Assessment of soil carbon dioxide efflux and its controlling factors in moist temperate forest of West Himalayas

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In this study, the soil CO_2 efflux was measured by closed dynamic system method along with soil and meteorological parameters at 1600, 1700 and 1800 m elevations along different directional-aspects over a period of one year. The annual CO_2 efflux rate (F_c) varied from 1.02 to 22.57 μmol m^{-2} sec^{-1}, which was highest in the rainy season. The annual average F_c was maximum (8.67 μmol m^{-2} sec^{-1}) at east facing slope followed by 7.58 and 7.32 μmol m^{-2} sec^{-1} at south facing slope and north facing slope respectively. Temperature (T_s), moisture (S_m) and evaporation of soil were found to be significant variables and selected to develop the regression model with R^2 value of 0.85. The effect of soil moisture on F_c above 15°C T_s exhibited a better relationship with R^2 value of 0.48 and temperature sensitivity (Q10) was found 3.25. This study reveals that the key controlling factors of CO_2 efflux rate are soil moisture and soil temperature, which explains 66% variation in soil CO_2 efflux.

Keywords: Seasonal variation, soil CO_2 efflux, soil moisture, soil temperature, spatial variation, west Himalayas.

SOIL is the largest terrestrial pool of stored carbon with over 1500 Pg, which is almost twice as much carbon as the vegetation and the atmosphere combined[1,2]. Moreover, soil CO_2 efflux is the major connecting link between the biosphere and atmosphere[3] through which 75–100 Pg carbon releases in the atmosphere every year[4]. Despite the importance of soil carbon pool and carbon cycle, understanding of CO_2 emission processes and their sensitivity to changing climatic conditions are unclear[5,6]. The soils of moist temperate forest of West Himalayas have 210.65 Tg organic carbon (OC) stored and continuously increasing temperature due to global warming is making the whole ecosystem vulnerable[7,8]. The soil CO_2 efflux has been studied in various forest ecosystems since last four decades[9–11] and several studies along physiographic gradients have also been conducted[12,13].

Nevertheless, soil CO_2 emissions are associated with land use, physiography and climatic conditions[3]. Moreover, biochemical processes such as root respiration and organic carbon decomposition are also important factors that determine the rate of soil CO_2 emissions[14]. In addition, species composition, age of forest and management practices also affect this emission[15,16]. Besides, all the associated factors that determine the soil CO_2 efflux rate (F_c) change over time and space[17]. Therefore, the assessment of soil CO_2 emissions and their associated biotic and abiotic factors are important to estimate the potential impact of environmental changes on soil carbon storage in the Himalayan ecosystem. Of all the factors that affect soil CO_2 emissions, soil temperature, soil moisture, plant carbon input and soil organic carbon are the most significant factors[10,18]. The soil temperature has an influence on litter decomposition and root respiration whereas soil moisture affects the microbial community by influencing substrate availability and oxygen exchange in soil[19,20]. The F_c varies with environmental conditions as reported in different ecosystems. Many studies have been done to quantify F_c and to understand the impact of environmental variables on it[21,22]. Although the relationship of soil temperature and soil moisture with soil CO_2 emission has been studied separately in many studies across ecosystems[23], the impact of soil temperature in conjunction with soil moisture is not well understood in Himalayan forest ecosystems. Many studies reported that the soil CO_2 efflux will change with changing climatic conditions[24,25], although the direction and extent are not clear. Moreover, soil temperature and soil moisture are the most important factors of soil CO_2 emissions. However, elevation and directional-aspect also affect the soil properties and micro-climatic factors and are responsible for the emissions. The main objective of the present study was to assess the soil CO_2 efflux rate and its controlling factors in the moist temperate forest of Uttarakhand, West Himalayas. Furthermore, various micro-climatic parameters, i.e. soil temperature, air temperature, soil moisture, relative humidity, evaporation rate, and wind speed to be used for development of linear model, can be used for prediction of soil CO_2 efflux rate and for the experimental environment similar to that of the reported study region.

