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RESEARCH

Carbon sink and source function of Eastern Himalayan forests: implications of change in climate and biotic variables

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Abstract Forests serve as a sink and source of carbon and play a substantial role in regional and global carbon cycling. The Himalayan forests act as climate regulators of the Hindukush region, which is experiencing climate change at a high pace, and a proper understanding of these systems is necessary to mitigate this problem. We hypothesize that the variance of abiotic factors and vegetation will influence the carbon sink and source function of the different forest types of the Himalayas. Carbon sequestration was computed from the increment of carbon stocks estimated allometrically using Forest Survey of India equations, and soil CO_2 flux was determined by the alkali absorption method. The carbon sequestration rate and CO_2 flux by the different forests exhibited a negative relation. The carbon sequestration rate was highest with minimum emission in the temperate forest, while the tropical forest recorded the least sequestration and maximum carbon flux rate. The Pearson correlation test between carbon sequestration and tree species richness and diversity revealed a positive-significant influence but negative relation with climatic factors. An analysis of variance indicated significant seasonal differences between the rate of soil carbon emissions due to variations in the forest. A multivariate regression analysis of the monthly soil CO_2 emission rate shows high variability (85%) due to fluctuations of climatic variables in the Eastern Himalayan forests. Results of the present study revealed that the carbon sink and source function of forests respond to changes in forest types, climatic variables, and edaphic factors. Tree species and soil nutrient content influenced carbon sequestration, while shifts in climatic factors influenced soil CO_2 emission rate. Increased temperature and rainfall may further change the soil quality by enhancing soil CO_2 emission and reducing soil organic carbon, thereby impacting this region's carbon sink and source function. Enhancing tree diversity in the forests of this region may be beneficial for retarding this impact.

Keywords Climate change · Carbon sequestration · CO_2 flux · Tropical forest · Subtropical forest · Temperate forest

Introduction

The earth is experiencing various climate change-related impacts such as drought, floods, rise in sea level, warming, erratic weather, and rainfall patterns, (Ades et al., 2019; Moomaw et al., 2020). Carbon sequestration is one of the promising and cheap solutions to combat these problems (Singh, 2013). Natural climate solutions (NCS) through the conservation,

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restoration, and improvement of ecosystems such as forests, wetlands, grasslands, and agricultural lands can effectively mitigate greenhouse gases by stabilizing warming (Griscom et al., 2017). Among the ecosystems, the role of forests in carbon mitigation is substantial and important due to the presence of trees, but forest ecosystems are at threat due to deforestation activities especially tropical forests in low-income countries (Kirilenko & Sedjo, 2007). Climate change-related atmospheric temperature increases and fluctuations in precipitation patterns often lead to the shifting of vegetation towards the poles or the boreal zones (Allen & Kirilenko, 2016; Cramer et al., 2001; Foley et al., 1998) and migration of tree species at a rapid rate towards the north and higher altitude (Clark, 1998; Liang et al., 2018; You et al., 2018).

Increased levels of CO_2 in the atmosphere enhanced net primary productivity (NPP) and soil carbon (Chertov, 2010; Ge et al., 2013; Kirschbaum et al., 2012; Poulter et al., 2013; Wang et al., 2012), alter precipitation patterns and growing seasons of plants (Rustad et al., 2012; Schindlbacher et al., 2012), change the soil and plant respiration, nitrogen mineralization, and dominance of commercial trees in natural and managed forests as a result of the adoption of different management practices (Ge et al., 2013; Noormets et al., 2015). Moreover, variance in soil water content due to changes in precipitation pattern and increase in temperature affects the species distribution (Petrie et al., 2015) and carbon allocation pattern in the plants (Ogaya et al., 2014), impacting the vegetation and soil carbon dynamics and nutrient status of forest ecosystems (Reich et al., 2006). For example, the litter of broadleaved species dominant in tropical areas with warm temperatures and high rainfall decomposes and releases faster nutrients than temperate coniferous species in the cold and less rainfall area (Priha et al., 2001).

The capability of carbon storage in the soil varies with a variance in forest types and vegetation types, for example, boreal forests can store 60% carbon, while tropical forests store only 32% carbon in soil (Pan et al., 2011). But an increased temperature from global warming might dry up the soil faster leading to the enhancement of litter decomposition rate and faster nutrient release (Santonja et al., 2015), thereby stimulating root growth (Norby & Zak, 2011) and ectomycorrhizal carbon accumulation in the temperate and boreal forests (Hobbie, 2006).

The carbon sink and source function of vegetation and soil is influenced by the carbon source, tree species composition, and removal of understory species (Winsome et al., 2017) and soil microorganisms and macrofauna (Lepcha & Devi, 2020). Several researchers have raised concerns that increased temperature accelerates soil C release (Davidson et al., 2000; Trumbore et al., 1996), while other studies reported enhanced-temperature-induced declination of primary production of plants leading to a low soil carbon content (Epstein et al., 1998; Giardina & Ryan, 2000). In addition, precipitation pattern also plays a substantial role in regulating decomposition and microbial activity in an ecosystem and soil C dynamics (Schindlbacher et al., 2012), which indicates a significant effect of climate change on forest ecosystems. Besides these, the amount and frequency of precipitation influence temperature-regulated organic matter decomposition due to the close interaction of plants, soil, and microorganisms (Davidson et al., 2006; Gu et al., 2004; Högberg & Read, 2006). Also, a study on climate change (Mahlstein et al., 2013) concluded that mountain ecosystems show early signs of climate change due to the shrinkage of the polar and alpine regions. A variation in geographical and climatic patterns affects the patterns of the monsoon of the Indian subcontinent and other neighboring countries (Qiu, 2008) and the "Third Pole" or the Hindukush Himalayan region (Cook et al., 2010). Additionally, around 915 million people depend on mountains for their livelihoods (Sharma et al., 2019) as mountain ecosystems provide various services such as food security, biodiversity conservation, climate regulation, water provision, timber, electricity, and habitat to wildlife (Molden & Sharma, 2013), and many more which may be affected by the climate change. Hence, studies on the impact of climate change on the mountain ecosystems are needed for a timely response to secure the lives of the people as well.

