Soil Carbon Fluxes and Sensitivity Analysis – A Study in *Pinus roxburghii* Forest

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ABSTRACT

The predicted increasing atmospheric carbon dioxide (CO_2) level is responsive to altering the future climate, and a small change in the soil carbon may significantly affect the forest carbon cycle and climate system. Soil respiration (SR) and its influencing factors like soil temperature (ST), soil water content (SWC) and surface litter-fall were measured monthly over one year in a sub-tropical Pine (*Pinus roxburghii*) forest of Bhaktapur district located in central Nepal to determine the SR of the forest and, its variations and sensitivity. The results showed that SR varied to the changes in ST by an exponential significant positive correlation between them. The optimum SR was observed between 10 and 22ºC, and the highest SR were obtained above ST at 20ºC. The temperature sensitivity value of SR (Q_{10}) was estimated at Q_{10} = 2.13. The significant exponential curve represented the effect of SWC on SR. The higher SR rate was mostly measured between 10 and 25% SWC. The monthly and seasonal variations of the SR rate were consistent with the ST, SWC and litter-fall variations. The study showed that the combined effect of temperature and precipitation might be the major cause of SR variations; however, ST is adequate for increasing SR. Hence, the warming further enhances carbon emission from the forest floor and inversely increases carbon to contribute to climatic change through this pine-dominated forest stand structure.

Keywords: *Pinus roxburghii* forest, Soil respiration, Soil temperature, Sub-tropical forest, Soil water content

1. INTRODUCTION

The contribution of soil carbon fluxes via soil respiration (SR) to the global carbon cycle cannot be neglected due to its major role and represents the second-largest carbon flux in the forests (Houghton 1995, Schlesinger and Andrews 2000). Owing to the forest carbon balance, it is of major concern that the increased atmospheric carbon dioxide (CO_2) is predicted, which is susceptible to alter future climate changes (Grace & Rayment 1999; Chen *et al.* 2011). It is hypothesized that climate warming is caused by the increased rates of SR, probably boosting further increases in global temperatures (Watts *et al.* 2021). Thus, proper accounting of SR and understanding of the climatic role facilitate knowing the future carbon balance (Xu & Shang 2016) and assist in predicting atmospheric carbon concentration in changing environmental conditions (Bond-Lamberty & Thomson 2010). Perhaps, the SR is strongly connected to different non-biological (e.g., soil temperature, soil moisture, sunlight) and biological factors (e.g. plant growth & photosynthesis) that complicate the mechanistic understanding of SR (Cui *et al.* 2020; Goodrick *et al.* 2016). Accurate estimation of SR and proper recognition of the affecting factors are exceptional to understanding the carbon cycle and global impact of climatic change (Bond-Lamberty & Thomson 2010). However, the CO_2 balance of the tropical forest remains highly uncertain (Valentini *et al.* 2008).

Pinus roxburghii Sarg. (Chir pine) is an important native conifer tree species of the sub-tropical region in the mid-hills of Nepal. It has dominated the coniferous forests of the country, which constitute 8.45% of the total forest area of Nepal (DFRS, 2015). *P. roxburghii* is one of the common species of pine forests distributed mostly in the western Himalayan region (Champion & Set 1968; Ohsawa *et al.* 1986). Chir pine forests predominate on all aspects of the slope. However, they are found in the central region of Nepal between 1,000 and 2,000 m and grow mostly on the southern slopes (Shrestha & Joshi 1996). Because of the high survival rate and simplicity in the establishment, *P. roxburghii* has been planted in Nepal since the 1980s, along with the support of the Community Forestry Program (CFP).

Research related to the ecological aspect of climate (Bajwa *et al.* 2015), forest carbon, biomass and sequestration (Aryal, 2016), and vegetation composition have been carried out in pine-dominated forest stands in different regions (Subedi *et al.*, 2018). Besides knowing the importance of the carbon fluxes and their vulnerability to climatic alteration, soil carbon fluxes and their susceptibility analysis in the pure *P. roxburghii* forest stand structure is yet lacking. However, a few related issues in discrete biomes were recently published by Dhital *et al.* (2019, 2020, 2022). Edaphic factors, most commonly soil temperature (ST) and soil water, were determined as regulating parameters of the SR in the forests (Davidson *et al.* 1998; Goodrick 2016; Watts *et al.* 2021).

Thus, this study was carried out in a *P. roxburghii* forest to extend the knowledge on carbon studies with the direct measurements of soil CO_2 emission through SR (via root and microbial respiration) and its associated climatic and biological factors. This dynamic research provides the parameters that regulate carbon emission, contributes to accurate estimation of soil carbon emission, and provides comprehensive baseline data for long-term forest management processes. Hence, this study aimed i) to determine the SR in a pure *P. roxburghii* forest stand throughout the year and ii) to elucidate the consequences of climatic and biological parameters on the SR process monthly.

