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Soil dissolved organic carbon in terrestrial ecosystems: Global budget, spatial distribution and controls

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Abstract

Aims: Soil dissolved organic carbon (DOC) is a primary form of labile carbon in terrestrial ecosystems, and therefore plays a vital role in soil carbon cycling. This study aims to quantify the budgets of soil DOC at biome and global levels and to examine the variations in soil DOC and their environmental controls.

Location: Global.

Time period: 1981–2019.

Methods: We compiled a global dataset and analysed the concentration and distribution of DOC across 10 biomes.

Results: Large variations in DOC are found among biomes across space and the soil DOC concentration declines exponentially along soil depths. Tundra has the highest soil DOC concentration in 0–30 cm soils [453.75 (95% confidence interval: 324.95–633.5) mg/kg], whereas tropical and temperate forests have relatively lower DOC concentrations, ranging from 30.20 (24.78–36.80) to 54.54 (49.77–59.77) mg/kg. DOC generally accounts for < 1% of total organic carbon in soils, and DOC in 0–30 cm contributes more than half of the total DOC in the 0–100 cm soil profile. Furthermore, variations in DOC are primarily controlled by soil texture, moisture, and total organic carbon.

Main conclusions: A global synthesis is combined with an empirical model to extrapolate the DOC concentration along soil profiles across the globe, and global budgets of DOC are estimated as 7.20 Pg C in the top 0–30 cm and 12.97 Pg C in the 0–100 cm soil profile, respectively, with a considerable variation among biomes. The strong soil texture control but weak total organic carbon (TOC) control on DOC variations suggest that the investigation of physical protection of soil organic carbon might need to expand to consider the labile C in soils. The global maps of DOC concentration serve as a benchmark for validating land surface models in estimating carbon storage in soils.

KEYWORDS
biomes, dissolved organic carbon, terrestrial ecosystems, vertical distribution

ZG, YW and ZW contributed equally to this manuscript.

1 | INTRODUCTION

Dissolved organic carbon (DOC), a mixture of dissolvable organic carbon (C) compounds, plays a crucial role in terrestrial C cycling (Kalbitz, Solinger, Park, Michalzik, & Matzner, 2000; Marschner & Bredow, 2002; Neff & Asner, 2001). DOC is the most important substrate for microorganisms (Marschner & Bredow, 2002), and it represents a labile C form that turns over fast in soils (Neff & Asner, 2001). Moreover, the mineralization and mobilization of DOC contribute substantially to the loss of C from terrestrial ecosystems (e.g., forest ecosystems; Christ & David, 1996; Don & Kalbitz, 2005), and the release and retention of DOC can influence the function and nutrient status of soils (Kaiser, Kaupenjohann, & Zech, 2001). The concentrations and dynamics of DOC have been explored in many terrestrial ecosystems, such as tropical forests (Montano, Sandoval-Perez, Garcia-Oliva, Larsen, & Gavito, 2009), temperate forests (Spears, Holub, Harmon, & Lajtha, 2003), shrublands (Sowerby, Emmett, Williams, Beier, & Evans, 2010), grasslands(Boddy, Hill, Farrar, & Jones, 2007) and croplands (Lundquist, Jackson, & Scow, 1999). However, a comprehensive global analysis of the DOC distribution and its controlling factors is lacking.

Soil DOC is derived from litter leachates, root exudates, and microbial degradation products (Don & Kalbitz, 2005; Hongve, 1999; Marschner & Bredow, 2002; Zsolnay, 1996). Therefore, all factors contributing to litter formation, root growth and microbial activities affect the DOC concentrations in soils (Neff & Asner, 2001). A large amount of studies have found large variations in DOC concentration among climate zones, vegetation type and soil properties (Christ & David, 1996; Guggenberger & Zech, 1993) across temporal and spatial scales (Langeveld et al., 2019). Numerous studies and experiments have been conducted to examine the controls on DOC concentrations (Filep & Rekasi, 2011), including temperature and moisture (Christ & David, 1996), soil pH (Andersson & Nilsson, 2001; Filep, Kincses, & Nagy, 2003), soil texture/clay (Thomsen, Olesen, Schjønning, Jensen, & Christensen, 2001), organic matter content (Hagedorn, Kaiser, Feyen, & Schleppi, 2000; Michel, Matzner, Dignac, & Kögel-Knabner, 2006), soil nitrogen (N) content, and microbial activity (Cookson et al., 2005; Nemeth, Bartels, Vogel, & Mengel, 1988). However, a mechanistic understanding of the environmental controls on DOC distribution across different biomes and at the global scale is still lacking (Camino-Serrano et al., 2014).

In this study, we investigated soil DOC concentrations in the 0–100 cm soil profile in terrestrial ecosystems at biome and global scales. The objectives are: (a) to investigate spatial and vertical distributions of DOC in different biomes; (b) to examine the major factors controlling the patterns of DOC distribution at the global scale; and (c) to estimate the budgets of DOC in 0–30 cm and 0–100 cm soil profiles at biome and global scales. We established an empirical model to quantify the environmental controls on DOC concentrations, and further used it to combine with global maps of soil properties and climate data to produce global maps of soil DOC concentration. In addition, we evaluated the effects of climatic and edaphic factors on the concentration and distribution of DOC, and created a structural equation model (SEM) to investigate the underlying mechanisms for DOC variations.

2 | DATA AND METHODS

2.1 | Data sources

The data for DOC concentrations were collected from the publications by searching 'soil DOC' in Google Scholar and the Web of Science. The data points were derived from tables containing soil DOC or extracted by the Engauge Digitizer software version 10.7 (http://digitizer.sourceforge.net/) from figures in collected publications. The data points with reported soil DOC concentrations greater than total organic C (TOC) concentration were excluded from the database. In total, 3,869 data points were retrieved from 107 papers published during 1981–2019 (Supporting Information Table S1). The database represents 171 sites from 33 countries, of which 34.1% are in Europe, 34.6% in Asia, 27.2% in North and South America and < 4% in other continents (Figure 1). These data points represent soil samples from various depths between 0 and 100cm. Available auxiliary information of the sampling sites was also retrieved, including the latitude and longitude, mean annual air temperature (MAT), mean annual precipitation (MAP), soil pH, TOC, total nitrogen concentration (TN), vegetation type, soil texture type and sampling date. The database used in this study was organized in April 2019 and was updated and finalized on 20 November 2019.