Sikkim, an Eastern Himalayan mountainous state of India situated at an ecologically important location, reported signs and evidence of global warming and climate change such as a change in day and night temperature (Seetharam, 2008), phenological and distribution change of plant species (Telwala et al., 2013), glacial changes, and changes in the cropping pattern of the higher altitude (Raina, 2004). Since mountain ecosystems are sensitive and vulnerable to climate change, therefore a study on the carbon sink and source function of the Himalayan forest ecosystems with different climatic conditions, edaphic factors, and vegetation types can help in understanding how climate change will impact the functions of the forests ecosystem for a timely response. In the recent past, several studies have been conducted in the Himalayas that highlight the impact of climate change on different aspects such as ecosystem services and biodiversity (Kattel, 2022), carbon storage in different forest types (Gogoi et al., 2022), and net carbon exchange in the pine forest of Western Himalayas (Singh et al., 2019). However, all these studies were limited to a single forest or process such as either carbon storage or carbon release. None of these studies addressed the carbon assimilation and release process in multiple forest types which is important for understanding the impact of abiotic and biotic variables on the carbon cycle. We hypothesize that a change in climatic variables and its induced effects such as species range shifts influence the carbon sink and source function of the forests, and through this study, we want to explore how a change in abiotic and biotic factors, climate, and its induced effect will impact the carbon source and sink function of forests. Therefore, we investigate (i) how the carbon sequestration (vegetation and soil) and soil CO_2 emission varies across forests in the different agroclimatic zone of Eastern Himalaya (ii) and identify influential drivers of carbon sequestration and emission and possible implications of climate change in this region.

Materials and methods

Study site

The study sites are at Sikkim, a mountainous Indian state in the Eastern Himalayan region (Fig. 1) with a diverse agro-climatic zone. The tropical forest for the present study is at South Sikkim district (27°6.842′ N, 88°21.392′ E) at an elevation of 320–875 m a.m.s.l, while the subtropical forest is at Dzongu, North Sikkim district (27°31.543′ N, 88°29.704′ E) located at an altitude of 1400–1700 m a.m.s.l, and the temperate forest at Maenam (27°19.407′ N, 88°22.498′ E) is part of Maenam Wildlife Sanctuary, South Sikkim district, at an altitude of 2300–3263 m a.m.s.l. The tropical forest and temperate forest are reserve-protected forests of the Government of Sikkim, but the former forest is subjected to burning of forest floor litter mass as a management practice to remove shrubs which compete with the trees for resources. The subtropical forest is young and converted from paddy fields about 20 years ago. All the study sites have a monsoonal climate which can be categorized into four seasons: summer (March–May), rainy (June–August), autumn (September–November), and winter season (December–February). However, summer is mild, the rainy season is very wet, autumn is cool and moist, and winter is dry and cold. The annual rainfall was highest for the tropical forest (2867 mm), followed by the subtropical forest (2787 mm), and the least for the temperate forest (2699 mm). Climatic data of the study sites (Source: State Meteorological Department) is placed (Fig. 2). Soils in the tropical and temperate forests originated from feldspathic greywacke, while the parent rock of the soil in the subtropical forest is gneissic (Sikkim ENVIS, 2017). All the study sites lie on the slope surface which has loamy and acidic soil and a soil pH ranging from 4.2 to 6.2.

Vegetation

Vegetation in the tropical forest dominates with Sal (*Shorea robusta*. Roth), but very few other trees of *Schima wallichii (D.C) Korth* and *Pinus roxburghii* (Sarg) were also recorded. The dominating tree species in the subtropical forest is *Alnus nepalensis* (D. Don) along with other tree species such as *Macaranga pustulata* (King ex Hook. *f)*, *Schima wallichii* (*D.C*) *Korth*, and *Lyonia ovalifolia* (*Wall*). The temperate forest represents a mixed oak forest dominated by *Quercus lamellosa* Sm., *Quercus lanceifolia* Roxb., *Symplocos theifolia* D. Don., *Quercus pachyphylla* (Kurz), and *Daphniphyllum himalayense* Benth. Shrubs were removed from all the forests as a management practice, but herbs were present.

Diversity and other indices of vegetation

Diversity indices such as Simpson (D) and Shannon Weiner (H) along with evenness and species richness (d) indices were estimated using the formula of Simpson (1949), Shannon (1948), Pielou (1969), and Margalef (1957), respectively.

$$\text{Simpson}, D = 1 - \sum (n(n-1)/N(N-1) \quad (1)$$

where n is no. of individual of each species and N is the total number of individuals of all the species, Shannon Weiner,

