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Dominant Edaphic Controls on Particulate Organic Carbon in Global Soils

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ABSTRACT

The current soil carbon paradigm puts particulate organic carbon (POC) as one of the major components of soil organic carbon worldwide, highlighting its pivotal role in carbon mitigation. In this study, we compiled a global dataset of 3418 data points of POC concentration in soils and applied empirical modeling and machine learning algorithms to investigate the spatial variation in POC concentration and its controls. The global POC concentration in topsoil (0–30 cm) is estimated as 3.02 g C/kg dry soil, exhibiting a declining trend from polar regions to the equator. Boreal forests contain the highest POC concentration, averaging at 4.58 g C/kg dry soil, whereas savannas exhibit the lowest at 1.41 g C/kg dry soil. We developed a global map of soil POC density in soil profiles of 0-30 cm and 0–100 cm with an empirical model. The global stock of POC is 158.15 Pg C for 0–30 cm and 222.75 Pg C for 0–100 cm soil profiles with a substantial spatial variation. Analysis with a machine learning algorithm concluded the predominate controls of edaphic factors (i.e., bulk density and soil C content) on POC concentration across biomes. However, the secondary controls vary among biomes, with solid climate controls in grassland, pasture, and shrubland, while strong vegetation controls in forests. The biome-level estimates and maps of POC density provide a benchmark for modeling C fractions in soils; the various controls on POC suggest incorporating biological and physiochemical mechanisms in soil C models to assess and forecast the soil POC dynamics in response to global change.

1 | Introduction

Soil particulate organic carbon (POC), the portion of soil organic carbon (SOC) with a size exceeding 53 μm based on the size fractionation scheme (Abiven, Menasseri, and Chenu 2009), makes up to half of soil organic carbon (Lavallee, Soong, and Cotrufo 2020; Marriott and Wander 2006; Zhao et al. 2021). POC refers to the carbon stored in particulate organic matter, comprising plant-derived and fungal-derived compounds, including phenols, celluloses, and chitin (Baldock and Skjemstad 2000; Christensen 2001; Kögel-Knabner et al. 2008; Sanderman, Maddern, and Baldock 2014; Six et al. 2001), resulting from the fragmentation and depolymerization of organic materials. POC is estimated to have a soil residence time from weeks to months (Lavallee, Soong, and Cotrufo 2020; Lehmann and Kleber 2015), given its high accessibility to soil microbes (Castellano et al. 2015). Combined with a high C/N ratio, this property is expected to affect the magnitude of SOC sequestration. Therefore, POC has been extensively used as an index of labile SOC status (Cambardella and Elliott 1992; Carter 2002; Christensen 1992; Golchin et al. 1994), and its mineralization and mobilization contribute dramatically to C losses in terrestrial ecosystems (Janzen 2006; Lavallee, Soong, and Cotrufo 2020).

Recent studies have demonstrated that SOC in the topsoil at high latitudes is dominated by the POC fraction, being more vulnerable to climate warming (García-Palacios et al. 2024). Additionally, soil POC affects nitrogen (N) transformation processes, including denitrification and N mineralization rates, as well as the content of heavy metals in sediments (Hill et al. 2000; Lovett et al. 2004; Sanei et al. 2012). Therefore, the dynamics of POC have a profound influence on terrestrial C and nutrient cycling. Hence, estimating the POC budget and elucidating its persistence mechanisms is key to understanding and modeling global change challenges.

Separating soil C stocks into fundamentally different fractions and recognizing global distributions and the controls of these fractions enable better predictions of soil vulnerability to global change because of the unique characteristics of each (Georgiou et al. 2022). The vertical distributions across biomes and the global patterns of other C fractions, including microbial biomass carbon (MBC) and dissolved organic carbon (DOC), have been reported in our previous studies (Guo et al. 2020; Xu, Thornton, and Post 2013). Although the concentrations and spatial variations of POC have been observed in various terrestrial ecosystems, such as tropical forests (Alongi 2014; Lee 2016; Zhang et al. 2009), temperate forests (Chen et al. 2012; Zhang et al. 2023), shrublands (Boix-Fayos et al. 2009; Kooch, Amani, and Abedi 2022), grasslands (Leifeld et al. 2009; Pringle et al. 2014), uplands (Kolka et al. 2001), and croplands (Xiao et al. 2021), these studies were implemented at regional or local scales. The global distribution of POC in terrestrial ecosystems and its controlling factors remain to be explicitly represented in climate models.

In soils, POC generally undergoes only partial processes by soil organisms and has high activation energies (Jilling et al. 2018; Kleber et al. 2015). Additionally, POC has a relatively shorter residence time (< 10 years) in soils due to the lack of protective mechanisms (Kleber et al. 2015; Kögel-Knabner et al. 2008). Generally, the mean residence time of POC in soils depends on microbial respiration and enzymatic reaction (DeGryze et al. 2004); thereby, the factors regulating litter formation and decomposition, root growth, and microbial activities potentially affect POC contents in soils. Substantial studies have documented the significant variations in POC concentrations among ecosystems, climate zones, vegetation communities, and soil characteristics across temporal and spatial scales (DeGryze et al. 2004; LiuSui et al. 2019). Moreover, many measurements and experiments have been implemented to reveal the controls on POC concentrations (Abramoff et al. 2018, 2022), including temperature (Benbi, Boparai, and Brar 2014; Wuchter et al. 2005), moisture (Li et al. 2022; Schlüter et al. 2022), soil pH (Liu et al. 2020; Relexans et al. 1988), soil texture (Huang et al. 2019; Kölbl and Kögel-Knabner 2004), organic matter (Kölbl and Kögel-Knabner 2004), soil N content (Gu 2009), and microbial activities (Denef et al. 2001; Witzgall et al. 2021). However, a mechanistic understanding of climatic and environmental factors on POC distribution across biomes and at the global scale is still unclear.

This study investigated POC concentration in the 0–100 cm soil profile in terrestrial ecosystems at biomes and global scales and its controls by combining a data synthesis with a machine learning approach. We reported the spatial and vertical distributions of POC in different biomes, attributed the POC variation to various factors, and finally quantified the budgets of POC in 0–30 cm and 0–100 cm soil profiles in multiple biomes and at the global scale.

2 | Materials and Methods

2.1 | Data Collection

The data for POC concentrations were collected from publications by searching "soil particulate organic carbon" in *Web of Science* and *Google Scholar*. We derived the data points from tables involving soil POC and/or extracted from figures vis the Engauge Digitizer software version 10.7 (http://digitizer.sourceforge.net/). A total of 3418 data points were finally collected from the LUCAS database and 244 publications from 1988 to 2020 (Table S1 and Figure 1a). The data are archived at Dryad (Guo et al. 2024). The database was divided into two groups: one group consists of 2507 data points for topsoil (0–30 cm) in 632 sites and 911 data points for soil profile (0–100 cm) in 55 sites. We also retrieved auxiliary information of the sampled sites, including vegetation type, soil texture, soil moisture (SM), sampling dates and depth, latitude (LAT), longitude, mean annual air temperature (MAT), mean annual precipitation (MAP), soil pH, bulk density (BD), total organic carbon (TOC), total nitrogen (TN), DOC, soil dissolved organic nitrogen (DON), soil microbial biomass carbon (MBC), soil microbial biomass nitrogen (MBN) and soil minerals-associated organic C.

