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Dynamics of organic and black carbon in high-altitude soils: Insights from morphological, chemometric, and environmental analyses☆

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ABSTRACT

Black carbon (BC), an emerging contaminant and significant climate forcer, enters soil through deposition after residing in the atmosphere. Despite its role in long-term carbon storage and cycling, BC remains understudied in soil due to limited knowledge of its complex physical and chemical characteristics, variability, and fate. This knowledge gap is particularly prominent in India, a global BC emission hotspot, especially in its fragile mountainous ecosystems. To address this, a three-year (2020–2023) study investigated BC and soil organic carbon (SOC) dynamics across various land-use types in Kodaikanal, a high-altitude region in the Western Ghats of southern India. BC and SOC variations were assessed over time using scanning electron microscopy with energy-dispersive X-ray spectroscopy (SEM-EDX) and Fourier transform infrared spectroscopy (FTIR) to analyse morphological, structural, and chemical characteristics. Results revealed strong seasonal and inter-annual variability in BC concentrations across land-use types. The BC/SOC ratio was highest in fire-prone forests, suggesting wildfire-induced BC accumulation, while urban BC was linked to tourism and vehicular emissions. SEM-EDX and FTIR confirmed the presence of condensed aromatic BC structures, with lignin and cellulose dominating forest and agricultural soils. Environmental factors such as temperature, precipitation, and soil mineral composition significantly influenced BC and SOC distribution. These findings challenge the assumption of BC's high recalcitrance, highlighting its dynamic nature and emphasizing the need for detailed seasonal-scale studies to better understand the stability and sequestration potential of BC that can enable devising better environmental management strategies.

1. Introduction

In the current era of climate emergency, the significance of soil carbon as a valuable resource and stabilizing factor has been undervalued. Since carbon circulates and connects the different carbon pools (atmosphere, ocean, and land) in the earth system, it is certain that carbon cycle has a dominant role in regulating the climate system (Schimel, 1995; Dheri and Nazir, 2021). The soil environment stabilizes the climate by storing 1500 Pg of carbon (1 Petagram (Pg) = 10^{15} g) twice its amount in atmosphere, which not only provides the benefit of storage (carbon sequestration) but also nourishes the health of soil microorganisms (Liao et al., 2024). Photosynthesis stores carbon in biomass (leaves, branches, trunks and roots). The biggest carbon flux between the terrestrial biosphere and the atmosphere is gross primary production (GPP), or carbon fixed by photosynthesis. The soil carbon pool is composed of both inorganic and organic carbon fractions. The inorganic forms of carbon such as bicarbonate (HCO_3^-), carbonate ($CaCO_3$), and gaseous CO_2 play a role in soil buffering capacity and long-term geochemical carbon storage. In contrast, organic carbon (OC) is highly dynamic and originates from a complex array of biological sources, including plant residues, leaf litter, root biomass, microbial cells, and their decomposition products (Jian et al., 2016). It is majorly categorized into labile (rapid turnover within hours to days) and passive (resides over decades to millennial scale) (Coppola et al., 2022; Dheri and Nazir, 2021). Labile carbon consists of available carbon, dissolved organic carbon, water SOC, rapidly oxidisable organic carbon, microbial biomass carbon, biodegradable carbon, and light fraction organic carbon (Jian et al., 2016). Non labile or passive carbon majorly accounted

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by BC (46.6–257.2 Tg/year) or condensed form of organic carbon (163–182 Tg/year) which after its residence time in atmosphere gets deposited in soil (Goranov et al., 2024; Zhang et al., 2024).

The global estimates on wildfires produced BC input to soil is on average 128 ± 84 Tg C per year (Goranov et al., 2024) and overall BC production ranges between 40 and 600 Tg C per year with 80 % of BC produced being deposited in soil (Rodionov et al., 2010). The BC/OC ratio in soil typically ranges between 10 and 50 %, reflecting the variable contribution of BC to the organic carbon pool (Glaser et al., 2001; Rodionov et al., 2010; (Gerke, 2019). BC can initially physically degrade into smaller forms/fragments (colloids, nanoparticles, dissolved BC) by various physical (rapid dissolution climate, soil conditions), chemical (carbonate dissolution, chemical oxidation), and biological processes (microbial degradation/mineralization) (Venkatraman et al., 2021; Lian and Xing, 2017). However, the mechanisms underlying changes in BC and SOC have not been understood due to lack of understanding in soil - their physical, chemical, and environmental and land use interaction with BC and SOC.

Global soil carbon studies focussed on exploring the influence of mean annual temperature (MAT), mean annual precipitation (MAP), elevation, land use, and soil physio-chemical parameters on SOC. The majority of studies investigating the effects of land management, land-use change, and climate change on SOC have been concentrated in China (>800), followed by North America (400–800), and Australia (200–400) (Beillouin et al., 2022). The major influence on relative SOC change is exerted by biochar (50 %) followed by soil properties (12 %), MAP (5–10 %), elevation (5–12 %), and land use management (0–20 %) (Don et al., 2011; Beillouin et al., 2022; Cheng et al., 2023). The major influence exerted on Particulate Organic Carbon (POC) are by MAT (relative influence: 85 %), followed by soil properties (relative influence: 75 %), land use (relative influence: 45–50 %), and elevation (relative influence: 10 %) (Zhou et al., 2024). However, studies exploring soil carbon dynamics in the mountain ecosystems are limited. Further, studies on BC in soil and its controlling factors were not conducted.

The mountainous ecosystem (25 % of land area), an important driver of global climate, acts as a carbon regulator, and serves as a biodiversity hotspot in the terrestrial ecosystem (Zhang et al., 2022). Current warming climates influenced by human activities affect mountains that are vulnerable and sensitive to small changes which may produce severe impacts on primary productivity, vegetation and biodiversity. Relatively few studies that focussed on mountainous ecosystems were on Tibetan plateau (Zhao et al., 2021), Yunan province, China (Zhang et al., 2021), Ladakh (Sharma et al., 2022), Indian Himalayan region (Ahirwal et al., 2021), Monte Curcio, GAW (Global atmospheric watch) station (Moretti et al., 2021), Qianghai plateau ((Wang et al., 2023)), (Liang et al., 2010) North Africa (Chenchouni and Neffar, 2022), Central Europe ((Fekete et al., 2021), South and North America (Zhang et al., 2022). These studies exhibited significant differences in SOC due to elevation, soil chemical characteristics, soil texture, and land use. Research on SOC dynamics was primarily concentrated in the Himalayan regions, particularly in India, which is a significant agricultural country and an air pollution hotspot. However, there are few to almost no studies that have investigated the impact of the aforementioned climatic parameters on BC and seasonal dynamics of BC in mountainous regions worldwide. The rate and degree of land degradation are increasing on a daily basis, despite the fact that the Western Ghats, one of the eight ecologically fragile biodiversity hotspots in the world, are facing significant environmental challenges, including temperature increase, dry months, reduced rainfall, and improper land use changes (Dharumarajan et al., 2021). Regrettably, the mechanisms that underlie the accumulation of BC and SOC, as well as their subsequent losses, are not sufficiently comprehended in the Western Ghats and India. These processes are crucial for the estimation of changes in terrestrial carbon dynamics and their associated climatic influence.

Hence, the objectives of the study are to (i) characterize BC and SOC in top soil of the various land use regions in Western Ghats, (ii) study the inter-, intra-seasonal and annual dynamics of BC and SOC in the terrestrial ecosystem, (iii) investigate the morphological, and chemical composition of BC to understand whether BC properties could be used as indicators to reflect fire intensity and fuel types in different land use regions, and (iv) understand the influence of climate parameters, and land use on mineralization of BC and SOC.

This detailed analysis will provide a comprehensive understanding of the distribution and characterization of BC in soil fractions, offering valuable insights into the dynamics of carbon sequestration and soil health across varying land use and depth profiles, hitherto unavailable. This multi-land-use study over the high altitude pristine mixed environment is expected to provide perspective-based insights into enhancing soil carbon management by considering the BC/SOC ratio and its implications to soil stability and long-term carbon sequestration. While the study does not directly compute a BC-based Carbon Management Index (CMI-BC), the observed variations in BC and SOC across seasons, land-use types, and soil depths highlight the potential for refining traditional indices like CMI and SMI (Soil Management Index). By incorporating BC data into these indices, future research can provide improved assessments of carbon persistence, soil quality, and resilience, particularly in ecosystems vulnerable to environmental changes. These insights can guide land managers in adopting tailored strategies to optimize carbon sequestration and mitigate climate change in similar high-altitude regions.