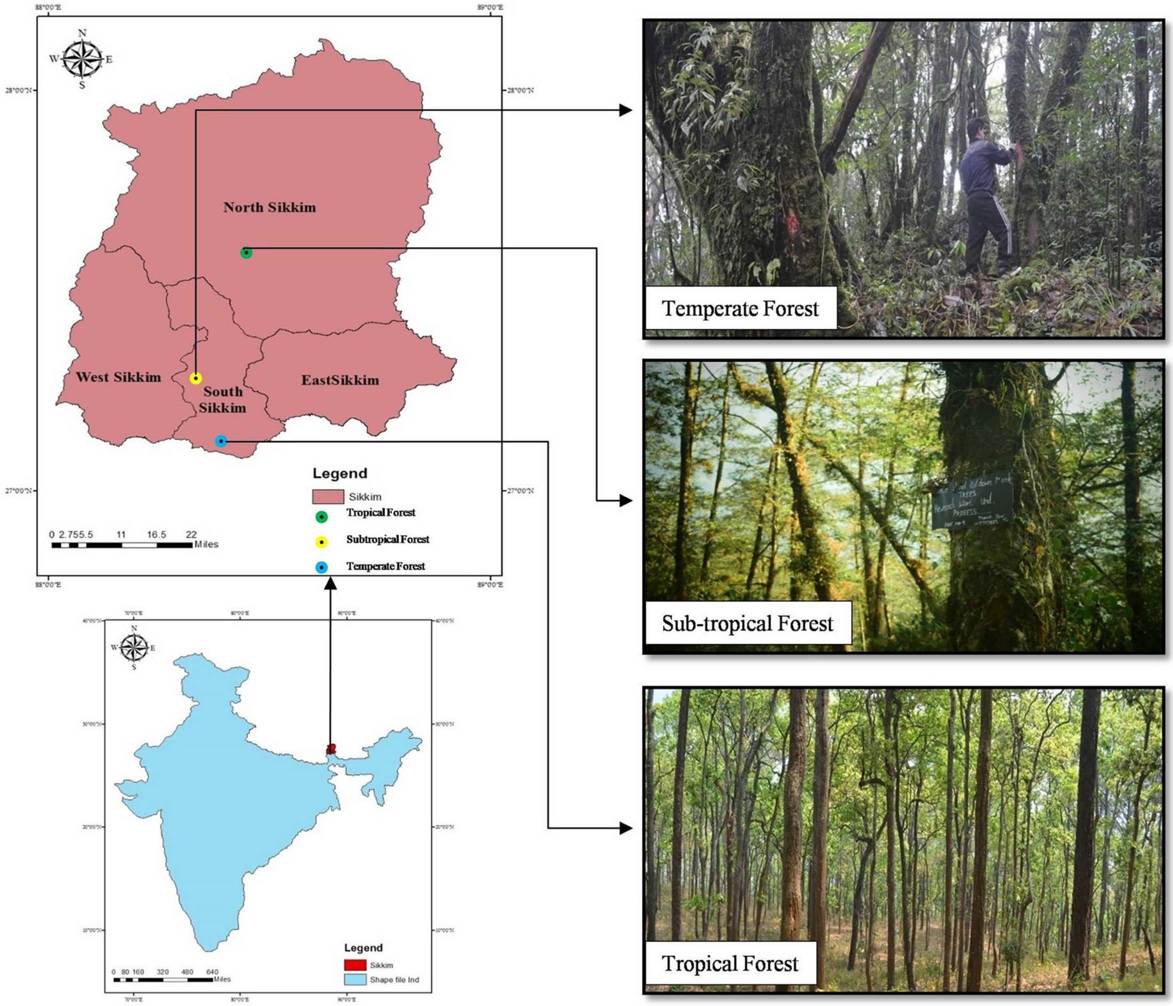

Fig. 1 Study sites of the present study

$$H = \mathrm{SUM}\ [(Pi) * \ln (Pi)] \tag{2}$$

where Pi is the proportion of individuals in the $i.^{\mathrm{th}}$ species, i.e., $(ni\,/\,N)$

$$\text{Pielou Evenness} = H/\ln\ N \tag{3}$$

where H is the Shannon index and N is the number of species, and

$$\text{Margalef}, d = (S-1)/\log(N) \tag{4}$$

where S is the number of species and N is the number of individual species.

Experimental design

Each of the forest types under study was demarcated into five different plots across the altitudinal gradient, and in each of the plots, two permanent quadrats of 0.1 ha were laid. Ten permanent quadrats were used for the sampling of vegetation and soil in each of the forest types.

Soil analyses

Soil samples for analysis of physical and chemical properties were collected (five replicates each