Based on vegetation types in our database and the classification criterion used in Xu, Thornton and Post (2013), the data points were classified into 10 biomes, including boreal forest, temperate coniferous forest, temperate broadleaf forest, tropical forest, grassland, shrubland, tundra, natural wetlands, cropland, and pasture. Glacier and bare soils (mainly urban and industrial sites) were not included in this study; no DOC concentration data were reported for desert; therefore, the desert ecosystem is excluded from the present analysis. Data for savanna (one data point) were insufficient for statistical analysis, we thus aggregated savanna into grassland. Peatland was classified as natural wetlands. Additionally, the data for the tropical forest, temperate coniferous forest and temperate broadleaf forest were combined to represent mixed forest. Temperate broadleaf forest, boreal forest, tropical forest, grassland and cropland contribute approximately 22, 17, 13, 13 and 12%, respectively, whereas the rest of biomes together contributed approximately 23% of the entire database. The database was grouped into two subsets: one subset contains 2,888 data points for 0–30 cm soil profiles with *c*. 74% for 0–15 cm profiles, and the other subset contains 941 data points along 30–100 cm soil profiles with each set of data points for at least three soil depths for one sampling site.

Other metadata, not measured in situ, were extracted from spatial datasets following our previous study (Xu et al., 2017). When not available at the site-level, we extracted point-level soil data [soil pH, soil texture (silt, clay and sand) and bulk density] from the Re-gridded Harmonized World Soil Database v1.2 in the Oak

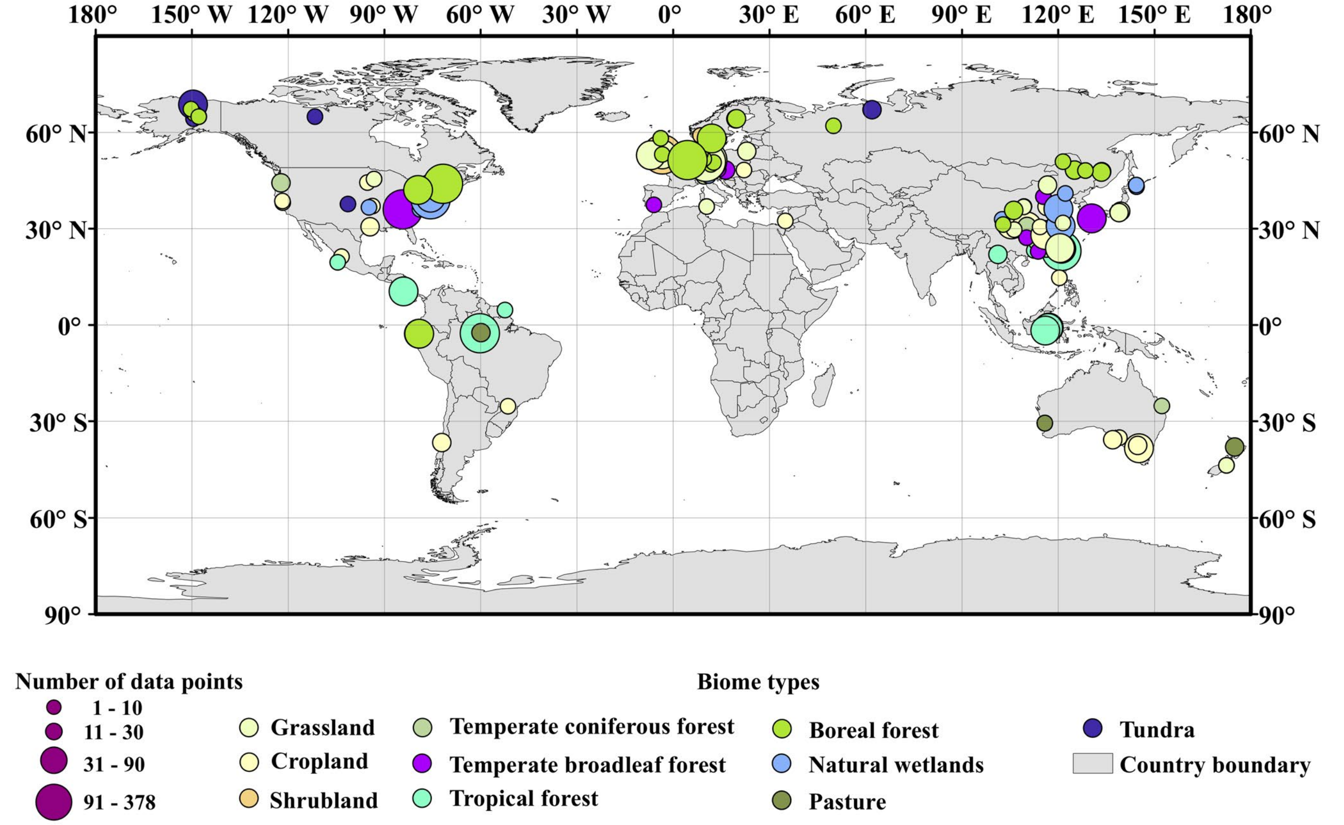

FIGURE 1 Distribution of the data points used in the study (3,869 data points with geographical coordinates are shown on the map) [Colour figure can be viewed at wileyonlinelibrary.com]

Ridge National Laboratory Distributed Active Archive Center for Biogeochemical Dynamics (available online) (FAO/IIASA/ISRIC/ISSCAS/JRC, 2009). Soil temperature and soil moisture data for the top 10 cm were downloaded and extracted from the National Center for Atmospheric Research/Department of Energy Atmospheric Model Intercomparison Project (NCEP/DOE AMIP-II) Reanalysis (Reanalysis-2) monthly average dataset on 12 June 2015 (available online; Kanamitsu et al., 2002; Ruesch & Gibbs, 2008; Song et al., 2017). The extraction of soil temperature and moisture was based on a 35-year average (1979–2014) to represent the site-level meteorology conditions. Annual net primary productivity (NPP) was obtained from the Moderate Resolution Imaging Spectroradiometer (MODIS) gridded dataset with a spatial resolution of 30 s during 2000–2015 (http://files.ntsg.umt.edu/data/NTSG_Products/). Because many meteorological data were missing in publications, the meteorological data (MAT and MAP) were obtained from the WorldClim database version 2 with a spatial resolution of 30 s during 1970–2000 (http://worldclim.org/worldclim21.html). The corresponding grid values were extracted based on their geographical coordinates.