2. MATERIALS AND METHODS

2.1 Study Area and Microclimate

The study was conducted in a pure pine (*Pinus roxburghii*) forest (27°38’ 31.3’’ N and 85°26’14.36’’ E, Elevation: 1558 m a s l), which is about 3km south of Bhaktapur city in the Suryabinayak Municipality. The study site is located in the lower southern part of the

Suryabinayak forest area, which is covered by 68 ha of land managed by the community forest user groups (Fig. 1). The forest consists of rugged topography with steep slopes but is covered by a dense canopy of pine trees and scars of past fires prominent in the forest. The climate is sub-tropical monsoon type which features rainy summer (June to September) and dry winter (December to February). Over the past ten years (2008–2017), the climatic data of 2008-2017 were procured from the Meteorological station, Tribhuvan International Airport (Fig. 2a, b) as the monthly average air temperature in the winter season ranged from 10.1°C to 15.9°C whereas in summer it varied from 24.2°C to 25.7°C. The minimum and maximum air temperatures (10 years average) were recorded in January and June at 11.4°C and 24.9°C, respectively. Similarly, ten years' average monthly mean precipitation varied from 4.0 mm in December to 395.1mm in July. The annual average air temperature was 19.7°C, and the average monthly precipitation was 124 mm over ten years.

The study site is mainly dominated by *P. roxburghii* (Chir pine) trees, and very few *Schima wallichii* trees were in the forest. The vegetation on the forest floor was sparsely covered by *Phyllanthus parvifolius*, *Pogonatherum crinitum, Ageratina adenophora*, etc.

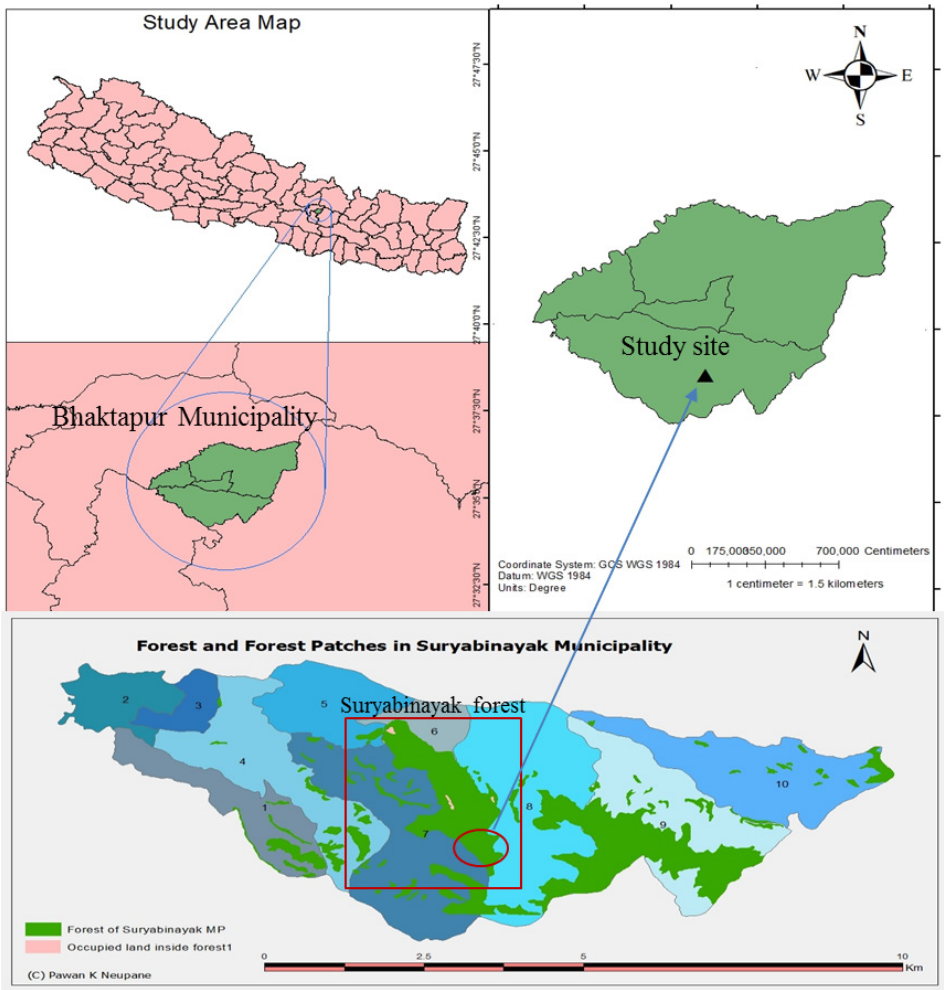

Fig. 1 Location map of the study area. Map of Nepal. Suryabinayak municipality. Suryabinayak forest (Source: https://resnature.blogspot.com/2017/12/forest-and-forest-patches-in.html)

