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Mapping turnover of dissolved organic carbon in global topsoil

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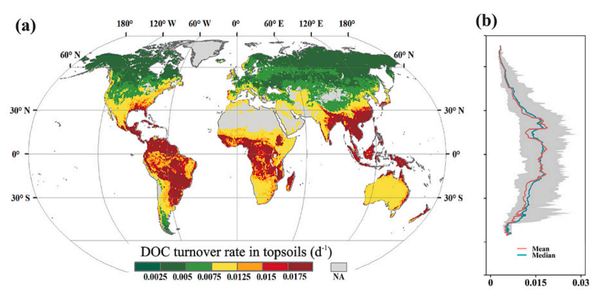
HIGHLIGHTS

- The global DOC turnover rate in 0–30 cm soil was estimated as 0.0087 day^{-1}.
- The DOC turnover rate exhibits a declining trend from low to high latitudes.
- The DOC turnover rate is primarily controlled by edaphic and climate factors.
- The annual turnover of DOC was estimated as 27.98 Pg C $year^{-1}$ in 0–30 cm topsoil.

GRAPHICAL ABSTRACT



Global distribution and latitudinal pattern of soil DOC turnover rate (day^{-1}) in 0 - 30 cm soil profile

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ABSTRACT

Dissolved organic carbon (DOC), the labile fraction of organic carbon, is a predominant substrate for microbes. Therefore, the turnover of DOC dominates microbial respiration in soils. We compiled a global dataset (1096 data points) of the turnover rates of DOC in 0–30 cm soil profiles and integrated the data with a machine learning algorithm to develop a global map of DOC turnover rate in global topsoil. The global DOC turnover rate in 0–30 cm soil was averaged as 0.0087 day^{-1}, with a considerable variation among biomes. The fastest DOC turnover rate was found in tropical forests (0.0175 day^{-1}) and the lowest in tundra (0.0036 day^{-1}), exhibiting a declining trend from low to high latitudes. The DOC turnover rate is primarily controlled by edaphic and climate factors, as confirmed by the analyses with the structural equation model and the Mental's test. With a machine learning algorithm, we produced global maps of DOC turnover rate at a monthly scale, which were further combined with a global dataset of DOC density to produce monthly maps of carbon mineralization from DOC turnover in topsoil. The annual carbon release from DOC was estimated as 27.98 Pg C $year^{-1}$ from topsoil across the globe, with the largest contribution from forest biomes, followed by pasture and grassland. Tundra released the least carbon from DOC due to its low turnover rate suppressed by low temperatures. The biome- and global-scale information

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of DOC turnover rate and carbon release from DOC provide a benchmark for ecosystem models to better project soil carbon dynamics and their contributions to global carbon cycling in the changing environment.

1. Introduction

Dissolved organic carbon (DOC) is primarily from vegetation and soil organic matter mineralization (Freeman et al., 2001; McDowell et al., 2006; Schwesig et al., 2003); it serves as a dominant carbon (C) source for soil microorganisms (Bowen et al., 2009; Cook and Allan, 1992; Guggenberger and Zech, 1993; Marschner and Bredow, 2002; Schwesig et al., 2003) and affects C and nitrogen (N) transformations in soils (Cook and Allan, 1992; Sjöberg et al., 2003). DOC turnover reflects the C assimilation by microorganisms and/or C being translocated into freshwater ecosystems (Amon and Meon, 2004; Bianchi, 2011; McDowell et al., 2006); DOC thus plays a crucial role in global C cycling. For example, approximately 10–44 % of DOC in mineral soil solutions of forests is mineralizable at a short time scale (Kalbitz et al., 2003; Schwesig et al., 2003; Solinger et al., 2001). Rapid turnover of DOC in temperate forests has been reported to account for increasing CO_2 production at warming conditions (Bengtson and Bengtsson, 2007). However, a global overview and analysis of DOC turnover in terrestrial ecosystems is still lacking.

DOC turnover is affected by climate, soil, and biological factors (Chow et al., 2006; Neff and Hooper, 2002). DOC in soils is primarily produced from litter leachates, root exudates, and microbial degradation, and it comprises a complex of low- and high-molecular-weight compounds (Boddy et al., 2008; Guggenberger and Zech, 1994; Zsolnay, 1996); therefore, the sources of DOC affect the quantity and composition of DOC and its turnover. Additionally, DOC turnover was regulated by temperature (Ghani et al., 2013; Marschner and Bredow, 2002), soil texture (Chapin et al., 2011), soil moisture (Schwesig et al., 2003; Wickland et al., 2007), and its biochemical composition (Bowen et al., 2009; Enriquez et al., 1993; Kalbitz et al., 2005). Thus, DOC turnover varies among biomes, given their differences in environmental conditions and microbial activities (Allison and Jastrow, 2006; Guggenberger and Zech, 1993). DOC turnover rates have been quantified in forests, agricultural land, peatlands, and tundra (Abbott et al., 2014; Bowen et al., 2009; Marschner and Bredow, 2002; Schwesig et al., 2003); however, the quantitative understanding of the association between DOC turnover and climate condition and soil properties, especially at biome level is still lacking.

DOC contributes a disproportionate role to the global C cycling (Moore, 2003; Neff and Asner, 2001; Wickland et al., 2007), despite its relatively small pool size in the terrestrial ecosystems (Guo et al., 2020). Spatial heterogeneity of climate conditions, vegetation types, and soil properties results in a considerable variation in terrestrial ecosystem features, especially for the vertical distribution of soil nutrients. The vertical movement of DOC along soil profiles can influence soil formation, C distribution, and microbial activities (Iqbal et al., 2010; Lundström et al., 2000; McDowell and Wood, 1984; Straathof et al., 2014). Therefore, a global inventory of DOC turnover in soils could contribute to accurately quantifying DOC mineralization and its roles in global C cycling. The dynamics and controls of DOC turnover rates have been investigated in numerous field and incubation experiments, but the spatial and temporal patterns of DOC turnover in terrestrial ecosystems at global scales remain to be elucidated.

This study investigated the DOC turnover rates in the 0–30 cm soil profile and estimated the monthly and annual C release from DOC at biome and global scales. We aimed to (a) explore the variations of DOC turnover rates among biomes to identify its primary controlling factors; (b) map the global distribution of terrestrial DOC turnover at seasonal and annual scales; (c) quantify the annual and monthly C release from DOC turnover at both global and biome scales.