We classified the data points into 14 biomes, including boreal forest, temperate coniferous forest, temperate broadleaf forest, tropical forest, mixed forest, grassland, shrubland, pasture, tundra, savanna, peatland, natural wetland, rice paddy, and cropland, according to our database and referencing the classification used in previous studies (Guo et al. 2020; Xu, Thornton, and Post 2013). Moreover, glaciers and deserts were excluded in this study. Cropland, forest, grassland, and pasture account for 49%, 15%, 14%, and 7%, respectively, whereas the remaining biomes account for 15% of the dataset (Table S1). Our dataset spanned diverse climates and soil types: clay content ranging from 3% to 62%, silt content ranging from 3% to 87%, mean annual temperature (range: −5°C to 20°C), and mean annual precipitation (range: 320–1600 mm) across distinct mineral and vegetation types (Figure 1b,c).

Climate, edaphic, and microbial data not mentioned in the papers were extracted from global datasets following our previous studies (Guo et al. 2020; Xu, Thornton, and Post 2013). SOC,

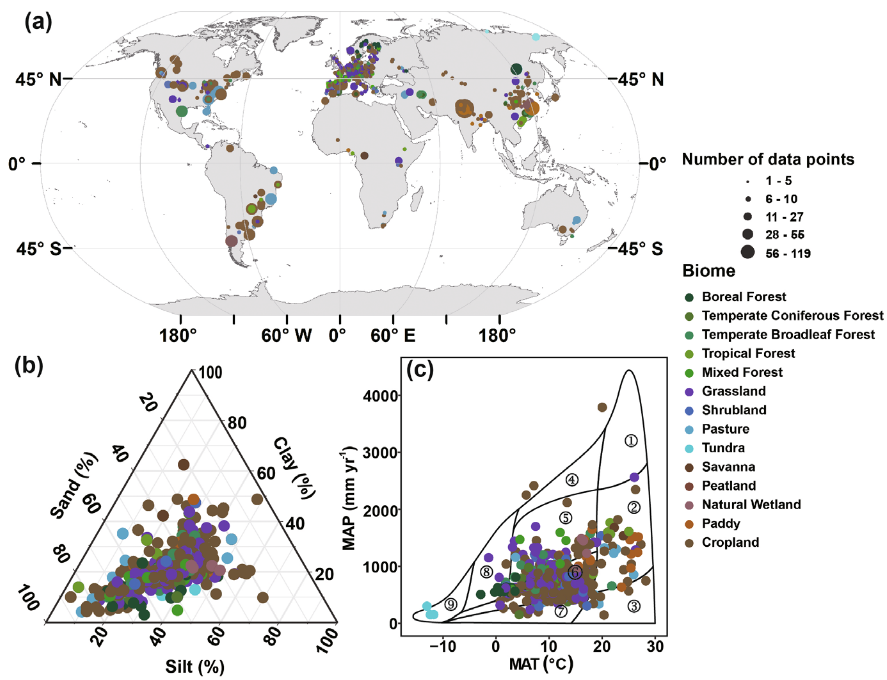

FIGURE 1 | Geographic, edaphic, and climatic information of sites used in this study. (a) Geographic distribution, (b) soil texture, and (c) climate of the data points. Black polygons depict Whittaker's biomes (Whittaker 1975) according to mean annual temperature (MAT;°C) and mean annual precipitation (MAP; mm year^{-1}) values, following: (1) tropical rainforest, (2) tropical seasonal rainforest/savanna, (3) subtropical desert, (4) temperate rainforest, (5) temperate seasonal forest, (6) woodland/shrubland, (7) temperate grassland/desert, (8) boreal forest, and (9) tundra.

TC, and BD were downloaded from the Harmonized World Soil Database (HWSD, https://daac.ornl.gov/cgibin/dsviewer.pl?ds_id=1247) at a 0.05°×0.05° resolution grid. Soil C, BD, and TN were extracted from the IGBP-DIS dataset (IGBP, https://daac.ornl.gov/SOILS/guides/igbp-surfaces.html) at a spatial resolution of 0.5′×0.5′. MAT and MAP were obtained from the WorldClim database version 2 with a spatial resolution of 30s during 1970–2000 (https://www.worldclim.org/data/worldclim21.html). The extraction of mean annual and monthly soil moisture (SM) and soil temperature (ST) in the top 10 cm during 1979–2018 was from the National Center for Atmospheric Research/Department of Energy Atmospheric Model Intercomparison Project (NCEP/DOE AMIP-II) Reanalysis (Reanalysis-2) monthly average dataset (https://www.esrl.noaa.gov/psd/data/gridded/data.ncep.reanalysis2.gaussian.html).

Root C density (C_{den}) data were extracted from a global dataset of a 0.5° resolution based on observation data (Ruesch 2008; Song et al. 2017). We extracted topsoil porosity data from a global dataset produced by Global Land Data Assimilation System (GLDAS, https://ldas.gsfc.nasa.gov/gldas/) at a spatial resolution of 0.25°×0.25°. Annual net primary productivity (NPP) for the period of 2000–2015 was obtained from the MODIS gridded dataset with a spatial resolution of 30s (http://files.ntsg.umt.edu/data/NTSG_Products/). Soil microbial biomass C (MBC) and nitrogen (MBN) were retrieved from a compiled global soil microbial biomass C and nitrogen (N) dataset archived at Oak Ridge National Laboratory (Xu et al. 2014; Xu, Thornton, and Post 2013).

The auxiliary datasets included the global land area database and vegetation distribution dataset. The global vegetation distribution dataset was obtained from a spatial map of 11 major biomes: boreal forest, temperate forest, tropical/subtropical forest, mixed forest, grassland, shrubland, tundra, desert, natural wetlands, cropland, and pasture, which have been used in our previous publications (Guo et al. 2020; He et al. 2020; Xu, Thornton, and Post 2013). The global land area database supplied by surface data map generated by the Community Land Model 4.0 (https://svn-ccsm-models.cgd.ucar.edu/clm2/trunk_tags/clm4_5_1_r085/models/lnd/clm/tools/clm4_5/mksurfdata_map/).

2.2 | Data Standardization

There are multiple procedures for POC fractionation in SOC; the physicochemical method contributes to approximately 76% (Cambardella and Elliott 1992), the size-density fractionation method accounts for 18% (Leifeld and KöGel-Knabner 2005; Lugato et al. 2021; Puget, Chenu, and Balesdent 2008; Six, Elliott, and Paustian 2000; Zimmermann et al. 2007), and the dry sieving method contributes to <1% of all reported methods in POC fractionation. In this study, we combined lighter POC (>53 μm, also lighter than 1.6–1.85 g/cm^3) and heavy POC (>53 μm but denser than 1.6–1.85 g/cm^3) to constitute an overall POC by referring to Lavallee, Soong, and Cotrufo (2020). Furthermore, the database of POC in 0–30 cm soil profile was rejected if the ratio of POC and TOC dataset was greater than 70%.

2.3 | Vertical Distribution of POC Along Soil Profiles

The concentration of POC in soil depends on organic matter input and decomposition driven by microorganisms, and soil microbial biomass and organic matter input have been demonstrated to decline exponentially along soil profiles relevant to the distribution of vegetation roots (Jackson et al. 1996; Xu, Thornton, and Post 2013). Therefore, in this study, we assumed that soil POC exhibits a similar pattern of vertical distribution as root systems, microbial biomass, and DOC in terrestrial ecosystems due to two reasons: (a) the chief occurrence of plant litter and labile organic matter near the soil surface leads to an exponential decrease of organic matter input (Guo et al. 2020), and (b) root can accelerate the microbial decomposition. The POC vertical distribution among biomes was fitted against soil depth using an asymptotic equation:

$$Y = 1 - \beta^{d}$$

where Y represents the cumulative fraction of soil POC from the soil surface to the depth of d in cm, and beta is the fitted coefficient. High β means a lower proportion of soil POC concentration near the soil surface, and vice versa.