2. Methodology

2.1. Study site characteristics

Kodaikanal is a high-altitude region in the eastward extension of the Western Ghats region of Tamil Nadu, India, with an area of 1039.46 km^2, which is geographically located between 77°14′26″E and 77°45′28″E longitudes, and between 10°6′25″N and 10°26′54″N latitudes (see Fig.1). According to the Koppen climate classification, Kodaikanal has a monsoon-influenced subtropical highland climate. Kodaikanal, located in the upper Palani Hills, is an internationally recognized hill station and ecologically sensitive zone that exemplifies the coexistence of natural ecosystems and anthropogenic pressures. The region is characterized by relatively pristine environmental conditions, making it an ideal natural laboratory for assessing the baseline behavior of atmospheric and deposited BC. Its unique land use mosaic, including undisturbed montane forests, cultivated farmland, and urbanized hill towns, enables comparative analysis of BC fluxes and retention in forest, agricultural, and urban soils, which is crucial for understanding spatial heterogeneity in BC sequestration. However, increasing tourism, vehicular activities, and expanding agriculture have introduced localized BC sources, creating a dynamic emission deposition interface within a geographically contained zone. Furthermore, most prior studies on BC (in the atmosphere) in India have concentrated on the Indo-Gangetic Plain, northern and Himalayan regions, leaving southern high-altitude zones like Kodaikanal underrepresented in national emission inventories and ecosystem studies. The characteristics of the study site have been discussed in detail in Karthik et al. (2023). Climate (e.g., temperature) in addition to atmospheric dynamics (e.g., long range transport) can modulate the pollution. Also, in Kodaikanal, a high-altitude location, people resort to wood burning among others to keep them warm, resulting in higher BC emissions.

2.2. Dataset

Meteorological parameters such as temperature and rainfall during the 2020–2023 were obtained from gridded daily data archive of Indian Meteorological Department (IMD) (https://www.imdpune.gov.in/Clim_Pred_LRF_New/Gridded_Data_Download.html). Daily gridded rainfall data at 0.25° × 0.25° resolution and daily maximum temperature at

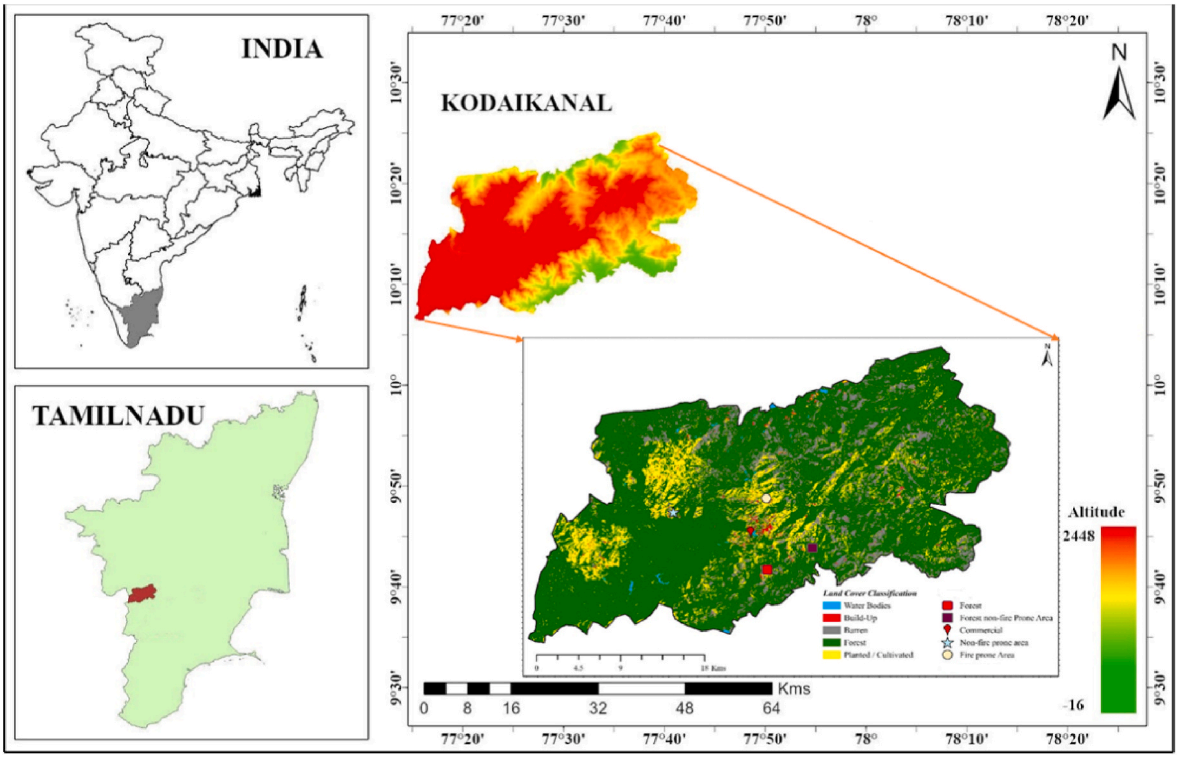

Fig. 1. Map of the study region with the inset showing altitudinal variation, and projection showing land use land cover characteristics of the study site.

$0.5^\circ \times 0.5^\circ$ resolution were procured for this study. The gridded data were available from 1959 to present which was developed based on the stations available within the region. It is important to note that the gridded data were produced based on the observations in the station (Kodaikanal-43339) from 2008 onwards (Srivastava et al., 2009).

The soil moisture levels in surface to subsoil layers were measured using satellite product having a monthly frequency on a global scale, with a grid size of $0.1^\circ \times 0.1^\circ$. Specifically, data at a depth of 10–40 cm were collected from the Famine Early Warning Systems Network (FEWS NET) Land Data Assimilation System (LDAS), which maintains a repository of data from 1982 to the present. The dataset shows a strong correlation of 40–80 % for the Indian region and 40–60 % for Southern India when compared with ground monitoring data from the IMD (Sathyanadh et al., 2016). The dataset can be accessed through following URL: https://disc.gsfc.nasa.gov/datasets/FLDAS_NOAH01_C_GL_M_001/summary.

Although gridded satellite and IMD datasets are coarser than point-based measurements of ours, they are spatially and thematically appropriate for this study. The ground sampling was conducted across a landscape-scale region of ~1039.46 km^2 in Kodaikanal, which spans multiple grid cells of the IMD gridded products (e.g., ~4–6 cells at $0.25^\circ \times 0.25^\circ$ for rainfall and ~2–3 cells at $0.5^\circ \times 0.5^\circ$ for temperature) and about 10–12 cells of the $0.1^\circ \times 0.1^\circ$ FEWS NET soil moisture grid (Srivastava et al., 2009). This degree of overlap ensures that the average meteorological and soil moisture values within each land use zone correspond well to the spatial footprint of the ground-based BC and OC sampling. The use of land use stratification in sampling further enhances compatibility, as correlations were not computed at isolated points, but rather aggregated at the land use zone level, which naturally aligns with the spatial resolution of the gridded data. Additionally, these datasets have been validated and widely applied in similar mountainous and monsoon-affected regions, and their integration with station observations (e.g., IMD station at Kodaikanal) further enhances their credibility and accuracy (Sathyanadh et al., 2016). Therefore, the satellite and gridded meteorological inputs are both spatially representative and methodologically consistent for correlating with BC and OC levels across the study area.

2.3. Sample collection and processing

Details of the sampling location, data collection method, land use and land cover characteristics are discussed in detail in Karthik et al. (2023). Soil sampling was conducted over close to a three-year period, from November 2020 to September 2023. However, field activities were temporarily suspended between May and August 2021 due to COVID-19-related restrictions, which impacted site access and mobility. A total of 217 soil samples were collected using a core sampler of known volume. Sampling locations were strategically selected across the study area to represent the major land use and land cover (LULC) types, ensuring sufficient spatial and ecological diversity. The samples were categorized into four groups: 62 from forested areas (FP), 62 from non-forested natural regions (NFP), 62 from agricultural lands (AG), and 31 from urban zones (UN). These sample sizes were determined to be statistically adequate for characterizing the dominant LULC classes within the region. In brief, the vertical core is divided into three layers: 0–10 cm, 10–20 cm, and 20–30 cm to analyse the profiles of BC and SOC. The laboratory maintained an ambient temperature of 25 °C during the pre-processing of the samples for analysis.