2. Data and methods

2.1. Database compilation

We compiled the published soil DOC turnover rate (k) in global terrestrial ecosystems by searching "soil dissolved organic carbon/DOC mineralization rate" or "soil dissolved organic carbon/DOC turnover rate" in Google Scholar. Data points were derived from tables containing soil DOC concentrations and k values or extracted from figures by the ENGAUGE DIGITIZER software version 10.7 (http://digitizer.sourceforge.net/). The final database was compiled in June 2020 and was updated and finalized in January 2021. The selection of articles was based on two criteria: 1) DOC concentrations in topsoil (0–30 cm) were measured at least three times in laboratory incubation and field experiments and followed a declining trend for calculating k values; meanwhile, the interval between two adjacent measurements was <15 days, because microorganisms take up DOC over a certain period, usually 7–42 days (McDowell et al., 2006) (Fig. S1) and <15-day interval has been widely used in incubation experiments (Cook and Allan, 1992; Schwesig et al., 2003); 2) the data for the first 90 days of incubation were used for the calculation of k to eliminate the effects of diverse incubation:

$$M\% = (100 - a)\left(1 - e^{k_1 t}\right) + a\left(1 - e^{-k_2 t}\right) \tag{1}$$

where a is the recalcitrant C that is slowly mineralized (%); (100 - a) is the labile DOC that is rapidly mineralized (%); k_1 and k_2 are the turnover rates of labile DOC and recalcitrant C (day^{-1}), respectively; and t is time (days) (Kalbitz et al., 2003). It is noted that the fitted k_1 is used in the following analyses. The 90 days were chosen as the appropriate duration for calculating the turnover rate of the biodegradable DOC (McDowell et al., 2006).

The database in this study contained 1096 k values calculated from 66 papers published in 1980–2018, covering 85 sites in 18 countries, of which 68 % were in Europe, 13 % in North and South America, 16 % in Asia, and <3 % in other continents (Fig. S2). Although all 1096 k values were obtained from 68 studies, they cover a large number of sites with various soil properties and meteorological data. The sites range from south 40 to north 70 in latitude, west 157 to east 176 in longitude, 7 to 22 in soil CN ratio, 0 to 34 (g C/kg dry soil) in soil organic carbon, 25 % to 84 % in sand, 1 to 28 (KgC/m^3) in carbon density, 30 to 1867 (gC/m^2/year) in net primary productivity, 4.3 to 7.9 in soil pH, −10 to 27 °C for mean annual temperature, 164 to 2130 (mm/year) for mean annual precipitation, 0.38 to 0.85 for soil porosity. Based on vegetation types and the classification method in (Xu et al., 2013), we classified our database into 12 biomes, including boreal forest, temperate coniferous forest, temperate broadleaf forest, tropical forest, mixed forest, grassland, shrubland, peatland, natural wetland, cropland, paddy, and tundra. Orchard was aggregated into cropland, and savanna was combined with grassland because data for those biomes were insufficient for robust statistical analysis. Additionally, deserts and glaciers were not included in our study. Temperate coniferous forest, cropland, grassland, and temperate broadleaf forests contributed about 44 %, 12 %, 11 %, and 7 %, respectively; other biomes contributed 26 % of the dataset. Available auxiliary information of sampling sites was also retrieved, such as incubation temperature, incubation days, sampling dates, latitude (LAT), longitude, mean annual air temperature (MAT), mean annual precipitation (MAP), soil moisture (SM), soil pH, total soil C concentration (TC), total soil nitrogen concentration (TN), soil organic C concentration (SOC), soil DOC concentration, soil C:N ratio (C/N), vegetation types, soil texture (silt, clay, and sand), soil porosity, and bulk density (BD).

Missing climate and edaphic data from collected publications were extracted from the International Geosphere-Biosphere Programme Data and Information System (IGBP-DIS) datasets based on geographical coordinates of sites, following our previous studies (Xu et al., 2017). SOC, TC, and BD were obtained from the *Re*-gridded Harmonized World Soil Database v1.2 with a spatial resolution of 0.05° latitude × 0.05° longitude in the Oak Ridge National Laboratory Distributed Active Archive Center for Biogeochemical Dynamics (FAO/IIASA/ISRIC/ISSCAS/JRC, 2009) (https://daac.ornl.gov/cgi-bin/dsviewer.pl?ds_id=1247). Mean annual and monthly data for soil temperature (ST) and SM in the top 10 cm soils were downloaded 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 (https://www.esrl.noaa.gov/psd/data/gridded/data.ncep.reanalysis2.gaussian.html). MAT and MAP were extracted from the WorldClim database version 2 with a spatial resolution of the 30s in 1970–2000 (https://www.worldclim.org/data/worldclim21.html). Annual net primary productivity (NPP) was obtained from the Moderate Resolution Imaging Spectroradiometer (MODIS) gridded dataset with a spatial resolution of 30 s in 2000–2015 (http://files.ntsg.umt.edu/data/NTSG_Products/). Root C density (C_{root}) was extracted from the IGBP-DIS dataset with a spatial resolution of 0.5° (Ruesch and Gibbs, 2008; Song et al., 2017). Data for soil porosity in the top layer was extracted from the global dataset produced by the Global Land Data Assimilation System (GLDAS, https://ldas.gsfc.nasa.gov/gldas/) with a spatial resolution of 0.25° latitude × 0.25° longitude. The global land area database was 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, calculation, and correction

The *k* values at the daily time scale were calculated in two ways, depending on the data availability. We first standardized the DOC concentration in soil solution and dry soils by using the formula (2) (Guo et al., 2020), then applied the least-squares method to calculate *k* values (about 40 % of total *k* values).

$$DOC_{soil} = \frac{DOC_{solution} \times V \times 1000}{W} \times \frac{1}{V \times (1 - W) \times BD \times 1000000} \quad (2)$$

where DOC_{soil} is the DOC concentration in soil (mg g^{-1}); $DOC_{solution}$ is the DOC concentration in soil solution (mg L^{-1}); *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}); 1000 is used for unit conversion from m^3 to *L*, and 1,000,000 is used for converting m^3 to cm^3.

Based on the mass data, k values were calculated as the changes of mass divided by its corresponding incubation period using the following equation (about 60 % of total *k* values):

$$k = \frac{\Delta M\%}{\Delta days} \quad (3)$$

where *ΔM%* (%) is the change in the percentage of mineralized DOC concentration during the incubation period Δdays (days).

Our database comprises 88 % incubation data and 12 % field data. In about 77 % of incubation experiments, the temperature was (+7.4 ± 5.4 °C) higher than its corresponding monthly mean ST at sampling sites, which could accelerate or slow down the DOC turnover. Thus, corrections for *k* values are necessary for diminishing the impacts of the mismatch between incubation temperature and actual ST on the DOC turnover (Raich and Schlesinger, 1992; Tjoelker et al., 2001; Xu et al., 2017). We corrected the *k* values using the annual mean ST in the sampling years with the following equation:

$$k_s = k_i \times Q_{10}^{(T_s - T_i)/10} \quad (4)$$

where T_s is the monthly mean soil temperature at sampling sites; T_i is the incubation temperature (assuming as 15 °C if the room temperature was set (roughly 50 % of total data)); and k_s and k_i are the DOC turnover rates at T_s and T_i, respectively. Here, we assumed Q_{10} = 2.0 since it was commonly used for studies of C turnover and favored the process of the C turnover (Davidson and Janssens, 2006; Koch et al., 2007).