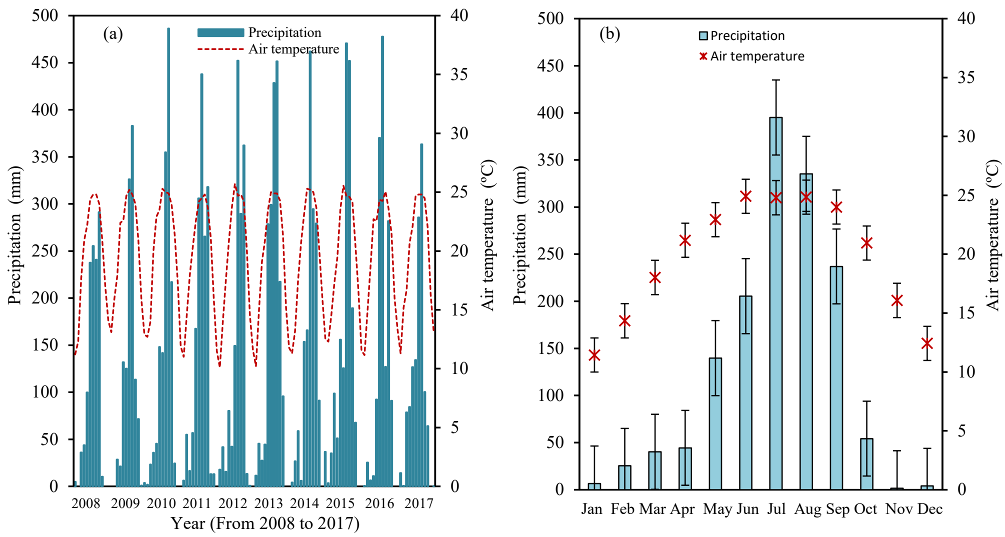

Fig. 2 Precipitation and air temperature of the study area. (a) Monthly mean precipitation and air temperature (b) Mean (2008 to 2017) precipitation and air temperature (Source: Department of hydrology and meteorology, DHM, Kathmandu, Nepal)

2.2 Methods of Data Collection

The study was conducted for one year, from June 2016 to May 2017. The soil respiration (SR) was measured in the field using the closed chamber method. The measurement data of soil respiration (SR), soil temperature (ST), soil water content (SWC) and litter biomass were collected from the study site each month a year.

2.3 Measurement of Soil Respiration (SR)

An area of 100 m × 70 m within the study site was selected for soil respiration (SR) measurements. The cylindrical chambers (n = 10) made of polyvinyl chloride of size 18 cm diameter and 16 cm height were installed in the forest floor soil. Vaisala CARBOCAP CO_2 probe GMP343 (Vaisala Oyj, FI-00421 Helsinki, Finland) was used to measure CO_2 concentration and gas temperature inside the chamber. Moreover, the probe recorded these measured data through the connected data logger meter (Vaisala HUMICAP Hand-Held Humidity and Temperature Meter HM70, Finland). This method involves placing a chamber over the soil surface, and the increase in the concentration of CO_2 within the chamber is measured as a function of time. Air temperature recorded within the chamber was used to calculate the density of CO_2 within the chamber. The chambers were placed in the study area with a difference of 10 m (about) distance between the chambers. The chambers were inserted properly into the soil at a 2 cm depth to prevent the chambers from air leakage during SR measurements. The chambers were installed in the study site one day before the measurements date to avoid the effect of chamber installation during measurements of SR (Dhital *et al.* 2019). The measurement of SR was conducted between 10:00 a.m. to 2:00 p.m. once a month (14th/15th) from June to May 2017 to receive the uniformity of data records throughout the year.

2.4 Measurement of Soil Temperature (ST)

Soil temperatures (ST) at 5 cm depth were recorded simultaneously monthly during SR measurements using the digital lab stem thermometer (AD-5622, A&D, Japan). Besides, continuous (1 h interval) soil temperature data of the study site were recorded separately using the TidbiT v2 Temperature logger (Onset HOBO data logger, Australia). The TidbiT data logger was installed at the center point of the study site at 5 cm soil depth and recorded ST from June 2016 to May 2017 throughout SR measurements.

2.5 Measurement of Soil Water Content (SWC)

Soil water content (SWC) at 5 cm depth was measured each month at the time of SR measurements through a time domain reflectometry (TDR) method by using the soil moisture sensor (TRIME-PICO Probes, Imko, Germany), and recorded the measured data with logger (HD2, mobile moisture meter, IMKO, Germany).

2.6 Measurement of Litter Biomass

For the measurement of litter-fall biomass, five samples (n = 5) of litter were collected randomly from the forest floor within the study area. The litter samples were collected within the cylindrical chamber of size 18 cm in diameter, and the samples were oven dried at 72°C for 48 h and weighed with an electronic balance. The dry weight of litter biomass was calculated using the following formula;

Biomass= Dry weight (g)/Area (m^2)

2.7 Analysis

The SR was calculated by using the following equation (Koizumi *et al.* 1999):

$F = (V/A)\ (\Delta c/\Delta t)$……(1);

Where, F is the soil respiration (mg CO_2 m^{-2} h^{-1}), V is the volume of air within the chamber (m^3), A is the area of the soil surface within the chamber (m^2), and Δc and Δt are the time rate of change of the CO_2 concentration in the air within the chamber (mg CO_2 m^{-3} h^{-1}).