2.4. Estimation of BC

Soil BC was analyzed using the thermo chemical oxidation method (CTO-375) the details of which have been presented in Karthik et al. (2023). In brief, a pre-concentrated sample of 500 mg is taken for the analytical procedure, whereby oxidation of sample at 375 °C for 24 h was performed followed by removing inorganic carbonates. The residual carbon was determined using an elemental analyser. Spiking technique was employed to validate the results which had a recovery percentage of 93 ± 0.1 %. The response factor was determined using 1–10 mg of highly pure calcium carbonate. The instrumental detection limit is 2 μg of carbon. Soil SOC was determined by adopting the Walkley–Black method (Mylavarapu et al., 2014).

2.5. SEM-EDX of BC

OC and BC content in soil are significantly influenced by land use patterns and soil depth. To assess this variability, soil samples were collected from different land uses at three depths: surface (0–10 cm), mid-layer (10–20 cm), and deeper layer (20–30 cm). The samples were pre-treated by air-drying for 2 days followed by oven-drying at 105 °C for 4 h. After homogenization using a mortar and pestle, fractionation was carried out to isolate different BC fractions. The wet-sieving method by Brodowski et al. (2005) was employed to separate the coarse sand fraction and to disperse stable micro-aggregates ultrasonically (440 J ml^{-1}) in suspension (300 ml). Fine sand was subsequently separated by wet sieving, while silt was settled by centrifugation at 40*g*, leaving the clay fraction in suspension. This process, repeated at least 15 times, ensured that the supernatant remained clear. After drying at 40 °C, 92.0 % of the initial sample weight and 88.6 % of the initial carbon content were recovered after fractionation. Sodium polytungstate solutions ($H_2Na_6O_{40}W_{12}$) and gentle ultrasonic dispersion were used to fractionate the fine earth, resulting in a recovery rate of 92.4 %.

BC grains were manually selected from the soil fractions based on their distinct physical characteristics. SEM-EDX analysis was performed by placing approximately 1 mg of soil sample on a glass slide and manually selecting dark grains under a microscope. Elemental characterization confirmed BC identification by approximating oxides and their association with carbon, with Fe^{2+} (3.3 wt%) and Fe^{3+} (1.8 wt%) presenting a ratio of 1.176, consistent with the earth's crust. To minimize errors, samples with carbon content above 40 % were considered representative. However, several samples produced negative results, which were further scrutinized following the recommendations by Brodowski et al. (2005).

2.6. Fourier Transform-IR spectroscopy

Soil particles were collected manually using microscope from 217 soil samples. Fourier transform-infrared spectra for different land-use regions soil BC particles were obtained using a JASCO 4100 spectrometer (Jasco Company, Tokyo, Japan) with a resolution of 2 cm^{-1} and a wavelength range of 4000–400 cm^{-1}. Scanable potassium bromide pellets comprising 2 mg of sample powder and 200 mg of KBr. To increase the signal-to-noise ratio, each measurement, and spectral data were adjusted to a reference spectrum, and some spurious absorptions, such as peaks from ambient CO_2, were deleted. Wavelength band of FTIR spectra were assigned to wavenumber following IR spectra table (https://www.sigmaaldrich.com/IN/en/technical-documents/technical-article/analytical-chemistry/photometry-and-reflectometry/ir-spectrum-table) and Nguyen et al. (2009). The samples were analyzed in duplicates and the results were averaged.

2.7. Statistical analysis

Statistical analyses and visualisation were performed using the Origin pro software. Soil BC and SOC data were analyzed by analysis of variance (ANOVA), and the means are considered significantly different for p-values less than 0.05, and presented.

3. Results and discussion

3.1. Inter and intra seasonal dynamics of SOC

Generally, SOC variation in the soil across the seasonal and annual scale is negligible when compared to climate scale variation (Nayak et al., 2020). However, increasing importance of carbon stock and its role in climate mitigation have recently propelled researchers to study its seasonal variation which is critical to understand the labile carbon pool and its role in atmospheric CO_2 addition. Further studies pertaining to SOC seasonal variation across land use type has been very sparsely accounted. SOC concentration variability is studied during summer (MAM), monsoon (JJAS), post monsoon (ON), and winter (DJF) seasons in the Kodaikanal region from 2020 to 2023 (Fig. 2).

The results indicated that during winter season, the SOC pool was maximum under non-fire-prone forest (31.40 g/kg) followed by agriculture (28.69 g/kg) and minimum under urban (17.49 g/kg). In summer season, the SOC pool was maximum under fire-prone forest (43.80 g/kg) followed by non-fire prone forest (27.73 g/kg) and minimum under urban (13.90 g/kg), in monsoon season, the SOC pool was maximum under non-fire-prone forest (32.19 g/kg) followed by fire-prone forest (19.78 g/kg), agriculture (14.64 g/kg) and minimum under urban (10.67 g/kg), whereas in post monsoon season, the SOC pool was maximum under non-fire prone forest was (15.47 g/kg) followed by non-fire prone forest (34.47 g/kg) and minimum under urban (9.06 g/kg) respectively. Overall, it was observed that the maximum SOC pool was in summer season under the fire prone forest (43.80 g/kg) and the minimum SOC pool was observed in post monsoon season under urban (9.06 g/kg). The results were comparable to mixed forest containing shrubland (characteristic of the study region) and non-mixed forest across Indian region wherein highest SOC pool is observed in summer season (Nayak et al., 2020). Fire significantly contributes to the rise in SOC concentrations in forests throughout the summer season. A total of 700 fire occurrences were recorded throughout the study period, with 150 fires in 2021, 239 in 2022, and 311 in 2023. In comparison to other forest fires in the Indian region, the wildfires at Kodaikanal were mild to moderate. This is due to the high precipitation level in Kodaikanal, which only partially scorched the trees and facilitated an increase in SOC. Additionally, the urban region, which is situated at a higher elevation (2156 m) than the other study regions, has a lower accumulation of litter, in general, compared to the other sites. Due to its high sensitivity to changes, the decrease in precipitation may have played a role in the reduction of SOC. Additionally, the sharp decline in soil temperature during the post monsoon period led to a significant decrease in root exudates and carbohydrates, as well as a reduction in the decomposition rate of litter and microbial activity. SOC decreases with elevation and less rainfall, particularly in soils that are rich in Fe and Al, as has been previously reported (Che et al., 2021; Li et al., 2023; Cheng et al., 2023).

The mean difference between the maximum and minimum concentration of SOC (ΔC, $C_{max}-C_{min}$) is found to be much higher during winter (ΔC = 17.2 g/kg) followed by monsoon (ΔC = 16.5 g/kg), summer (ΔC = 15.8 g/kg) and post monsoon (ΔC = 3.0 g/kg) seasons. From the observations it is evident that post monsoon has little seasonal variation in SOC concentration while winter has the highest. Differences in quality of litter and rainfall patterns have been reported to be influencing these parameters in the humid climate regions (characteristics of region) for higher SOC in winter season (Vidyanagar, 2010). Furthermore, the low microbial decomposition of litters may also be reason for such high deviations in a season. It is important to note that the post monsoon has lesser SOC concentration and therefore the variation also is very less. Similar results were observed in Western Ghats region consisting of vertisol (characteristic of study site) where SOC concentration was affected due to differences in precipitation intensity, segregation of shrubland and forest sites, consequently, affecting the balance between plant carbon inputs and decomposition of SOC (Bellè et al., 2022).