2.4 | Global Distribution and Budget of POC

Distribution of POC concentration in 0–30 cm and 0–100 cm soil profiles at biome- and global level was estimated by the random forest (RF) model; available variables were chosen like the absolute value of the latitude, MAP, MAT, annual mean ST and SM, soil pH, porosity, texture, SOC, TC, NPP, and C_{den} (Table S7). The database for POC was removed if it was greater than 70% of TOC in the Information System Database (IGBP-DIS), and it was split into training samples (70%), and test samples (30%) with the method of "train_test_split", hyperparameters used in the RF model were listed in Table S6. We randomly set an ensemble of all parameters in light of different total organic datasets, including TC from IGBP, TC, and SOC from the HWSD dataset. Ultimately, the average of three dataset simulations was used for producing the global map. The global distribution and budget of POC were evaluated for 11 biomes except for paddies and peatlands; the former was aggregated into croplands, and the latter was combined with natural wetlands. Predictions to simulate POC concentrations showed a reasonable trend with a variance of $R^2 = 0.726$ (Figure S2). The RF model used Scikit-learn packages (version 0.23.2, https://scikit-learn.org) for Python (version 3.7.5, https://www.python.org/) to predict POC concentration. Based on POC fractions in 0–30 cm soil profiles (Table S2) for each biome, the distribution and concentration of POC were estimated along 0–100 cm soil profiles.

2.5 | Quantification of the Relative Contributions of Controlling Factors on POC

Multiple regression was used to evaluate the relative contribution of 15 control factors on POC concentration. The result was categorized into three main categories: edaphic factor contains BD, TC, TN, Sand, Clay, Porosity, and pH; ST and SM represented climatic factor; NPP, Cden, MBC, and MBN were merged as biological factors. The relative contribution of other factors was estimated with the following formula:

$$\mathrm{Rel_o} = 1 - \left(\mathrm{Rel_b} + \mathrm{Rel_e} + \mathrm{Rel_c}\right) \times \mathrm{R}^2$$

where the $\mathrm{Rel_o}$ is the relative contributions of other factors on POC; $\mathrm{Rel_e}$ is the relative contributions of edaphic factor; $\mathrm{Rel_c}$ is the relative contributions of climatic factor; $\mathrm{Rel_b}$ is the relative contributions of biological factor, and R^2 is the variance of multiple linear regression.

2.6 | Statistical Analysis

POC concentration data were log-transformed to convert for robust statistical analyses. The mean and 95% confidence intervals of POC concentration were converted back to the original values for reporting. The variability of POC concentration among biomes was assessed by analysis of variance (ANOVA). A Mantel test was chosen to investigate the relationship between POC concentration and climate, vegetation, and soil properties by using Pearson's correlation. Structural equation modeling (SEM) was used to identify the multivariate effects (climatic, biological, and edaphic variables) on POC concentration. A ternary diagram was performed to determine the effects of different soil textures on POC concentration. All statistical analyses and graphs were conducted by the RStudio software version 4.0.3 (http://www.rstudio.com/) and ORIGIN Pro 2023 (http://www.originlab.com/). The global maps were generated by the ArcGIS software (version 10.8, ESRI, Redlands, CA) in Windows 11.

3 | Results

3.1 | Soil POC Concentrations Among Biomes

The global average and median of POC concentrations in topsoil were 3.02 (2.47–3.73) gC/kg dry soil and 3.20 (1.88–5.25) gC/kg dry soil, respectively, and varied across biomes (Table 1; Table S8). Biomes such as boreal forests, shrublands, and natural wetlands had relatively higher POC concentrations, at 4.58 (3.51–5.99), 4.35 (3.82–4.95), and 4.18 (3.52–4.98) gC/kg dry soil, respectively. Compared to savannas and croplands values of 1.41 (0.98–2.03) and 1.9 (1.8–2) gC/kg dry soil, respectively. There were no significant differences in POC concentrations among the remaining biomes (Table 1). In addition, temperate coniferous forests, mixed forests, and tundra showed higher POC concentrations than the global average, at 3.65 (3–4.44), 3.75 (2.96–4.76), and 3.14 (1.93–5.11) gC/kg dry soil, respectively. Meanwhile, temperate broadleaf forests, tropical forests, grasslands, pastures, peatlands, and paddies exhibited lower concentrations than the global average (Table 1).

POC concentrations generated through a random forest algorithm showed a similar pattern across biomes. The global average and median values of POC concentrations were 3.61 (3.58–3.65) and 3.47 (2.93–4.21) gC/kg dry soil, respectively. Boreal forests, natural wetlands, mixed forests, and tundra exhibited higher POC than the global average, with mean values of 4.41 (4.34–4.49), 4.46 (4.43–4.49), 4.27 (4.25–4.30), and 5.07 (5.02–5.13) gC/kg dry soil and the median of 4.38 (2.88–6.01), 4.27 (3.83–4.89), 4.12 (3.51–4.96), and 4.68 (3.77–6.16) gC/kg dry soil, respectively. In addition, upland and pastures showed lower POC concentrations than the global average (Table 2).

TABLE 1 | Soil organic carbon fraction at biome and global scales derived from the compiled data.

Biomes	POC (53–2000 μm, gC/kg dry soil) this study		MBC (gC/kg dry soil)	DOC (gC/kg dry soil) 0.45 μm
	Mean	Median		
Boreal forest	4.58^{a} (3.51–5.99)	4.06 (2.42 ~ 9.23)	1.04^{b} (0.71 ~ 1.51)	0.13^{c} (0.11 ~ 0.14)
Temperate coniferous forest	3.65^{abc} (3–4.44)	3.55 (2.59 ~ 4.90)	0.51^{cd} (0.42 ~ 0.61)	0.03^{i} (0.02 ~ 0.04)
Temperate broadleaf forest	2.98^{abcd} (2.65–3.35)	3.06 (1.95 ~ 4.49)	0.54^{cd} (0.46 ~ 0.62)	0.05^{ef} (0.05 ~ 0.06)
Tropical forest	2.07^{cd} (1.56–2.74)	1.81 (1.07 ~ 4.17)	0.43^{de} (0.37 ~ 0.50)	0.04^{h} (0.04 ~ 0.04)
Mixed forest	3.75^{abc} (2.96–4.76)	3.19 (2.22 ~ 7.02)	0.54^{cd} (0.49 ~ 0.59)	0.05^{fg} (0.04 ~ 0.05)
Grassland	2.85^{bcd} (2.57–3.16)	2.90 (1.50 ~ 5.65)	0.52^{cd} (0.47 ~ 0.58)	0.09^{d} (0.08 ~ 0.11)
Shrubland	4.35^{a} (3.82–4.95)	4.51 (3.10 ~ 6.00)	0.34^{e} (0.26 ~ 0.46)	0.11^{cd} (0.10 ~ 0.18)
Pasture	2.71^{cd} (2.46–2.99)	2.85 (1.67 ~ 4.33)	0.66^{c} (0.58 ~ 0.76)	0.11^{d} (0.07 ~ 0.16)
Tundra	3.14^{abcd} (1.93–5.11)	3.93 (1.67 ~ 6.26)	4.09^{a} (2.84 ~ 5.87)	0.45^{a} (0.33 ~ 0.63)
Desert	NA	NA	0.08^{g} (0.06 ~ 0.10)	NA
Savanna	1.45^{d} (1–2.11)	1.34 (1.00 ~ 2.51)	NA	NA
Peatland	2.43^{cd} (1.94–3.04)	3.22 (1.77 ~ 4.11)	NA	NA
Natural wetland	4.18^{ab} (3.52–4.98)	4.95 (2.98 ~ 6.52)	1.34^{b} (1.01 ~ 1.76)	0.20^{b} (0.18 ~ 0.22)
Paddy	2.29^{cd} (1.91–2.74)	3.44 (1.40 ~ 4.69)	0.25^{f} (0.24 ~ 0.26)	NA
Cropland	1.9^{d} (1.8–2)	2.04 (1.02 ~ 3.59)		0.06^{e} (0.05 ~ 0.07)
Global	3.02 (2.47–3.74)	3.20 (1.88 ~ 5.25)	0.68	0.08

