ± 0.8^{b}	7.3 ± 0.3^{a}	7.9 ± 0.5
May 2019	4.8 ± 0.3^{a}	6.3 ± 0.4^{bc}	6.2 ± 0.2^{abc}	5.8 ± 0.3	5.5 ± 0.3^{ab}	7.0 ± 0.3^{c}	6.5 ± 0.2^{bc}	6.3 ± 0.3
Jun. 2019	7.8 ± 0.3^{a}	9.2 ± 0.3^{abc}	8.1± 0.2^{a}	8.4 ± 0.2	8.4 ± 0.4^{ab}	10.4 ± 0.5^{c}	9.8 ± 0.2^{bc}	9.5 ± 0.3
Jul. 2019	14.7 ± 0.3^{a}	16.8 ± 0.3^{a}	15.3 ± 0.6^{a}	15.1 ± 0.22	15.8 ± 1.1^{a}	20.7 ± 0.9^{b}	16.2 ± 1.0^{a}	17.6 ± 0.9
Aug. 2019	20.1 ± 0.9^{a}	24.2 ± 0.8^{a}	21.2 ± 0.7^{a}	21.2 ± 0.45	21.6 ± 0.7^{a}	25.4 ± 0.4^{a}	22.1 ± 3.2^{a}	23.1 ± 1.2

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

3.3 Impact of Lantana on annual soil respiration

The total annual soil respiration values from September 2018 to August 2019 were 4105.3 and 4759.2 mg CO_2 m^{-2} yr^{-1} for UI and LI sites respectively. The highest cumulative annual soil respiration was observed in Site-I (4383.7 mg CO_2 m^{-2} yr^{-1} in UI and 5112.7 mg CO_2 m^{-2} yr^{-1} in LI), followed by Site-II (4223.5 mg CO_2 m^{-2} yr^{-1} in UI and 4846.4 mg CO_2 m^{-2} yr^{-1} in LI) and Site-III (3708.7 mg CO_2 m^{-2} yr^{-1} in UI and 4318.4 mg CO_2 m^{-2} yr^{-1} in LI).

3.4 Relationships: soil respiration, Ts, Ms with *Lantana* density and other variables

Soil respiration was significantly positively related with *Lantana* density (r = 0.76, *P* = 0.001), *Lantana* basal area (r = 0.79, *P* = 0.001), standing crop litter (r = 0.92, *P* = 0.001), T_S (r = 0.49, *P* = 0.05), M_S (r = 0.59, *P* = 0.05), SOC (r = 0.66, *P* = 0.001), SOM (r = 0.66, *P* = 0.001), pH (r = 0.56, *P* = 0.05) and with mean annual precipitation (MAP) (r = 0.94, *P* = 0.0001). However, soil respiration exhibited significant negative relationships with bulk density (r = -0.84, *P* = 0.001) and mean annual temperature (r = -0.65, *P* = 0.05) in LI sites. A significant negative correlation has also been observed between Ts (R = 0.49, *P* = 0.05), M_S (r = 0.59, *P* = 0.05) and *Lantana* density and litter cover in LI sites (Table 6).

Table 6 Correlations (r-values) between CO_2 efflux, Ts and Ms with Lantana density and other predictable variables at 10 cm soil depth.

Predictor variables	*r*-value	*P*-value
Soil CO_2 efflux	0.763	0.001
Soil moisture (Ms)	0.498	0.051
Soil temperature (Ts)	0.59	0.057
SOC stocks (0-10 cm)	0.666	0.001
SOM (0-10 cm)	0.663	0.001
pH (0-10 cm)	0.568	0.053
Bulk density (0-10 cm)	-0.843	0.004
Standing crop litter	0.922	0.001
MAT (°C)	-0.656	0.053
MAP (mm)	0.947	0.001
Aspect (°)	0.988	0.001
Altitude (m asl)	0.901	0.001