Inter-seasonal variation of top soil SOC for multiple years was analyzed to understand the SOC mineralization across different land use types. During winter season SOC declined by 27.85 %, 35.29 % and 36.55 % for non-fire, fire-prone forest, urban and agricultural region compared to base year (2021). Similar trend was witnessed in summer season as SOC declined across all land use except for non-fire prone forest which showed an increase of 1.65 %. In contrast SOC concentration increased in monsoon season ranging between 18.15 % and 107.69 % except for urban region where it declined by 8.69 %. A multitude trend of increase and decrease was observed in post monsoon season where SOC increased in non-fire prone forest and urban (ΔC =

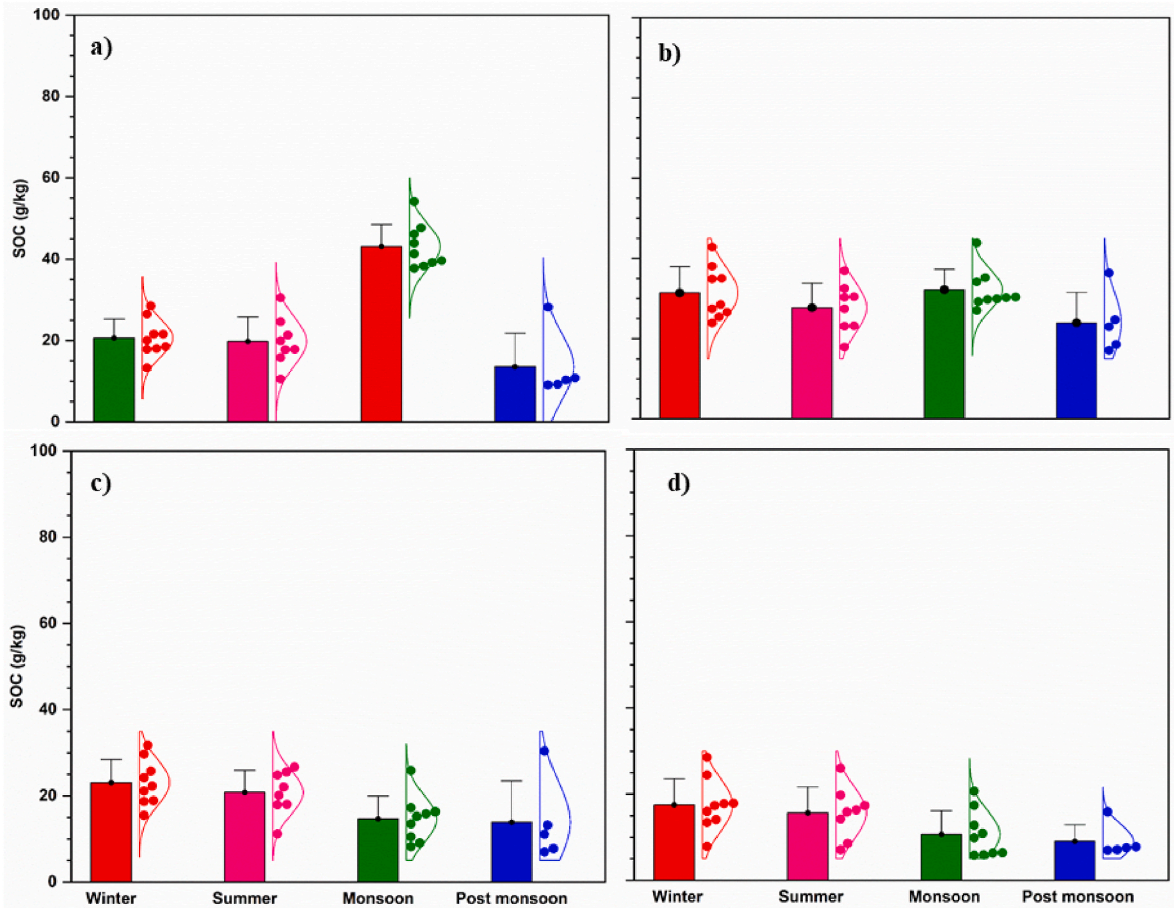

Fig. 2. Seasonal variation of SOC across (a) fire prone, (b) non-fire prone, (c) agriculture and (d) urban locations during the study period. Swarm plots represent distribution points, and the dot (black) indicate mean SOC values for each season.

18.03 g/kg) while it declined in agriculture and fire-prone region (ΔC = 10.06 g/kg) respectively. Overall SOC declined in winter and summer while it increased in monsoon and post monsoon seasons. In case of inter-annual variation, highest variation was observed in fire-prone forest region (ΔC = 6.73 g/kg) and lowest variation was observed in non-fire prone forest region (ΔC = 3.62 g/kg). It is important to note that SOC increased across land use regions except for agriculture region where it declined by 5.63 % when compared to base year (2021). Further, the role of BC on SOC decline or increase has been discussed in latter section using the BC/SOC ratio.

Study region is a mixed forest type (shola, pine, acacia) along with region consisting entirely of grassland (Rangan et al., 2010). Invasion of Australian black wattle (A. *mearnsii*) is predominant since 1960. Litter fall of A. *mearnsii* declines in winter and summer while it is higher in monsoon and post monsoon seasons in the study region which is comparable to litter fall across sub-tropical regions (Railoun et al., 2021). Seasonal dynamics of Australian black wattle litter fall agrees well with the changes observed in SOC concentration in the study region. However inter-seasonal variations between multiple years were result of differences in the quantity of litter fall, environmental conditions, microbial load and land management. The intensity of rainfall increased between post monsoon and winter seasons by 45 % while it declined by 72.50 % during summer and monsoon seasons during the study period. Due to the above factors SOC declined in winter and post monsoon season as a result of dissolution and transport favored by high intensity rainfall and vice versa.

In the study region, Shola forest (71 %) has been managed to 24 % by converting them to timber plantations (increase by 170 %), acacia plantation and agricultural land (108 %) compared to 1973. The shola forest has been fragmented and tends to coexist with Australian black wattle. Further, the people of Kodaikanal depend upon Australian black wattle for firewood leading to an increase in its plantation and continuous management of forest (Arasumani et al., 2018). In case of agricultural region, predominant practice was reported to be rice cultivation whereby rice is soaked in water for nine months followed by three-month dry period. However, currently vegetable cultivation is dominant across agriculture region whereby rotation of crop is carried out and land use is increased depending upon rainfall (Rangan et al., 2010). The cropping pattern agrees well with seasonal change in SOC Timber increased at an average rate of 5.77 %/year and agriculture grew by 3 % per year (Arasumani et al., 2018).

3.2. Inter and intra seasonal dynamics of BC

Significant seasonal and inter-annual variations in the BC pool across different land-use types are seen over the study region (Fig. 3). During the winter season, the highest BC pool was observed in non-fire-prone forests (5.42 g/kg), while during the summer season, fire-prone forests exhibited the highest BC concentration (8.68 g/kg). The monsoon season recorded the maximum BC pool under fire-prone forests (10.79 g/kg), whereas the post monsoon season showed the lowest BC pool in non-fire-prone forests (1.65 g/kg). A unique trend with the highest BC concentration in the monsoon season can be attributed to reduced biotic oxidation and mineralization under waterlogged conditions due to the region's high clay fraction (Nguyen and Lehmann, 2009; Jauss et al., 2015). Wildfires during the summer season played a major role in BC enrichment, and tourist activity contributing around 4000 vehicles per day during peak seasons, further increased BC input in urban soils