Note: Values are presented as mean with 95% CI, median with 25%, and 75% confidence boundaries in parentheses. Different superscript letters in the same column indicate the difference at a significance level of $p = 0.05$, while the same letters indicate no significant difference.
Abbreviations: DOC, dissolved organic carbon, data cited from Guo et al. (2020); MBC, microbial biomass carbon, data cited from Xu, Thornton, and Post (2013); NA, not available.

3.2 | Environmental Control on Soil POC Concentrations

The fluctuations in POC concentrations at the global scale were predominantly controlled by climatic, biological, and edaphic factors (Figure 2a; Tables S2 and S3). Specifically, BD ($r = -0.21$, $p < 0.05$), TC ($r = 0.29$, $p < 0.05$), SM ($r = 0.22$, $p < 0.05$), MAT ($r = -0.29$, $p < 0.05$), ST ($r = -0.24$, $p < 0.05$) and porosity ($r = 0.3$, $p < 0.05$) were the primary factors determining POC concentrations. Moreover, POC concentrations were positively associated with the C/N ratio ($r = 0.17$, $p < 0.05$) and Cden ($r = 0.04$, $p < 0.05$), but negatively correlated to pH ($r = -0.1$, $p < 0.05$). Additionally, the C/N ratio was dominated by BD ($r = -0.52$, $p < 0.05$), TC ($r = 0.55$, $p < 0.05$), pH ($r = -0.56$, $p < 0.05$), porosity ($r = 0.54$, $p < 0.05$), and soil texture such as sand ($r = 0.34$, $p < 0.05$) (Figure 2a).

The SEM framework further revealed the indirect and direct influences of soil characteristics on POC concentrations (Figure 2b). Clay and silt contributed to 17.8% and 11.4% of the variation in POC concentrations, respectively (Figure 2b). TC ($r = 0.251$, $p < 0.05$), SM ($r = 0.147$, $p < 0.05$) and C_{den} ($r = 0.054$, $p < 0.05$) had positive impacts, and ST ($r = -0.194$, $p < 0.05$) showed a negative influence. Additionally, pH was the primary factor controlling TC ($r = -0.412$, $p < 0.05$) to further regulate POC concentrations. Furthermore, the soil ternary diagram suggested that silt clay, sandy clay, clay loam, silt clay loam, and loam had lower POC concentrations, whereas loam sandy, sandy clay loam, and sandy loam showed higher values (Figure S1).

Additionally, edaphic, climatic, and biological factors explained over 50% variation of POC contents in all the biomes except for

TABLE 2 | Machine learning-derived mean, median particulate organic carbon (POC) concentration, and budget in 0–30 cm and 0–100 cm soil profiles at biome and global scales.

Biomes	Predicted POC (gC/kg dry soil) Median	Predicted POC (gC/kg dry soil) Mean	POC (gC/kg dry soil) LUCAS dataset Median	POC (gC/kg dry soil) LUCAS dataset Mean	Global budget (Pg C) 0–30 cm	Global budget (Pg C) 0–100 cm
Boreal forest	4.68 (3.77 ~ 6.16)	5.07 (5.02 ~ 5.13)	7.99 (4.42 ~ 16.60)	8.41 (6.73 ~ 10.50)	13.36	15.79
Temperate coniferous forest	3.38 (2.88 ~ 4.08)	3.52 (3.47 ~ 3.57)			3.79	4.48
Temperate broadleaf forest	2.95 (2.66 ~ 3.35)	3.07 (3.04 ~ 3.10)			4.70	6.27
Tropical forest	3.26 (2.70 ~ 4.03)	3.34 (3.31 ~ 3.37)			22.35	29.56
Mixed forest	4.12 (3.51 ~ 4.96)	4.27 (4.25 ~ 4.30)			19.87	26.49
Grassland	2.62 (2.28 ~ 3.15)	2.74 (2.72 ~ 2.77)	6.12 (3.44 ~ 13.2)	6.50 (5.42 ~ 7.80)	14.50	27.01
Shrubland	3.09 (3.04 ~ 3.21)	3.35 (3.27 ~ 3.43)	5.48 (3.21 ~ 6.52)	5.70 (3.58 ~ 9.08)	8.42	15.24
Tundra	4.27 (3.83 ~ 4.89)	4.46 (4.43 ~ 4.49)	na	na	10.08	13.25
Natural wetland	4.38 (2.88 ~ 6.01)	4.41 (4.34 ~ 4.49)	na	na	10.60	12.99
Cropland	2.82 (2.41 ~ 3.41)	2.84 (2.82 ~ 2.86)	2.35 (1.72 ~ 3.92)	2.60 (2.33 ~ 2.89)	18.36	27.94
Pasture	2.57 (2.23 ~ 3.11)	2.64 (2.63 ~ 2.66)	na	na	32.11	43.73
Globe	3.47 (2.93 ~ 4.21)	3.61 (3.58 ~ 3.65)			158.15	222.75

Note: Values are presented as mean with 95%, median with 25% and 75% confidence boundaries in parentheses. Different superscript letters in one column indicate the significant difference at a significant level of $p = 0.05$, while the same letters indicate no significant difference.

tropical forests (Figure 2c). Globally, compared with climatic and biological factors, edaphic factors exhibited a higher relative contribution to explain variation in POC, ranging from 32% to 77% (Table S4). Furthermore, in natural wetlands, shrublands, pastures, grasslands, and cropland, the relative contribution of climatic factors was higher than biological factors, whereas, in tundra and all types of forests, biological factors had a higher contribution to shaping POC (Figure 2c).

3.3 | Vertical Distribution of Soil POC at the Biome Level

The fitted curves of vertical distribution showed that POC in the topsoil makes up over 50% of its total observed throughout the soil profile (Figure 3), and the β value varies among biomes, ranging from 0.9395 to 0.9746 (Figure 3; Table S5). Forests and peatlands have a higher proportion of POC in topsoil. Among biomes, temperate coniferous forests with the lowest β value had the highest proportion of POC concentrations in topsoil along their soil profiles, followed by peatlands, tundra, tropical forests, temperate broadleaf forests, peatlands, croplands, savannas, shrublands, and paddies, whereas grasslands stored more POC in deep soils.

