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Controls on soil dissolved organic carbon along the 4000 km North-South forest transect in Eastern China

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ABSTRACT

Dissolved organic carbon (DOC) is both a potential source and stability indicator of soil organic carbon (SOC), and plays a pivotal role in global C cycling and sequestration. However, at a large scale, still not enough information is known about relations between DOC in soils and various controlling factors in natural forest ecosystems. We sampled 252 soil samples (6 replicates and 3 depths for each site) from four long-term forest ecosystem stations in Changbaishan, Beijng Donglingshan, Shennongjia and Dinghushan along a 4000 km North-South transect in Eastern China. We found that higher soil DOC concentrations were observed in subtropical forests over the North-South transect. The highest and lowest DOC concentrations in the upper 60 cm soil layer were found in monsoon evergreen broadleaved forest (DIII, 113.8 ± 1.4 mg C/L) and Yue spruce-fir forest (CIII, 57.6 ± 3.0 mg C/L), respectively. The Haplic ferralsol (DII-DIV, 89.7 mg C/L) and Haplic Andosol (CIII, 57.6 mg C/L) showed the highest and the lowest DOC concentrations in the upper 60 cm soil layer, respectively. The soil DOC concentrations generally decreased from surface soil to subsoil in the forests with mean annual precipitation (MAP) ≥ 1500 mm. The lower proportion of DOC accounting for SOC in the upper 20 cm soil layer in temperate forests, among which Yue spruce-fir forest (CIII, 3.2 %) presented the lowest ratio, indicated a larger long-term soil C sequestration potential. The DOC concentrations in the upper 60 cm soil layer significantly correlated with mean annual temperature (MAT) ($R^2 = 0.50$) and MAP ($R^2 = 0.46$). However, in the upper 20 cm soil layer, forest type ($R^2 = 0.48$) was the most significant correlation factor to DOC concentration. We concluded that in the North-South transect of Eastern China, MAT, MAP and forest type are the most significant large-scale factors controlling soil DOC, with temperate forests (especially Yue spruce-fir forest) possessing the highest long-term soil C sequestration potential.

1. Instruction

Forest soil is an important reservoir for carbon (C). Soil C sequestration is a crucial process in mitigating global warming and climate change (Amelung et al. 2020; Basile-Doelsch et al. 2020; Brodowski et al. 2006). Soil dissolved organic carbon (DOC) is one of the most active and mobile C pools, and affects soil acid-basic reactions, retention and translocation of various nutrients (Gmach et al. 2019) or microorganism, further to influence terrestrial C dynamics. Soil DOC is recognized as an indicator of soil organic carbon (SOC) since it is not only a potential source of stabilized C (Ghani et al, 2013; Marschner and Kalbits 2003), but also released as CO_2 to atmosphere (Fröberg et al. 2007; Kalbitz and Kaiser 2008), resulting in the increase or decrease of SOC. DOC fluxes in terrestrial ecosystem (Kalbitz and Kaiser 2008) are several times more than that in aquatic system (Harrison et al.2005). Large DOC input into soil could boost the accumulation of SOC (Goldin and Hutchinson 2013; Kahl et al 2012; Kalbitz and Kaiser 2008), which can enhance soil C sequestration (Li et al. 2018). DOC is recognized to influence emissions of greenhouse gases from soil into atmosphere (Freeman et al. 2001; Moore 2002) by affecting microbial activity or metabolism. Consequently, soil DOC is of great important component of the global carbon cycling and plays a vital role in climate change mitigation strategies (Hedges et al. 1997).