2.2 | Data standardization

The compiled dataset consists of 30.0% measured DOC concentrations in soils and 70.0% DOC in soil solutions (Supporting Information Dataset S1). The reported methods for extracting soil solutions include lysimeters, piezometers, ceramic suction or centrifugation. Different methods were used to measure DOC concentrations, such as the TOC analyser method (81.31% of database, various analyser models were used, such as Shimadzu, Japan; Rosemount Dohrmann, OH; Messtechnik, Austria; Analytik, Germany; DimaTOC, Essen, etc.), ultraviolet absorption method (3.74%; Deflandre & Gagne, 2001), and the spectrophotometric method (2.80%; Bolan, Baskaran, & Thiagarajan, 1996; Moore, 1985). Other methods, including the persulphate digestion method (Doyle, Weintraub, & Schimel, 2004) and the dichromate oxidation method (Jenkinson & Powlson, 1976), the volumetric method (Lu, 1999), the colorimetric method (Bartlett & Ross, 1988), the dry oxidation method (Bolan et al., 1996) and some other methods, accounted for 12.15% of the dataset. To standardize the data for DOC concentrations measured in different soil samples, we converted the reported DOC concentrations in soil solutions to be consistent with measured soil DOC concentration in soils with the following formula:

$$DOC_{soil} = \frac{DOC_{solution} \times V \times 1000}{W} \times \frac{1}{V \times (1-W) \times BD \times 1000000} \quad (1)$$

where DOC_{soil} is DOC concentration in soil (mg/g); $DOC_{solution}$ is DOC concentration in soil solution (mg/L); W is the volumetric soil moisture (m^3/m^3); V is the unit volume for the soil column used for extracting soil solution (m^3); *BD* is the bulk density (g/cm^3); 1,000 is used for unit conversion from m^3 to L, and 1,000,000 is used for converting m^3 to cm^3.

2.3 | Vertical distribution of DOC along soil depth

Soil DOC production is highly associated with soil microbial activities (Guggenberger & Zech, 1993), and soil microbial biomass has been proved to decrease exponentially with the soil depth in association with the root distribution (Jackson et al., 1996; Xu et al., 2013). We hypothesized that soil DOC exhibits the same pattern of vertical distribution as root systems and soil microbial biomass in terrestrial ecosystems, because (a) leaching of plant litter and labile organic matter usually occurs near the soil surface (Kaiser & Kalbitz, 2012), and (b) the microbial decomposition of organic matter is tightly associated with the root distribution (Cheng & Kuzyakov, 2005). To estimate soil DOC distribution along soil depth, an asymptotic equation as below was applied:

$$Y = 1 - \beta^d, \tag{2}$$

where the *Y* is the cumulative soil DOC fraction (a proportion between 0 and 1) from the soil surface to depth *d* (cm), and β is the fitted 'coefficient' (Jackson et al., 1996). High β is associated with a smaller proportion of soil DOC content near the soil surface, and vice versa (Jackson et al., 1996).

2.4 | The empirical model for DOC distribution among biomes

An empirical model was established to estimate the DOC concentrations in 0–30 cm soil profiles with considerations of its primary controlling factors. The log-transformation was used to convert DOC concentrations (mg/g) to ensure normality for robust statistical analyses. This model was built in a combined forward/backward multiple-linear regression analysis using two-thirds of the data points, and the 'best' model was chosen based on the lowest Akaike information criterion (AIC) value (Langeveld et al., 2019).

Finally, 31.64% of variations in DOC concentrations among biomes in top 30 cm soils can be explained by selected factors in the empirical model as following:

$$\begin{aligned} Log(DOC) &= a_0 + a_1 ST + a_2 SW + a_3 Sand + a_4 Clay + a_5 NPP \\ &+ a_6 TC + a_7 TN + a_8 BD + a_9 STTC + a_{10} SWTC + a_{11} STSW \\ &+ a_{12} NPPTC + a_{13} STNPP + a_{14} SW{:}NPP + a_{15} STSWTC \\ &+ a_{16} STNPPTC + a_{17} SWNPPTC + a_{18} STSWNPP + a_{19} STSWNPPTC \end{aligned} \tag{3}$$

where $a_0 \sim a_{19}$ are the coefficients for the corresponding controlling variables (Supporting Information Table S3). The selected variables are soil temperature (ST; °C), soil water content (SW; %), soil sand content (Sand; %), soil clay content (Clay; %), NPP (g/m^2/year), total soil carbon content (TOC; mg/g), TN (mg/g) and BD (g/cm^3). The other one third of the data points were used for model validation. The model validation showed empirical model-derived DOC concentrations were highly correlated to observational data of DOC concentrations ($R = .869$, $p < .001$) (Supporting Information Figure S1), which confirmed the accuracy and reasonability of our empirical model for simulating DOC concentrations.

2.5 | Global budgets of DOC

Based on the vertical and spatial distribution of DOC from Equation 2 and the empirical model shown in Equation 3, we estimated the distribution and budget of DOC at the global scale by combining with global maps of biome distribution, soil properties, and meteorological data. The distribution and concentration of DOC in 0–30 cm soil profiles were estimated for 10 biomes, and the estimated DOC was removed if the computed DOC was greater than 2.5% of TOC in the International Geosphere-Biosphere Programme Data and Information System (IGBP-DIS) dataset. Then, based on DOC fractions in 0–30 cm and 0–100 cm soil profiles (Supporting Information Table S4) for each biome, the distribution and concentration of DOC were estimated along 0–100 cm soil profiles. Due to the lack of vertical data for tundra, we used the β-values provided by Jackson et al. (1996) to calculate the vertical distribution of DOC in the tundra ecosystem.

2.6 | Statistic analysis

Because the DOC concentrations and DOC : TOC ratio did not follow a normal distribution, we used the log-transformation to convert them to ensure normality for robust statistical analyses. The mean and 95% confidence intervals of DOC concentrations and DOC : TOC ratios were then converted back to original values for reporting. Analysis of variance (ANOVA) was conducted to test the differences in DOC concentrations and DOC : TOC ratios among biomes. A Mantel test and correlation analysis were applied to quantify the effects of climate, vegetation and soil variables on DOC concentrations. In addition, a ternary plot displaying the soil texture controls on DOC was created using the package 'soiltexture' in the RStudio software version 1.0.143 (http://www.rstudio.com/), and a structural equation model (SEM) was applied to develop a framework to understand the controlling factors on DOC variations. Generalized linear regression was used to validate the Empirical Model 3 for simulating DOC concentrations in the 0–30 cm soil profile (Supporting Information Figure S1). All statistical analyses were conducted using the RStudio software version 1.0.143 (http://www.rstudio.com/). The global maps (Figures 1 and 5) were generated using the ArcGIS software (version 10.2, ESRI, Redlands, CA) in Windows 10.