2.3. Global-scale DOC turnover rates

A random forest (RF) algorithm was used to estimate the *k* values for top 30 cm soils at global scales, involving primary controlling features such as the absolute value of the latitude, MAP, MAT, annual mean ST and SM, soil pH, porosity, texture, SOC, TC, NPP, and C_{root}. RF is an ensemble approach for classification and regression, which uses decision trees as the base estimator (Breiman, 2001) and has been extensively used (Jung et al., 2020; Liu et al., 2021). Scikit-learn packages (version 0.23.2, https://scikit-learn.org) for Python (version 3.7.5, https://www.python.org/) were used to predict *k*. The database for k values was split into training samples (70 %) and test samples (30 %) with the method of "train_test_split". Finally, the predictions for test samples described the primary trend as reasonable, with the highest explained variance of R^2 = 0.966 (Fig. S3).

Based on the RF algorithm and the global biome map, annual average *k* values at global scales were estimated for 10 biomes except for peatland and paddy because peatland was aggregated into natural wetland and paddy was combined with cropland in the global biome map created by (Xu et al., 2013). To estimate each biome's monthly average k values, we applied Eq. (4), where T_s is the monthly mean *ST*, T_i is the annual mean *ST* and k_s and k_i are the DOC turnover rates at T_s and T_i, respectively. Then, we generated global maps for monthly average *k* values and compared the seasonal patterns of DOC turnover rates among different biomes (Fig. S4).

2.4. Calculation of DOC turnover

At the monthly time scale, the C loss due to DOC turnover can be calculated for each land grid cell with the Eq. (5):

$$DOC_{turnover} = k_i \times DOC_i \times d_i \quad (5)$$

where k_i is the DOC turnover rate in the i^{th} month for each land grid (d^{-1}), DOC_i is the estimated soil DOC storage in the i^{th} month (kg C·m^{-2}) derived from Guo et al. (2020), d_i is the number of days of the i^{th} month (days), and i is from 1 to 12. The annual C mineralization of DOC for each land grid cell is the sum of the C loss for twelve months.

2.5. Statistic analysis

The log transformation was applied on all *k* values to ensure the normality for robust statistical analyses. For each biome, the mean and 95 % confidence intervals of *k* values were converted back to the original values for reporting. The analysis of variance (ANOVA) was carried out by using the 'agricolae' package to examine the differences in biome-level *k* values. A Mantel test based on Pearson's production-moment correlation was applied using 'vegan' package to quantify the effects of climate, vegetation, and soil properties on DOC turnover rates. Structural equation modeling (SEM) was performed with the 'lavaan' package to investigate the potential effects of meteorological, biological, and edaphic variables on DOC turnover rates. Specifically, we developed a priori model, which allows a hypothesized causal interaction of the linkages among soil pH, SM, SOC, DOC, ST, texture, log(k) for different biomes. Then, the conceptual model was established, and the best fitting determined the optimal model. In addition, a ternary diagram was created using the 'soiltexture' package in the RSTUDIO platform to visualize the impacts of soil textures on DOC turnover rates. All statistical analyses were conducted by the R_{STUDIO} version 4.0.3 (http://www.rstudio.com/). The global maps for data distribution, soil DOC turnover rates, and annual mineralized DOC were generated by the ArcGIS software (version 10.2, ESRI, Redlands, CA) in Windows 10. The global maps of monthly mineralized DOC were generated by MATLAB software (version R2016b).

3. Results

3.1. Soil DOC turnover rates among biomes

The biome-level DOC turnover rates in topsoil (0–30 cm) ranged from 0.0025 to 0.0274 day^{-1}, with a global average of 0.01 (0.0067–0.0160) day^{-1} (Table 1). Among these biomes, paddy had the highest turnover rate at 0.0274 (0.0187–0.0400) day^{-1}, followed by the tropical forest at 0.0248 (0.0165–0.0371) day^{-1}, whereas tundra had the lowest rate at 0.0025 (0.0018–0.0033) day^{-1} (Table 1). There were no significant differences in DOC turnover rates among other biomes (Table 1). Additionally, shrubland and peatland showed greater average rates than the global average rate, at 0.0129 (0.0042–0.0397) day^{-1} and 0.0114 (0.0085–0.0153) day^{-1}, respectively, whereas natural wetlands, grassland, cropland, temperate broadleaf/coniferous forests, and boreal forest exhibited lower rates than the global average rate, ranging from 0.0032 day^{-1} in the boreal forest to 0.0088 day^{-1} in the natural wetlands (Table 1).

3.2. Environmental controls on soil DOC turnover rates

The DOC turnover rates were primarily controlled by meteorological, biological, and edaphic factors (Fig. 1a and Supporting information Table S3). Specifically, MAP ($r = 0.27$, $p < 0.01$), C/N ratio ($r = 0.22$, $p < 0.01$), LAT ($r = -0.27$, $p < 0.01$), and Clay ($r = -0.21$, $p < 0.01$) were the major factors regulating DOC turnover rates. Moreover, DOC turnover rate was positively related to MAT ($r = 0.07$, $p < 0.05$), SM ($r = 0.09$, $p < 0.01$), BD ($r = 0.11$, $p < 0.01$), and SOC ($r = 0.07$, $p < 0.05$), and was negatively correlated with soil pH ($r = -0.13$, $p < 0.01$) and DOC concentration ($r = -0.09$, $p < 0.01$) (Fig. 1a and Supporting information Table S3). In addition, DOC associations with MAT, MAP, and

Table 1
DOC turnover rate at biome and global scales derived from compiled data.

Biome	DOC turnover rate (day^{-1})	DOC concentration (mg C/kg soil)
Tundra	0.0025[d] (0.0018–0.0033)	453.750[a] (324.952–633.598)
Boreal Forest	0.0032[d] (0.0019–0.0054)	127.348[c] (112.174–144.576)
Temperate Coniferous Forest	0.0039[d] (0.0033–0.0045)	30.199[i] (24.784–36.797)
Temperate Broadleaf Forest	0.0035[d] (0.0024–0.0051)	54.541[ef] (49.766–59.773)
Tropical Forest	0.0248[ab](0.0165–0.0371)	38.238[h] (35.160–41.584)
Mixed Forest	0.0087[cd](0.0052–0.0145)	46.084[fg] (43.223–49.136)
Grassland	0.0082[cd] (0.0066–0.0102)	92.079[d] (79.854–106.177)
Shrubland	0.0129[a] (0.0042–0.0397)	110.158[cd] (102.915–117.910)
Peatland	0.0114[bc] (0.0085–0.0153)	n.a.
Natural Wetland	0.0088[d] (0.0074–0.0105)	199.440[b] (180.227–220.701)
Cropland	0.0052[d] (0.0040–0.0069)	60.578[e] (53.011–69.226)
Paddy	0.0274[a] (0.0187–0.0400)	n.a.
Globe	0.01 (0.0067–0.0160)	77.387 (73.838–81.106)

Note: Values are presented as mean with 95 % confidence boundaries in parentheses. Different superscript letters in one column indicate the significant difference at a significance level of P = 0.05, while the same letters indicate no significant difference. n.a. = no value due to insufficient data. DOC concentration values are cited from Guo et al. (2020).