When the CO_2 concentration is plotted against time, linear regression relationships can be ascertained (Koizumi *et al.* 1999). The Δc/Δt is calculated using this linear regression coefficient. The SR was estimated with the relation of ST; an equation of exponential regression (Dhital *et al.* 2010; Shen *et al.* 2021), which were used as follows:

$F(T) = a \times \exp(b \times T)$……(2)

Where, F (T) is the estimated SR rate (mg CO_2 m^{-2} h^{-1}) at ST (T˚C) at 5 cm soil depth, a represents the intercept of SR rate when ST is zero, and b represents the temperature sensitivity of SR.

The b value was used to calculate a coefficient of temperature sensitivity (respiration quotient, Q_{10}), which describes the change in SR over a 10˚C increase in ST by equation (3).

$Q_{10} = \exp(b \times 10)$…….(3)

Three different measurements of SR were conducted in each chamber to avoid any systematic measurement errors. Similarly, the ST and SWC were measured three times in each chamber during the SR measurements at separate points near the chamber. The average of three measurements was used for the value of each chamber. The total annual SR for the year was estimated from the equation obtained from the ST effect on SR and the continuous (1 h interval) measurements of ST data recorded by the data logger throughout the measurements date and then separated into total SR of the seasons.

The different statistics such as percentage, average, bar diagram, table and graphs were interpreted using quantitative data in Microsoft Excel 2010, and the significance P-value for the significance test was used to analyze the relationship between SR and its influencing factors like ST and SWC by the statistical AVOVA one-way t-tests.

3. RESULTS

3.1 Soil respiration (SR) and Soil Temperature (ST)

The ST is recognized as one of the best indicators of SR dynamics. A significant ($P < 0.05$) positive correlation between the SR and ST was established during a year around the period of measurements (Fig. 3). It is described by an exponential regression model: y = 80.93e0.076x ($R^2 = 0.601$), which shows the SR rate increased with the ST. The most SR values were recorded between 10 and 25ºC ST, and the highest was observed above the ST at 20ºC. The temperature sensitivity of SR represented by Q_{10} as defined by each 10ºC increase in ST increasing the SR rate of this pine forest was estimated at; $Q_{10} = 2.13$.

3.2 Soil Respiration (SR) and Soil Water Content (SWC)

The SWC of the forest interacts with the SR differently. A significant ($P < 0.05$) positive correlation between the SR and SWC was detected during the measurements in this study (Fig. 4). An exponential regression model: y = 218.9e0.0196x ($R^2 = 0.134$) described the soil water effect of SR. The higher SR values were recorded between 10 and 25% SWC.

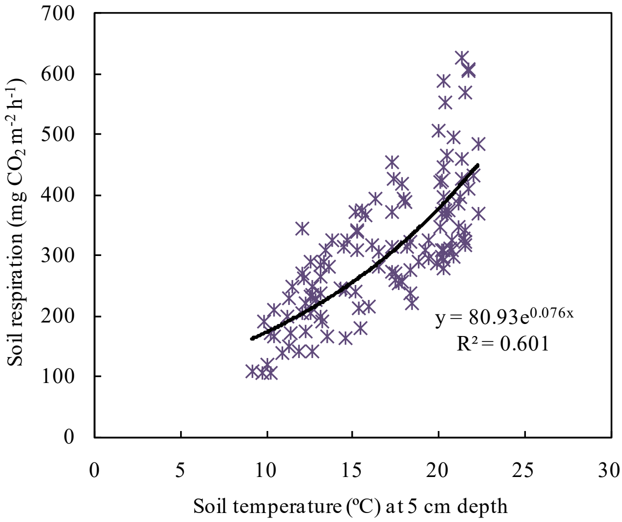

Fig. 3 Relationship between soil respiration (SR) and soil temperature (ST) (n=10) throughout a year

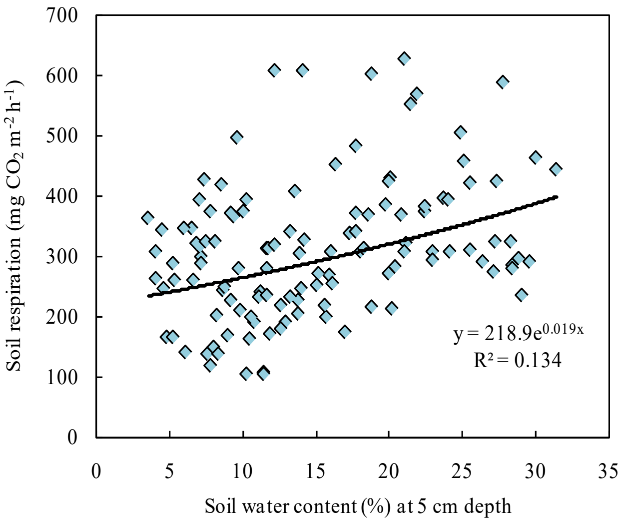

Fig. 4 Relationship between soil respiration (SR) and soil water content (SWC) (n=10) throughout a year