TABLE 1 Biome-level soil dissolved organic carbon (DOC) concentrations and DOC : total organic carbon (DOC : TOC) ratios

Biome	DOC (mg/kg)	DOC : TOC (%)
Boreal forest	127.348[c] (112.174–144.576)	0.697[a] (0.155–3.124)
Temperate coniferous forest	30.199[i] (24.784–36.797)	0.182[de] (0.111–0.297)
Temperate broadleaf forest	54.541[ef] (49.766–59.773)	0.359[bc] (0.252–0.511)
Tropical forest	38.238[h] (35.160–41.584)	0.225[de] (0.187–0.272)
Mixed forest	46.084[fg] (43.223–49.136)	0.245[cd] (0.209–0.287)
Grassland	92.079[d] (79.854–106.177)	0.231[d] (0.153–0.349)
Shrubland	110.158[cd] (102.915–117.910)	na
Tundra	453.750[a] (324.952–633.598)	0.147[e] (0.072–0.302)
Natural wetlands	199.440[b] (180.227–220.701)	na
Cropland	60.578[e] (53.011–69.226)	0.180[de] (0.154–0.211)
Pasture	105.315[d] (71.377–155.392)	0.418[b] (0.286–0.609)
Global average	77.387 (73.838–81.106)	0.232 (0.212–0.255)

Note.: na = no value available due to insufficient data. Values are presented as mean with 95% confidence intervals in parentheses. Different superscript letters in one column indicate a significant difference at a significance level of $p = .05$, while the same letters indicate no significant difference.

3 | RESULTS

3.1 | Biome-level DOC concentrations

DOC concentrations in the 0–30 cm soil profile vary among biomes (Table 1). The global average of DOC concentrations is 77.39 (73.84–81.11) mg/kg (Table 1). Across biomes, six biomes had DOC concentrations greater than the global average. Specifically, tundra has the highest DOC concentration among biomes, where the DOC is estimated at 453.75 (324.95–633.60) mg/kg (Table 1). Meanwhile, DOC concentrations in natural wetlands, boreal forest, shrubland, pasture, and grassland are significantly different, with soil DOC being estimated at 199.44 (180.23–220.70), 127.35 (112.17–144.58), 110.16 (102.91–117.91), 105.32 (71.38–155.39) and 92.08 (79.85–106.18) mg/kg, respectively (Table 1). Other biomes, including cropland, temperate broadleaf forest, mixed forest, tropical forest and temperate coniferous forest, had lower DOC compared with the global average, ranging from 30.20 (24.78–36.80) mg/kg in temperate coniferous forest to 60.58 (53.01–69.23) mg/kg in cropland (Table 1).

3.2 | Fraction of TOC in DOC

The fraction of TOC in DOC is generally less than 1% across all key biomes, with a global average of 0.23 (0.21–0.26)% (Table 1). There is a small variation in DOC : TOC ratio among biomes. Boreal forest has the highest soil DOC : TOC ratio at 0.70 (0.16–3.12)%, followed by pasture at 0.42 (0.29–0.61)% and temperate broadleaf forest at 0.36 (0.25–0.51)%, whereas tundra has the lowest DOC : TOC ratio at 0.15 (0.07–0.30)% (Table 1). Meanwhile, soil DOC : TOC ratios for mixed forest, grassland, tropical forest, temperate coniferous forest, and cropland range from 0.18 to 0.25%, consistent with the global average (Table 1).

3.3 | Vertical distribution of soil DOC

The β-value differs among biomes, ranging from .965 to .982 (Figure 2), which is in good agreement with those for roots reported in Jackson (1996). The fitted curves of vertical distribution show that DOC in the topsoils contributes more than half of the total DOC in the soil profile (Figure 2). Specifically, biome-level DOC concentrations in the 0–30 cm soil profile range from 42 to 65% (Figure 2). Temperate broadleaf forest with the lowest β stores more DOC in the 0–30 cm soil profile, whereas natural wetlands with the highest β store more DOC in deep soils (Figure 2). DOC in the 0–30 cm soil profile contributes more than 50% of the total DOC in the 0–100 cm soil profile in all other biomes (Figure 2).

3.4 | Associations between soil DOC and environmental factors

There are strong associations between soil DOC and multiple factors including meteorological, biological and soil factors (Figure 3).