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Materials and methods

Study area

Himalayan moist temperate forests cover about 30,165.83 sq. km area of India which is about 0.92% of the total geographical area[26]. The study was conducted in the natural evergreen forest of Kempty watershed, Mussoorie which lies between 30°27′–30°29′N lat. and 78°00′E–78°02′E long. on the outermost ridge of the Himalayas in west–east direction. The micro-watershed having about 290.33 ha catchment area with elevation varying from 1650 m to 2000 m amsl and topography of the study area is undulating. For this study we stratified the elevation range into 1700 m, 1800 m and 1900 m amsl. The principle rock here is limestone and gypsum mineral is present in abundant quantities. The soil order is inceptisol and texture is sandy loam but its composition, depth, moisture, and humus content vary considerably depending on the aspect, slope and soil cover. Vegetation of the study area is banj oak mixed forest and major tree species are *Quercus leucotrichophora* (Banj oak), *Daphniphyllum himalayense* (Ratnali), *Machilusod oratissima* (Kaul), *Toona serrata* (Darli) and *Rhododendron arboretum* (Burans). The shrub species are *Hypericum oblongifolium* (Phiunli), *Zanthoxylum alatum* (Timru), *Coriaria nepalensis* (Masura/Mansuri), *Pyracantha crenulata* (Ghingaru), etc. and the herbaceous plants include *Thalictrum foliolosum* (Mimari), *Reinwardtia indica* (Basant), *Oxalis* spp. (Tirpatia) and *Fragaria indica* (Wild strawberry).

Site selection

The study was undertaken in five sampling points and these were selected on the basis of physiography, i.e. elevation, slope and aspect (Figure 1). Moreover, sampling points were selected at three different elevations, i.e. 1700 m, 1800 m and 1900 m amsl. Out of the five sampling points, three sampling points were selected at 1800 m elevation along with different directional-aspects (south, east and north-facing), whereas one sampling point each was selected at 1700 m and 1900 m elevation respectively.

Meteorological data

The weather parameters were recorded by the meteorological station established in the study area. Climatically, the area is predominantly temperate receiving annual rainfall of 2000–2500 mm. A major share (85%) of rainfall is received during southwest monsoon from June to September. The mean annual temperature varies from 11°C to 16°C and monthly mean temperature varies from 3°C to 5°C during December–January to 20°C to 22°C in May–June respectively.

Soil analysis

Soil samples from 0–15 cm and 15–30 cm depths were collected from each sampling point (Figure 1) and soil physico-chemical properties, i.e. pH, texture, bulk density (BD), OC, nitrogen, phosphorus and potassium were analysed to assess the soil health and nutrient status (Table 1). Moreover, the litter samples were collected from 1 m × 1 m quadrates by monthly basis and oven-dried at 72°C for 96 h to obtain constant moisture content. Litter carbon content was calculated as 50% of the dry biomass which was considered as total carbon addition to the soil[27].

Soil CO_2 efflux measurement in forest ecosystem

The soil CO_2 efflux rate (F_c) was measured using closed dynamic system method[28]. Under this method, a closed chamber of PVC sheet with dimensions 0.2 m × 0.2 m × 0.2 m was used to monitor the CO_2 emission and it was connected to the console of portable photosynthesis system (LICOR, Inc. USA). The chamber was placed on the soil surface after removing litter and fixed properly to avoid leakage. The F_c was monitored for 3 min and repeated three readings were recorded at each sampling point. The F_c was measured between 9 : 00 am and 12 : 00 noon and was considered as the representative of mean flux rate of a day[10]. The F_c was calculated using the following equation[29].

$$F_c = \frac{PV}{\mathrm{RTS}} \times \frac{\mathrm{d}C}{\mathrm{d}t}, \qquad (1)$$

where P is the pressure, V the chamber volume, R the gas constant, T the temperature, S the soil surface area covered by the chamber and $\mathrm{d}C/\mathrm{d}t$ is the change in CO_2 gas concentration in chamber with time.

The soil temperature (T_s) was measured at 0–10 cm depth by using soil thermometer, and soil moisture (S_m) for the depth of 0–30 cm was measured by the gravimetric method. Other micro-climatic variables such as monthly evaporation, wind speed and relative humidity data were collected from the meteorological observatory established at the study area.

Soil CO_2 efflux models

In order to identify the factors affecting F_c, predictive statistical analysis was performed. The meteorological parameters, i.e. soil and air temperature, soil moisture, relative humidity, evaporation rate and wind speed were correlated with F_c to understand the relationship. A