3.4 | Global Budget and Distribution of POC

The global POC budget was estimated as 158.15 Pg C in the 0–30 cm soil profile, which accounts for approximately 40% of the total POC budget in 0–100 cm soil profiles, at 222.75 Pg C (Table 2), and constitutes approximately 10% of TOC (1570 Pg C) derived from IGBP database (Guo et al. 2020). The estimated global budget of POC in 0–100 cm soil profiles contributes about 14% of the TOC, substantially larger than the proportion of soil microbial biomass C (MBC) and soil dissolved organic carbon (DOC) of TOC (Guo et al. 2020; Xu, Thornton, and Post 2013). The POC budgets tremendously differ among biomes in 0–30 cm and 0–100 cm soil profiles, with the largest stock in pastures and the smallest in temperate coniferous forests (Table 2). The POC distribution in both 0–30 cm and 0–100 cm soil profiles suggest substantial spatial variations at the global scale (Figure 4a,b). Specifically, POC

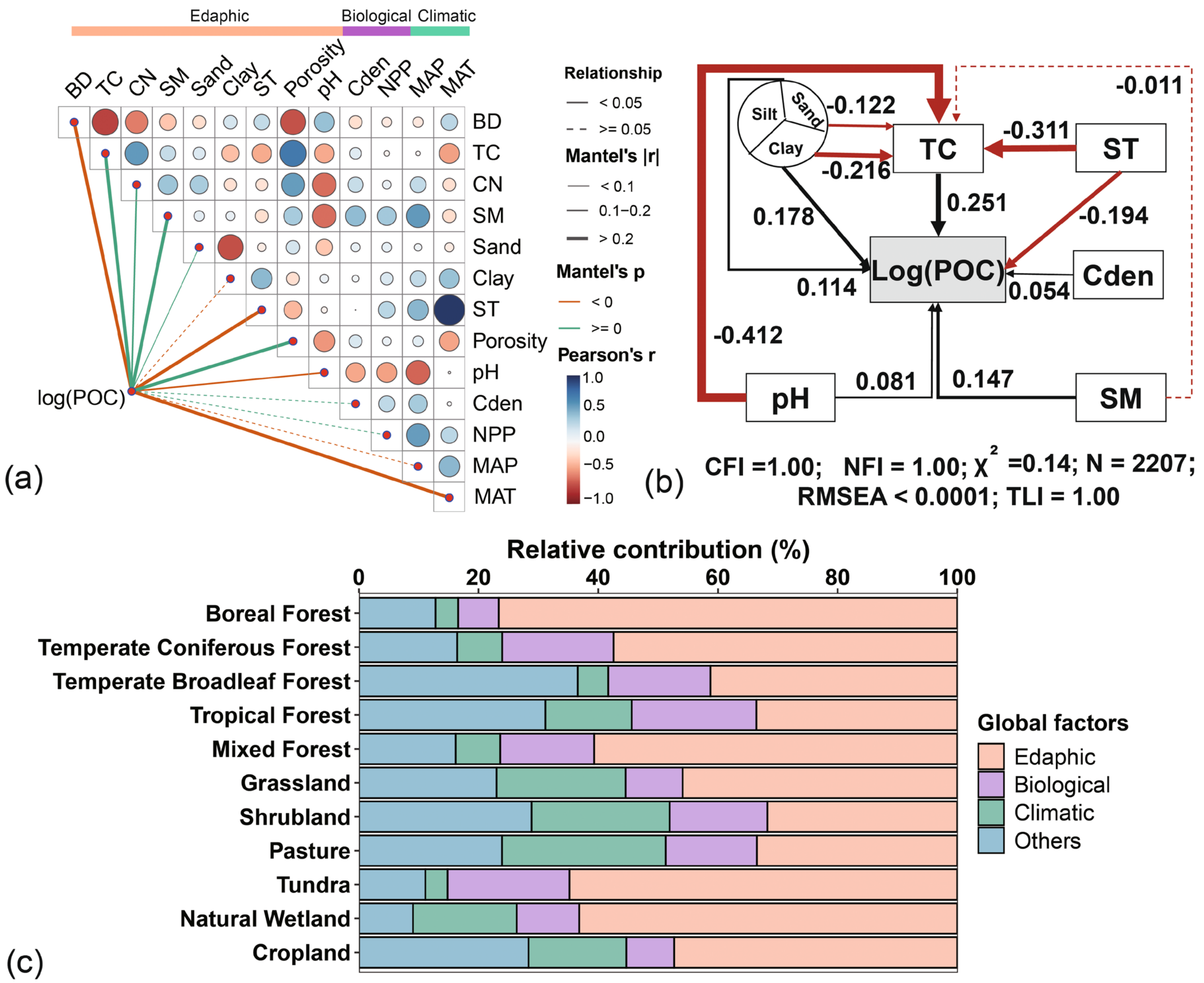

FIGURE 2 | (a) Mantel test showing the relationships between log (POC) and environmental variables. Pairwise comparisons of environmental factors are displayed with a color gradient denoting Pearson's correlation coefficient; orange lines represent positive correlation ($p < 0.05$), green lines represent negative correlation ($p < 0.05$), and gray lines represent non-significant effects ($p > 0.05$). (b) Structural equation model of TC, SM, pH, ST, Clay, Sand, and POC. In the SEM structure, solid black arrows represent positive paths ($p < 0.05$, piecewise SEM), solid red arrows represent negative paths ($p < 0.05$, piecewise s.e.m.), and dotted arrows represent non-significant effects ($p > 0.05$). We report the path coefficients as standardized effect sizes. The overall fit of piecewise s.e.m. was evaluated using comparative fit index (CFI), normed fit index (NFI), Tucker–Lewis index (TLI), and a CFI, NFI, and TLI larger than 0.95 indicate relatively good model-data fit in general. 2207 data points were used in the model: (c) Relative contribution of different control factors on soil particulate organic carbon (POC) at biomes scales. BD, bulk density; Clay: soil clay content; CN, soil total C:N ratio; MAP: mean annual precipitation; MAT: mean annual air temperature; NPP: net ecosystem primary production; Sand: Soil sand content; SM: soil moisture; ST: soil temperature.

budgets are high in northern high-latitude regions (50°–70°), attributed to the wide distribution of boreal forests and natural peatlands, while the low POC recorded at low latitudes is associated with the occupation by tropical ecosystems (Figure 4c,d).