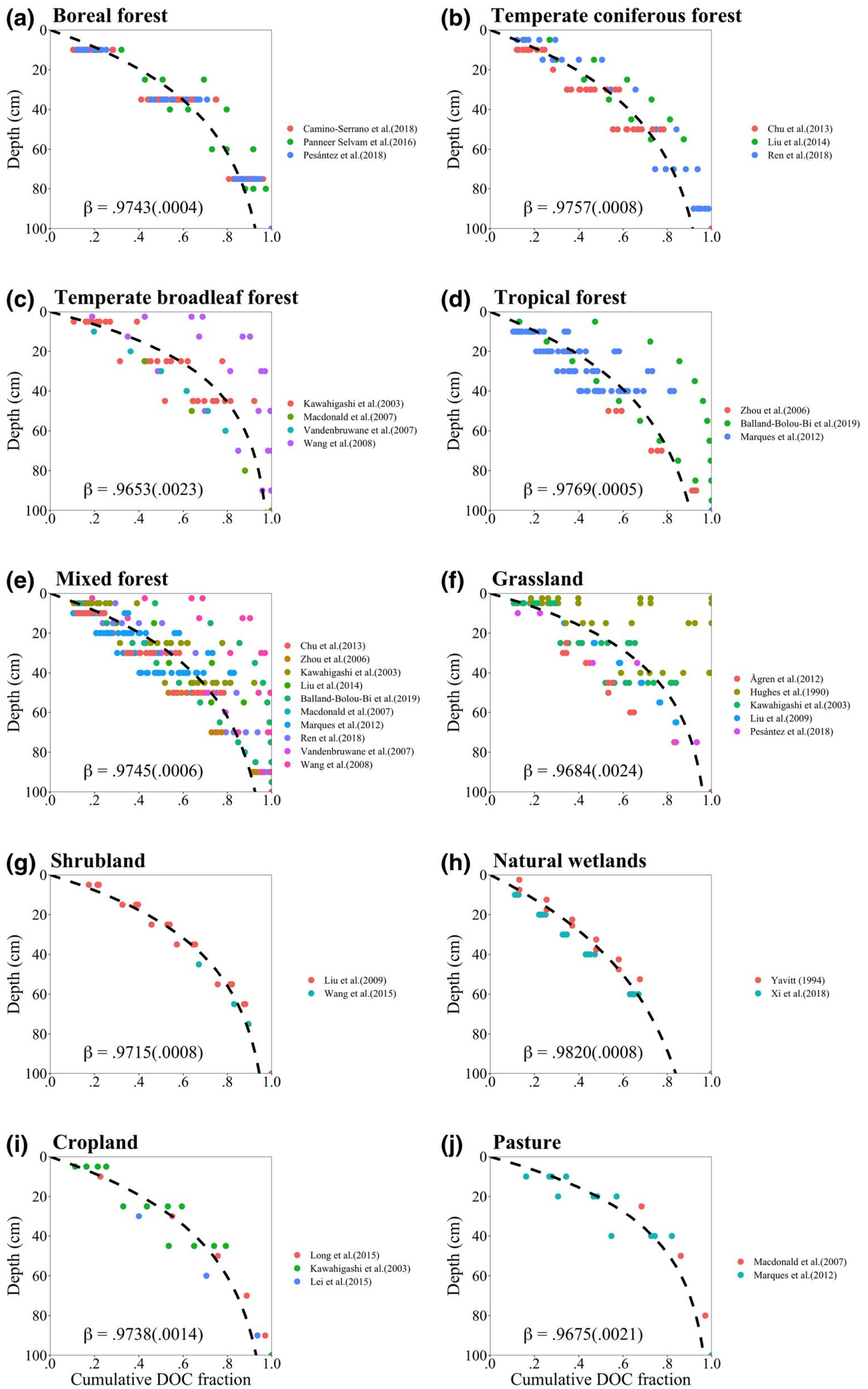

FIGURE 2 Vertical distribution of soil dissolved organic carbon (DOC) in major biomes (boreal forest, temperate coniferous forest, temperate broadleaf forest, tropical forest, mixed forest, grassland, shrubland, natural wetlands, cropland and pasture). Different colours represent the subsets of data points and each subset contains data points from at least three soil depths. The β-value with standard error is displayed for each biome [Colour figure can be viewed at wileyonlinelibrary.com]

Variation of soil DOC is well explained by the MAT (r = .138, p = .001) and NPP (r = .114, p = .001) (Figure 3a and Supporting Information Table S5). In addition, MAP (r = .087, p = .001), ST (r = .068, p = .001) and TN (r = .088, p = .001) are also significantly correlated with soil DOC (Figure 3a and Supporting Information Table S5). MAT is positively correlated with MAP and both have

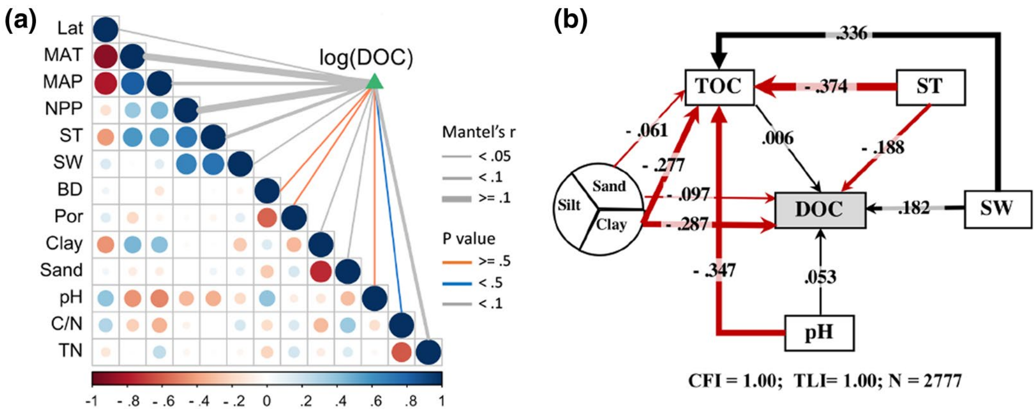

FIGURE 3 (a) Mantel test showing the relationships between log dissolved organic carbon [log(DOC)] and environmental factors. (b) Structural equation model (SEM) of soil temperature (ST), soil water content (SW), soil pH (pH), soil clay content (Clay), soil sand content (Sand) and soil total organic carbon (TOC) as predictors of soil dissolved organic carbon (DOC). Pairwise comparisons of environmental factors are displayed with a colour gradient denoting Spearman's correlation coefficient. Lat = latitude; MAT = mean annual air temperature; MAP = mean annual precipitation; NPP = net primary production; ST = soil temperature; SW = soil water content; BD = bulk density; Por = soil porosity; Clay = soil clay content; Sand = soil sand content; pH = soil pH; C/N = soil C : N ratio; TN = soil total nitrogen content. In the SEM structure, solid red arrows represent positive paths ($p < .05$, piecewise SEM) and solid black arrows represent negative paths ($p < .05$, piecewise SEM). The path coefficients are reported as standardized effect sizes. Overall fit of the piecewise SEM was evaluated using the comparative fit index (CFI) and Tucker–Lewis index (TLI). A CFI and TLI both larger than .95 indicates a relatively good model–data fit in general (Hu & Bentler, 1999). Two thousand seven-hundred and seventy-seven of the data points were used in the model [Colour figure can be viewed at wileyonlinelibrary.com]

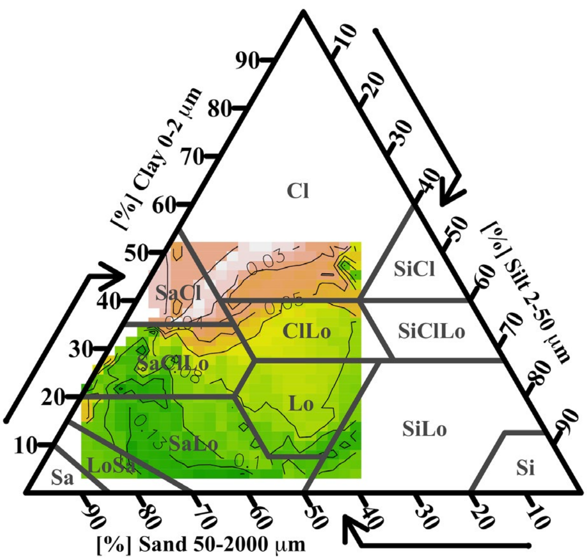

FIGURE 4 Relationships between soil texture and the soil dissolved organic carbon (DOC) concentrations. Cl = clay; SiCl = silty clay; SaCl = sandy clay; ClLo = clay loam; SiClLo = silty clay loam; SaClLo = sandy clay loam; Lo = loam; SiLo = silty loam; SaLo = sandy loam; Si = silt; LoSa = loamy sand; Sa = sand. The mapped texture classes represent the distribution of DOC in surface soil (0–30 cm) [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 2 Dissolved organic carbon (DOC) budgets at biome and global scales (Pg C)