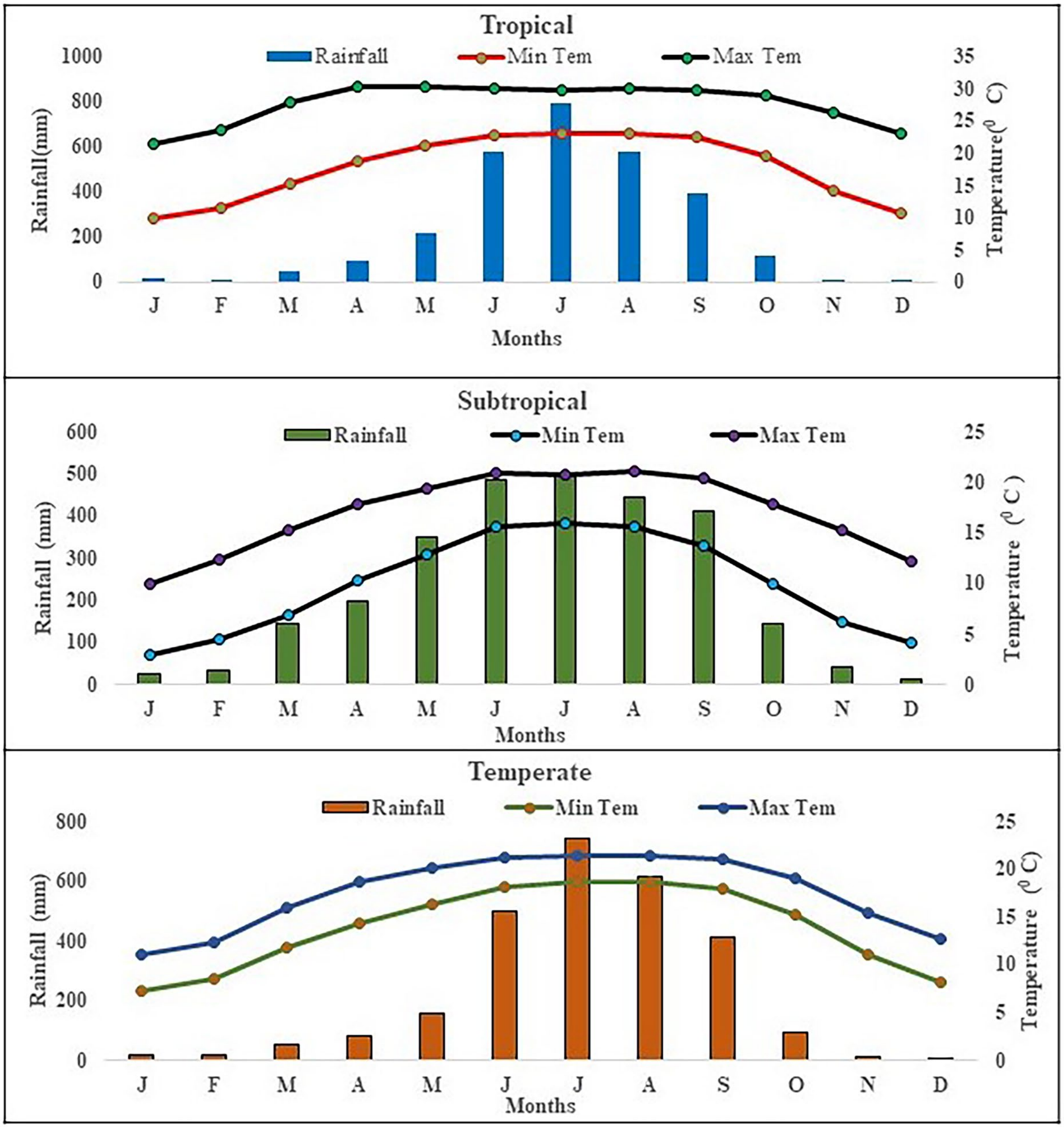

Fig. 2 Ombrothermic diagram of the study sites based on the ten years (2008–2018)

from each of the five plots of every forest type) from the 0–45 cm soil layer of each of the vegetation sampling plots from each forest type. Soil pH was measured by using a pH meter (1:5 soil water suspension), soil moisture, and bulk density by oven drying a known amount of soil at 80 °C till weight becomes constant. Soil temperature was recorded during the time of sampling at the study sites with a soil thermometer (Devi & Yadava, 2006).

Determination of soil organic carbon (SOC) content was by colorimetric method (Anderson & Ingram, 1993), total *N* by using Kjeltec 8500 (FOSS), and available phosphorus (AP) by ammonium molybdate stannous chloride method (Allen et al., 1974).

Analysis of microbial biomass carbon was done by using the chloroform-fumigation extraction method (Anderson & Ingram, 1993).

Carbon sequestration

For the computation of carbon sequestration, five plots at different elevations were demarcated in each forest type, and two quadrats of 0.1 ha were laid in each plot. The aboveground biomass of trees in the forests was computed by using species-specific volume equations and general equations of FSI (1996) and converted into carbon stock using the wood densities of tree species determined by the moisture content method (Kanawjia et al., 2013) and biomass expansion factor (BEF) of IPCC (2008). The estimation of annual carbon sequestration for each forest type was from the difference in carbon stock measured in 2016 and 2018 divided by 2. Belowground biomass was estimated using a standard root-to-shoot ratio and the default value of 0.26 (Ravindranath & Ostwald, 2008). Computation of herbaceous and litter biomass was carried out through a complete harvest of herbs and collection of litter biomass from ten quadrats of $1 \times 1\mathrm{m}^2$ in each of the forest sites. Biomass values were then converted to carbon stock values using the carbon default fraction 0.47 of the Intergovernmental Panel on Climate Change (IPCC). Carbon content and stock in soil were estimated colorimetrically by using the procedures of Anderson and Ingram (1993) and Ravindranath and Ostwald (2008), respectively.

CO_2 flux from soil

Monthly soil CO_2 emission of the study sites was determined by the alkali absorption method (Anderson & Ingram, 1993). Six open-ended cylinders of 13 cm diameter and 25 cm height were inserted in each of the demarcated vegetation sampling plots in every forest site, and one out of six cylinders served as a blank sample in each of the plots. Of the total 30 cylinders used in each of the study sites, 5 cylinders serve as blank samples in every forest site. A known volume of 0.25 N NaOH was kept overnight in vials inside the airtight cylinder after removing all green herbaceous vegetation within the cylinder. After 24 h, NaOH in each of the vials was titrated with a standard HCL solution of 0.25 N concentration using phenolphthalein as an indicator. CO_2 absorbed by the alkali (NaOH) is then calculated by using the procedure of Anderson and Ingram (1993)

$$\mathrm{CO_2mg} = V \times N \times 22$$

Statistical analyses of data

Tukey's HSD test was used to test the significant differences between means. Pearson correlation test was used to test the influential factors of carbon sequestration and emission in the forests. A multivariate regression test was performed to test the variance of soil CO_2 flux from the study sites due to climatic variables such as air temperature and rainfall. Two-way ANOVA was carried out to understand the influence of seasons and forest types on CO_2 flux.

Result

Bio-climatic factors of the study sites

Tree density was the highest in the tropical forest, followed by the temperate forest, and least in the subtropical forest. But the basal area of trees was maximum in the temperate forest and least in the subtropical forest, while litter biomass was least in the temperate forest and the maximum in the tropical forest. Shannon Wiener's diversity index, Pielou's evenness index, and Margalef's species richness index were highest for the temperate forest, followed by the subtropical and tropical forests. The trend of Simpson's dominance index was temperate > tropical > subtropical forest (Table 1). The annual mean minimum and maximum air temperature varied across the study sites with the least in the subtropical forest (9.89 °C and 16.92 °C) followed by the temperate forest (13.83 °C and 17.53 °C) and tropical forest (17.69 °C and 27.59 °C). Variations of the monthly temperature and rainfall in the different forest types are in Fig. 2. Annual rainfall was highest for the tropical forest (2867 mm), followed by the subtropical forest (2787 mm) and the temperate forest (2699 mm). The minimum rainfall was during December, and the peak rainfall occurred during July in all the study sites (Fig. 2).

Edaphic factors of the study sites are listed in Table 1. All the forests have acidic soil, with the highest soil pH in the tropical forest and the least in the temperate forest.