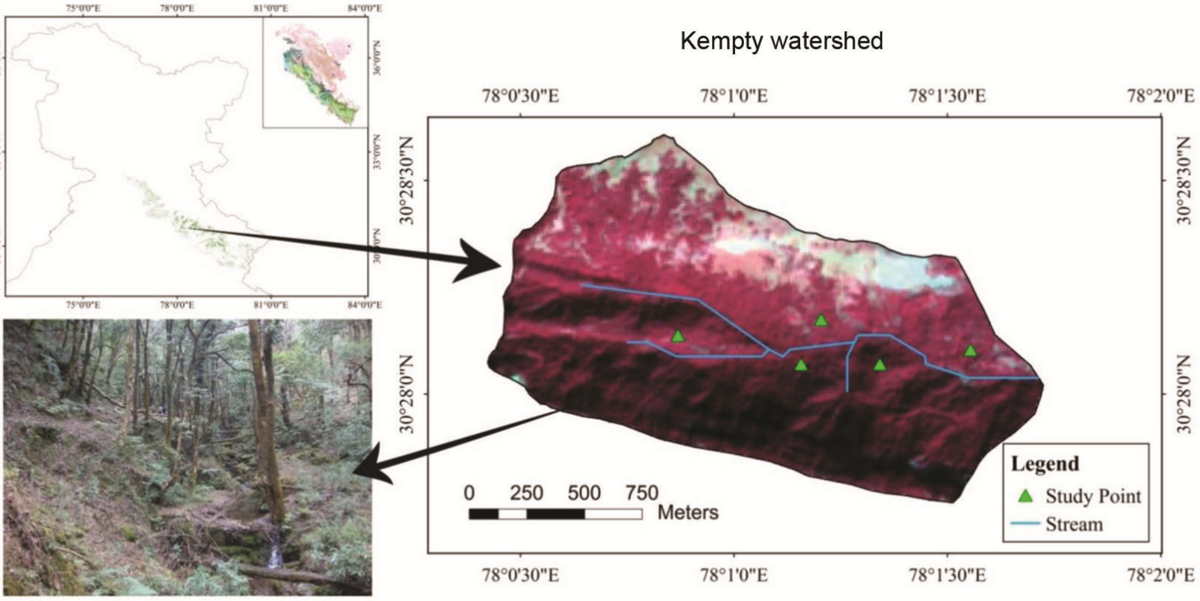

Figure 1. Location of study area and map of moist temperate forest of West Himalaya[26].

Table 1. Physico-chemical properties of soil from different depth and altitudinal gradient

Elevation (m amsl)	1700 m		1800 m		1900 m	
Soil depth	0–15 cm	15–30 cm	0–15 cm	15–30 cm	0–15 cm	15–30 cm
pH	07.70	07.95	07.50	07.68	07.70	07.75
Sand	67.10	66.02	58.15	59.13	64.08	58.16
Silt	10.06	09.14	28.01	27.03	30.08	35.00
Clay	22.84	24.84	13.84	13.84	05.84	06.80
BD (g cm^{-3})	01.59	01.13	01.10	01.19	01.02	01.29
OC (%)	07.73	05.89	05.81	04.94	03.80	01.82
N (kg ha^{-1})	1344.0	1590.4	1142.4	963.2	1075.2	672.0
P (kg ha^{-1})	19.04	14.56	23.52	25.76	16.80	19.04
K (kg ha^{-1})	313.60	291.20	358.40	313.60	134.40	156.80

regression model was developed for F_c by using meteorological parameter with the help of stepwise forward selection method. Furthermore, the relationship between F_c and soil temperature was established, and linear, exponential and temperature sensitivity (Q_{10}) regression models were developed as follows

$$F_c = a \times T_s + b, \quad (2)$$

$$F_c = a \times e^{(b \times Ts)}, \quad (3)$$

$$F_c = R_{10} \times Q_{10}^{(Ts - 10)/10}. \quad (4)$$

Linear and quadratic model was developed by using soil moisture as a variable

$$F_c = a \times S_m + b, \quad (5)$$

$$F_c = a \times S_m + b \times S_m^2 + c. \quad (6)$$

The combined effect of soil temperature and soil moisture on F_c was established as follows

$$F_c = a \times T_s + b \times S_m + c, \quad (7)$$

$$F_c = (R_{10} \times Q_{10}^{(Ts - 10)/10}) \times (a \times S_m + b \times S_m^2 + c), \quad (8)$$

where F_c is the measured soil CO_2 efflux rate (μmol m^{-2} sec^{-1}), T_s the soil temperature at 10 cm depth, S_m the soil moisture content at 0–30 cm depth, and R_{10}, Q_{10}, a, b, c are the fitted parameters. Furthermore, Q_{10} is the temperature sensitivity factor of soil CO_2 efflux which represents the change in CO_2 efflux rate with 10°C rise in temperature, and R_{10} represents fitted soil CO_2 efflux at 10°C.

$$Q_{10} = (R^2/R_1)^{(10/T_2 - T_1)}, \quad (9)$$

where R_1 and R_2 are soil CO_2 efflux rates at T_1 and T_2 temperature respectively. The temperature sensitivity function (Q_{10}) was used for annual soil CO_2 efflux rate in different ecosystems[22,30].

Statistical analysis

The stepwise linear regression was performed using *R* package[31] and the measured soil CO_2 efflux rates were applied to the eqs (2)–(8) using least square regression in *R* language. The best model was selected based on R^2 and AIC (Akaike's information criterion) criteria.

$$\mathrm{AIC} = n \times \log(\sigma^2) + 2 \times K, \tag{10}$$

where σ^2 = (residual sum of squares)/n, n the sample size and K is the number of estimated parameter where variance was also counted as an estimated parameter[32].