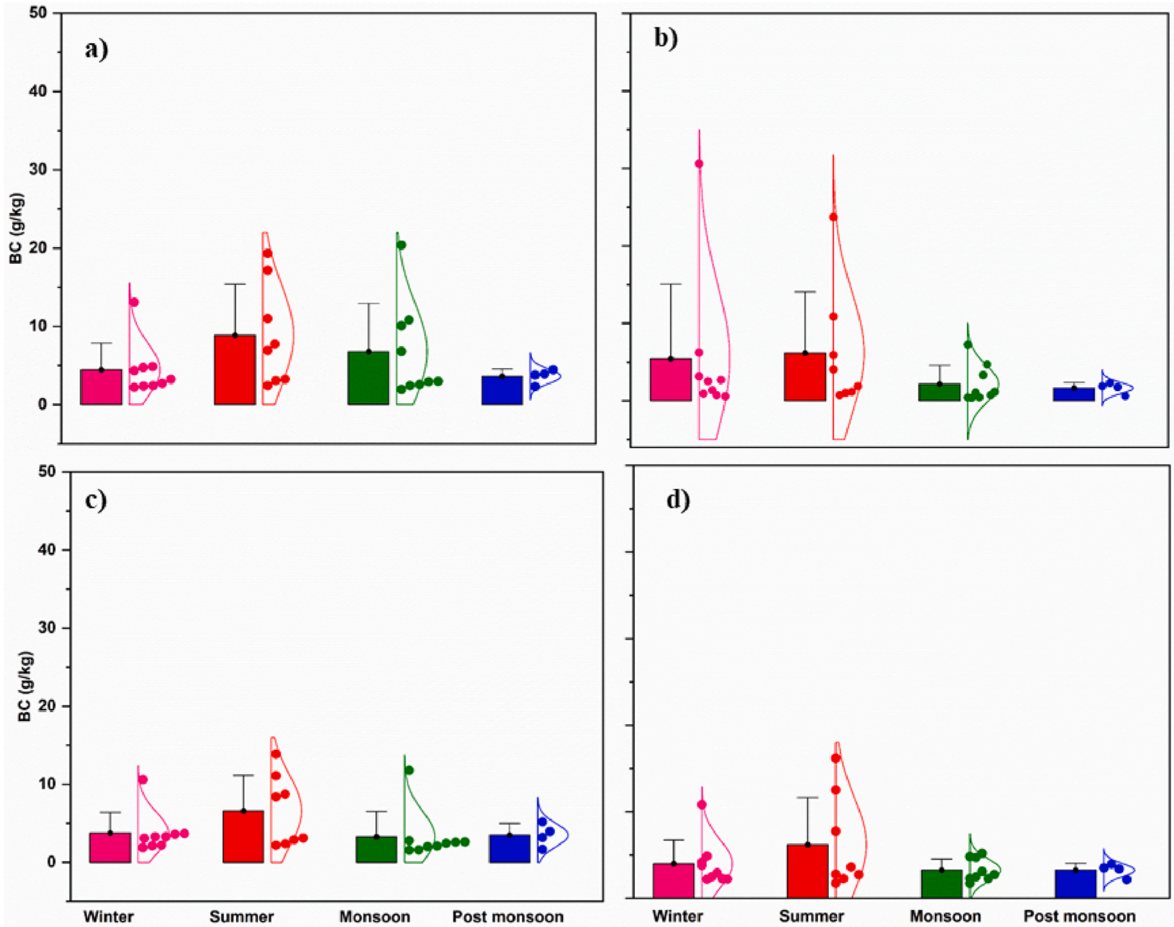

Fig. 3. Seasonal variation of BC across (a) fire prone, (b) non-fire prone, (c) agriculture and (d) urban locations during the study period. Swarm plots represent distribution points, and the black dots indicate mean BC value for each season.

(Kumaran et al., 2018). Intra-seasonal comparisons over multiple years revealed a decline in BC concentration in agricultural regions, with the highest decline in the post monsoon season (33.33 %) and the least in summer (6.14 %), whereas forest regions exhibited mixed trends with BC declining in winter and post monsoon but increasing in summer and monsoon. Urban regions also showed a BC decline in post monsoon ($\Delta C = 1.02$ g/kg) and summer ($\Delta C = 6.90$ g/kg), while it increased in winter ($\Delta C = 0.20$ g/kg) and monsoon ($\Delta C = 1.84$ g/kg). Inter-annual variations showed the highest change in fire-prone forests ($\Delta C = 4.1$ g/kg) and the lowest in agriculture regions ($\Delta C = 0.8$ g/kg), with BC concentration increasing across land-use regions except for agriculture, where it declined by 6.66 % compared to the base year (2021). Increased rainfall intensity during the post monsoon season, likely driven by climate change, led to BC removal from topsoil due to erosion, especially in high-erodibility regions (Karthik et al., 2023). The BC/SOC ratio analysis indicated an overall increase in the relative contribution of BC to SOC across all land-use types, except for agricultural areas, where it decreased by 17.85 %. The highest BC contribution was recorded in fire-prone forest regions (35.48 %), suggesting that wildfire activity contributed more significantly to BC accumulation than litter fall inputs. A similar pattern was observed in Central Asian regions (Uzbekistan, Tajikistan, and Kyrgyzstan) where BC increased from agricultural land to hill regions, with altitude above 1000 meters having highest BC concentrations, similar to our study site (Rupakheti et al., 2021) .Soil mineral complexes played a key role in preventing BC loss and promoting accumulation, with BC-rich soils experiencing lower mineralization compared to SOC-rich soils (Liang et al., 2010). Seasonal and inter-annual BC variations aligned with SOC trends, suggesting continuous carbon input from forest and agricultural regions, while the seasonal changes in BC were primarily driven by wildfire events, rainfall-induced erosion, and biotic oxidation. The study underscores the need to account for seasonal and land-use dynamics when assessing BC concentration changes and their implications for long-term soil carbon dynamics.

3.3. Toposequence of BC, SOC, and BC/SOC profile

The concentrations of SOC and BC across different land use types (agriculture, forest, and urban) at various depths (0–30 cm) revealed distinct trends (Fig. 4), with BC concentrations ranging between 6.63 and 10.44 g/kg (mean: 8.08 g/kg) and SOC concentrations between 8.20 and 29.87 g/kg (mean: 24.97 g/kg). When compared to the Central Asian countries i.e., Uzbekistan (197%), Tajikistan (192%) and Kyrgyzstan (184%) our study region in Kodaikanal showed higher concentration (Rupakheti et al., 2021). The higher concentration can be attributed due to topography, soil type and climatic conditions. BC concentrations increased with depth by 56 % (agriculture), 59.01 % (non-fire-affected forest), 111.60 % (fire-affected forest), and 20.23 % (urban), whereas SOC decreased by 51.32 %, 73.82 %, 12 %, and 56.14 %, over the respective land use types. These patterns suggest a relative stability of BC compared to the lability of SOC. The relative proportion of BC to SOC at different depths ranged from 18.16 % (agriculture) to 77.06 % (urban), with highest BC contributions found at 20–30 cm.

These results, while being consistent with some global trends, also reveal region-specific contrasts. For example, our observed 111.6 % increase in fire-prone forests aligns with deep BC accumulation patterns

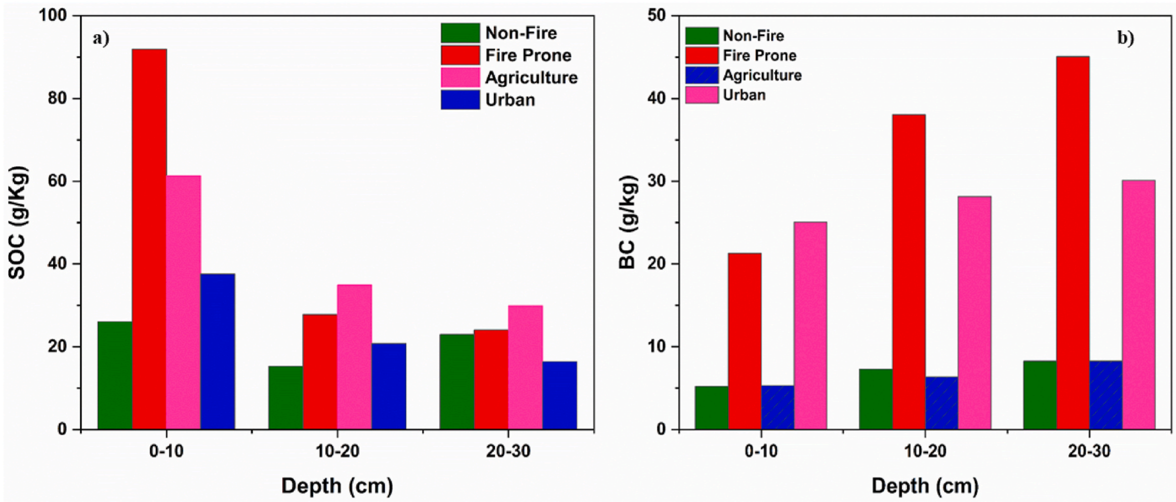

Fig. 4. Toposequence of (a) SOC and (b) BC across the vertical profile of 0–30 cm in different land use regions of Kodaikanal.

in boreal Alaskan forests, where a 38 % increase was reported due to intense combustion and mineral interactions (Kane et al., 2010). Similarly, agricultural sites in the Pacific Northwest showed a 27.3 % BC increase (Jauss et al., 2015), which corroborates well our 56 % increase in cultivated soils. However, our results contrast sharply with observations from Kenyan Nitosols and Amazonian Dark Earths (ADE), where BC declined by 60 % and 57 % with depth, respectively, likely due to intense weathering, leaching, or anthropogenic disturbance (Rumpel et al., 2006; Glaser et al., 2001). Steppe soils exhibited minimal change (3.54 %), possibly due to lower fire inputs and limited translocation, while Brazil's oxisols showed extreme increases (up to 137 %) in pristine Amazonian soils (Koele et al., 2017), likely driven by natural fire regimes and strong Fe/Al complexation.