4 Discussion

In the present study, *Lantana* invasion was found to enhance soil respiration via the interplay of several factors. Soil respiration rates are chiefly dependent on T_S and M_S, besides other regulating factors like availability of C-rich substrates, soil physico-chemical properties, plant root densities, soil organismal composition and population, etc (Boudot et al., 1986; Raich and Tufekcioglu, 2000). In this study, soil respiration was observed to be higher in LI sites (4759.2 mg CO_2 m^{-2} yr^{-1}) than UI sites (4105.3 mg CO_2 m^{-2} yr^{-1}) for the period September 2018 to August 2019 and it exhibited both monthly and seasonal variations. When the plant community composition gets altered, variations occur in energy balance, biogeochemical cycles and SOM quality and quantity, which affect factors such as T_S and M_S that ultimately control soil CO_2 efflux (Raich and Schlesinger 1992). A key mechanism by which a plant species could control the rate of soil CO_2 efflux is the formation of litter on which soil organisms feed (Prasad and Baishya, 2019). Site-I had the highest rate of soil respiration (4383.7 mg CO_2 m^{-2} yr^{-1} in UI and 5112.7 mg CO_2 m^{-2} yr^{-1} in LI) among all the sites. This could be because this site held the highest M_S (0 - 10 cm), SOM and SOC stock contributed by litter inputs. Thickets of

Lantana typically trap a great amount of windblown litter, leading to litter accumulation and build-up of SOM (Sharma and Raghubanshi, 2011). Furthermore, *Lantana* itself produces litter that markedly varies in quality and quantity from that of native plant litter, which in turn affect soil quality and the rate of soil respiration. The litter of *Lantana* decomposes faster than the litter of native plants which therefore increases the rate of soil respiration. According to a global meta-analysis, rates of litter decomposition could increase up to 117% in invaded ecosystems (Liao et al., 2008). Litter mixing between native and invasive species lead to microbial composition shifts which often affects the invasive species positively and native species negatively (Si et al., 2013; Wang et al., 2015). Mixed litter has enhanced rates of decomposition due to nutrient transfers between component plant litters (Zhang et al., 2014) and this results in enhanced rates of soil microbial respiration (Bu et al., 2015) and hence, the rate of soil CO_2 efflux.

Soil respiration exhibited monthly variation peaking in August (mean: 574.8 ± 17.4 mg CO_2 m^{-2} h^{-1} in UI and 679.6 ± 19.3 mg CO_2 m^{-2} h^{-1} in LI) and weakening in January (mean: 152.1 ± 10.0 mg CO_2 m^{-2} h^{-1} in UI and 190.9 ± 10.9 mg CO_2 m^{-2} h^{-1} in LI). The average soil CO_2 efflux was 342.1 ± 37.6 mg CO_2 m^{-2} h^{-1} among UI sites and 396.6 ± 42.8 mg CO_2 m^{-2} h^{-1} among LI sites, which signifies a 7.4% increase in soil CO_2 emission due to *Lantana* invasion. The values observed in our study are slightly higher than those reported from the tropical lowland rainforest of Borneo (140 - 302 mg CO_2 m^{-2} h^{-1}; Wanner, 1970), tropical evergreen forest of Venezuela (80 - 311 mg CO_2 m^{-2} h^{-1}; Medina and Zelwar, 1972), tropical deciduous forest of western Odisha (40-210 mg CO_2 m^{-2} h^{-1}; Basu et al., 1991), tropical moist deciduous forest (55-360 mg CO_2 m^{-2} h^{-1}; Mohanty and Panda, 2011); comparable with those of tropical dry deciduous forest of Costa Rica (373 mg CO_2 m^{-2} h^{-1}; Schulze, 1967), tropical dry deciduous forest of Uttar Pradesh (76 - 705 mg CO_2 m^{-2} h^{-1}; Pandey and Singh, 2018); and lower than those of tropical forests of Panama (469 - 914 mg CO_2 m^{-2} h^{-1}; Kursar, 1989), Costa Rica (430 - 675 mg CO_2 m^{-2} h^{-1}; Schwendenmann et al., 2003), and primary and secondary forests of Malaysia (948 and 707 mg CO_2 m^{-2} h^{-1}; Adachi et al. 2006). The variations observed with other studies could be due to differences in the forest type, soil conditions, experimental protocols, etc (Mohanty and Panda, 2011). The highest soil CO_2 efflux observed in August could be because it is the peak growth period of understorey vegetation which increases root and microbial respiration (Wang et al., 2014). In contrast, the lowest soil respiration observed in January could be because of low incoming solar radiation and low T_S leading to low microbial activity (Han et al., 2012; Dar et al., 2015).