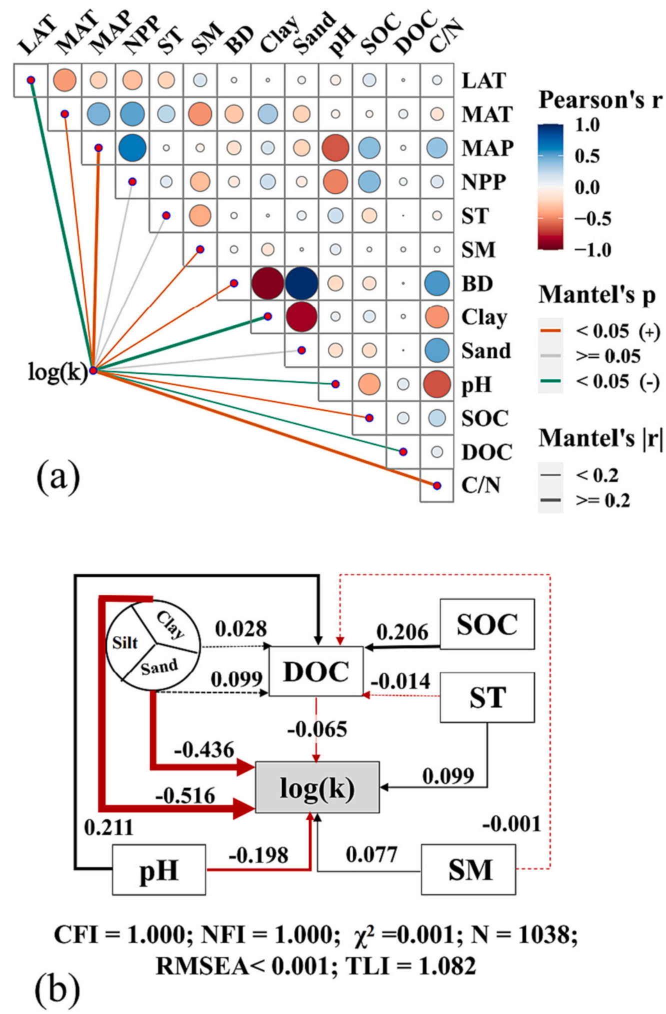

Fig. 1. (a) Mantel test showing the relationships between log(k) and environmental variables. Pairwise comparisons of environmental factors are displayed with a color gradient denoting Pearson's correlation coefficient; orange lines represent positive correlation ($p < 0.05$), green lines represent negative correlation ($p < 0.05$), and gray lines represent non-significant effects ($p > 0.05$). (Lat: latitude; MAT: mean annual air temperature; MAP: mean annual precipitation; NPP: net ecosystem primary production; ST: soil temperature; SM: soil moisture; BD: bulk density; Por: soil porosity; Clay: soil clay content; Sand: soil sand content; C/N, soil total C:N ratio; DOC: soil dissolved organic carbon); **(b)** Structural equation model of ST, SM, pH, Clay, Sand, and soil organic carbon (SOC), DOC as predictors of soil DOC turnover rate (*k*). 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 (Hu and Bentler, 1999). 1038 data points were used in the model.

NPP were weak in high latitudes (Fig. 1a). The associations between environmental factors were found. The C/N ratio was associated with soil pH ($r = -0.65$, $p < 0.01$), BD ($r = 0.55$, $p < 0.01$), and soil texture such as clay ($r = -0.49$, $p < 0.01$) and sand ($r = 0.52$, $p < 0.01$) (Fig. 1a and Supporting information Table S4); BD was strongly correlated with sand ($r = 0.96$, $p < 0.01$) and clay ($r = -0.91$, $p < 0.01$) (Fig. 1a and Supporting information Table S3).

Clear evidence confirmed the direct and indirect impacts of soil properties on DOC turnover rates (Fig. 1b). Clay and sand explained 51.6 % and 43.6 %, respectively, of the variations in DOC turnover rates (Fig. 1b). Moreover, the soil ternary diagram showed that clay loam, sandy loam, loam, sand clay loam, and loamy sand soils had relatively smaller k values, whereas sandy clay and silty loam soils had relatively high k values (Supporting information Fig. S). ST ($\beta = 0.10$, $p < 0.01$) and SM ($\beta = 0.08$, $p < 0.01$) had positive influences, whereas soil pH ($\beta = -0.20$, $p < 0.01$) and DOC concentration ($\beta = -0.07$, $p < 0.01$) yielded negative effects on DOC turnover rates (Fig. 1b). Additionally, soil properties can indirectly determine DOC turnover rates by affecting DOC concentration. Of those soil properties, SOC density was the primary factor affecting DOC turnover rate via regulating DOC concentration ($\beta = 0.206$, $p < 0.01$) (Fig. 1b).

3.3. Global and seasonal patterns of soil DOC turnover rate

The DOC turnover rate showed a substantial spatial heterogeneity across the globe, with large k values in the equatorial regions but small values in high latitudes (Fig. 2), contrasting to the spatial pattern of DOC concentration in top 30 cm soils (Guo et al., 2020). A tropical forest located in the equatorial regions was estimated to have the fastest annual DOC turnover process with a rate of 0.0175 day^{-1} on average (Table 2). Boreal forests and tundra are primarily distributed in northern high-latitude regions, with relatively lower annual turnover rates at 0.004 and 0.0036 day^{-1} on average, respectively (Table 2).

The seasonal patterns in DOC turnover rate varied across biomes; all biomes had peak turnover rates during June – August except tropical forests in April and October (Supporting information Fig. S4). DOC turnover rates were the highest in the tropical forest with minor seasonality but the lowest in the tundra with weak seasonality (Supporting information Fig. S4). In the rest of the biomes, DOC turnover was faster in shrubland than in the other five biomes, including temperate broadleaf and coniferous forests, mixed forest, grassland, and cropland. Those five biomes exhibited similar seasonal patterns with relatively great variations, comparable to DOC turnover rates in the northern hemisphere (Supporting information Fig. S4).