Results

Soil properties

The soil of study area was sandy loam to sandy clay loam in texture and slightly basic in nature having pH range from 7.5 to 7.95. The BD of soil varied from 1.02 to 1.59 g cm^{-3} at different elevations. The OC content was high in upper layer of soil (0–15 cm) compared to deeper soil (15–30 cm) and it varied from 1.82% to 7.73% indicating high carbon content. OC decreased with increase in elevation and the maximum OC (7.73%) was measured at 1700 m whereas, minimum (3.8%) was at 1900 m elevation for the upper layer of soil. Similar trend was also observed for available nitrogen and it was quite high, ranging from 672 to 1590 kg ha^{-1}. The maximum nitrogen (1590 kg ha^{-1}) was measured at 1700 m whereas, minimum (672 kg ha^{-1}) was at 1900 m elevation for the deeper layer of soil. Phosphorus content in the soil varied from 14.56 to 25.76 kg ha^{-1} whereas, potassium content varied from 134.4 to 358.4 kg ha^{-1} (Table 1). Furthermore, the results showed that the elevation level of 1800 m was richer in terms of phosphorus and potassium availability than the other two elevation levels.

Total carbon addition in the soil

The total biomass in the form of litterfall and total carbon addition in the soil during the study period is shown in Figure 2. Litterfall was more in two seasons, i.e. spring (March–April) and autumn (October–November) due to leaf shedding of *Q. leucotrichophora* (spring) and *D. himalayanse* (autumn) trees at the study site. Between the two seasons, maximum litterfall was received during October and November which added more carbon to the soil system. The average monthly total biomass addition and total carbon addition was 24.39 gm^{-2} and 12.20 gm^{-2} respectively.

Monthly and seasonal trend in soil CO_2 efflux rate

The trend of average monthly soil CO_2 efflux rate is presented in Figure 3. The maximum F_c (17.60 ± 1.68 μmol m^{-2} sec^{-1}) was observed in August while minimum was observed (1.58 ± 0.20 μmol m^{-2} sec^{-1}) in December. The results showed that F_c was highest during rainy season followed by summer and winter season.

Spatial variability in soil CO_2 efflux rate

The average annual CO_2 efflux measured along elevation showed that maximum F_c was at 1800 m followed by 1700 m and 1900 m amsl, i.e. 7.86, 6.42 and 3.90 μmol m^{-2} sec^{-1} respectively. In the summer season, F_c was maximum (5.78 ± 2.14) at lower elevation (1700 m) whereas, during rainy and winter season, maximum F_c was recorded at 1800 m. The coefficient of variation (CV) for soil CO_2 efflux during different seasons along elevation

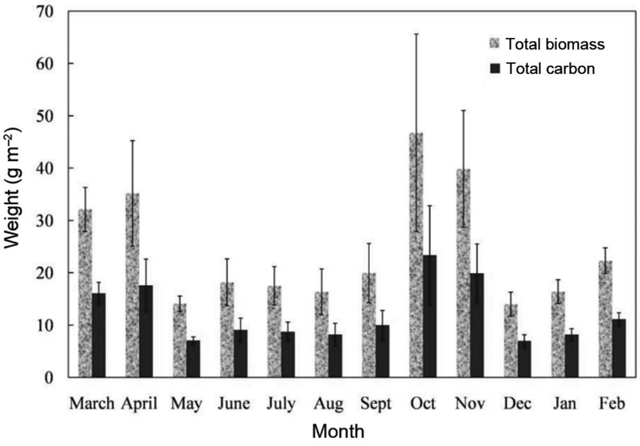

Figure 2. Monthly biomass and carbon additions in forest floor through litterfall (bars represent standard error).

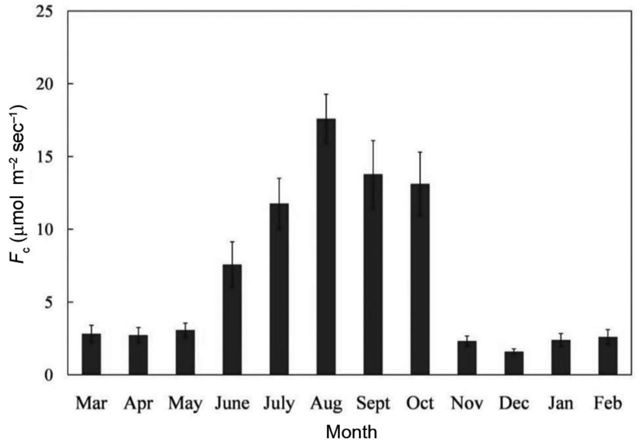

Figure 3. Measured values of average F_c (μmol m^{-2} sec^{-1}) in different months (bars represent standard error).