Table 1 Bioedaphic characteristics of the study sites. Means with the same letter show no significant differences by Tukey HSD test at 5%

Bio-edaphic factors	Tropical forest	Subtropical forest	Temperate forest
Biotic			
Tree density (individual ha^{-1})	276 ± 45.23a	208 ± 32.47a	256 ± 26.19a
Basal area (m^2 ha^{-1})	55.80 ± 2.89a	33.52 ± 1.85b	113.40 ± 7.94c
Litter biomass(t C ha^{-1})	4.12 ± 0.64a	3.69 ± 0.01a	3.80 ± 0.63a
Annual MBC (μg g^{-1})	676.95 ± 88.12a	496.19.15 ± 67.40a	595.19 ± 68.29a
Simpson's dominance index	0.993	0.677	0.995
Shannon-Weiner diversity index	0.878	1.653	2.074
Pielou's evenness index	0.550	0.689	0.790
Margalef's species richness index	0.810	1.909	2.660
Edaphic			
Soil pH	5.44 ± 0.19a	5.30 ± 0.20a	5.20 ± 0.19a
Moisture content (%)	31.85 ± 0.64a	35.40 ± 3.60b	52.56 ± 0.64c
Soil temperature (°C)	17.23 ± 0.35a	19.30 ± 0.50a	18.73 ± 0.35a
Bulk density (g cm^{-3})	1.07 ± 0.02a	0.95 ± 0.36a	0.99 ± 0.02a
Organic Carbon (%)	1.97 ± 0.20a	2.26 ± 0.35a	2.27 ± 0.20a
Total nitrogen (%)	0.21 ± 0.06a	0.40 ± 0.01b	0.35 ± 0.06c
Available phosphorous (%)	0.07 ± 0.03a	0.05 ± 0.07a	0.09 ± 0.03a
C: N ratio	9.33	5.65	6.48

MBC soil microbial biomass carbon

The soil moisture in the different forest types follows the trend of tropical > subtropical > temperate forest, while that of soil temperature is subtropical > temperate > tropical forest. The tropical forest exhibited a maximum bulk density of soil, while the minimum was in the sub-tropical forest. Both the temperate and tropical forests exhibited the highest concentration of soil organic carbon (SOC) and available phosphorus (AP), but the peak total nitrogen (TN) concentration was in the subtropical forest. However, the concentration of SOC and TN was least in the tropical forest and that of AP in the subtropical forest.

Carbon sequestration in different forest types

Carbon sequestration of both the vegetation and soil exhibited the same trend with the highest in the temperate forest, followed by subtropical forest and tropical forest; however, soil carbon was not sequestered but mineralized/lost from the soil in the tropical forest (Table 2). Also, a two-tailed Pearson correlation test revealed a significant positive relationship between soil carbon sequestration and tree species diversity ($p < 0.01$) and species richness of the site ($p < 0.05$), but vegetation C sequestration did not show any significant relationship with any of the bio-edaphoclimatic factors (Table 3).

CO_2 flux from soils of the different forests

The monthly soil CO_2 evolution was highest in the tropical forest 156.54 mg CO_2 m^{-2} h^{-1} (January)–260.94 mg CO_2 m^{-2} h^{-1} (March), followed by subtropical forest 114.58 mg CO_2 m^{-2} h^{-1} (January)–245.03 mg CO_2 m^{-2} h^{-1} (July), and temperate forest 30.32 mg CO_2 m^{-2} h^{-1} (February)–177.6 mg CO_2 m^{-2} h^{-1} (June) in the present study (Fig. 3). Tropical and subtropical forests have a similar seasonal trend of CO_2 emission, i.e., rainy > summer > autumn > winter, but in the temperate forest, the trend was rainy > winter > summer > autumn (Table 4). The Tukey test revealed that both the tropical and temperate forests exhibited significant seasonal differences while the subtropical forest failed to exhibit significant seasonal differences from other forest types except in the autumn season (Table 4). Two-way ANOVA (analysis of variance) indicated a significant difference in the rate of soil CO_2 emission due to the influence of forest types and seasons (Table 5). Multivariate regression analysis of soil CO_2 emission (Y) and climatic variables, i.e., minimum temperature (X_1), maximum temperature (X_2), and rainfall (X_3), indicates no autocorrelation (Durbin-Watson = 2.8) and revealed 85% variability of soil CO_2 emission in the study sites due

Table 2 Vegetation and soil carbon sequestration in the different forests of Eastern Himalaya (mean ± SE)

Land-use systems	First-year (2016) (t C ha^{-1})					Second-year (2018) (t C ha^{-1})					Annual carbon sequestration (t C ha^{-1})
	AGBC	BGBC	Herbs	Litter	Total	AGBC	BGBC	Herbs	Litter	Total	
Tropical forest	67.81 ± 9.93a	17.63 ± 3.22a	0.75 ± 0.23a	1.78 ± 0.32a	87.97 ± 7.88a	69.67 ± 9.21a	18.11 ± 3.12a	1.21 ± 0.21a	2.49 ± 0.29a	91.48 ± 8.04a	1.76
Sub-tropical forest	58.00 ± 11.98b	15.08 ± 3.11b	4.22 ± 0.38a	1.87 ± 0.27a	79.09 ± 6.53b	60.36 ± 11.33b	15.69 ± 2.95b	4.37 ± 0.24a	1.92 ± 0.20a	82.34 ± 6.79b	1.63
Temperate forest	102.54 ± 10.03c	26.67 ± 2.46c	2.29 ± 0.42a	1.49 ± 0.32a	132.99 ± 11.64c	105.44 ± 10.06c	27.41 ± 2.52c	3.13 ± 0.41a	2.22 ± 0.30a	138.20 ± 11.80c	2.61

Soil carbon

Land-use systems	First-year (2016) (t C ha^{-1})				Second-year (2018) (t C ha^{-1})				Annual carbon sequestration (t C ha^{-1})
	0–15	15–30	30–45	Mean	0–15	15–30	30–45	Mean	
Tropical forest	51.16 ± 0.81a	44.82 ± 0.81a	35.03 ± 0.89a	43.67 ± 2.24a	62.14 ± 0.54a	34.74 ± 2.44a	28.04 ± 2.59a	41.64 ± 5.44a	-1.02
Subtropical forest	40.99 ± 2.99a	38.17 ± 1.08a	31.00 ± 2.11a	36.72 ± 19.13a	43.03 ± 0.96a	36.76 ± 0.87a	33.97 ± 0.48a	37.59 ± 2.30a	0.87
Temperate forest	56.76 ± 0.79b	52.97 ± 0.67b	48.35 ± 0.56b	52.69 ± 2.6b	62.49 ± 0.60b	56.49 ± 2.12b	50.06 ± 2.57b	56.35 ± 5.33b	1.84

Means with the same letters denote no significant differences by the Tukey HSD test at 5%