3.4. DOC turnover at the global scale

The DOC mineralized in the global top 30 cm soils was estimated as 27.98 Pg C year^{-1} (Table 2). Grassland, tropical forest, and cropland contributed about 40.9 % (11.47 Pg C), 19.6 % (5.48 Pg C), and 14.1 % (3.92 Pg C) of the global estimate, respectively. Other seven biomes contributed about 25 % of the global estimates, of which tundra (0.26 Pg C) contributed the least, given its lowest DOC turnover rate (Table 2). Despite the highest turnover rate, tropical forests contributed 5.48 Pg C to the global estimate, less than grasslands (Table 2).

The spatial pattern of DOC mineralization at the global scale was consistent with that of DOC turnover rates, with a smaller mass in high-

Table 2
Machine learning-derived mean DOC turnover rate and mineralized DOC mass at biome and global scales.

Biome	Area (million km^2)	DOC turnover rate (day^{-1})	DOC storage (Pg C)	Mineralized DOC mass (Pg C year^{-1})
Tundra	5.49	0.0036^{h} (0.0036–0.0037)	0.61	0.26
Boreal Forest	15.27	0.0040^{g} (0.0040–0.0041)	1.73	1.18
Temperate Coniferous Forest	2.49	0.0084^{de} (0.0081–0.0086)	0.12	0.36
Temperate Broadleaf Forest	3.41	0.0096^{bc} (0.0094–0.0099)	0.13	0.50
Tropical Forest	14.90	0.0175^{a} (0.0174–0.0176)	0.47	5.48
Mixed Forest	3.42	0.0089^{cd} (0.0087–0.0091)	0.35	0.53
Grassland	38.34	0.0102^{b} (0.0101–0.0102)	1.99	11.47
Shrubland	7.89	0.0102^{b} (0.0101–0.0103)	0.36	2.25
Natural Wetland	6.65	0.0066^{f} (0.0064–0.0067)	0.60	2.03
Cropland	14.40	0.0083^{e} (0.0081–0.0084)	0.83	3.92
Globe	112.3	0.0087 (0.0086–0.0088)	7.2	27.98

Note: Values are presented as mean with 95 % confidence boundaries in parentheses. Different superscript letters in one column indicate a significant difference at P = 0.05, while the same letters indicate no significant difference. DOC storage values are from Guo et al. (2020). Biome area was extracted from the spatial map used in (Xu et al., 2013).

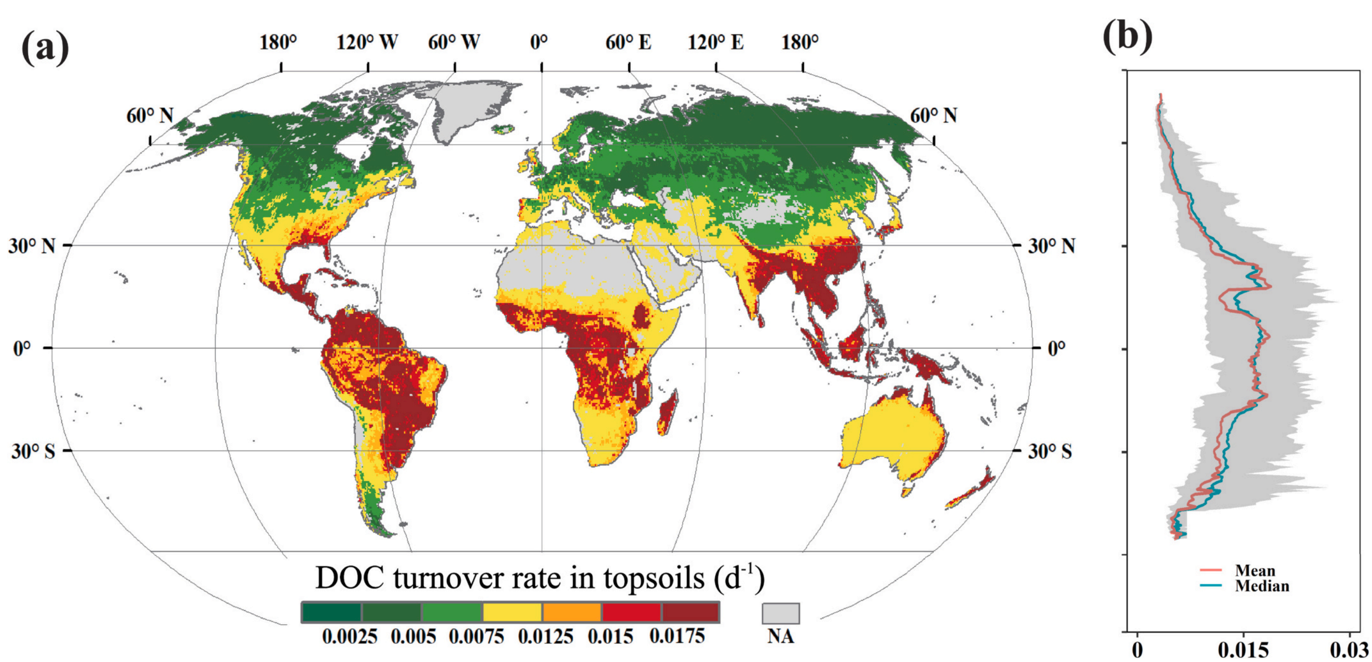

Fig. 2. (**a**) Global distribution and (**b**) latitudinal pattern of soil DOC turnover rate (day^{-1}) in 0–30 cm soil profile.

latitude regions and a larger mass in low-latitude regions (Fig. 3). Additionally, spatial patterns of mineralized DOC mass exhibited seasonal dynamics at the global scale (Fig. 4). The stronger seasonal fluctuation was observed in high latitudes where most temperate broadleaf/coniferous forests, mixed forests, and boreal forests were distributed, while weaker seasonality was observed in low latitudes (Fig. 4). Thus, total global mineralized DOC mass increased in the growing seasons, then decreased in cold seasons, consistent with the seasonal dynamics in the northern hemisphere (Fig. 4). Specifically, the mass of mineralized DOC peaked in July and August, and it approached zero from October to April in some high-latitude areas (Fig. 4). The southern hemisphere had opposite seasonal changes of mineralized DOC relative to the northern hemisphere, and it played a limited role in global seasonal patterns of mineralized DOC mass due to its small land area.