In the present study, soil respiration exhibited a strong seasonal pattern as it was highest during the rainy season (mean: 480.0 ± 23.5 mg CO_2 m^{-2} h^{-1} in UI sites and 553.5 ± 27.8 mg CO_2 m^{-2} h^{-1} in LI sites), moderate during summer (mean: 328.6 ± 15.2 mg CO_2 m^{-2} h^{-1} in UI sites and 377.1 ± 16.6 mg CO_2 m^{-2} h^{-1} in LI sites) and lowest during winter (mean: 217.7 ± 16.2 mg CO_2 m^{-2} h^{-1} in UI sites and 259.2 ± 19.8 mg CO_2 m^{-2} h^{-1} in LI sites). Similar observations were reported by Mohanty and Panda (2011), Arora and Chaudhary (2017), Prasad and Baishya (2019) and Meena et al. (2020). Seasonal variations in soil CO_2 efflux are predominantly driven by the interactive effects of T_S and M_S (Zhang et al. 2019). High rates of soil CO_2 efflux in rainy season could be because M_S was highest, and T_S was optimum during this season. High M_S content could have increased autotrophic respiration due to percolation of water into the rhizosphere (Huxman et al., 2004). Also, this is the favourable season for plant growth and elevated photosynthesis which further enhances soil CO_2 efflux (Prasad and Baishya, 2019). Rainfall causes physical disruption of soil micro- and macro-aggregates that enhance organic matter decomposition and soil microbial respiration (Li et al., 2018). Availability of soil water due to rainfall after a long dry period could lyse microbial cells or rapidly mineralize the cytoplasmic solutes and release CO_2 into the surrounding environment which led to high soil CO_2 efflux in the rainy season (Schimel et al., 2007; Meena et al., 2020). Moderate rates of soil respiration during summer could be because T_S was highest, and M_S was lowest during this season. Rates of soil respiration usually rise with increase in T_S, but on attaining a particular threshold level, M_S becomes limited which slows down soil CO_2 efflux due to enzyme inhibition and associated reduced microbial and plant physiological activities (Jha and Mohapatra, 2011). In contrast to the rainy season, summer is considered to be a ‘non-growing’ season with very less root/shoot biomass and decreased respiration (Meena et al., 2020). Low rates of soil respiration during winter could be because T_S was the lowest in this season. Low T_S and less incoming solar radiation in winter cause a decline in soil microbial populations leading to low decomposition of SOM which, in turn, results in lowest soil CO_2 emission (Pandey et al., 2010; Sundarapandian and Dar, 2013).