4 | Discussion

4.1 | Soil POC Variations Among Biomes

Substantial variations in soil POC concentration among biomes were found in this study (Table 1 and Figure 4a,c). High latitudes contained relatively higher POC concentrations, consistent with DOC and MBC studies (Guo et al. 2020; Xu, Thornton, and Post 2013). The concentration of POC in soils mainly depends on the organic input and microbial decomposition as POC derives from plant materials and is substantially more available to microorganisms than other soil C fractions such as mineral-associated carbon (Lavallee, Soong, and Cotrufo 2020). Although the lightweight fragments derived from vegetation are in minor proportion in high latitude regions owing to the low net primary productivity (NPP), the colder temperature in high latitude regions inhibits microbial consumption of POC, which is susceptible to the change in enzymatic activities (Benbi, Boparai, and Brar 2014). Therefore, biomes located at high latitudes generally exhibit relatively

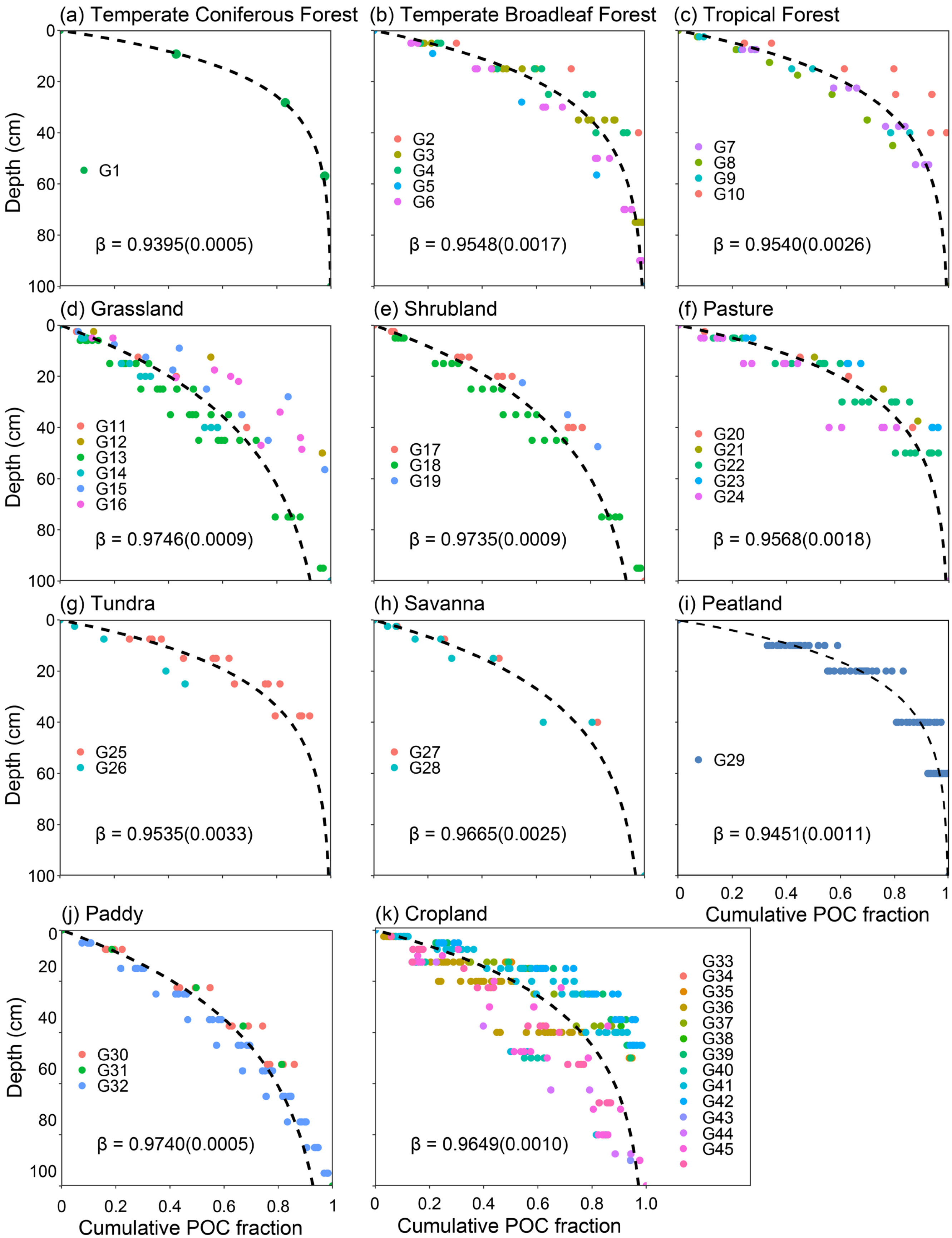

FIGURE 3 | Vertical distribution of soil particulate organic carbon (POC) in major biomes (a, temperate coniferous forest; b, temperate broadleaf forest; c, tropical forest; d, grassland; e, shrubland; f, pasture; g, tundra; h, savanna; i, peatland; j, paddy; and k, cropland). Different colors represent the subsets of data points, and each subset contains data points from at least three soil depths. The β value with standard error is displayed for each biome.

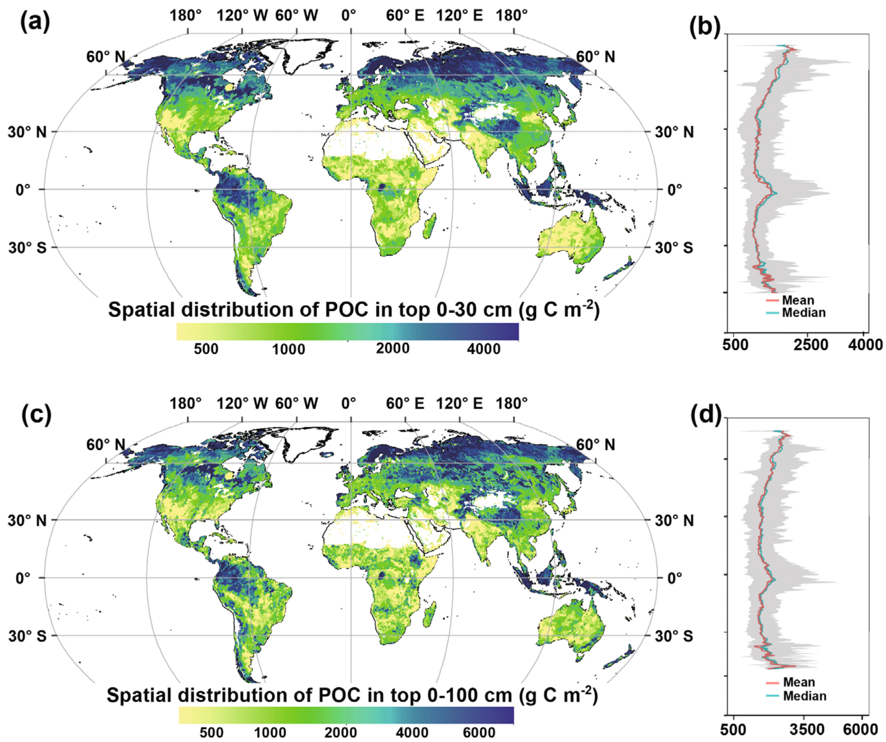

FIGURE 4 | Global distribution and latitudinal pattern of soil POC concentration (g C m^{-2}) in terrestrial ecosystems in (a, b) 0–30 cm soil profile and (c, d) 0–100 cm soil profile. Map lines delineate study areas and do not necessarily depict accepted national boundaries.

higher POC concentrations. Furthermore, POC contents in cold regions are predominately determined by NPP; thereby, boreal forests show the highest POC concentration across biomes. A recent study focusing on POC in cold regions emphasized substantial POC in high latitudes, whereas the POC concentration is higher than our study (García-Palacios et al. 2024) (Table S9). The data points of POC accounting for over 70% of SOC were excluded in the global simulation (Chan 2001; Jagadamma et al. 2014), potentially leading to lower POC contents via the random forest. Meanwhile, our dataset contains a higher proportion of POC measurements in cold regions; therefore, the estimates of this study might be a little overestimated given the higher POC concentration in cold regions (Table 1).