Table 2. Pearson's correlation coefficients between micro-climatic parameters

	Soil CO_2 efflux	Soil temperature	Air temperature	Soil moisture	Relative humidity	Evaporation rate	Wind speed
Soil CO_2 efflux	1.00						
Soil temperature	0.70*	1.00					
Air temperature	0.44	0.91**	1.00				
Soil moisture	0.58*	0.03	–0.17	1.00			
Relative humidity	0.70*	0.50*	0.26	0.26	1.00		
Evaporation rate	–0.33	0.31	0.65*	–0.60*	–0.36	1.00	
Wind speed	–0.68*	–0.21	0.10	–0.63*	–0.71*	0.74*	1.00

*Significant at 0.05 level; **Significant at 0.01 level.

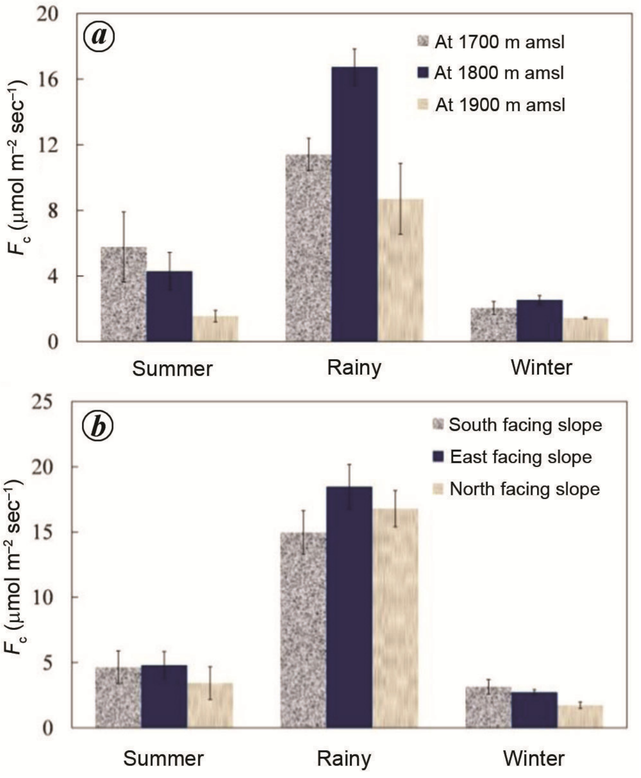

Figure 4. Soil CO_2 efflux during different seasons. ***a***, Along elevation gradient. ***b***, Along directional-aspect (bars represent standard error).

was minimum (27.62%) in winter and was maximum (55.10%) in summer season (Figure 4 *a*).

The annual average efflux rate measured along different aspects showed that maximum F_c (8.67 µmol m^{-2} sec^{-1}) was recorded for the east-facing slope whereas, it was 7.58 µmol m^{-2} sec^{-1} and 7.32 µmol m^{-2} sec^{-1} for south- and north-facing slopes respectively. During winter season, soil CO_2 efflux was maximum (3.15 ± 1.11 µmol m^{-2} sec^{-1}) at south-facing slope followed by east-facing (2.73 ± 0.49 µmol m^{-2} sec^{-1}) and north-facing slope (1.74 ± 0.42 µmol m^{-2} sec^{-1}) respectively. The CV for different directional aspects was 10.50% in rainy season to 28.54% in winter season (Figure 4 *b*).

Factors controlling soil CO_2 efflux rate

It was interesting to observe that the monthly average F_c exhibited a significant positive correlation with soil temperature, soil moisture, relative humidity and air temperature, whereas wind speed showed inverse relationship (Table 2). Moreover, these parameters were used to develop linear regression model for estimation of monthly F_c associated with other meteorological parameters by forward stepwise selection method. The R^2 value of the model was of 0.85 and $P < 0.05$ (eq. (11)).

$$F_c = -13.33 + 0.95T_s + 0.37S_m - 3.0E, \qquad (11)$$

where E is the evaporation rate.

Temperature and moisture dependent soil CO_2 efflux models

The non-linear least square regression models were developed to assess the impact of soil temperature and soil moisture on F_c independently, and in combination as shown in Table 3. The variation in soil CO_2 efflux due to soil temperature effect was estimated by exponential model with R^2 of 0.40 and soil moisture effect was expressed by quadratic model with R^2 of 0.23. The temperature sensitivity factor (Q_{10}) was estimated for temperature (eq. (4)) and combined effect (eq. (8)) was found to be 3.25 and 3.37 respectively (Table 3). In addition, the combined effect of soil temperature and soil moisture on soil CO_2 efflux was established with R^2 of 0.66 and $P < 0.05$ (eq. (8)). Moreover, the combined effect of these parameters was also shown in 3D plot for linear and non-linear model (Figure 5).