3.3 Variations of SR, ST, SWC and Litter Biomass

The rate of SR varied according to the month and season (Fig. 5). As increasing the days during the plant growing season, the SR rate (n = 10) increased and reached its maximum at 462.39 mg CO_2 m^{-2} h^{-1} in July, i.e. mid-summer. There was a gradual decline in the respiration rate from the summer to the winter months, reaching its minimum at 161.79 mg CO_2 m^{-2} h^{-1} in January.

Monthly and seasonal variations of SR followed the ST, and maximum ST (n = 10) was recorded at 21.68 ºC in July and minimum at 10.68ºC in January (Fig. 5a). The forest's SWC followed the SR in its monthly and seasonal variations (Fig. 5b). The maximum SWC (n = 10) was recorded at 27.77 % in September, i.e. early autumn, as rain extended from the summer months to the early autumn, and the minimum SWC was detected at 5.62 % in December. Similarly, the variations of litter biomass were observed according to the month and season. The litter biomass of the forest floor was mostly higher during the summer months and lowered in winter, which is most likely with the SR variation. The maximum litter-fall biomass (n = 5) was 614.96 g d w m^{-2} in June, and the minimum was recorded at

124.96 g d w m^{-2} in September (Fig. 5c). The community users collected the litter regularly from the forest and during the months of fall at the time of forest sensation.

The seasonal pattern and differently ranged SR and its determining factors are most important for the forest carbon balance. Table 1 shows the ST was highest at 22.30ºC in July and the lowest at 9.31ºC in January. Similarly, the SWC of the forest ranged from 3.51% in December to 31.37% in September. The large range; of 10.23 g d w m^{-2} in August and 793.91 g d w m^{-2} in June of litter-fall was recorded. Similarly, the SR ranged between 105.44 mg CO_2 m^{-2} h^{-1} in January and 627.23 mg CO_2 m^{-2} h^{-1} in August. The ST, SWC, litter-fall, and the forest's SR varied accordingly with the variations of seasons. The ST, litter-fall and SR were highest in the summer season at 21.03ºC, 394.89 g d w m^{-2} and 426.73 mg CO_2 m^{-2} h^{-1}, respectively. Nevertheless, the SWC was recorded as the highest at 22.66% in the early autumn season. The lowest ST, SWC, litter-fall values and the SR observed during winter were 11.90ºC, 7.90%, 155.78 g d w m^{-2} and 214.71 mg CO_2 m^{-2} h^{-1}, respectively. However, the autumn and spring seasons' litter-fall biomass were in-between the range of winter and summer seasons biomass at 18.23ºC, 22.66%, 172.26 g d w m^{-2} and 328.64 mg CO_2 m^{-2} h^{-1}, and 15.55 ºC, 14.84%, 351.29 g d w m-3 and 277.22 mg CO_2 m-3 h-1, respectively.

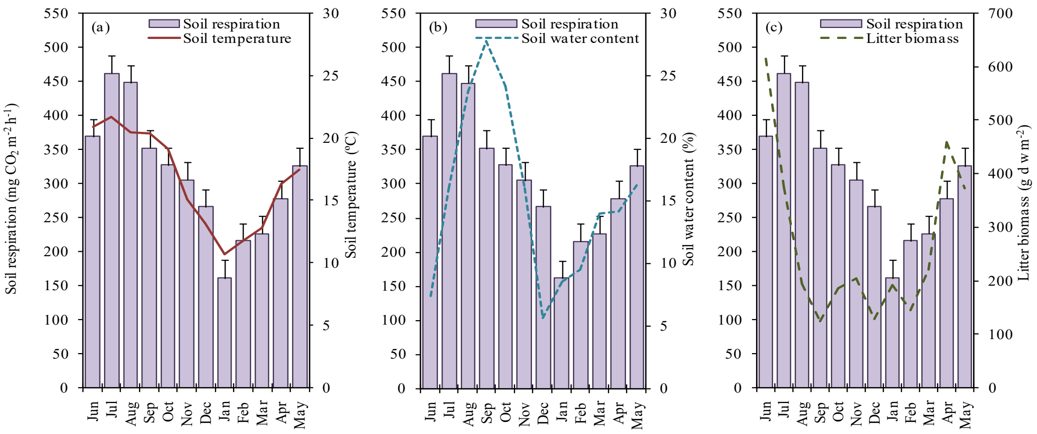

Fig. 5 Variations of (a) soil respiration and soil temperature, (b) soil respiration and soil water content and (b) soil respiration and litter biomass in each month