Notably, the largest BC increases in our study occurred in fire-prone forests, consistent with global findings that highlight fire as a major driver of subsurface BC stabilization via high-temperature combustion residues and organo-mineral associations (Edmondson et al., 2015; Agarwal and Bucheli, 2011) . These profiles also reflect the recalcitrant nature of BC, in contrast to SOC's vulnerability to microbial decomposition. Urban soils exhibited lower BC variation (12–20 %) due to surface erosion and construction-related disturbances, though BC remained stable at depth. This observation mirrors findings from urban soils in England (BC range: 21–66.9 %; Edmondson et al., 2015).

Such cross-site comparisons emphasize that BC profile variation is not universally monotonic, rather shaped by a combination of climatic, pedogenic, and anthropogenic processes. For instance, whereas German Chernozems (with known fire histories) showed 45 % BC content (Schmidt et al., 1999), Alaskan Vertisols reported a 46 % decrease, likely due to saturation-limited decomposition and cryoturbation. Thus, the present data fall within the expected range for disturbed and fire-affected sites, with BC increases driven by depth-specific stability mechanisms, particularly in forested landscapes.

SOC decreased by 69 %, 42.39 %, and 44 % between 10 and 20 cm in fire-prone forests, agriculture, and urban soils, respectively, with total declines of 73.82 %, 51.30 %, and 56.14 % at 30 cm. Unburned forest soils exhibited a unique pattern, with a 41.53 % decrease in SOC in the 10–20 cm layer but only an 11.9 % decrease (or 40.41 % increase compared to 10–20 cm) in the 20–30 cm layer, indicating protection by mineral compounds such as Al and Fe hydroxides, which promote SOC stabilization (Li et al., 2023). High SOC concentrations in forest soils were linked to cold temperatures and high rainfall in Kodaikanal, which reduce organic matter decomposition. However, global meta-analyses (Cheng et al. (2023)) have shown a negative relationship between elevation and organic carbon in forest ecosystems, where higher elevations decrease organic matter content. Overall, BC concentrations increased with depth due to their structural resistance to degradation, while SOC exhibited greater lability and decreased with depth due to mineralization. Fire, mineral interactions, and land-use patterns played critical roles in controlling BC and SOC distribution, with fire-prone forests showing the highest BC stability and urban soils exhibiting BC loss due to anthropogenic activities. These findings underscore the role of BC in long-term carbon sequestration and highlight the vulnerability of SOC to environmental changes.

3.4. Environmental controls on SOC and BC

The study examined environmental factors influencing both BC and SOC using multiple linear regression. Approximately 45.96 % (F: 22.11, df: 208, $p < 0.05$) of the variation in SOC was attributed to combined predictors. MAT (24.45–30.09 °C) had a slight negative effect on SOC (coefficient: 0.06, $p > 0.05$), with the strongest decline observed in forests (21.10 g C/kg) followed by fire-prone forests (19.28 g C/kg) and urban regions (17.49 g C/kg), while a positive correlation was noted in agricultural areas. The variability in monthly mean temperature can influence the soil biomass, leading to either an increase or decrease in its abundance. However, it is important to consider that soil biomass in the field may be affected by various environmental conditions. The cumulative effect of these different factors may offset any prospective rise or decline in soil biomass (Wan et al., 2019). MAP (0.16–10.91 mm) had a significant negative effect on SOC (coefficient: 0.18, $p < 0.05$), leading to increased microbial activity and SOC mineralization through the dispersion of soil aggregates. SOC was more sensitive to precipitation than temperature, with slopes of −0.56, −0.55, −0.60, and −0.58 for forest, fire-prone forest, urban, and agricultural regions, respectively. In general, the temperature primarily influences the build-up and breakdown of soil SOC via regulating soil temperature, which ultimately determines the fluctuation in SOC content. Microbial activities were the primary driver of SOC decomposition, with temperature being the primary factor influencing these activities and processes (Zhou et al., 2019). In contrast, the drop in temperature will limit the process of soil mineralization, which will be helpful for the sequestration of additional carbon in the soil. Higher elevations positively influenced SOC due to lower temperatures, reduced microbial activity, and vegetation differences. Commercial and fire-prone land uses decreased SOC, while non-fire areas had higher SOC content.

In case of BC, fire-prone areas had a significant positive influence, while temperature positively influenced BC ($r = 0.3$, $p < 0.05$) and rainfall had a negative effect ($r = -0.11$, $p < 0.05$), likely due to BC washout (Fig. 5). Fire count had a negative effect ($r = -0.11$, $p < 0.05$) on BC, as frequent burning paradoxically reduced BC over time, consistent with Ding et al. (2015), who reported that only 3–5 % of carbon consumed by fire is converted to BC. While higher burning efficiency results in greater ash production (Forbes et al., 2006). Elevation and slope had minor positive effects on BC ($r = 0.03$, $p < 0.05$), with slash-and-burn agriculture at higher altitudes contributing to BC accumulation, aligning with findings from Kane et al. (2007) and Huang et al. (2018), which showed greater BC on north-facing slopes in boreal forests. Soil moisture had minimal impact on BC ($r = -0.08$, $p < 0.05$), corroborating Cheng et al. (2008), who suggested that BC decomposition remains unaffected by variations in soil moisture. Overall, 19.86 % of the variation in BC was explained by covariates (F-value: 6.443, $p < 0.05$), highlighting the strong influence of environmental factors on BC and SOC dynamics.

3.5. Morphological and chemical characterization

BC in different land-use and source soils in Kodaikanal has been studied using SEM-EDX. The EDX spectrum is utilized in the research of environmental contamination, the detection of heavy metals pollution, as well as in the disciplines of medicine and biology. It is essential to note that EDX delivers semi-qualitative and semi-quantitative information on a minimal amount of material, which might raise concerns with respect to sample homogeneity, however, we draw our inferences based on numerous literature-based justifications.

BC particles identified in the soil fractions can be classified as porous spherical, porous irregular spherical, and irregular solid blocky shapes (Fig. 6). The combustion reactions generate porous, spherical BC particles. The secondary coagulation reactions result in the formation of solid particles with various morphologies. The BC particles exhibit different morphologies ranging from spherical to irregular shapes with porous structure. The porous spherical BC particles are observed in the BC particles were collected from traffic and residential site in Kodaikanal (Moonjikal and Lake area) (Fig. 6a). Zong et al. (2017) also reported that porous structure is a characteristic of urban soils. The particles in the forest soil exhibited multitude of shapes such as sharp edged, elongated, irregular fragments. The surface texture was pitted and also with smooth surface texture (Fig. 6b). These structural characteristics resemble particles that are found in clay fraction of Brazilian Terra Preta (Rainforest region similar to characteristics of study site) (Brodowski et al., 2005; Glaser et al., 2000). In agricultural regions the collected BC particles has plant cellular structures preserved with the irregular fragments (high density fraction) which were assigned to biomass burning. In case of low density fraction the particles were smooth surfaces including visible edges (Fig. 6c). However, in some low density fractionation the samples also contained intermediate fractions which are assumed to be caused by the particle interaction with the mineral matrix. Similar results were observed in the light soil fraction of chernozem soil (Brodowski et al., 2005).

Chemical composition comprehensively accounts for C, O, N, K, Si, Al, Fe, Ca, Ti and Mg, respectively. Since, Kodaikanal has a geology of charnokite rocks with lateritic soil, Ca and Si which is found associated with BC particles in the agricultural regions (0–30 cm) tend to stabilize the BC in soil. The presence of Si and Ca in deep soil is attributed to the top layer which is characterized with chars and residue (only biomass) followed by the presence of only BC in intermediate depth (15–30 cm) while deeper layer consists of BC with minerals. The study site experiences high rainfall of (1600 mm/year) and high temperature with alternate wet and dry periods, which leads to leaching of soil with high minerals. It is reported that Ca can be leached easily to the depths by frequent turnover and in clayey-loam soil (characteristic of the study site, Pallangi). Since it is an agricultural region turnover of soil happens regularly favoring mixing of minerals at depths. Further, BC particles also contained lesser fractions of iron and silica. Liu et al. (2011) also reported that leachate of minerals is high in clay loam fractions of soil than the clay soil. In case of forest soil BC particles contained elements in the order of Ti > O > C > Al > Si > N. The presence of high titanium is due to the geology of the study site which has charnokite bedrock soil (Park, 1989). Higher oxygen is observed in the top soil (0–15 cm) and lower oxygen in deep soil (15–30 cm) in forest soils. The higher oxygen ratio is attributable to humus (100 g of carbon m^{-2}), higher oxidation by microorganisms and favorable climate of the study site. A similar higher oxygen to carbon ratio in top soil and lesser oxygen to carbon ratio in deeper soil was observed in Georgian forest soil (Cheng et al., 2008). Similar results were observed in Chernozems (Kubiena, 1938; Altemüller, 1992). Natural sources of char and charcoal primarily include forest and bush fires, while anthropogenic sources—both recent and historical—are largely attributed to biomass and fossil fuel combustion. The accumulation and stabilization of BC in soils are significantly influenced by the mineral matrix, particularly in clayey soils, as observed in the study region (Fernandez et al., 2017; Heckman and Rasmussen, 2018). The mineralogical composition of soil affects BC retention by facilitating interactions between BC and soil particles, thereby reducing its mobility and enhancing long-term sequestration.