The scatter plot provided here (Figure 6) showed relationship of soil CO_2 efflux with soil temperature (Figure 6 *a*) and soil moisture (Figure 6 *b*) using exponential and quadratic models respectively. The F_c varied from 1.15 to 4.32 µmol m^{-2} sec^{-1} (Figure 6 *a*) for soil temperature below 15°C, whereas it varied widely between 1.02 and 22.57 µmol m^{-2} sec^{-1} for soil temperature above 15°C. Furthermore, it was found that the increased variation in

Table 3. Comparison of statistical parameters for developed regression models

Regression model	R^2	P	SEE	DF	AIC
Temperature					
$F_c = -3.93 + 0.70T_s$	0.33	<0.01	5.06	58	368.83
$F_c = 0.75 \times e^{0.12T_s}$	0.40	<0.01	0.72	58	135.59
$F_c = 3.17 \times 3.25^{(T_s-10/10)}$	0.31	<0.01	5.10	59	367.90
Moisture					
$F_c = -3.59 + 0.47S_m$	0.21	<0.01	5.47	58	378.08
$F_c = -10.65 + 1.14S_m - 0.01S_m^2$	0.23	<0.01	5.46	57	378.90
Combined effect					
$F_c = -15.28 + 0.49S_m + 0.73T_s$	0.56	<0.01	4.11	57	344.76
$F_c = 3.07 \times 3.37^{(T_s-10/10)} \times (-1.53 + 0.16S_m - 0.001S_m^2)$	0.66	<0.01	3.64	58	332.58

F_c, Soil CO_2 efflux rate; T_s, Soil temperature; S_m, Soil moisture; R^2, Coefficient of determination; P, Significance level; SEE, Standard error; DF, Degree of freedom; AIC, Akaike's information criteria.

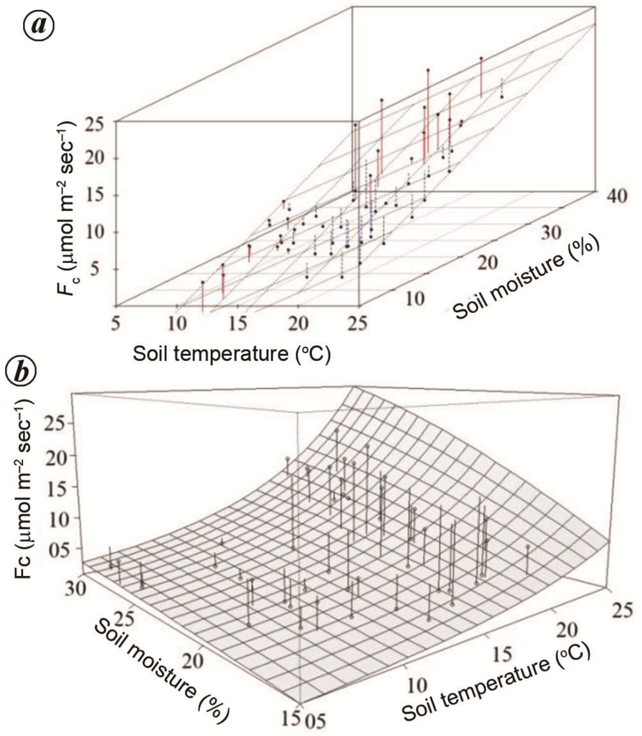

Figure 5. Three-dimensional scatter plot of soil temperature (T_s), soil moisture (S_m) and soil CO_2 efflux (F_c). ***a***, Linear model; ***b***, Non-linear model.

F_c above 15°C temperature was influenced by soil moisture content. The relationship between F_c and soil moisture varied significantly with temperature regime as R^2 of 0.48 and 0.05 for above and below 15°C respectively (Figure 7 *a* and *b*).

Discussion

Average soil CO_2 efflux rates

The *in situ* measurement of F_c allows us to observe the combined effect of autotrophic respiration from plant and heterotrophic respiration from microbes decomposing soil organic matter in natural condition[33]. The F_c measured during the study period ranged from 1.58 ± 0.20 to 17.60 ± 1.68 µmol m^{-2} sec^{-1} which was within the range for temperate forests reported in previous studies[34,35]. Soil CO_2 efflux rate in temperate forest was reported in the range of 0.02 to 25.35 µmol m^{-2} sec^{-1} whereas, for temperate grassland it was reported in the range of 4 to 18 µmol m^{-2} sec^{-1} (refs 34, 35). The high CO_2 efflux in the study area may be attributed to high carbon content[34].