Table 1 Comparison of the soil temperature, soil water content, litterfall and soil respiration in different months and seasons in year-round measurements

	Soil temperature	Soil water content	Litterfall	Soil respiration
	(°C)	(%)	(g d w m^{-2})	(mg CO_2m^{-2} h^{-1})
Highest	22.30 (July)	31.37 (September)	793.91 (June)	627.23 (August)
Lowest	9.31(January)	3.51 (December)	10.23 (August)	105.44 (January)
Seasonal average				
Summer (June-August)	21.03	15.72	394.89	426.73
Autumn (September-November)	18.23	22.66	172.26	328.64
Winter (December-February)	11.9	7.9	155.78	214.71
Spring (March-May)	15.55	14.84	351.29	277.22

3.4 Estimation of soil respiration (SR)

The total soil carbon emission via SR of this Chir pine (*Pinus roxburghii*) forest was estimated (Equation 2) at 872.25 g C m^{-2} y^{-1}. The integrated values of the total annual SR in different seasons, i.e. summer, autumn, winter and spring, were 276.40, 233.79, 163.73 and 198.33 g C m^{-2} S^{-1}, respectively (Fig. 6). Contributions of summer, winter, spring and autumn to the annual SR were 31.7%, 18.8%, 22.73% and 26.80%, respectively, and the highest contribution was made from the summer season and the lowest from the winter.

The monthly and seasonal variations of the SR were illustrated in this forest (Fig. 7). The estimated hourly SR values were higher during warm and moist summer, i.e. plant growing a year, than the cold and dry winter, i.e. non-growing season.

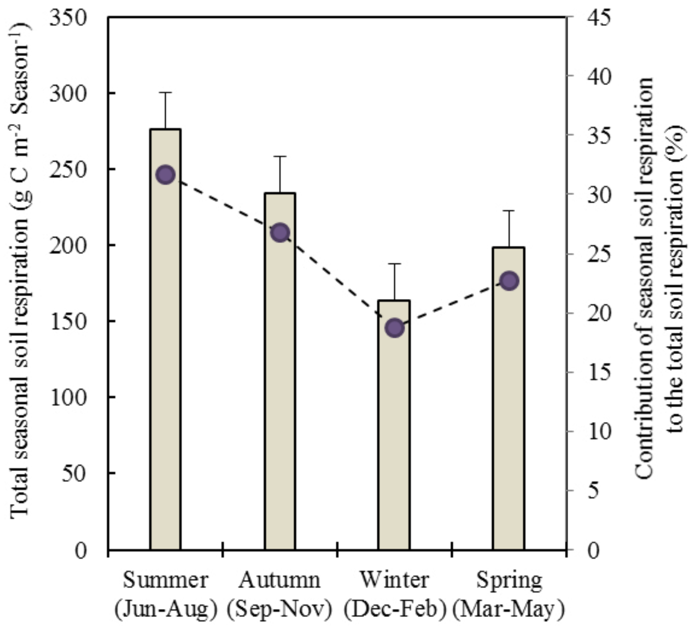

Fig. 6 Estimated total seasonal SR of a year and its contribution (%) to the annual SR. Bars-Seasonal soil respiration; filled circle-Contribution of seasonal respiration to the total annual soil respiration

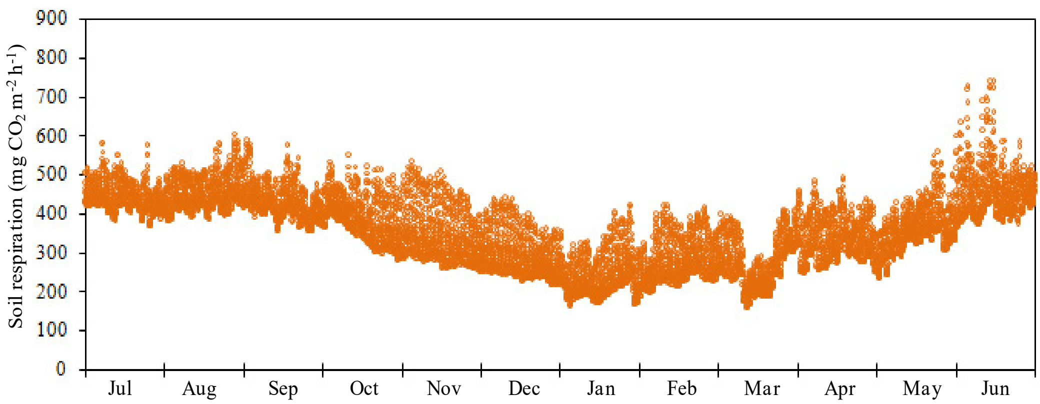

Fig. 7 Estimation of monthly and seasonal variations of soil respiration over a year by using the exponential equation established between the soil respiration and soil temperature at 5 cm depth measured each month throughout the year