A great of concern focus on the role, retain, transportation of DOC

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and most studies believe that DOC is the most labile oxidizable and migratory carbon fraction of SOC (Bolan et al. 2011; Ding et al. 2021; Stanley 2012), however, other studies found that this view is invalid, namely DOC contributed to the accumulation of stable organic carbon in soil (Kalbitz and Kaiser 2008; Kaiser and Guggenberger 2000). No matter what, it could be an indicator for the stability of SOC (Moore et al. 2013; Butman et al. 2014; Lu et al. 2014). Moreover, there were studies showed that DOC concentrations decreased with soil depth (Leinemann et al. 2018; Camino-Serrano et al. 2014; Nie et al. 2018) due to the soluble compounds leaching into deep soil with water percolating, while other scientists believed that in deeper soil profile the older, degraded, previously bonded DOC could be remobilized by input of fresh highly surface-reactive and then leaded to the greater DOC accumulation observed (Hagedorn et al. 2004; Sanderman et al. 2008). Some studies showed that soil DOC concentration was higher in tropical regions than in temperate regions (Zhou et al., 2015), while other studies suggested that DOC concentrations at lower latitudes were less than in higher latitudes (Camino-Serrano et al. 2014). Also, scientists have paid lots of attention on controlling factors of soil DOC concentrations (Chantigny 2003; Filep and Rékási 2011; McDowell 2003). The DOC production, quantities, movement and chemistry characteristics were affected by a suit of soil physiochemical properties (Saidy et al. 2013), climate conditions (Kalbitz et al. 2000a, 2000b), as well as water percolation from surface to deep soils (Möller et al. 2005). Regarding forest type, some studies reported that coniferous possessed larger DOC concentrations than broadleaved forests in temperate zones (Bantle et al. 2014; Fröberg et al. 2011; Currie et al. 1996) whereas other studies presented the opposite conclusion (Michalzik et al. 2001). Furthermore, temperature dependency of DOC is a known phenomenon (Gödde 1996; Kalbitz et al. 2000a, 2000b). Some studies presented that temperature negatively correlated with DOC (Moore 2002; Roth et al. 2015) whereas other scientists reported the opposite conclusion that more DOC released into soil in higher temperature season (Herrmann and Bauhus 2013). Besides the temperature, there are studies showed that DOC flux significantly increased with increasing precipitation (Borken et al. 2011; Schmidt et al. 2011; Gielen et al. 2011; Neff and Asner 2001) while other studies found the opposite result that DOC release only weakly correlated with precipitation (Bantle et al. 2014). In the broader context of carbon sequestration and climate change, most studies emphasized on the understanding of soil DOC dynamics in a local, regional scale (Borken et al. 2011; Van den Berg et al. 2012), lack of data on subtropical or tropical forests (Gmach et al. 2019) or natural forests almost without human disturbing, and researches of large continental or global scale are scarce (Camino-Serrano et al. 2014). In addition, obtaining detailed data on a continental scale concerning the distribution of dissolved organic carbon with respect to soil depth, climate gradient, soil type and forest type would help with sustainable forest management, including C sequestration plans (Goddéris et al. 2013; Kalbitz et al. 2013).

Therefore, we chosen a 4000 km North-South transect of Eastern China, recognized as the 15th International Geosphere Biosphere Programme (IGBP) standard transect (Zhang and Yang 1995; Xu et al. 2017), to sample soils from four long-term experimental research stations (including 14 forest types). We would aim to (1) investigate the distribution of soil DOC concentrations in different variable gradients in natural forest ecosystems in a large continental transect (2) and assess the relation between various influencing factors (e.g. MAT-MAP-forest type) and DOC concentrations along the North-South transect of Eastern China. So, our study can provide an innovative selection of a specific forest type within set temperature regimes, which can contribute to the stabilization and sequestration of soil DOC on a national to near-continental scale to mitigate climate change.

2. Materials and methods

2.1. Study site and soil sampling

The study was conducted in the 15th transect of International Geosphere Biosphere Programme (IGBP), North-South Transect of Eastern China (109.5°E to 128°E, 18.7°N to 53°N), with the MAT and MAP ranging from -4 to 24 °C and 420 to 1750 mm, respectively. The transect covering soil types from cold temperate Haplic Podzol to subtropical Haplic Acrisol, tropical Rhodic Ferralsol, containing most of the Northern Hemisphere forest types from cold temperate coniferous forests to tropical rain forests, which are mainly controlled by the East Asian summer monsoon (Zhang and Yang 1995), is more than 4000 km from south to north (Fig.1,Table 1).

Soil samples were collected in September and October 2019 and June 2020 from four long-term forest ecosystem research stations, which are evenly distributed along the North-South transect and represent corresponding crucial climate zones (south subtropical, north subtropical, warm temperate, cold temperate), and are almost all located in China's national nature reserves. These stations are Changbaishan Forest (CF, 128.47°E, 42.4°N), Beijing Donlingshan Forest (BF, 115.43°E, 39.97°N), Shennongjia Forest (SF, 110.05°~110.57°E, 31.32°~31.6°N) and Dinghushan Forest (DF, 112.5°~112.55°E, 23.15°~23.18°N), respectively. At CF, Korean pine broadleaved, Korean pine spruce-fir, Yue spruce-fir and Yue birch forest were selected. At BF, temperate deciduous broadleaved forest was selected. For SF, evergreen broadleaved, evergreen deciduous broadleaved mixed, deciduous broadleaved, subalpine coniferous-broadleaved mixed and subalpine coniferous forest were selected, and finally mountain evergreen broadleaved, conifer-broadleaved mixed, monsoon evergreen broadleaved, and warm coniferous forest were selected in DF. In each forest type, we selected six representative plots (6 replicates). The plots were measured as 20 m × 20 m with a distance of at least 15 m between each plot. The three subplots were randomly settled using the S-shaped sampling method in each plot and within each subplot the fresh, green undecomposed litter material (~0.5 cm) and small pebbles or stones were removed. Three soil layers (0–20 cm, 20–40 cm, 40–60 cm) were sampled with a 5 cm diameter stainless steel corer and thoroughly mixed the corresponding layer to prepare a representative sample of the whole plot. At the same time, soil samples were collected by the ring knife with a volume of 100 cm^3 for soil bulk density calculation (Blake 1965). The information on position including longitude, latitude, rough slope, and elevation were recorded by a GPS device. The soil samples were homogenized by sieving for determining the physical and chemical parameters. The soil samples were sealed in polyethylene bags prior to use.