Temporal and spatial pattern of soil CO_2 efflux

The soil temperature has an influence on litter decomposition and root respiration whereas, soil moisture affects the microbial community by influencing substrate availability and oxygen exchange in soil[19,20]. The study showed that there was significant temporal and spatial variation in F_c. The F_c started increasing with the onset of summer and was high (17.6 µmol m^{-2}sec^{-1}) during rainy season which coincided with high soil temperature and soil moisture (i.e. 21°C and 31.7%). With decrease in temperature during winters, F_c also decreased and reached low in December when temperature was also lowest. This indicated that soil temperature was the main controlling factor of soil microbial activity and respiration resulting in soil CO_2 efflux rate[36]. The F_c varied seasonally as well as with altitudinal variations and the annual F_c was observed maximum at 1800 m amsl. It might be due to the difference in nutrient content at different elevation levels as evident from high phosphorus and potassium at 1800 m elevation compared to other two elevations. Since, the source of soil CO_2 efflux is predominantly a soil microbial activity, any change in biotic and abiotic factors influencing this activity would result in a change of soil CO_2 efflux. The results showed that the annual CO_2 efflux was more at east-facing slope than south and north-facing slope. It might be due to the higher availability of solar radiation at east-facing slope which was responsible for higher temperature than the other aspects, which was favourable for microbial growth and resulted in high annual F_c. The soil and micro-climatic components vary with physiography which might be responsible for changes in F_c (refs 15, 16). In recent past, studies have shown the effect of micro-climatic parameters on soil CO_2 efflux along spatial variations[17,37]. Some studies reported that F_c decreased with increase in elevation[38] whereas, some reported its rise with elevation[39]. However, the results of the present study are not in direct conformity with the previous findings as it did not deal with linear relationship with elevation. These diverse results could be due to varying nutrient content and micro-climatic parameters such as soil temperature, soil moisture at different elevation levels which are directly responsible for the growth of soil microbes and thus explain the variations in F_c along different elevations as observed in this study.

Controlling factors

The present study showed that soil temperature, soil moisture and evaporation are the principle limiting factors with R^2 value of 0.85 at significance level of 0.05, which controls the soil biochemical processes and soil CO_2 efflux (eq. (11)). The main influencing factors, i.e. soil temperature and soil moisture, control most of the soil processes affecting microbial activities. Soil moisture and soil temperature have been reported as the major controlling factors that manipulate soil CO_2 emissions[10,36]. In the rainy season both the factors were favourable for microbial growth which triggered CO_2 emissions while during winters, the temperature was very low resulting in low F_c. The heterogeneous distribution of F_c can be suitably explained by soil temperature and soil moisture content[40,41].

The effect of soil temperature was best explained by exponential model. This might be due to the exponential growth of microbes as the temperature increases. The effect of soil moisture was explained by the quadratic model. The findings were in conformity with the previous studies[22]. The combined effect of soil temperature and soil moisture was better explained by non-linear model with higher R^2 value as reported by previous studies[22,42].

The temperature sensitivity factor (Q_{10}) which represents degree of dependence of soil CO_2 efflux on soil temperature was 3.25 for the study area, and it was within the range of other reported Q_{10} values for natural forest[43,44]. It