According to the IPCC fifth assessment report (2013), approximately 0.3 gigatons (Gt) of carbon are lost annually due to mineral weathering in soils, whereas an estimated 2.6 (±1.2) Gt of carbon is sequestered in terrestrial organic reservoirs each year. This substantial difference underscores the critical role of mineralogy and climatic conditions in BC stabilization. High rainfall, temperature fluctuations, and soil turnover contribute to BC redistribution, while mineral interactions help prevent its degradation and loss. These findings emphasize that soil composition, along with environmental factors, plays a pivotal role in BC persistence, ultimately influencing carbon storage and long-term sequestration potential in terrestrial ecosystems.

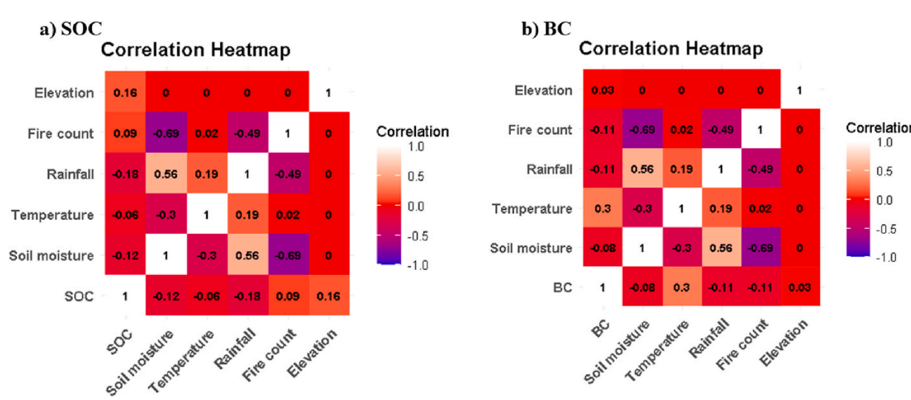

Fig. 5. Heat map displaying the relationship between covariates with (a) SOC, and (b) BC during the study period.

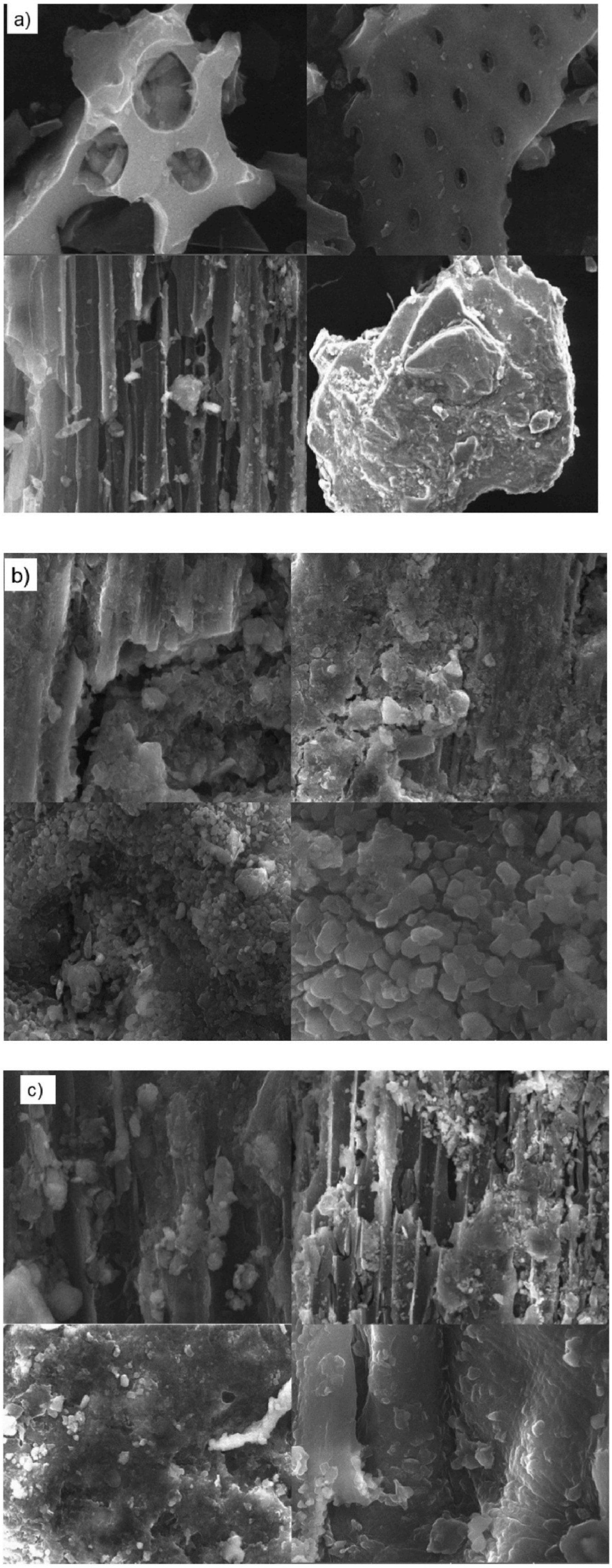

Fig. 6. Morphological images of black carbon (BC) particles collected in the (a) urban, (b) forest and (c) agricultural top soils of Kodaikanal.

3.6. Identification of potential sources

BC collected from different land use is studied for source identification using oxygen to carbon (O/C) and hydrogen to carbon (H/C) ratio as a tool. O/C ratio is an important tool to understand the oxidation of BC which gives insights into age and stability in the environment. Further, it can be compared with the H/C ratio to understand its potential source to the environment. Agriculture region has an O/C ratio varying between 0.5 and 1.2 with a mean of 0.76. Brodowski et al. (2005) reported that the O/C molar ratios greater than 0.7 is the result of biomass burning. The study site i.e., Kodaikanal, whose cultivation began only sixty years ago, has contributed significantly to BC stock. Since, the ratio of oxygen to carbon is high which represents aged BC, it can be inferred that BC's contribution is not only due to agricultural activities but also from forest conversion to agriculture using slash-and-burn technique. The O/C ratios representing biomass burning in Kodaikanal were similar to historical BC production sites and natural biomass burning (wildfire) regions in Canada (0.4–1.2) and USA (0.4–0.8) (Cheng et al., 2008). In the organic phase, O/C ratio is higher than the average suggesting higher levels of oxidation and reduced BC stability (Bakshi et al., 2020). While urban soils have O/C ratios varying from 0.07 to 0.12 which represent fossil fuel combustion. Similar O/C ratios were observed in China (0.09–0.11) (Zong et al., 2017), and Delhi (0.06–0.2) ((Agarwal and Bucheli, 2011). It is important to note that certain studies reported higher values for soot and biochar in soil which is the result of high temperature burning. Hence, the O/C ratio of BC in soil produced from fossil fuel sources can be variable with production temperature. In the natural forest soil and fire-prone forest soil O/C ratio varied between 0.6 and 1.4. The variability in the O/C ratio depending on the land use is attributable to the following factors such as soil type, topography, environment and source. In detail, the forest's higher carbon input into the soil increases its organic carbon pool compared to agricultural and urban regions thus resulting in higher oxidation. Soil type, texture, and clay mineral type all have a substantial impact on organic carbon or oxidation change in soils. Organic carbon increases as soil becomes more clay-like, while it drops as soil becomes more loamy; hence, changes in soil characteristics, such as agriculture (loamy), urban (clay), and forest (clay-loam), result in a change in O/C ratio across land cover types. Higher clay content (characteristic feature of the present study region) can also inhibit microbial breakdown, favoring oxidation of BC in top soils, due to which O/C is higher in top soil in the study region. After BC deposition in forest soil, oxidation makes it soluble (hydrophobic to hydrophilic), followed by water transport. In the case of urban soils, settlements, and construction followed by the fallow clay soil land results in quick turnover or removal of BC by erosion in topsoil while background BC stock remains stable due to recalcitrance properties. Further, soil erosion (forest-moderate, urban-low, agricultural-moderate), weathering (forest-high and also drainage (urban-low, forest, and agriculture-medium) result in differences in O/C ratio of BC with the depth (Bagyaraj and Bhuvaneshwari, 2015). Agricultural regions exhibit high H/C and low O/C, and forest sources give rise to litter sources with high H/C and O/C ratio. While the urban region is characterized by high H/C ratio (0.58) indicating the source of waste, and fossil fuel burning.