2.2. Soil physical and chemical parameter

Soil organic carbon was determined by dichromate oxidation and titration with ferrous ammonium sulfate (Walkley and Black 1934). Soil pH value was measured with a pH electrode placed into soil suspension with soil to distilled water ratio of 1: 2.5 (McCauley 2009). Soil dissolved organic carbon (DOC) was measured referencing the method of Jones (Jones 2006; Li et al. 2016). 1.5 g of fresh soil sample was mixed with 15 mL deionized water into 50 cm^3 polypropylene centrifuge tubes (the soils and extract distilled water were pre-chilled overnight in the fridge) and then were put into a reciprocating shaker at a speed of 200 r min^{-1} for 15 min at about 20℃. The soil extracts were centrifuged at 8000 g for 10 min and the supernatant was filtered by 0.45 μm hybrid fiber filter membrane (Xinya China). The filtrate was collected and stored in polypropylene bottles in −20℃ freezer and was thawed at 4 ℃ prior to analysis. The organic carbon concentration was measured by the total carbon analyzer (Elemental vario TOC cube, Germany).

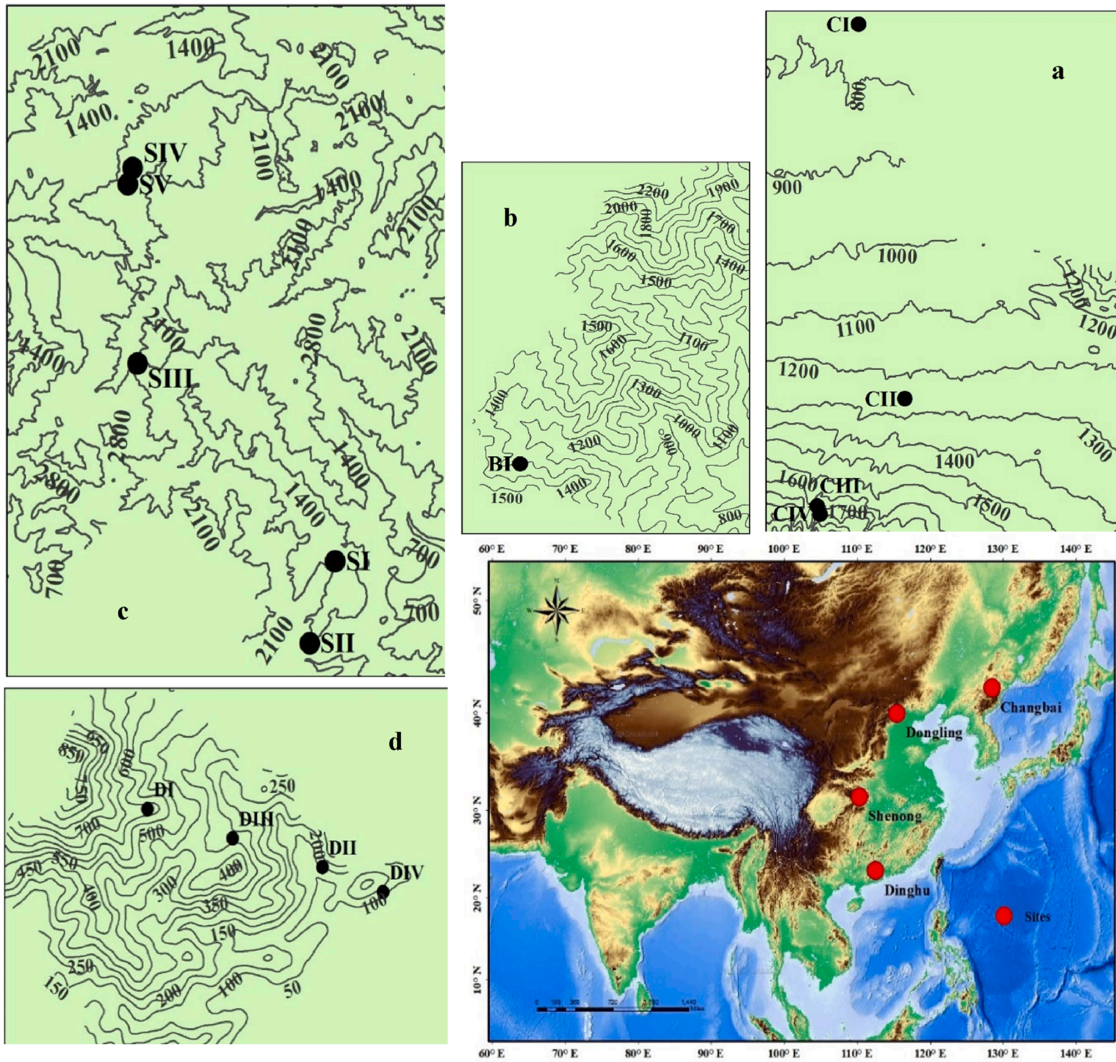

Fig. 1. Map of study area and distribution of soil sampling sites along the North-South transect of Eastern China. Graphs a-d are different forest ecosystems of Changbai, Beijing Doling, Shennong, and Dinghu, respectively. The abbreviations are as follows: DI, mountain evergreen broadleaved forest; DII, conifer-broadleaved mixed forest; DIII, monsoon evergreen broadleaved forest; DIV, warm coniferous forest; SI, evergreen broadleaved forest; SII, evergreen deciduous broadleaved mixed forest; SIII, deciduous broadleaved forest; SIV, subalpine coniferous-broadleaved mixed forest; SV, subalpine coniferous forest; BI, warm temperate deciduous broadleaved forest; CI, Korean pine broadleaved forest; CII, Korean pine spruce-fir forest; CIII, Yue spruce-fir forest; CIV, Yue birch forest.

2.3. Statistical analysis