Biome	Area (million km^2)	0–30 cm soil profile	0–100 cm soil profile
Boreal forest	7.0	0.892	1.648
Temperate coniferous forest	2.5	0.124	0.238
Temperate broadleaf forest	3.6	0.133	0.204
Tropical forest	15.6	0.474	0.939
Mixed forest	11.9	1.185	2.194
Grassland	12.2	0.610	0.987
Shrubland	8.1	0.359	0.619
Tundra	5.7	0.613	1.019
Desert	13.5		
Natural wetlands	6.7	0.599	1.424
Cropland	14.8	0.833	1.516
Pasture	26.8	1.376	2.187
Total	128.3	7.197	12.974

strong negative correlations with latitude (Figure 3a). NPP is significantly positively correlated with ST ($r = .713$, $p < .001$) and SW ($r = .655$, $p < .001$) (Figure 3a and Supporting Information Table S6). Additionally, a strong correlation exists between ST and SW ($r = .739$, $p < .001$), Clay and Sand ($r = -.740$, $p < .001$), and soil C : N ratio and TN ($r = -.613$, $p < .001$) (Figure 3 and Supporting Information Table S6).

We further applied the SEM approach to evaluate the potential environmental controls on DOC concentrations (Figure 3b). TOC has a minor direct impact on DOC concentration ($\beta = 0.006$, $p < .001$), while the direct impacts of SW ($\beta = 0.182$, $p < .001$) and soil pH ($\beta = 0.053$, $p < .001$) on DOC are moderate. In addition, ST, Clay and Sand have slightly negative impacts on soil DOC (Figure 3b).

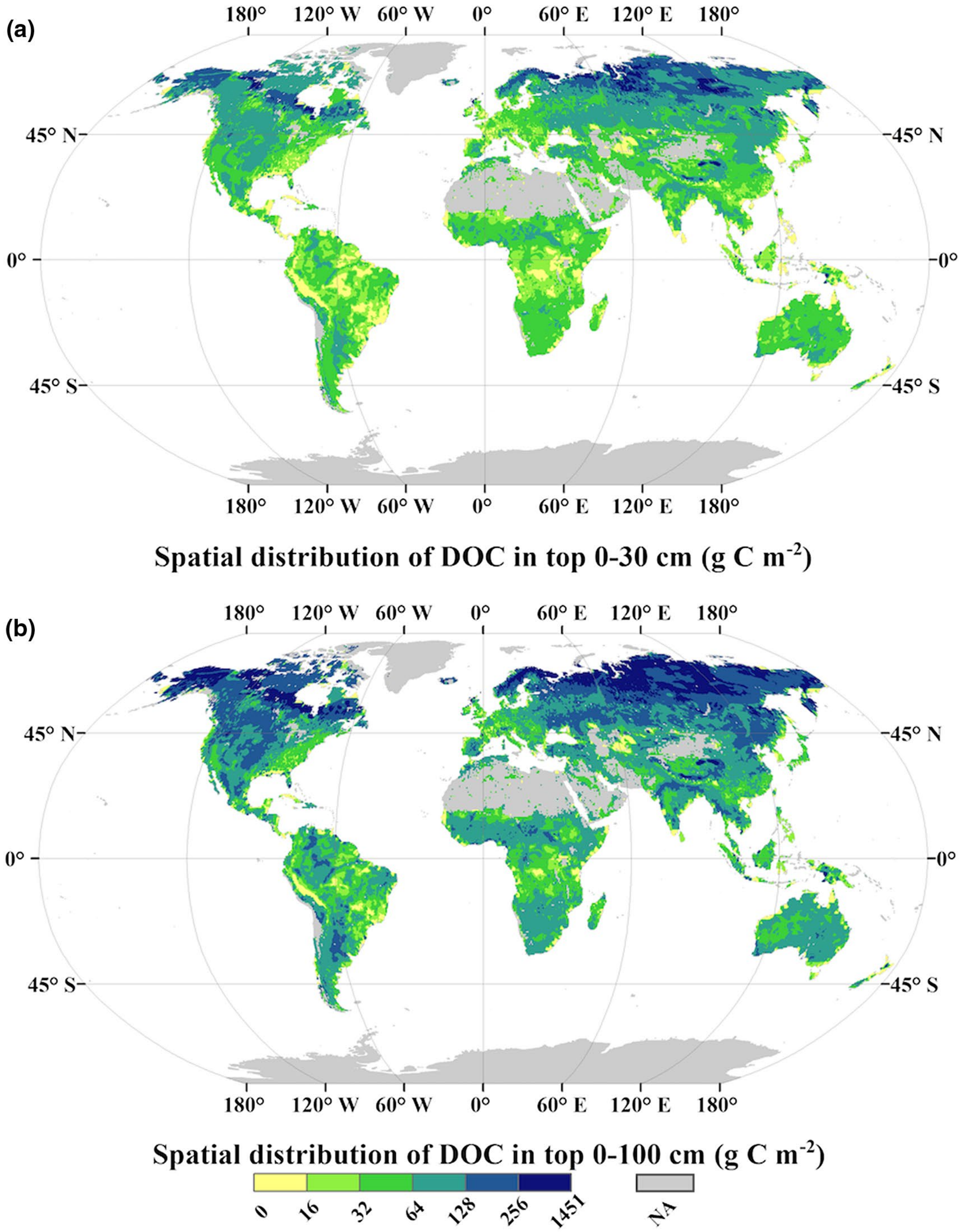

FIGURE 5 Global distribution of soil dissolved organic carbon (DOC) in terrestrial ecosystems in (a) 0–30 cm soil profile and (b) 0–100 cm soil profile [Colour figure can be viewed at wileyonlinelibrary.com]

A further analysis emphasizes the important role of soil texture in controlling DOC concentration. Due to data limitations, a partial ternary plot was produced with the present dataset (Figure 4). DOC concentration is higher in sandy loam soils, whereas it is lower in sandy-clay soils and clay soils. A clear gradient is observed along with the soil structure, with a low DOC concentration in clay soil, intermediate level of DOC concentration in clay loam and medium loam soil, and high DOC concentration in silty loam (Figure 4).

3.5 | Global budget and distribution of DOC

The global DOC budget is estimated as 7.197 Pg C in the 0–30 cm soil profile, which exceeded 50% of the total DOC budget in 0–100 cm soil profiles (*c.* 12.974 Pg C) (Table 2), and accounts for *c.* 0.485% of TOC (*c.* 1,570 Pg C) derived from the IGBP database. The global budget of DOC in 0–100 cm soil profiles contributes approximately 0.880% of the TOC, which is smaller than the proportion of soil microbial biomass C (MBC) in TOC (Xu, Thornton &

Post, 2013). DOC budgets in the 0–30 cm soil profile substantially differ among biomes, with the largest amount in pasture and the smallest in temperate coniferous forest (Table 2). The pattern of DOC budgets in the 100 cm soil profile shows slight differences among biomes, with the largest amount in mixed forest and smallest in temperate broadleaf forest (Table 2).