Table 3 Pearson correlation test to study the influence of bio-edaphoclimatic factors on the rate of carbon sequestration and emission from the forests

	ABG seq	Soil seq	Avg temp	*RF*	*CO_2 emission*	*Simpson index*	*Diver index*	*Evenness index*	*Sp. richness index*	*Litter input*	*p^H*	*SM*	*ST*	*BD*	*SOC*	*TN*	*AP*	*MBC*
ABG seq	1.000																	
Soil seq	0.675	1.000																
Avg tem	−0.162	−0.837	1.000															
RF	−0.815	−0.978	0.704	1.000														
CO_2 emission	−0.853	−0.961	0.654	**0.998***	1.000													
Simpson index	0.606	−0.177	0.687	−0.033	−0.102	1.000												
Diversity index	0.685	**1.000****	−0.830	−0.981	−0.965	−0.164	1.000											
Evenness index	0.740	0.996	−0.783	−0.993	−0.982	−0.086	0.997	1.000										
Sp. rich index	0.729	**0.997***	−0.794	−0.991	−0.979	−0.103	0.998	1.000	1.000									
Litter C input	−0.152	−0.832	**1.000****	0.697	0.646	0.694	−0.824	−0.777	−0.787	1.000								
p^H	−0.737	−0.996	0.786	0.992	0.982	0.090	**−0.997***	**−1.000****	**−1.000****	0.780	1.000							
SM	0.960	0.854	−0.431	−0.944	−0.965	0.360	0.861	0.899	0.891	−0.422	−0.897	1.000						
ST	0.131	0.820	**−1.000****	−0.682	−0.630	−0.709	0.812	0.763	0.774	**−1.000****	−0.766	0.403	1.000					
BD	−0.068	−0.782	0.996	0.634	0.579	0.752	−0.773	−0.721	−0.732	0.996	0.724	−0.344	−0.998	1.000				
SOC	0.417	0.952	−0.964	−0.867	−0.831	−0.470	0.948	0.920	0.926	−0.962	−0.922	0.655	0.956	−0.935	1.000			
TN	0.144	0.827	−1.000	−0.691	−0.640	−0.700	0.820	0.772	0.783	**−1.000****	−0.775	0.415	1.000	−0.997	0.959	1.000		
AP	0.921	0.333	0.236	−0.524	−0.581	0.869	0.346	0.419	0.404	0.246	−0.415	0.775	−0.267	0.327	0.029	−0.254	1.000	
MBC	−0.297	−0.905	0.990	0.796	0.752	0.579	−0.899	−0.862	−0.870	**0.989***	0.864	−0.552	−0.986	0.973	−0.992	−0.988	0.100	1.000

*$p<0.05$, **$p<0.01$

ABG aboveground biomass, *RF* rainfall, *SM* soil moisture, *ST* soil temperature, *BD* bulk density, *SOC* soil organic carbon, *TN* total nitrogen, *AP* available phosphorus, *MBC* microbial biomass carbon to the climatic factors (Eq. 1). The rate of CO_2 emission in the different forests exhibited significant positive influence due to rainfall ($p < 0.05$) and was negatively influenced by carbon sequestration ($p < 0.05$) (Table 3).

$$Y = -32.579 - 14.112X_1 + 16.290X_2 + 0.196X_3 \quad R^2 = 0.85; DW = 2.8 \tag{5}$$

Discussion

Carbon sequestration in the different forest types

The insignificant correlation between the vegetation carbon sequestration and the bio-edaphoclimatic factors of the present study indicates that any bio-edaphoclimatic variances may not substantially

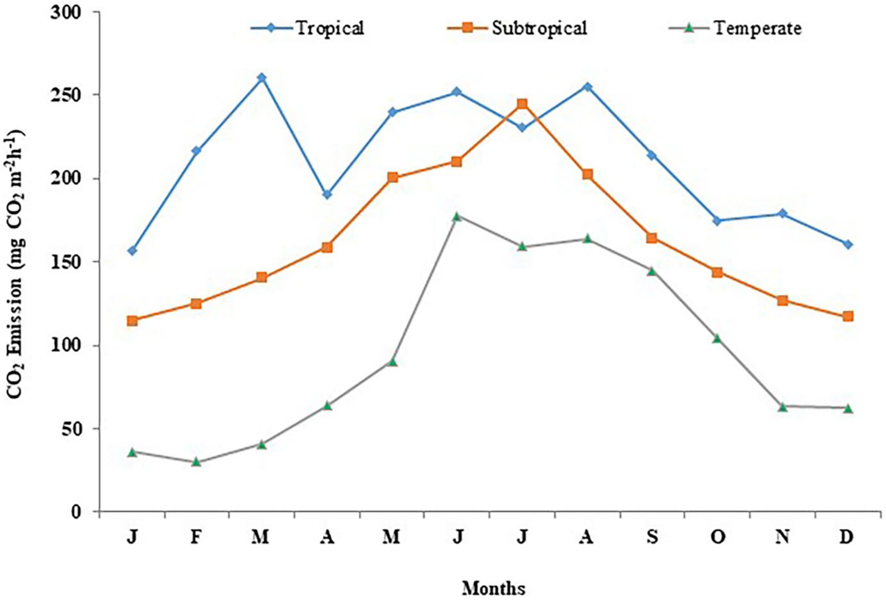

Fig. 3 Monthly variation of soil CO_2 flux in the different forests of Sikkim Himalaya

Table 4 Seasonal variance of soil CO_2 emission from different forest types (mg CO_2 m^{-2} h^{-1})

Seasons	Tropical forest	Subtropical forest	Temperate forest
Summer	229.95 ± 12.06^a	141.49 ± 05.59^b	65.17 ± 8.28^c
Rainy	245.81 ± 04.49^a	230.34 ± 09.80^{ab}	166.88 ± 03.20^c
Autumn	177.73 ± 07.29^a	171.14 ± 11.73^{ac}	104.12 ± 13.57^c
Winter	189.15 ± 11.13^a	117.71 ± 1.20^b	42.95 ± 05.74^c
Mean	210.66 ± 10.88^a	165.17 ± 14.06^b	94.78 ± 15.54^c
HSD (α = 5%) = 4.33			