4. DISCUSSION

This study provides the emission of the soil carbon via SR and its sensitivity analysis with the multiple eco-parameters, and we found ST is the most visible soil parameter to the changes in SR. The closely tied significant exponential relationship between the ST and SR (Figure 3) of this study explained that the warming increases the carbon emission from the soil in pure pine forest stand structure. Consistent with earlier studies (e.g. Davidson *et al.* 1998; Dhital *et al.* 2010 & 2020; Zhao *et al.* 2016; Klimek *et al.* 2021), the temperature was the most important ecological driver of SR at this site and sensitivity to its variations. The ST from 10 to 25ºC increased SR (Dhital *et al.* 2014; Zeng and Gao 2016; Kochiieru *et al.* 2021) was comparable to our study, and similar results ranged from 17 to 26ºC (Tavares *et al.* 2016; Boguzas *et al.* 2018) reported previously supports the higher SR detected above the ST beyond 20 ºC of this study.

Sensitivity of SR towards temperature; Q_{10} value, known as the increase of SR by a 10 ºC of ST increment, ranged from 1 to higher than 12 (Hamdi *et al.* 2013) and even differed in the different forests of the same geographical region (Klimek *et al.* 2020). However, it is considered one of the key uncertainties in climate change research, and its assessment is very time-consuming though its estimation in predicting the soil carbon fluxes is critically important in carbon modeling (Watts *et al.* 2021). The estimated (Equation 3) Q_{10} value (2.13) from this study was better ranged and most consistent with the previous studies of pine forests (1.55; Tang *et al.* 2005) in the Sierra Nevada, (2.37 & 2.36; Klimek *et al.* 2021) in Poland and (1.85–1.99; Zhao *et al.* 2016) in China, Coniferous forest (1.09–2.43; Makita *et al.* 2018) in Japan and deciduous forest (2.20–2.46; Tang *et al.* 2005). The value shows that the Q_{10} value of pine-dominated forests mostly consists of the temperature increase and is not much varied to the ecological zones.

One of the most effective and influencing ecological factors of soil carbon emission was represented by the soil moisture in different biomes (Zeng & Gao 2016; Deng *et al.* 2017; Kochiieru *et al.* 2021; Watts *et al.* 2021), and it is the most effective parameter to estimate the SR (Shen *et al.* 2021). The positive significant exponential regression model (Fig. 4) of the soil water effect on SR of this study could better define the forest soil water model on soil carbon emission. The highly significant exponential relationship between these variables in Sub-tropical mixed forests (Dhital *et al.* unpublished), temperate forests (Klimek *et al.* 2021), semiarid shrub-land (Shen *et al.* 2021) and grassland (Dhital *et al.* 2020) well explained the SWC is specific to define the SR variations. Moreover, the invisibly non-significant dependency of soil water effect on SR detected previously (Dhital *et al.* 2010; Balogh *et al.* 2011) explained that the particular data point area could better represent and define the SWC effect on SR. The lower SR during this study's dry period was due to the less activity of roots and biological processes that started to increase with increasing the ST and SWC (Dhital *et al.* 2010).

The variations of SR accordingly with changing the days of a year and months (Fig. 5) was the usual pattern of most forests in tropical regions with wet and hot summers and dry and cold winters with mild shoulder seasons. In summer (Jun-Aug), the SR rate inclined to its seasonal peak when ST (Fig. 5a) and SWC (Fig. 5b) were increased. The decreasing rate of SR in August and beyond was owed to increased SWC with rain events and decreased ST (Fig. 5 a,b). The root respiration and microbial decomposition contributed to the high value of the total ST (Tang *et al.* 2005) and were most common in the growing period of the pine-dominated forest (Rezgui *et al.* 2016). In some pine forests of central California (Carbone *et al.* 2011), the conifer forest of San Rossore (Matteucci *et al.* 2015) and the Tunisian Aleppo pine forest (Rezgui *et al.* 2016) reported that autotrophic SR peaks after the precipitation events.

The soil water level of up to 30% could increase SR (Valentini *et al.* 2008; Darenova *et al.* 2016) was as well observed in this study, and the records of higher SWC beyond 30% decreased SR of this study (Fig. 5b) were most compatible to the previous studies (Tavares *et al.*, 2016); however, ST was stood most limiting factor of the SR variations. After prolonged rain suppresses the CO_2 exchange between the soil and atmosphere by SR (Pla *et al.* 2017) in most tropical climate forests (Dhital *et al.* unpublished; Deng *et al.* 2017). Hence, instead of higher ST (Fig. 5a), the SR decreased much in September due to the increased SWC beyond 25% and reached its highest point (Figure 5b). This evidence better explains the soil-water effect of SR in the pine forest.