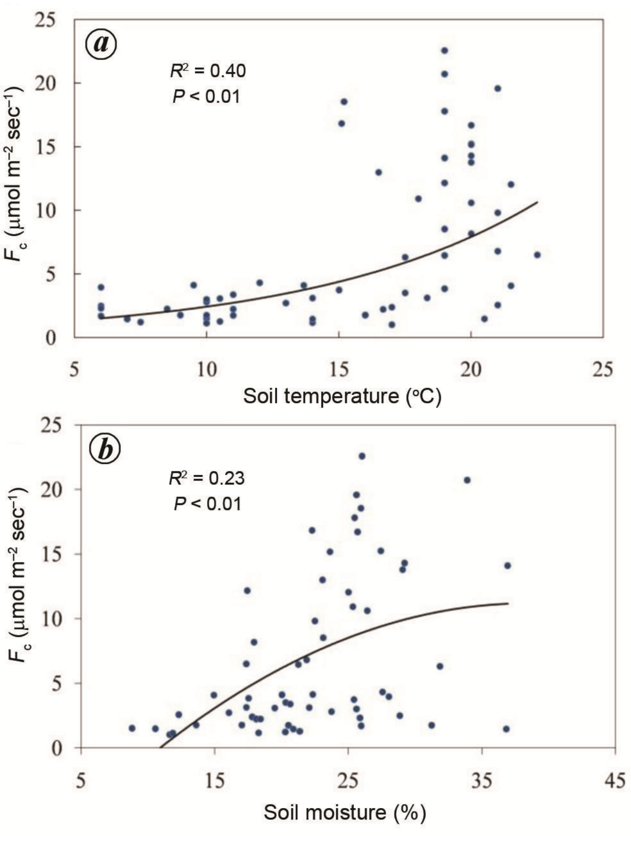

Figure 6. Relationship between (***a***) soil CO_2 efflux and soil temperature, (***b***) soil CO_2 efflux and soil moisture (0–30 cm).

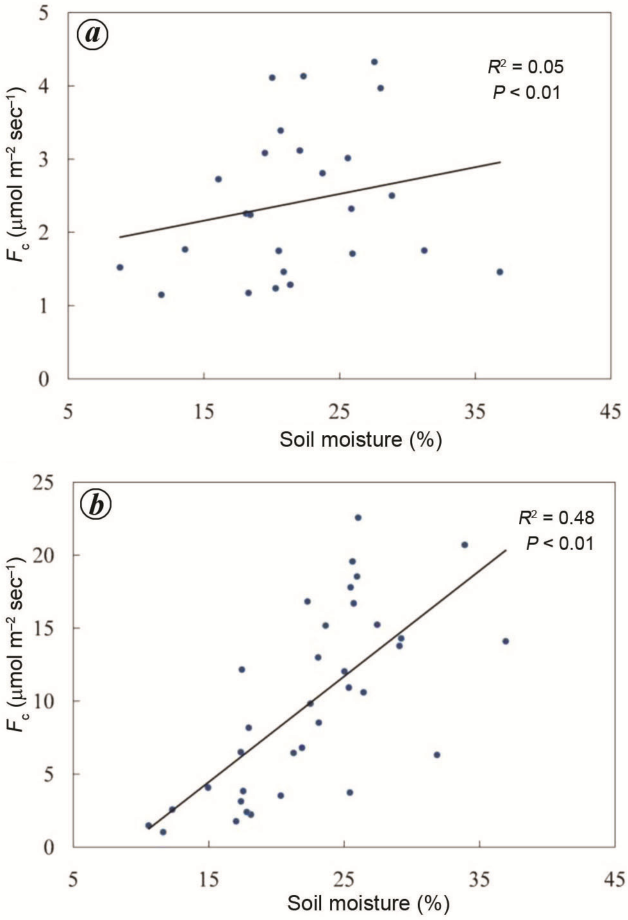

Figure 7. Relationship between soil CO_2 efflux F_c (µmol m^{-2} sec^{-1}) and soil moisture (%): ***a***, soil temperature (T_s) <15°C; ***b***, $T_s \geq 15$°C.

was found that influence of soil moisture was negligible when soil temperature was below 15°C, whereas its effect on F_c above 15°C exhibited better relationship with R^2 value of 0.48. The F_c was not sensitive to temperature under low moisture (<7.5%), but was more responsive to temperature under high moisture content (10%–25%)[45]. Moreover, the soil microbes need optimum moisture level whereas too high or too low moisture can limit soil CO_2 efflux rate. Furthermore, high soil moisture content limits aeration and low level leads to desiccation and reduced substrate supply, which restricts microbial metabolism[46]. Therefore, the present study explains the importance of both soil temperature and soil moisture as controlling factors of soil CO_2 emissions[10]. In addition, increasing temperature and erratic rainfall pattern due to global warming and climate change could significantly affect the soil carbon storage of the moist temperate forest ecosystem of West Himalayas.

Conclusion

It is concluded that the CO_2 efflux rate is significantly influenced by seasonal changes and physiography (elevation and aspect) of the study area including various soil factors such as temperature, moisture and nutrients conditions. Summer and rainy season, being most favourable for microbial growth, displayed maximum F_c values. The east-facing slope by virtue of receiving more solar radiation than the other directional aspects, showed higher F_c. In addition, the effect of soil temperature and soil moisture was better explained by non-linear models compared to traditional linear models. Further, it was established that the soil temperature and soil moisture are both needed at an optimum level for microbial growth below which the soil CO_2 emissions range was limited. Therefore, stored soil carbon of moist temperate forests of West Himalayas is sensitive to global warming and changing climatic conditions. Moreover, long-term monitoring of soil CO_2 efflux along with soil nutrient changes such as organic carbon, nitrogen, phosphorus, and potassium, etc. and micro-climatic parameters are needed to enhance the understanding of soil carbon dynamics and contribution of soil processes to atmospheric CO_2.

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