4. Discussion

4.1. Soil DOC turnover rates among biomes

Soil DOC turnover rates varied substantially among biomes. Both compiled data and global prediction reported that tundra with long cold seasons had the lowest DOC turnover rates, whereas tropical forests with high air temperature and precipitation possessed the fastest DOC turnover rate (Tables 1 and 2). Temperature and soil moisture are the primary controlling factors for DOC turnover rates shown in this study, consistent with previous studies. For example, in tundra, the permafrost strongly influences the temperature and hydrology of the active layer (Kawahigashi et al., 2006), further impacting DOC production, mineralization, sorption, and formation of pedogenic oxides that alter DOC turnover rates (Schwesig et al., 2003). Low decomposition in tundra promotes the accumulation of litter and organic matter, as well as DOC concentrations (Everett and Brown, 1982; Guggenberger et al., 2001). Additionally, tundra in the Arctic with large soil C density tends to be potentially highly susceptible to warming, as permafrost thaw with warming and longer vegetation growth seasons could induce soil organic matter mineralization and greatly alter the quantity, quality and biodegradation of DOC (Abbott et al., 2014; Boddy et al., 2008; Grogan and Jonasson, 2005; Michaelson et al., 1998; Weintraub and Schimel, 2005). Similar to tundra at high latitudes, natural wetlands, and boreal forests showed comparably slow DOC turnover and seasonal dynamics because of the suppressed microbial activities and low fresh litter and organic matter input (Weintraub and Schimel, 2005). Meanwhile, the water-logged condition and poor soil aeration in natural wetlands also reduced microbial degradation of organic C, further inhibiting DOC production and turnover (Mitsch et al., 2013). In contrast, tropical forests had lower DOC concentrations because of dilution by the great amount of rainfall, but its DOC flux was large due to large amounts of litterfall, rapid decomposition, and percolating water (Fujii et al., 2009; Zech et al., 1997). Moreover, the DOC leaching carried by runoff is an important C source from the organic layer to mineral soils in tropical forests (Fujii et al., 2009).

Moreover, DOC turnover rates varied throughout the year, depending on the patterns of temperature and precipitation, as well as microbial activities (Kalbitz et al., 2000). DOC turnover in biomes of the northern hemisphere showed similar seasonality with higher rates in warm seasons (June–August) and lower rates in cold seasons (December–February), except in tropical forests because of the apparent distinct dry and wet seasons (Fig. S4). Increasing soil temperature and moisture in warm seasons led to vigorous plant growth, enhanced the organic matter supply, and accelerated microbial decomposition of organic C. Moreover, large seasonal variations of temperature and precipitation caused obvious seasonality of DOC turnover rates in temperate broadleaf forests, temperate coniferous forests, mixed forest, grassland, cropland, and shrubland (Fig. S4). On average, the seasonal patterns of DOC turnover rates in the northern hemisphere were comparable to those in temperate biomes due to their large land area.

Vegetation affects DOC turnover rates because DOC is primarily generated by vegetation-affected processes - biological decomposition, throughfall or litter leaching, and root exudates (Camino-Serrano et al., 2014). Besides tropical forests, shrubland and grassland displayed a relatively faster DOC turnover than temperate and polar biomes, probably due to differences in vegetation cover. Ultraviolet (UV) degradation in shrubland and grassland was stronger due to greater exposure to light than in temperate biomes (Wang et al., 2017). In addition, temperate broadleaf forests, temperate coniferous forests, and mixed forests had comparable DOC turnover rates based on collected data and global prediction. However, DOC turnover rates generally followed a ranking of temperate broadleaf forest > mixed forest > temperate coniferous forest (Fig. S4), which might be caused by their differences in plant composition and litter quality. Temperate broadleaf forests had more

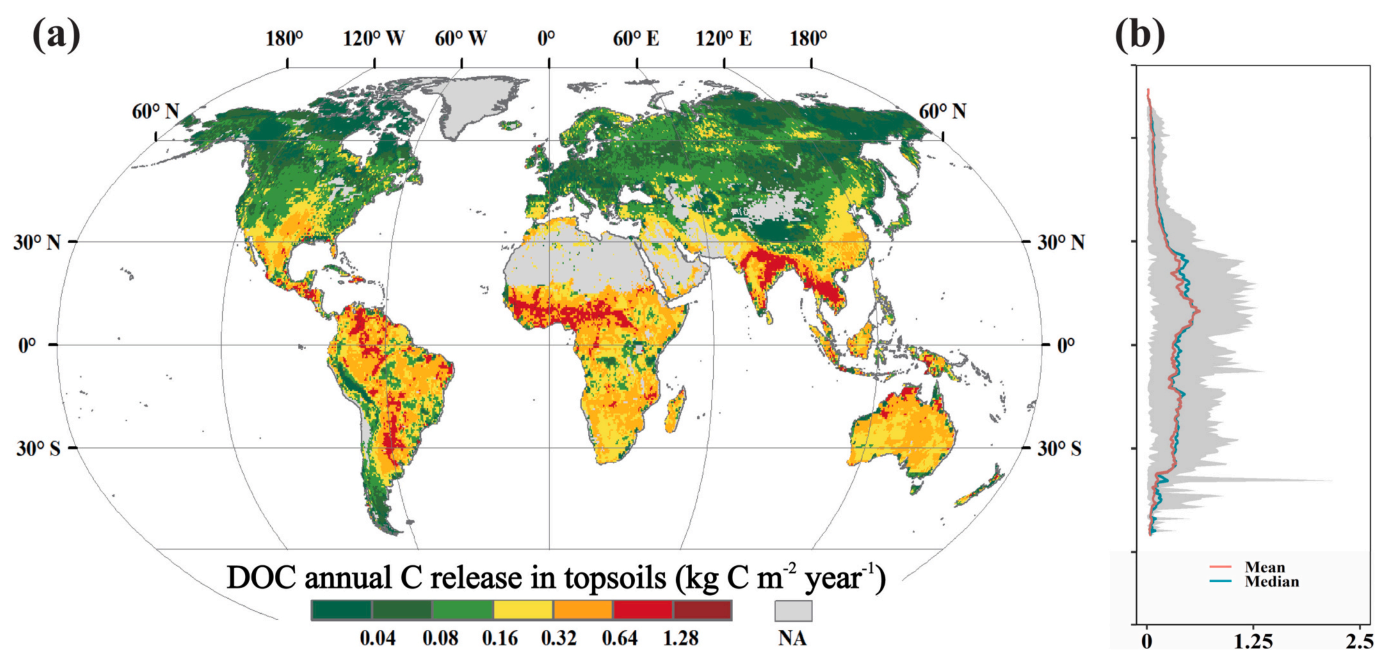

Fig. 3. Contemporary annual C release due to DOC turnover (kg C m^{-2}) in 0–30 cm soil profile at (a) the global scale and (b) along latitude.