Furthermore, DOC distribution in both 0–30 and 0–100 cm soil profiles shows large spatial variations at the global scale (Figure 5). For example, DOC budgets are high in northern high-latitude regions (60–70° N) due to widely distributed boreal forest and natural wetlands, while the low DOC recorded at low latitudes is associated with tropical forests with high mean annual temperature (Figure 5).

4 | DISCUSSION

4.1 | Variations in soil DOC among biomes

Large variations in soil DOC concentration have been observed among biomes (Table 1 and Figure 5). The amount of DOC stored in soils is largely affected by vegetation types, especially their differences in C allocation between shoots and roots (Jackson et al., 1996). For example, although there is no significant difference in DOC concentration between shrubland and grassland, shrubland shows a slightly higher DOC concentration than grassland, probably due to its higher portion in deep soil, consistent with their root distribution (Jackson et al., 1996). Moreover, in forests, species composition influence the quality of C input, which affects microbial decomposition and thus leads to changes in soil DOC concentration. For example, temperate coniferous forest features a lower DOC concentration than temperate broadleaf forest, which is consistent with previous studies (Camino-Serrano et al., 2014; Currie, Aber, McDowell, Boone & Magill, 1996; FernandezSanjurjo, Vega, & GarciaRodeja, 1997; Langeveld et al., 2019). This is a result of the mechanism by which higher lignin content lowers the quality of plant litter and thus hinders microbial decomposition, leading to less DOC being released (Wang et al., 2015). In addition, the thick epidermis layer in coniferous leaves can slow down decomposition, one of the key mechanisms for DOC formation (Don & Kalbitz, 2005).

The effects of vegetation on soil DOC are also associated with climate conditions. Despite the lower NPP, tundra contains a huge amount of DOC in soils due to low temperature and likely saturated soils. This can be explained by reduced DOC degradation due to low microbial activity in the permafrost (Petrone, 2005). Additionally, among the five forest types, boreal forest shows two- to fourfold greater soil DOC concentration than temperate broadleaf forest, mixed forest, tropical forest and temperate coniferous forest individually, which may be caused by the weakened microbial degradation of DOC under low temperature in high-latitude regions. In addition to the effects of low temperature, anoxic conditions due to soil oversaturation can also alter the DOC concentration in terrestrial ecosystems. Under anoxic conditions, microbial activities and growth are greatly restricted, which lowers the decomposition of DOC into carbon dioxide (CO_2). For instance, natural wetlands have the second-highest DOC concentration, which is likely caused by strictly anoxic conditions caused by oversaturation (Mitsch et al., 2012).

Furthermore, different land-use types can lead to changes in soil DOC concentration due to differences in the management intensity. In general, cropland is more affected by intensive anthropogenic activities including management and artificial disturbances compared with pasture. Although nutrient addition in cropland is more common than in pasture, the harvest frequency is also much higher than in pasture, which leads to a large loss of soil organic matter, and further reduces the concentrations of SOC and DOC. This is consistent with our results that cropland contains *c*. 58% of the soil DOC concentration in pasture.

4.2 | Vertical distribution of soil DOC in different biomes

Soil DOC primarily results from the leaching of substances from fresh litter and the decomposition of plant residue and organic matter (Qualls, Haines, & Swank, 1991). We hypothesized that the vertical distribution of soil DOC is correlated with the distribution of root systems and soil MBC in terrestrial ecosystems (Xu, Thornton & Post, 2013), exhibiting an exponential decline along soil depth. Our results indicate that most biomes store more than 50% of total soil DOC in 0–30 cm soil profiles (Supporting Information Table S4), consistent with the root distribution in different biomes. In a global review of root distributions, grasses have the shallowest root profiles, trees are intermediate and shrubs have the deepest profiles (Jackson et al., 1996). As a result, grass- and tree-dominated biomes, such as temperate broadleaf forest, pasture, and grassland, have larger proportions of soil DOC in topsoils than other biomes in our study. The correlation between soil DOC and root distribution can be explained by the fact that soil DOC is affected by soil microbial community composition and activity, which are further limited by C supplies from root exudation and turnover (rhizodeposition) (Raich & Tufekciogul, 2000). But natural wetlands retain large volumes of water with a great potential to be DOC sinks in deep soils, which may be caused by: (a) the movement of soil water bringing more dissolved nutrients including DOC into deep soils, and (b) the high absorption capacity of mineral soils for DOC in deep soils (Kalbitz et al., 2000).

4.3 | Environmental controls on soil DOC concentration

The environmental controls derived from this study are generally in line with previous studies that reported meteorological, biological and edaphic factors to be the key controls (Camino-Serrano et al., 2014). A previous studyreported a positive correlation between DOC concentration with high SW and long water retention times in natural wetlands (Hongve, 1999), which is consistent with our results. However, the correlation between DOC and soil pH is contradictory to previous studies suggesting higher DOC concentrations in acid soil solutions (Camino-Serrano et al., 2014; Clarke, Rosberg, & Aamlid, 2005; Lofgren & Zetterberg, 2011). TOC is the source of microbial decomposition to produce DOC; higher TOC can lead to greater production of DOC. In addition, TOC is correlated with all the other controls (Figure 5), which indicates that the environmental controls can not only directly alter the DOC concentration, but also indirectly influence the mechanisms of DOC production and retention in soils.

In addition, soil DOC is negatively correlated with ST, Sand and Clay (Figure 3b). It has been reported that a pulse release of DOC at high temperatures (e.g., 15–20ss°C) in many incubation and field experiments is generally caused by the stimulation of microbial activity (Christ & David, 1996; Marschner & Bredow, 2002). Moreover, in forests, changes in soil solution chemistry or dead microbial biomass that starved from substrate depletion could also contribute to DOC release at a warmer temperature (Andersson, Nilsson, & Saetre, 2000; Marschner & Bredow, 2002). Soil texture has been reported to affect soil DOC concentration through effects on DOC sorption capacity and soil organic matter (SOM) stabilization potential (Camino-Serrano et al., 2014; Filep & Rekasi, 2011; Schwendenmann & Veldkamp, 2005). Moreover, soil classes partly account for differences in hydrological flow paths, leading to identified differences in subsoil DOC concentrations between the US Department of Agriculture (USDA) soil classes (Don & Schulze, 2008; Johnson, Lehmann, Couto, Novaes, & Riha, 2006; Langeveld et al., 2019). In this study, DOC concentration is high in sandy-loam soils and low in sandy clay soils and clay soils (Figure 5), likely due to differences in the water holding capacity and cation exchange capacity among soil types.