In the present study, both T_S and M_S varied monthly and seasonally causing corresponding variations in soil respiration. The maximum T_S was recorded in June (37.4 ± 0.7°C in UI sites and 36.6 ± 0.7°C in LI sites) and during summer (34.1 ± 0.6°C in UI sites and 33.4 ± 0.5°C in LI sites), while the minimum was in January (18.3 ± 0.9°C in UI sites and 17.4 ± 1.0°C in LI sites) and winter (22.0 ± 0.6°C in UI sites and 21.4 ± 0.6°C in LI sites). The average monthly T_S values were 28.5 ± 1.7°C in UI sites and 27.9 ± 1.7°C in LI sites, signifying a 1.1% decrease in invaded sites. On the other hand, the maximum M_S was recorded in August (21.2 ± 0.45% in UI sites and 23.1 ± 1.2% in LI sites) and during rainy season (17.4 ± 0.8% in UI sites and 18.5 ± 1.2% in LI sites), while the minimum was in May (5.8 ± 0.3% in UI sites and 6.3 ± 0.3% in LI sites) and summer (7.4 ± 0.5% in UI sites and 8.2 ± 0.7% in LI sites). The average monthly M_S values were 11.4 ± 1.3% in UI sites and 12.4 ± 1.5% in LI sites, signifying a 4.2% increase in invaded sites. As the study sites were open dry deciduous forest patches, the soil of the UI sites was barely exposed to incoming solar radiation which resulted in higher T_S and lower M_S due to evaporation. In contrast, the invasion by *Lantana* provided considerable shade to the soil beneath it by covering it up with litter and profusely branching above, which resulted in lower T_S and retention of M_S. The variations caused by plant invasion influence the pace of SOM decomposition and soil respiration rates (Qi and Xu, 2001; Chen et al., 2013).

In the present study, soil respiration was found to be significantly positively correlated with T_S (P = 0.051), M_S (P = 0.057), SOC stock (P = 0.050), SOM (P = 0.051), tree density (P = 0.03), aspect (P = 0.0001), altitude (P = 0.001) and mean annual precipitation (P = 0.0001). Contrarily, it was significantly negatively correlated with soil bulk density (P = 0.004) and mean annual temperature (P = 0.050). Several studies have demonstrated that T_S and M_S are the key controlling factors of soil CO_2 efflux (Davidson et al., 2006; Liu et al., 2010; Sundarapandian and Dar, 2013; Wang et al., 2014; Pandey and Singh, 2018). While T_S affects metabolic activities directly, M_S acts as a solubilizing agent and a medium for soil microbial activity, all of which together affect soil respiration (Koizumi et al., 1999). An increase in T_S and M_S, in the presence of optimum pH and adequate amounts of nitrogen, SOM and SOC stock speeds up the processes of decomposition, mineralization, microbial activities and evolution of soil CO_2 (Hosea et al., 2018). Regression analysis indicated that variation in T_S accounted for 24 - 41% and 19 - 41% variations in soil respiration in UI and LI sites respectively. T_S alters the microclimatic conditions and kinetics of microbial and autotrophic respiration, which reflects on the rate of soil CO_2 efflux (Fang and Moncrieff, 2001). On the other hand, M_S explained 24 - 46% and 35 - 47% variations in soil CO_2 efflux in UI and LI sites respectively. M_S influences soil CO_2 efflux as it is associated with forest floor litter, soil substrate, oxygen consumption, microbial activity, etc. (Buyanovsky and Wagner, 1983; Hosea et al., 2018). As mean annual precipitation raises M_S levels, it is also strongly related with soil CO_2 efflux. A positive influence of SOC stock on the rate of soil CO_2 efflux was also reported by Fang et al. (1998), Zheng et al. (2009), Luo et al. (2012), and Pandey and Singh (2018). The SOM and SOC stock derived from litterfall affect autotrophic respiration, substrate decomposition, microbial biomass and activity (Zhou et al., 2013; Meena et al., 2020). The negative relationship between soil CO_2 efflux and bulk density indicates that pore spaces play a crucial role in water movement, electric conductivity, maintenance of aerobic conditions and microbial activity (Hosea et al., 2018). The negative association of soil respiration with mean annual temperature could be because the latter causes soil dryness and water stress, thus limiting the rate of the former (Li et al., 2018).

5 Conclusion

The present study indicates that soil CO_2 efflux is significantly enhanced in the studied tropical dry deciduous forest sites with invasion by *Lantana*. Soil CO_2 efflux also exhibits monthly and seasonal variations with changes in T_S and M_S. Therefore, the *Lantana* invasion, together with any change in the existing temperature and precipitation regimes could drastically alter the rate of global carbon cycling.

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