The above ground photosynthesis is strongly promoted with the soil carbon emission jointly from the root and microbial respiration (Kuzyakov & Gavrichkova, 2010). Moreover, the litter fall substantially contributes to the forest's SR through the carbon addition to the soil via microbial decomposition (Zak *et al.* 1994; Krishna & Mohan 2017) in tropical land (Li *et al.* 2004; Valentini *et al.* 2008). The litter biomass of the forest complied with the SR in the seasonal variation as the ST, and SWC followed (Fig. 5c). The higher litter biomass observed during summer and lower during the winter compared to autumn and spring was attributed to the higher SR, but the values might vary due to the removal of litter from the forest floor. Thus, the SR could be affected by the substrate availability and input of the litter fall (Hibbard *et al.* 2005; Baldocchi *et al.* 2006). A large range of litter-fall recorded between 10.23 g d w m^{-2} in August and 793.91 g d w m^{-2} in June of this study was ranged within the records of different global pine forests (416.93 g d w m^{-2} in shallow soil and 854.82 g d w m^{-2} in the deep soil) in northern Tunisia of Mediterranean climate having summer drought (Rezgui *et al.* 2016), (446 g d w m^{-2} and 790 g d w m^{-2}) in southern France (Kurz *et al.* 2000; Rapp 1984), (411. 6 g d w m^{-2}) in central Spain (Martinez-Alonso 2007).

The total seasonal SR was highest in summer (Jun-August) and lowest in winter (December-February) season, and the shoulder months in spring (March-May) and autumn (October-December) were the intermediates (Fig. 6). The highest contribution of summer season SR to the annual respiration when the ST was warmer in this forest (31.69%) was comparable to the tundra and boreal ecosystems (58%) of Arctic regions (Watts *et al.* 2021) caused by increased root activities and microbial decomposition of SOC. The remarkable seasonal fluctuation of SR during this study was due to the differences in ST between the wet and dry seasons, with the forest's highest and lowest biological activity with the precipitation pattern (Table 1). As compared to this study (627.23 mg CO_2 m^{-2} h^{-1} in August and 105.44 mg CO_2 m^{-2} h^{-1} in January), the highest and lowest uncertainties of soil respiration emissions occurred in moist growing (640 mg CO_2 m^{-2} h^{-1}) summer and dry non-growing (60 mg CO_2 m^{-2} h^{-1}) winter seasons of Mediterranean pine-dominated forest in Italy (Pantani *et al.* 2020) and Boreal forests in Alaska and Northwest Canada (Watts *et al.* 2021). However, the ST was independently promoting the SR throughout the study, but the increasing soil water content suppressed the respiration rate. The litter input and microbial decomposition in soil are directly concerned with the ST and soil water influencing the SR. However, ST independently suppresses the SR during winter (Pantani *et al.* 2020).

The total SR rate of a year in this Chir Pine (*P. roxburghii*) forest (872.25 g C m^{-2} y^{-1}) was much consistent with those in Mediterranean pine forests in Tunisia (870.4 g C m^{-2} y^{-1}, Rezgui *et al.* 2016), in Spain (766 g C m^{-2} y^{-1}, Almagro *et al.* 2009) and the Sierra Nevada (915 g C m^{-2} y^{-1}, Tang *et al.*, 2005). However, this study's annual SR was higher than those of a young pine forest in Oregon (427–519 g C m^{-2} y^{-1}, Irvine & Law 2002).

Well-established temporal/diurnal, monthly and seasonal variations of SR of this pine forest over a year (Fig. 7) were all about the effects of ST and seasonal fluctuation of precipitation effect on SWC, along with the effect of litter fall, which directly or indirectly influenced by the changing temperature and precipitation. Similar patterns of seasonal variations, along with the diurnal and temporal fluctuations of SR over the years reported in evergreen coniferous forests (Makita *et al.*, 2018). As determined in this study, the concentrated higher SR during summer seasons could further amplify climatic warming, as SR increasingly offset the gross primary productivity of the forest (Watts *et al.* 2021).

5. CONCLUSION

Measurements of SR in a sub-tropical pine (*Pinus roxburghii*) forest revealed that ST was the most influencing factor to SR, illustrated by the well-defined significant positive correlation established, and the temperature sensitivity of SR (Q_{10}) was estimated at; Q_{10} = 2.13. A significant regression model described the SWC effect of SR, and higher SR was concentrated between the soil water limit of 10 and 25%. Monthly and seasonal SR well followed the variations of ST, SWC and litter-fall with their maximum and minimum values in the summer and winter seasons, and the rate of SR gradually declined towards the winter season from summer. The ST was determined as the most sensitive ecological driver of SR, and the magnitude of respiration patterns varied on seasonal fluctuations across the temperature dependence. The effect of temperature and precipitation changes might be the major cause of SR variations; however, ST is the effective major to the increasing SR; and this directly affects the photosynthesis and carbon assimilation. Hence, the carbon emission from the forest floor is further enhanced by climate warming, and inversely, increased carbon contributes to climatic change in this pine-dominated forest. Further research is needed to understand other soil parameters such as organic carbon, microbial carbon, soil fertility and vegetation types that quantify the contributions of multiple effects on carbon flux and sequestration in forest soils.

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