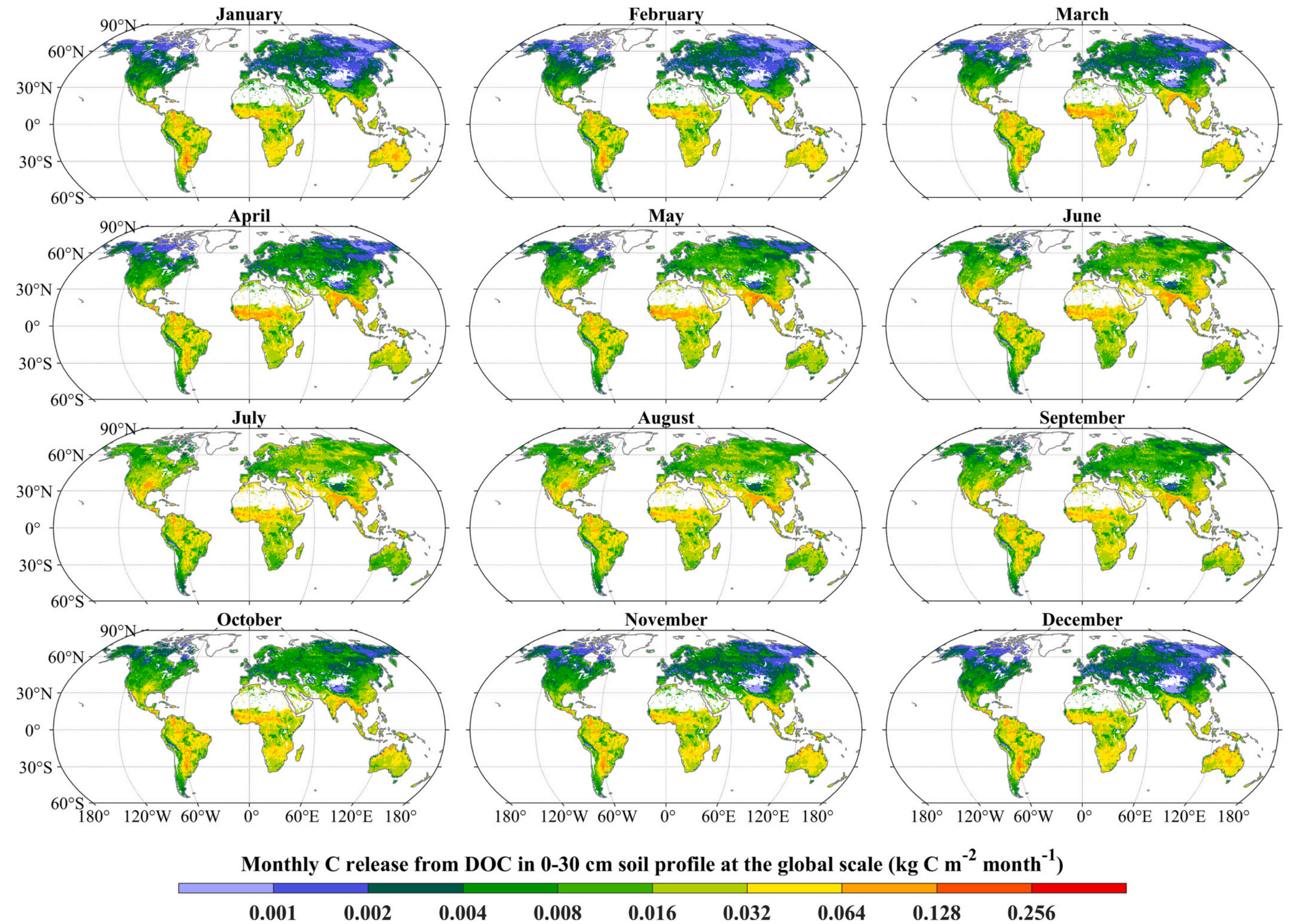

Fig. 4. Monthly C loss due to DOC turnover (kg C m^{-2}) in 0–30 cm soil profile at the global scale.

easily degradable and soluble organic C in plant litter and soil organic matter, whereas temperate coniferous forests contained more cellulose and lignin that are hard for decomposition (Chapin III et al., 2011).

In addition, DOC turnover varied across land use types. Rice paddy exhibited the highest DOC turnover rate, indicating the stronger promotion impacts of land use on DOC turnover (Boyer and Groffman, 1996; Kalbitz et al., 2003; Wang et al., 2017). As the main source of soil DOC in paddy, root exudates can be rapidly consumed at a rate of as high as 0.0274 day^{-1} (He et al., 2015; Kogel-Knabner et al., 2010; Krupa et al., 2012; Said-Pullicino et al., 2016), leading to a fast DOC turnover. Meanwhile, widely applied fertilizers in cropland (e.g., paddy) could promote plant and microbial growth; in turn, more root exudation and diverse microbes might lead to stronger microbial decomposition of DOC. Furthermore, disturbances can accelerate organic matter fragmentation. For instance, DOC turnover in grassland rose in growing seasons, probably due to livestock trampling and fecal inputs that facilitated fragmentation and microbial decomposition (Wang et al., 2015). DOC compounds were highly decomposable and readily utilized by microbes in grasslands (Ghani et al., 2013).

4.2. Environmental controls on DOC turnover rates

Large biome-specific variations of DOC turnover rates were attributed to climate, vegetation, and soil conditions for each biome. Soil DOC turnover rates can be affected by MAT, MAP, ST, SM, soil texture, soil pH, soil C/N ratio, vegetation, and microbial community (Fig. 1). DOC turnover rates were positively correlated with MAP and soil C/N ratio, indicating their dominant roles in promoting DOC turnover. Precipitation could reinforce the leaching of DOC from organic layers into mineral soils. Higher SM due to more precipitation can directly speed up DOC turnover, but indirectly slow down the turnover by reducing DOC concentrations. Moreover, expanded soil anoxic conditions caused by oversaturation may inhibit microbial respiration and DOC turnover; for example, a relatively low DOC turnover rate was observed and modeled in natural wetlands (Zuo et al., 2022). DOC turnover was also positively correlated with MAT. Increased temperature accelerated the microbial decomposition of soil organic matter by promoting the enzyme-mediated reaction (Conant et al., 2011; Karhu et al., 2014; Lawrence et al., 2009; Wallenstein et al., 2009). The stimulation of warming on DOC turnover was observed on a temporal scale of hours to weeks; however, a projection for long-term warming impacts on DOC turnover still hinders future research (Currie et al., 2010; Davidson and Janssens, 2006). Effects of SM and ST would be complex, especially under the influences of climate, vegetation, microbes, and other soil factors. DOC turnover also depends on soil C/N ratio, which can restrict plant and microbial growth that alters DOC input, production, and turnover (Fig. 1).

Soil texture, particularly clay content, affected DOC turnover rates and concentrations. High clay minerals can efficiently stabilize organic matter due to large surface area (Weil and Brady, 2016). SOC was the primary source for microbes to produce DOC; thus, limited access to SOC in clay soils could reduce the DOC turnover rates (Fig. 1b). In addition, soil DOC concentration was negatively correlated with its turnover rate because microbes consumed more soil DOC at high turnover rates. For instance, the tropical forest had a faster turnover but lower DOC concentrations, whereas the tundra contains large DOC but with a slow DOC turnover rate.