Table 5 Two-way ANOVA exhibiting significant variation of the soil CO_2 flux due to seasons and forest types

Two-way ANOVA						
Source of variation	*SS*	*df*	*MS*	*F*	*P*-value	*F* crit
Forest types	27,338.85	1	27,338.85	25.70542	7.98E-05*	4.41
Seasons	40,402.73	2	20,201.37	18.99439	3.67E-05*	3.55
Forest x season	1222.83	2	611.42	0.574885	0.57^{NS}	3.55
Within	19,143.79	18	1063.54			
Total	88,108.21	23				

*$p < 0.001$, ^{NS} Non-significant

impact the rate of carbon sequestration of the forests in this region. However, a positive and significant relationship between soil carbon sequestration and plant species richness and tree diversity of the study sites (Table 3) implies a significant alteration in soil carbon due to a variance in vegetation/species diversity and richness, thereby explaining higher carbon sequestration in the temperate forest with higher plant diversity, species richness, and soil moisture content**.** A higher tree species diversity in the temperate forest with a higher elevation than that of tropical forests (Joshi et al., 2022) increases soil carbon sequestration (Chen et al., 2018; Valentini et al., 2000), which conforms with our findings. Moreover, higher tree density, basal area, and microbial biomass C in the temperate forest in contrast to the other type of forests could be another reason for more vegetation C sequestration in this forest (Kothandaraman et al., 2020). Also, a higher diversity of tree species or species richness in the temperate forest reduces carbon loss as plant diversity enhances belowground carbon, microbial activity, and diversity, thereby increasing soil carbon storage and sequestration (De Deyn et al., 2011; Fornara & Tilman, 2008; FSI, 1996; Lange et al., 2015). Our results extend the findings of other previous studies that reported enhancement of carbon storage due to an increase in tree basal area, plant growth, higher soil water availability (Alvarez Davila et al., 2017), and other bio-environmental factors in different forest ecosystems (Poorter et al., 2018; Vayreda et al., 2012).

The lower rate of C sequestration in the present tropical and subtropical forests despite higher rainfall could be related to the higher temperature in these sites making the soil unable to retain moisture, thereby reducing the rate of carbon sequestration in these sites (Brienen et al., 2010; Dai et al., 2015). The negative but insignificant relationship between carbon sequestration and average temperature and rainfall of the present study (Table 3) supports the finding that increased rainfall, temperature, and extreme events lead to the reduction of carbon stock both in vegetation and soil (Baker et al., 2004; Souza & Longhi, 2019). An extremely wet climatic condition in this region could have led to exceeding the critical point of carbon sequestration, beyond which an increase in C is negligible (Dai et al., 2015). However, other studies reported a positive relationship between C sequestration and rainfall (Li et al., 2019; Toledo et al., 2012), which is contrasting with our result. Carbon mineralization or loss instead of C sequestration in the soil of the tropical forest corresponds to the highest soil pH and temperature in this site which reduces the carbon storage and nutrient supply in soil by enhancing the rate of decomposition, thereby affecting the rate of soil respiration and belowground biomass (Weil & Brady, 2016). Moreover, despite more forest litter biomass in the tropical forest, the dominating species in this site are deciduous trees with more readily degradable labile C fractions compared to the tough recalcitrant carbon fractions in the temperate species (Wiemann & Williamson, 2002). In contrast, the highest soil C sequestration in the temperate forest is because of higher tree diversity which promotes C accumulation (Chapin III, 2003), low rainfall by preventing loss of soil nutrients (Lukina et al., 2019), and less temperature by retarding decomposition and enhancing subsequent C addition through the litter. Our result conforms with the findings of other studies that reported a decline in soil organic carbon sequestration due to an increase in soil pH and increased temperature (Chen et al., 2018; Devi, 2021) in different forests and biomes.

CO_2 flux from soils of the different forests

The significantly higher rate of soil CO_2 flux in the tropical forest than that of the temperate forest coincides with a higher amount of litter biomass, temperature, and more intense rainfall with longer duration in the former site which might have enhanced the microbial activity and decomposition (Chen et al., 2013b; Ding et al., 2007; Jia et al., 2006; Patil et al., 2014). A positive significant relationship between the rate of CO_2 emission from the soil and rainfall in the present study ($p<0.05$) indicates that rainfall is one of the influential factors of soil CO_2 emission and an erratic rainfall pattern, duration, and amount will significantly impact the carbon source function of an ecosystem (Table 3). Our result supports the findings of other studies that conclude short-duration intense rainfall lowers soil respiration (Jeong et al., 2018), while uninterrupted and precise rain can stimulate soil respiration (Davidson et al., 1998; Liu et al., 2002; Raich & Schlesinger, 1992), and soil moisture conditions can regulate the response of temperature to soil CO_2 emission (Joo et al., 2012). Temperate ecosystems due to low root respiration (Groffman et al., 2006) and less litter biomass (Luo et al., 2013) reduce carbon emissions from soils. The amount of organic matter in an ecosystem influences soil respiration in an ecosystem by altering the water retention capacity, pore space, and microbial activity in the soil (Moyano et al., 2013). Multivariate regression analysis between monthly soil CO_2 emission rates and climatic variables, i.e., minimum and maximum temperature and rainfall, revealed 85% variability of soil CO_2 emission due to these factors, and among the climatic variables, rainfall is the most influential climatic driver that regulates the rate of carbon sequestration of the present forests ($p < 0.05$) (Table 3). This implies that in the Eastern Himalayan forests, climatic factors are more influential drivers of soil CO_2 flux than biotic and edaphic factors such as root biomass, litter biomass, stand age, vegetation type, soil pH, moisture, and nutrient content. However, the influence of tree species and the age of vegetation on soil respiration has been reported by several studies (Gong et al., 2012; Oertel et al., 2016; Saiz et al., 2006) in different forest ecosystems. The two-way ANOVA of soil CO_2 emission across seasons ($p < 0.001$) and forest types ($p < 0.001$) indicates a significant temporal variation due to different species in the present study. Rainy season recorded peak CO_2 emission due to high rainfall and warmer temperature triggers microbial activity and decomposition during this season in all the study sites. Moreover, the increase in soil CO_2 emission during the rainy season can be attributed to the growth and respiration of plant roots as it is the growing season of plants. An increase in carbon emission due to microbial and vegetation root respiration during the growing season of plants has been reported by various earlier studies (La Scala et al., 2010; Norman et al., 1992; Ray et al., 2020; Ren et al., 2017) which concurred with our result. Also, many studies from different forest types revealed higher soil CO_2 emission in the wet season, for example, tropical forest (Makita et al., 2018), subtropical (Devi & Yadava, 2009), temperate (Laishram et al., 2002), warm temperate (Mo et al., 2005), mixed forest (Chen et al., 2013a; Takahashi et al., 2011), and Afromontane forest (Yohannes et al., 2011) which conforms with our result. The least soil CO_2 emission rate during the winter season in all the forest sites coincides with the least amount of precipitation and cold climate that reduces soil moisture inhibiting cell metabolism and respiration of the microbes (Moyano et al., 2013). In the monsoonal areas of Asia, rainy days during the summer season accelerate microbial decomposition while drier months inhibit the process (Cook et al., 2010), and temperature change due to seasonal variation and water stress resulted in the fluctuation of soil respiration rates (Makita et al., 2018).