Wetlands also exhibit high POC concentration, which is associated with soil conditions. The low permeability in wetland soils prevents the transformation of the fragments constituting particulate organic matter to low molecular weight compounds driven by microbial communities, accumulating large amounts of POC (Ganju et al. 2019). In addition, forest biomes and shrublands exhibited more POC than the global average, which can be explained by the high inputs of plant materials and residues of fungi and insects in forests (Abramoff et al. 2018). Grasslands, savannas, and pastures had low POC concentrations because the climate and environmental conditions limit the NPP in these biomes, reducing organic matter input. Livestock trampling and excess fecal input have been confirmed to aggravate fragmentation and microbial depolymerization, leading to POC being highly decomposable and readily utilized by microorganisms. Meanwhile, natural fires in savannas remove a substantial amount of plant biomass, reducing the organic input into the soil. Low POC concentration in paddies and croplands indicated a non-negligible impact of land use change on POC persistence. The acceleration of anthropogenic perturbations, including agricultural activities, could promote the consumption and transformation of POC (Bouajila and Gallali 2010; Chan 2001; Zhu et al. 2021).

Globally, POC concentration is much higher than the concentrations of DOC and MBC (Table 1), indicating its essential role in the global carbon cycle and maintaining ecosystem stability. As the organic C fraction, POC is highly available to the soil microbiome (Lavallee, Soong, and Cotrufo 2020), which has been demonstrated to dominate the SOC stocks in cold regions as POC without aggregate protection is vulnerable to being impacted by environmental changes and NPP dynamics (García-Palacios et al. 2024). A recent study reported that mineral-associated organic carbon (MAOC) contents were much higher than POC at the global scale (Zhou et al. 2024), whereas the protection mechanisms associated with minerals and aggregates suppress the availability of organic matter for plants and microorganisms in MAOC and thus impede the contribution of MAOC to the global carbon cycle (Lavallee, Soong, and Cotrufo 2020). Therefore, targeting POC variation to address global change challenges potentially has important and consequential significance, considering its higher content and availability in soils.

4.2 | Environmental Control on Soil POC Concentration

Globally, edaphic factors, including TC, BD, pH, sand, and porosity, exhibited significant relationships and the highest contribution to POC concentration (Figure 2a), indicating a primary impact of soil characteristics on POC, which is generally consistent with previous studies (Eze et al. 2023; Li et al. 2021; Qi et al. 2016). As an active portion of soil TC, the concentration of POC is significantly influenced by C storage (Abramoff et al. 2018). The increase in concentrations of sand and slit is expected to enhance the mineral association of soil C, promoting the decomposition of POC through microbial metabolism (Georgiou et al. 2022; Lavallee, Soong, and Cotrufo 2020). In addition, TC is associated with soil pH and texture (Figure 2b), indicating that these edaphic factors can not only directly alter POC concentration but also indirectly impact POC turnover and retention in soils.

However, the global view found a relatively minor regulation of NPP to POC concentration in our study, consistent with a recent study (Hansen et al. 2024). POC storage and persistence are mainly controlled by microbes, as microorganisms directly participate in POC mineralization, and POC without chemical protection is more accessible to and effectively used by microbes (Lavallee, Soong, and Cotrufo 2020). The same global distribution patterns of DOC with POC also confirmed the essential impacts of microbes on POC storage (Hansen et al. 2024). Microbial activities are significantly impacted by edaphic and climatic characteristics (Guo et al. 2020; Zhu et al. 2021), leading to the fluctuation of the biosynthesis and transformation of soil organic matter. For instance, MAT and pH were confirmed to change the physiological characteristics of microbes, indirectly changing POC degradation, with both lower pH and MAT contributing to lower microbial decomposition and greater POC concentration and storage (Hansen et al. 2024). Our previous studies demonstrated the direct and indirect impacts of soil factors on MBC and DOC (Guo et al. 2020), which indicated an essential influence on the composition of soil organic matter. Therefore, although the generation and decomposition of soil POC were closely associated with vegetation, animals, and microbes, the POC persistence in terrestrial soils was dominated by edaphic and climatic factors.

The variation of the relative contributions of other factors to POC residence in soils indicates multivariate mechanisms of POC retention. For example, in natural wetlands, the anaerobic environment and high C storage maintain the POC concentration elevated; thereby, edaphic and climatic factors have a significant relative contribution to POC (Zhu et al. 2023). In forests, N availability has been widely reported to play an important role in POC persistence (Lavallee, Soong, and Cotrufo 2020) but excluded in this study. In addition, the primary productivity and microbial activities in grassland are limited by phosphorus, regulating POC concentration in soils. The freezing and thawing conditions are essential regulators of POC turnover, as they control microbial activity. Anthropogenic perturbations such as agricultural practices and land management dramatically influence soil properties and N inputs, leading to the POC variation among land use types.

4.3 | Causes of Vertical Distribution of Soil POC Among Biomes

The vertical distribution of soil POC is consistent with the distribution of vegetation root systems and soil microbial biomass in terrestrial ecosystems (Guo et al. 2020; Jackson et al. 1996; Xu, Thornton, and Post 2013). Soil POC predominantly derives from the leaching of substances from fresh litter and the partial decomposition of organic matter driven by microbes (DeGryze et al. 2004; Lavallee, Soong, and Cotrufo 2020); therefore, the exponential reductions of organic matter inputs from the rhizosphere and microbial biomass along the soil profile cause the vertical distribution pattern of POC concentration. The association of POC with root and MBC distribution confirms that POC generation and persistence in soil depends on C supplies from rhizodeposition and microbial activities, including depolymerization (Abramoff et al. 2022). At the biome level, grasslands have the smallest proportion of soil POC in topsoil. In contrast, forests store relatively more enormous proportions of POC on the surface of their soils (Figure 3). Although grasslands store a large amount of soil C on a global scale (Mannetje 2007), the soil characteristics and relatively more frequent human disturbances such as grazing accelerate the transformation from POC to low molecular weight carbon (Abramoff et al. 2022; Leifeld et al. 2009), especially in surface soils.

4.4 | POC Budget and Implications to Climate Modeling

POC budgets in 0–30 cm and 0–100 cm soil profiles are estimated to be 158.15 and 222.75 Pg C at the global scale, respectively, approximately 21 times the global DOC storage and 10 times the global MBC storage (Guo et al. 2020; Xu, Thornton, and Post 2013) (Table 2), which can be explained by the longer residence time of POC than DOC and MBC (Boddy et al. 2007; Leifeld et al. 2009). Given that environmental changes such as thawing and human disturbances can immediately promote POC decomposition to low molecular compounds (DeGryze et al. 2004), soil POC variations contribute to the temporal and spatial variations in soil microbial respiration, consistent with previous studies (Abramoff et al. 2018, 2022). The variation of budgets for the different soil fractions among biomes is also distinct. In contrast to DOC and MBC concentrations, pastures store the largest amount of POC in 0–30 cm and 0–100 cm soil profiles, probably due to human disturbances, especially grazing, which can stimulate NPP, leading to abundant POC stored in soils (Crow et al. 2009). Consistent with the MBC and DOC budget (Guo et al. 2020; Xu, Thornton, and Post 2013), POC storage in temperate coniferous forests is the lowest in 0–30 cm and 0–100 cm soil profiles. Previous studies have demonstrated that high lignin content reduces the quality of C input and suppresses the microbial decomposition of litter to POC (Crow et al. 2009; Czimczik et al. 2003). Regarding total POC storage, pastures, mixed forests, uplands, and tropical forests contribute approximately 58%, with all other biomes contributing only about 42%, emphasizing the importance of POC sinks in these biomes.