4.3. Mineralized DOC at the global scale

Mineralized DOC mass in 0–30 cm soil profile was estimated to be 27.98 Pg C per year at the global scale, which was approximately four times of the DOC storage. The amount of DOC mineralized was determined by DOC storage, input, and turnover rates. Although DOC storage was small among various terrestrial C pools, the roles of DOC were critical in terrestrial C cycling (Freeman et al., 2001). Compared with tropical regions (30°N - 30°S), temperate regions (30° - 60° N) showed smaller mineralized DOC mass at global scales corresponding to the global patterns of DOC turnover rates. A possible explanation was that warm and wet soils in tropical regions facilitated the microbial degradation of organic matter, leading to a faster DOC turnover. By contrast, a study demonstrated 12.8–40.9 % DOC mineralized after a 40-day incubation of thawing permafrost soils due to increasing DOC degradability (Abbott et al., 2014). However, the long and cold seasons were still a constraint for DOC mineralization in active layers (Chow et al., 2006; Neff and Hooper, 2002). But temperate regions had larger seasonal variations due to stronger seasonality of temperature and precipitation, which was consistent with monthly DOC turnover changes (He and Xu, 2021).

Human-disturbed ecosystems such as grassland and cropland had annual turnover of DOC at 11.47 Pg C year^{-1} and 3.92 Pg C year^{-1}, accounting for about 55 % of global estimates. In contrast, natural ecosystems contributed to the rest of global DOC turnover; tropical forests contributed the most among natural ecosystems, with 5.48 Pg C DOC mineralized in a year, mainly due to its high turnover rate and large organic matter inputs. Mineralized DOC in shrubland and natural wetland were comparable, with 2.25 Pg C year^{-1} and 2.03 Pg C year^{-1}, respectively; although DOC turnover was faster in shrubland, higher DOC storage was in natural wetlands. Boreal forests, temperate broadleaf forests, temperate coniferous forests, and mixed forests, in total, contributed 2.57 Pg C of DOC turnover in a year, less than that in tropical forests, highlighting the important role of tropical forests in DOC turnover among forest ecosystems. Tundra contributed the minimal mineralized DOC to global estimates, but its contribution can potentially double or triple due to its massive C storage in deep soils and high temperature sensitivity.

4.4. Implications

This study reports the first comprehensive analysis of DOC turnover rate and its controls at the global scale. There are three major implications of this study. First, the estimated global budget of DOC in topsoil provides quantitative information of the labile C in soils. This study evaluated the turnover rates at biome and global scales, which was slower but in a similar range to the turnover rate of the soil microbial biomass ($r_{biome} = 0.70$, $r_{globe} = 0.41$, $p < 0.01$) (He and Xu, 2021). The consistency between DOC and microbial biomass turnover rate indicates the reliance of microbial activities on DOC as a C source, as incorporated in most microbial models (Wang et al., 2013; Xu et al., 2014). Second, this study estimated the global distribution of C emission from DOC to be 27.98 Pg C year^{-1}. If the DOC provides the sole C source for microbial C respiration, the top 0–30 cm DOC accounts for 29 % of the soil microbial respiration (Bond-Lamberty and Thomson, 2010). Third, the turnover rate of DOC is a critical parameter for many process-based ecosystem models (He and Xu, 2021; Wang et al., 2013; Xu et al., 2014); therefore, the DOC turnover rate and its global distribution reported in this study would benefit the ecosystem models in predicting soil C cycling and emission at various scales (Wang et al., 2022; Wang et al., 2019; Xu et al., 2015).

4.5. Uncertainties and future works

This study reported the global distribution of DOC turnover and its controls; caution must be taken when interpreting the results, and the uncertainties will be addressed in future works. First, DOC turnover rate varies with soil depth; about half of soil organic C is typically below 20 cm depth (Jobbagy and Jackson, 2000); it could be mineralized up to 93 % in the O and A horizons (Kalbitz et al., 2003), whereas only 10 to 40 % of DOC in mineral soil was mineralizable (Jandl and Sletten, 1999; Sachse et al., 2001; Yano et al., 2000). In this study, soil samples are concentrated in the top 0–30 cm; the turnover rate in deeper soil (horizon B) is slower due to unfavorable environment and fewer microbes (Xu et al., 2013). Second, the different incubation periods (1–90 days) could also affect the estimated DOC turnover rate, causing a portion of DOC to be washed away through precipitation and fresh DOC production in long-term incubation., the DOC turnover rate was calculated using different methods; 51 % of the dataset was estimated with the double exponential model, and the rest was calculated by the least square method. A consistent approach is valuable for a feasible estimate but has not been reached yet. Finally, a bias could have occurred in the global summary due to the disproportion of data points among biomes, in which forest contributes about 57 % of total data. Shrubland, paddy, tundra, and natural wetland represent <4 % each; these uncertainties exist in all global scale meta-analyses due to an imbalanced scientific investment (Guo et al., 2020; He et al., 2020; He and Xu, 2021; Xu et al., 2017; Xu et al., 2013). As field observational data were cumulated, and efficient artificial intelligence algorithms were developed, this estimate should be addressed in the near future.

5. Conclusion

The DOC turnover rate for 0–30 cm soils was estimated at 0.0087 day^{-1} at the global scale by integrating a compiled dataset and a machine learning algorithm. The DOC turnover rate varies among biomes, with the most rapid turnover rate in tropical forests and the slowest in the tundra, forming a latitudinal trend of DOC turnover rate. Soil properties, plant species, and climatic factors were crucial in the DOC turnover rate by controlling microbial activity, DOC substrate production, and environmental conditions. The DOC turnover rate was positively correlated with ST and SM and negatively correlated with DOC concentration, pH, and soil clay content.

Global annual C release from DOC turnover was estimated as 27.98 Pg C year^{-1}, with the largest contribution from grassland (approximately 41 %). Temperate coniferous forests and tundra have a smaller DOC turnover estimated at 0.36 Pg C year^{-1} and 0.26 Pg C year^{-1}, respectively. Although some uncertainties remain, the soil DOC turnover rate estimated at the biome level and a global overview of DOC turnover in this study contributed to the mechanistic understanding of soil DOC metabolism and improved prediction of the roles of DOC in the global C cycle.

CRediT authorship contribution statement

Xiaofeng Xu: Conceptualization. **Ziyu Guo, Liyuan He**: Data Curation. **Ziyu Guo, Yihui Wang**: Writing- Original draft preparation. **Jianzhao Liu**; Software. **Xinhao Zhu, Yunjiang Zuo, Nannan Wang, Fenghui Yuan, Ying Sun, Lihua Zhang, Yanyu Song, Xiaofeng Xu**: Visualization, Writing – Reviewing and Editing. **Changchun Song; Xiaofeng Xu**: Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing interests regarding the publication of this work.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2023.167621.

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