The annual mean CO_2 emission from soils of the present forests was lower than the emission rates from different forests of the world. For example, CO_2 fluxes from the tropical forest of Hawaii, 26.34 Mg CO_2 $ha^{-1}y^{-1}$ (Townsend et al., 1995); tropical monsoon forest of Thailand, 25.6 Mg CO_2 $ha^{-1}y^{-1}$ (Hashimoto et al., 2004); a subtropical moist forest of Queensland, Australia, 51.6 Mg CO_2 $ha^{-1}y^{-1}$ (Butterbach-Bahl et al., 2004); tropical forest of South America, 36.94–52.68 Mg CO_2 $ha^{-1}y^{-1}$ (Garcia-Montiel et al., 2004; Sotta et al., 2007); subtropical broad-leaved forest and tropical monsoon forest of China, 34.54–35.40 Mg CO_2 $ha^{-1}y^{-1}$ (Fang et al., 2010); and temperate and boreal forests 11.59–40.15 Mg CO_2 $ha^{-1}y^{-1}$ from all over the world (Falk et al., 2005; Fang et al., 2010; Sulzman et al., 2005; Zerva & Mencuccini, 2005). The reason for a low average annual soil CO_2 flux in our forests could be related to the rainfall pattern, amount, intensity, and temperature extremes in these sites, i.e., high and intense rainfall during the rainy season and dry and cold severe winter season that limits microbial activity.

Implications of change in climate and species composition to carbon dynamics

Our results revealed that the tree species diversity and carbon sequestration potential of forests changes along an altitude gradient of the Eastern Himalayas due to the variance in plant species, forest types, and other edaphic and environmental variables. A higher carbon sequestration rate with the least CO_2 flux from the cold temperate forest in the present study suggests that a vertical expansion of tropical ecosystems due to species range shift or migration may reduce the species diversity and carbon sequestration potential of the forests in this region. In the present study, sites with a higher temperature and rainfall (tropical ecosystems) exhibited enhanced soil carbon flux and reduced C storage and sequestration, suggesting that global warming and climate change may decline the carbon sequestration and storage in the soil by reducing the tree species richness and enhancing soil organic matter decomposition. Also, an erratic rainfall pattern such as rainfall in the dry season which has become a frequent trend in tropical ecosystems may further increase the rate of carbon emission from the soil in this region. Previous studies have shown that climatic factors, temperature, and rainfall regulate the distribution of species more than the edaphic factors of the sites (Holmgren & Poorter, 2007; McKenzie et al., 2003; Toledo et al., 2012), affecting the species distribution pattern. Tropical species are sensitive to temperature change, and a slight change in temperature results in drastic effects resulting in a shift in distribution patterns for these species (Wright, 2010). Also, shifting the tropical and subtropical forests along the altitudinal gradient will enhance soil CO_2 flux from the forests of this region and transform the quality of the soil. Apart from the decrease in carbon storage, the transformation of soil quality will also reduce soil fertility which might contribute to further loss of species diversity. Present findings extend the results of other studies that the adoption of mixed tree species or high tree species diversity improves the soil organic matter and quality of soil (Chapin III, 2003; Andivia et al., 2016), C storage, and sequestration. Our results also corroborate the findings of earlier studies that soil organic carbon is susceptible to changes in climate (Tian et al., 2015), altitude (Tashi et al., 2016), and temperature (Sun & Liu, 2019). Therefore, enhancing species richness in tropical forests might boost more C sequestration and slow the impact of climate change. However, the present study is limited to the three forests of Eastern Himalaya only, and more studies in this context from different geographical areas, climates with diverse species, stand age, and management practices need to be carried out for a better understanding of the change in carbon sink and source function of forests in response to climate change. Also, the findings of the present study are limited to data collected from 2 years only, and long-term studies might provide better and clear results of the studied parameters.

Conclusion

The present study concludes that a forest with low temperature and rainfall, high tree diversity, and species richness, i.e., temperate forest, can sequester more carbon and emit less soil CO_2 as compared to tropical forests. Carbon sequestration increases with an increase in plant species diversity and reduces with an increase in temperature and rainfall. In the present study, soil CO_2 flux exhibits seasonality and variation with forest types and is influenced by the variation in climatic factors, especially rainfall. Additionally, it may be concluded that changes in the climatic variables and warming will not only affect the vegetation but may also lead to the degradation of soil which may affect the productivity and functionality of ecosystems risking the lives of the mountain people.

Author contribution N Bijayalaxmi Devi: conceptualization, methodology, resources, supervision, writing review and editing, writing original draft, visualization, fund acquisition. Nima Tshering Lepcha: formal analysis, validation, investigations.

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Data availability All data are included in the MS; however, raw data if required will be available on request to the corresponding author.

Declarations

Conflict of interest The authors declare no competing interests.

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