3.7. Chemometric analysis of BC in soil

FTIR analysis was conducted on topsoil samples (0–30 cm) across various land-use regions in Kodaikanal, with band assignments referencing studies on biochar, pyrogenic carbon, and natural/commercial biochar (Table 1). The major functional groups observed were C=O, C=C, OH, C–O, C=C–H, and C–H, with variations across forest, agricultural, and traffic sites. In forest soils, prominent aromatic C=C peaks (1400–1600 cm^{-1} and 830–770 cm^{-1}) and phenolic signals (1409 and 1280 cm^{-1}) indicative of BC were detected, consistent with findings from Rumpel et al. (2006) and Bornemann et al. (2008). Fe/Al oxides

Table 1
Details of functional groups based on the literature survey and used in the study.

Wavelength (cm^{-1})	Vibrations	Components	Reference
~3695–3630	Fe-O/Al-O	Minerals	(Madejová, 2002)
~3300–2900	O-H	Hydroxy group of Phenol	Nguyen et al., (2009)
~2900–2600	C-H	Aromatics	
~2125–1900	C-O	Carbonyl	
~1870–1540	C=O	Ketones	
~1685–1650	N-H	Amide	
~1625–1425	C=C	aromatics/aryl vibration	Li et al. (2023); Nguyen et al., (2009);(Bornemann et al., 2008); (Lehmann et al., 2005)
~1585–1380	-COO	Carboxylate group	Nguyen et al., (2009)
~1340–1250	-C-N	Primary, secondary, tertiary amine (aromatic)	
~1110–830	Si-O	Silicon	
~885–750	C-H	Out of plane deformation of aromatic C-H (polyaromatic stretching)	(Wurster et al., 2015)
~440–500	Si-O/Fe-O/Al-O	Soil minerals	(Rosa et al., 2019)

were also noted at 3693–3666 cm^{-1}. Agricultural soils exhibited bands at 2750–2950 cm^{-1} (C–H), 1712 cm^{-1} (COOH), 1624 cm^{-1} (C=C), and 1420–1230 cm^{-1} (lignin and C–H stretches), similar to charred BC observed by (Rosa et al., 2019). Si–O groups (440–500 cm^{-1}) in bulk soils suggest mineral stabilization of BC. In traffic site soils, prominent bands at 1642 cm^{-1} (C=C), 1100–1000 cm^{-1} (C=C–H), and 1230 cm^{-1} (C=O) indicated lignin and cellulose-derived compounds, likely from biomass combustion. Peaks at 2925 cm^{-1} confirmed organic carbon, matching observations from (Bora et al., 2021). Spectral evidence of O–H and N–H stretching at 3433.6 cm^{-1} aligned with urban aerosol deposition reported by Zong et al. (2016). A control sample of laboratory-prepared activated charcoal (derived from pine wood) exhibited medium C–N stretching (1033.6, 1222.36 cm^{-1}), C–H stretching (1363.43 cm^{-1}), alkene stretching (1632.45 cm^{-1}), and carboxyl stretching (1712.4 cm^{-1}), consistent with results by (Pimentel et al., 2023). The results suggest that condensed aromatic BC is present across all land-use types, while lignin-derived BC dominates in agricultural and forest soils, indicating a natural source. Traffic site samples contain lignin-derived BC, primarily from biomass burning rather than fossil fuels. BC degradation is influenced by mineral interactions, with forest and agricultural soils showing stabilization, while traffic site soils lacked mineral peaks, suggesting greater resistance to degradation.

3.8. Environmental perspective

The Carbon Management Index (CMI) and the Soil Management Index (SMI) are commonly used to assess the impact of land-use practices on soil carbon dynamics and soil quality by evaluating changes in SOC and its stability. Incorporating BC into these indices enhances their predictive power by accounting for BC's role as a recalcitrant carbon pool, contributing to long-term carbon sequestration. Including BC in CMI (as CMI-BC) improves the assessment of carbon persistence, while modifying SMI with BC data refines insights into soil stability and nutrient cycling (Blanco-Canqui and Lal, 2009).

In this study, the BC/SOC ratio provided critical insights into the balance between labile and recalcitrant carbon pools, helping to design appropriate soil management strategies. A higher BC/SOC ratio was observed in deeper soil layers (20–30 cm), indicating enhanced carbon stability and sequestration potential. Agricultural lands exhibited the lowest BC/SOC ratio (18.16 %) with high H/C and low O/C ratios, suggesting the dominance of thermally altered residues, which can be managed by reducing tillage, mulching, cover cropping, or adding biochar to improve stability and nutrient facilitation (Lehmann et al., 2006). In contrast, fire-prone forest and urban regions showed significantly higher BC/SOC ratios (69.48 % and 77.06 %, respectively), with high H/C ratios indicating the presence of condensed fire-derived compounds. These regions require interventions such as fire control measures, emission management, and post-fire rehabilitation to regulate BC levels. Additionally, non-fire-prone forest lands benefit from organic matter monitoring, mulching, and litter management to maintain soil carbon stability (Bird et al., 2015).

Seasonal variability and source-specific contributions (e.g., wildfire-derived BC vs. anthropogenic BC) significantly influenced BC and SOC dynamics in the study region. Inter-seasonal and inter-annual variations in BC and SOC were attributed to the differences in soil characteristics, litter input, environmental factors, and microbial activity, emphasizing the need for long-term monitoring to understand soil sequestration potential and guide land management practices (Glaser et al., 2001).

In conclusion, integrating BC, its seasonal variability, and source-specific contributions into SOC-based indices provides a more comprehensive framework for developing robust strategies for maintaining soil quality, enhancing carbon sequestration, and mitigating climate change.

4. Conclusions

This study highlights the influence of land use, fire regimes, and climatic factors on black carbon (BC) and soil organic carbon (SOC) in the Western Ghats. Forest soils, especially fire-prone ones, had the highest SOC and BC stocks, while urban and agricultural soils showed lower levels due to human disturbance. BC levels in agriculture varied with land management (e.g., slash-and-burn vs. terracing), and urban BC was influenced by tourism activity.

SOC peaked in winter and declined post-monsoon, correlating well with elevation and rainfall. BC accumulation in fire-prone forests was highest during monsoon, while in other land-use types, it peaked in summer. Temperature accelerated SOC decomposition in forests and urban areas whereas it favored SOC accumulation in agricultural soils. Excess rainfall promoted mineralization through microbial and physical soil changes.

Fire-prone areas showed a positive correlation with BC accumulation, though fire frequency negatively correlated, indicating complex burn dynamics. Source apportionment (H/C and O/C ratios) and chemometric analyses confirmed site-specific BC origins: traffic sites showed condensed aromatics, while lignin and cellulose derivatives dominated in forests and farms.

These findings emphasize the need for long-term, process-based studies to understand microbial and biogeochemical controls on carbon dynamics and support region-specific carbon management strategies.

CRediT authorship contribution statement

V. Karthik: Visualization, Software, Formal analysis, Data curation, Conceptualization, Writing – review & editing, Writing – original draft. **B. Vijay Bhaskar:** Writing – review & editing, Writing – original draft, Methodology, Funding acquisition, Conceptualization. **S. Ramachandran:** Writing – review & editing. **Qianlai Zhuang:** Writing – review & editing.

Consent for publication

Not applicable.

Ethics approval

Not applicable.

Consent to participate

Not applicable.

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Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Vijay Bhaskar reports financial support was provided by Anusandhan National Research Foundation. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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