Variations in POC spatial distribution at a global scale are consistent with DOC distribution observed in previous studies (Guo et al. 2020; Langeveld et al. 2019). Compared with temperate regions (30°–60° N), tropical regions (30° N–30° S) store less soil POC in both 0–30 cm and 0–100 cm soil profiles (Figure 4a,c). Given that the spatial distribution of POC is altered by climate, vegetation, and soil conditions, a possible explanation is that warm and wet conditions in tropical ecosystems promote microbial decomposition of organic matter, leading to large amounts of POC being consumed (Benbi, Boparai, and Brar 2014). The long and cold seasons constrain POC degradation in active layers in temperate regions.

The global distribution, storage, and controlling factors of POC are also illustrated in a recent study (Zhou et al. 2024). Zhou et al. (2024) reported the regions with higher C inputs and lower decomposition have higher POC concentration on a global scale, which is consistent with our study (Figure 4). However, the concentration and global storage of POC in the top meter at Zhou et al. (2024) (330 Pg) are higher than our study (223 Pg). The variation in data resources is the main reason for the difference in the estimation of POC global storage. For example, data measured in cropland with low POC content accounts for 49% of our study. Some variables in our study including SOC, TC, and BD are excluded in Zhou et al. (2024). The NPP data were derived from the MODIS gridded dataset at a spatial resolution of 30 s in this study, whereas collected from EARTHDATA in Zhou et al. (2024). The difference in covariate is expected to lead to discrepancies. Meanwhile, paddy and peatland were classified as separate biomes in the present study while lumped into other biomes by Zhou et al. (2024). Additionally, the dominant factors controlling POC are edaphic properties in our study, whereas are climatic factors Zhou et al. (2024). In our research, more edaphic factors closely relevant to POC persistence and turnover were used to quantify the impacts on POC concentration. The discrepancies between the two studies suggest a complicated mechanism underlying the dynamics of soil C fraction under changing environments.

The biogeographical patterns of soil POC and their controls are essential for predicting POC stock fluctuation in changing environments and for management practices facilitating C sequestration to cope with global warming. The data provided by this study can help better understand the mechanisms underlying the complex interconversion between different organic C fractions, which is beneficial for simulating the below-ground biogeochemical processes. Additionally, the database for POC concentrations, budget, and environmental controls can provide critically valuable information for the ongoing development of biological models.

4.5 | Prospectives

Our study compiled a global database of soil POC in terrestrial ecosystems and further estimated soil POC contents and budget at the biome and global levels. However, a few research directions were identified that could be done in future studies. First, the data collected from previous studies are reported using various measurement approaches, which might affect global estimates. Second, the distribution of data points is disproportionate among biomes, with only a few data points in temperate coniferous forests. This may cause biases when establishing the SEM and empirical model for investigating the mechanisms underlying POC distribution at a global scale. Third, all data for POC concentrations and environmental factors represent the annual average; no seasonal information is available. The missing information for the seasonality of POC concentrations may lead to biases in the reported patterns and dynamics of POC storage and content. Further works would help understand the indication mechanisms of POC patterns: (1) an effectively comparative analysis of different methodologies in terms of reporting POC will be available for a robust budget estimation; (2) the supplements of data points in some biomes such as temperate coniferous forest can improve the identification of dominant factors controlling POC distribution; (3) the collection of seasonal data especially in boreal regions will improve our understanding the seasonality of POC.

5 | Conclusion

By combining a compiled global dataset and statistical models, we estimated the soil POC concentration across biomes and quantified the global budget of POC in terrestrial ecosystems. We found that boreal forests and wetlands exhibit the highest POC concentration, whereas cropland and savannas have low POC content. Edaphic factors, including TC and texture, dominate the spatial variation of POC concentration. As POC derives from plant materials and is processed by microbes, the vertical distribution of POC follows the same patterns of soil microbial biomass, roots, and DOC along the soil profile. The global budget of POC is estimated to be 158.15 Pg C in 0–30 cm and 222.75 Pg C in 0–100 cm soil profiles. Our results show the importance of soils in tropical forests and pastures for storing POC.

The study produced a worthy dataset for soil C fraction in terrestrial ecosystems combined with DOC and MBC studies, which serves as a benchmark for simulating the turnover and transformation between different C fractions in soils. In addition, along with the increasing recognition of biogeography of microbial abundance, diversity, and community composition, the global patterns of soil C fractions deem further investigation. As more and more experimental and modeling research is implemented on soil POC dynamics and its controls, the study serves as a platform for data-model integration to better understand the dynamics of the global C cycle and more accurately simulate and project C dynamics in global soils.

Author Contributions

Ziyu Guo: data curation, formal analysis, investigation, methodology, software, writing – original draft, writing – review and editing. **Jianzhao Liu:** data curation, methodology, software, visualization. **Liyuan He:** formal analysis, methodology, validation, visualization, writing – original draft. **Jorge L. Mazza Rodrigues:** resources, supervision, writing – review and editing. **Ning Chen:** data curation, formal analysis, methodology, writing – original draft. **Yunjiang Zuo:** formal analysis, methodology, software, writing – original draft. **Nannan Wang:** methodology. **Xinhao Zhu:** data curation, methodology, writing – original draft. **Ying Sun:** data curation, methodology, visualization. **Lihua Zhang:** methodology. **Yanyu Song:** data curation, methodology, resources, visualization, writing – original draft. **Dengjun Zhang:** methodology, writing – review and editing. **Fenghui Yuan:** methodology, project administration, resources, writing – review and editing. **Changchun Song:** conceptualization, methodology, project administration, resources, supervision. **Xiaofeng Xu:** conceptualization, funding acquisition, methodology, project administration, resources, software, supervision, writing – original draft, writing – review and editing.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are openly available in Dryad at https://doi.org/10.5061/dryad.sbcc2frhh. The compiled variables include particulate organic carbon, vegetation type, soil texture, soil moisture, sampling dates, sampling depth, latitude, longitude, mean annual temperature, mean annual precipitation, soil pH, bulk density, total organic carbon, total nitrogen, soil dissolved organic carbon, soil dissolved organic nitrogen, soil microbial biomass carbon, and soil microbial biomass nitrogen. Soil fraction data are available from the LUCAS database at http://esdac.jrc.ec.europa.eu/content/lucas-2009-topsoil-data. Soil organic carbon, total carbon, and bulk density data are available from the Oak Ridge National Laboratory Distributed Active Archive Center (ORNL DAAC) at https://doi.org/10.3334/ORNLDAAC/1247. Soil carbon and total nitrogen data were from the ORNL DAAC at https://doi.org/10.3334/ORNLDAAC/1247. Mean annual temperature and mean annual precipitation data are available from WorldClim at https://www.worldclim.org/data/worldclim21.html (version 2). The mean annual and monthly soil moisture and soil temperature are available from the National Center for Atmospheric Research/Department of Energy Atmospheric Model Intercomparison Project (NCEP/DOE AMIP-II) at https://www.esrl.noaa.gov/psd/data/gridded/data.ncep.reanalysis2.gaussian.html (Reanalysis-2). Topsoil porosity data are available from the NASA Global Land Data Assimilation System at https://doi.org/10.5067/342OHQM9AK6Q. Annual net primary productivity is available from NASA LP DAAC at the USGS EROS Center: https://doi.org/10.5067/MODIS/MOD17A3.006. Soil microbial biomass carbon and nitrogen are available from the ORNL DAAC at https://doi.org/10.3334/ORNLDAAC/1264.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section.