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 CO₂ 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 CO₂ 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 CO₂ efflux rate are soil moisture and soil temperature, which explains 66% variation in soil CO₂ efflux.

Keywords: Seasonal variation, soil CO₂ efflux, soil moisture, soil temperature, spatial variation, west Himalayas.

Nevertheless, soil CO₂ emissions are associated with land use, physiography and climatic conditions³. Moreover, biochemical processes such as root respiration and organic carbon decomposition are also important factors that determine the rate of soil CO₂ emissions¹⁴. In addition, species composition, age of forest and management practices also affect this emission¹⁵. Besides, all the associated factors that determine the soil CO₂ efflux rate ($F_c$) change over time and space¹⁷. Therefore, the assessment of soil CO₂ 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 CO₂ emissions, soil temperature, soil moisture, plant carbon input and soil organic carbon are the most significant factors¹⁰,¹⁸. 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 soil¹⁹,²⁰. 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 it²¹,²². Although the relationship of soil temperature and soil moisture with soil CO₂ emission has been studied separately in many studies across ecosystems²³, the impact of soil temperature in conjunction with soil moisture is not well understood in Himalayan forest ecosystems. Many studies reported that the soil CO₂ efflux will change with changing climatic conditions²⁴,²⁵, although the direction and extent are not clear. Moreover, soil temperature and soil moisture are the most important factors of soil CO₂ 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 CO₂ 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 CO₂ 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. 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), Daphniophyllum himalayense (Ratnali), Machilusod oratissima (Kaul), Toona serrata (Darli) and Rhododendron arboretum (Burans). The shrub species are Hypericum oblongifolium (Phiuwali), 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 Fagraaria 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.

Soil CO2 efflux measurement in forest ecosystem

The soil CO2 efflux rate (Fc) was measured using closed dynamic system method. 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 CO2 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 Fc was monitored for 3 min and repeated three readings were recorded at each sampling point. The Fc was measured between 9:00 am and 12:00 noon and was considered as the representative of mean flux rate of a day. The Fc was calculated using the following equation.

\[
F_c = \frac{PV \times dC}{RTS \times dr},
\]

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 dC/dr is the change in CO2 gas concentration in chamber with time.

The soil temperature (Ts) was measured at 0–10 cm depth by using soil thermometer, and soil moisture (Sm) 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 CO2 efflux models

In order to identify the factors affecting Fc, 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 Fc to understand the relationship. A
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

$$F_c = a \times T_s + b,$$
$$F_c = a \times e^{(b \times T_s)},$$
$$F_c = R_{10} \times Q_{10}^{(T_s - 10)/10}.$$

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

$$F_c = a \times S_m + b,$$
$$F_c = a \times S_m + b \times S_m^2 + c.$$

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

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

where $F_c$ is the measured soil CO$_2$ efflux rate ($\mu$mol 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.

$$Q_{10} = \left(\frac{R_{10}}{R_1}\right)^\frac{(T_2 - 10)}{(T_2 - T_1)},$$

where $R_1$ and $R_2$ are soil CO$_2$ efflux rates at $T_1$ and $T_2$ temperature respectively. The temperature sensitivity
Statistical analysis

The stepwise linear regression was performed using $R$ package 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.

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

where $\sigma^2 = (\text{residual sum of squares})/n$, $n$ the sample size and $K$ is the number of estimated parameter where variance was also counted as an estimated parameter.

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. himalayense (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
Table 2. Pearson’s correlation coefficients between micro-climatic parameters

|                         | Soil CO₂ efflux | Soil temperature | Air temperature | Soil moisture | Relative humidity | Evaporation rate | Wind speed |
|-------------------------|-----------------|------------------|-----------------|--------------|-------------------|------------------|-----------|
| Soil CO₂ 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.

Factors controlling soil CO₂ 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)).

\[
F_c = -13.33 + 0.95T_s + 0.37S_m - 3.0E, \quad (11)
\]

where \( E \) is the evaporation rate.

Temperature and moisture dependent soil CO₂ 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 CO₂ 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 CO₂ 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 CO₂ efflux with soil temperature (Figure 6a) and soil moisture (Figure 6b) using exponential and quadratic models respectively. The \( F_c \) varied from 1.15 to 4.32 \( \mu \)mol m⁻² s⁻¹ (Figure 6a) for soil temperature below 15°C, whereas it varied widely between 1.02 and 22.57 \( \mu \)mol m⁻² s⁻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  |       |     |     |    |     |
| $F_c = -15.28 + 0.49S_m + 0.737T_s$ | 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 7a 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. 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. 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.

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. 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. 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 (eq. (11)). Some studies reported that $F_c$ decreased with increase in elevation whereas, some reported its rise with elevation. 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. 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.

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. 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.

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 forests.
was found that influence of soil moisture was negligible when soil temperature was below 15 °C, whereas its effect on \( F_e \) above 15 °C exhibited better relationship with \( R^2 \) value of 0.48. The \( F_e \) was not sensitive to temperature under low moisture (<7.5%), but was more responsive to temperature under high moisture content (10%–25%)\(^{10}\). 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\(^{10}\). 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 \( F_e \) values. The east-facing slope by virtue of receiving more solar radiation than the other directional aspects, showed higher \( F_e \). 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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