4.4 | DOC budget and its implications for global C cycling

DOC as a critical labile C pool performs essential roles in multiple biochemical processes. Estimation of global DOC budgets in terrestrial ecosystems can enrich our knowledge about the magnitude and composition of C storage and the potential influence of DOC distribution on controlling ecosystem processes. In this study, global DOC budgets in 0–30 and 0–100 cm soil profiles were estimated to be 7.62 and 13.81 Pg C, which contributed *c.* 0.49 and *c.* 0.88%, respectively, to global soil organic C storage. These proportions are comparable to soil DOC : TOC ratios derived for different biomes, but are less than the fraction of soil organic C in soil microbial biomass C reported by Xu et al. (2013). The magnitudes of DOC storage are distinct among biomes. In contrast with DOC concentrations, pasture stores a large amount of DOC in the 0–30 cm soil profile, probably due to the stimulating effects of grazing on NPP. Temperate coniferous forest has the lowest amount of DOC storage in the 0–30 cm soil profile; the low quality of C input due to the high lignin content is the key constraint determining microbial decomposition rates (Wang et al., 2015). In terms of total DOC storage, mixed forest, pasture, boreal forest, natural wetlands, and croplands contribute approximately 65%, with all other biomes together only contributing about 35%, which emphasizes the importance of C sinks in these biomes.

Variations in soil DOC distribution at a global scale are consistent with a previous study (Langeveld et al., 2019), with greater DOC storage in high-latitude regions and lower DOC storage in equatorial regions. However, in contrast with this study, Langeveld et al. (2019) reported much lower DOC levels in Arctic regions. This difference may be caused by ignoring DOC concentrations in soil solution and in dry or frozen soils in Langeveld et al. (2019). Our empirical model has the advantage of estimating the DOC storage with a higher accuracy, due to the combined data of DOC concentration in both dry soils and soil solution. As previously discussed, the spatial distribution of soil DOC is influenced by climate, vegetation, and soil conditions, but it is also affected by geographical location according to the global maps of DOC budgets. For example, northern high-latitude regions (60–70° N) contain higher amounts of soil DOC, probably due to inhibition effects of low temperature on microbial degradation of organic matter.

The global DOC budget is estimated as 12.97 Pg C for the 0–100 cm soil profile, which accounts for 0.880% of TOC, smaller than the fraction of soil organic C in soil microbial biomass C (Xu et al., 2013). The residence time of soil DOC ranges from a few hours to a few days, with some low molecular compound cycling on a minute timescale (Boddy et al., 2007). Given the fact that soil DOC is the ultimate substrate for soil microorganisms, the soil DOC variations contribute to the temporal and spatial variations in soil microbial biomass C and microbial respiration, consistent with the previous findings of controlling factors on DOC and microbial abundance and microbial quotient (Sinsabaugh & Follstad Shah, 2012; Xu et al., 2017; Xu, Thornton & Post., 2013).

The biogeographical patterns of DOC and their controls are valuable information for parameterizing global C models in simulating the labile C in soils. Along with the recent development of microbial models, the data produced in this study can help better simulate the belowground biogeochemical processes. Therefore, the database compiled and the environmental controls derived in this study provide critical information for the ongoing development and improvement of microbial models (Xu et al., 2014).

4.5 | Uncertainties and future research needs

This study compiled a global dataset of soil DOC in terrestrial ecosystems, and further estimated the DOC concentrations at the biome and global levels. A few issues need special attention when interpreting the results. First, the data compiled in this study are reported with various measurement approaches; for example, the TOC analyser method accounts for 85% of total measurements. The biases caused by different approaches might affect global estimates; a robust comparative analysis of various approaches for their bias in terms of reporting DOC will be valuable for a robust budget estimation. Second, the distribution of data points is disproportionate among biomes, with about 52% of total data in forests and less than 4% in tundra and pasture. This may cause biases when establishing the empirical model and SEM for understanding the DOC distribution at a global scale. Third, all data for DOC and environmental variables represent the annual average; no seasonal information is available. Yet substantial seasonality of DOC has been reported (Wickland et al., 2018). The missing information concerning the seasonality of meteorological variables (e.g., air temperature and precipitation) may also lead to biases in the reported patterns of DOC concentration and distribution (Langeveld et al., 2019). Therefore, the seasonal variations in soil DOC deserve further investigation. Fourth, the empirical model developed in this study considers the primary environmental factors in controlling DOC concentrations; more mechanistic understanding would be beneficial for improving the model for better extrapolating soil DOC to the global scale.

5 | CONCLUSION

By combining a compiled global dataset and an empirical model, we estimated the spatial variation in soil DOC and quantified the global budget of DOC in terrestrial ecosystems. We found that tundra has the highest DOC concentration, whereas tropical and temperate forests have relatively low DOC concentrations in topsoils. Climate, vegetation, and soil properties interactively control the DOC variations. As the products of soil microbial decomposition and leaching of fresh litter, the DOC follows similar patterns of soil microbial biomass and roots along the soil profile. DOC in the 0–30 cm soil profile contributes more than half of the total DOC in the 0–100 cm soil profile in all biomes except natural wetlands, which show larger potentials to store DOC in deep soils. The global budget of DOC is estimated to be 7.62 Pg C in 0–30 cm and 13.81 Pg C in 0–100 cm soil profiles. Our estimates indicate the importance of pasture and mixed forest in DOC budgets. Furthermore, DOC concentrations increase with ST and Clay and decrease with SW.

This study produced a valuable dataset for soil DOC in terrestrial ecosystems, which serves as a benchmark for modelling of DOC in soils considering the fast turnover of soil DOC. Along with the growing recognition of biogeography of microbial abundance, diversity and functions, the geographical patterns of DOC and its contribution to the formation of microbial macroecology deem further investigation (Xu et al., 2020). As more and more experimental and modelling studies are conducted on soil DOC dynamics and its concentration and contributions to the global C cycle, this study serves as a platform for data–model integration to better simulate and project C dynamics in global soils.

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DATA AVAILABILITY STATEMENT

The majority of the data used for analysis in this study is clearly documented in the Data and methods section or in the Supporting Information. All data used for analysis are archived at Dryad: https://doi.org/10.5061/dryad.73n5tb2v6.

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SUPPORTING INFORMATION

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

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