Statistical analysis was performed using SPSS statistics 26.0 and Arcgis 10.4. Graphical processing was used by Origin 2022. One-way analysis of variance (ANOVA) with post hoc multiple comparisons using a least significance difference (LSD) test with $p < 0.05$ as the cut-off value indicated statistical significance between the results of soil DOC concentration under different influencing factors. Correlation measures how closely related soil DOC concentrations and influencing factors (i.e. MAT, MAP, ALT, pH and forest type, soil type) by calculating the correlation coefficient using Pearson linear regression and Spearman correlation analysis. The specific slope value was acquired by analyzing digital elevation model (DEM) of corresponding study areas using 3D analyst tools with raster surface in Arcgis 10.4 and referencing to some records of sampling.

3. Results

3.1. Variation in DOC concentration along the North-South transect

The DOC concentrations differed significantly ($p < 0.01$) in the 14 forest ecosystems along the North-South transect. The highest and lowest DOC concentrations in the upper 60 cm soil layer were observed in DIII (113.8 ± 1.4 mg C/L) and CIII (57.6 ± 3.0 mg C/L), respectively (Fig. 2). Most larger DOC concentrations at any soil depth were observed in southern low latitudes subtropical forest ecosystems (i.e. Dinghushan and Shennongjia forest ecosystems) along the transect. The highest DOC concentration in the upper 20 cm soil layer measured at 38.2 ± 1.0 mg C/L was found in DIII, i.e. monsoon evergreen broadleaved forest, while the lowest DOC concentration with 19.0 ± 1.3 mg C/L was observed in CIII, i.e. Yue-spruce fir forest (Table S1).

At CF, the highest and the lowest DOC concentrations in the upper 60 cm soil layer were observed with 68.0 ± 5.3 mg C/L and 57.6 ± 3.0 mg C/L in Yue birch forest (CIV) and Yue spruce-fir forest (CIII), respectively. Similarly, at SF, we found that the highest and the lowest DOC concentrations in the upper 60 cm soil layer occurred in evergreen deciduous broadleaved mixed forest (SII) and subalpine coniferous-broadleaved mixed forest (SIV) with 80.8 ± 3.7 mg C/L and 65.8 ± 2.9 mg C/L, respectively. For DF, the monsoon evergreen broadleaved forest (DIII) and the conifer-broadleaved mixed forest (DII) showed the highest and the lowest DOC concentrations measured at 113.8 ± 1.4 mg C/L and 65.8 ± 3.3 mg C/L, respectively (Table S1). The highest DOC

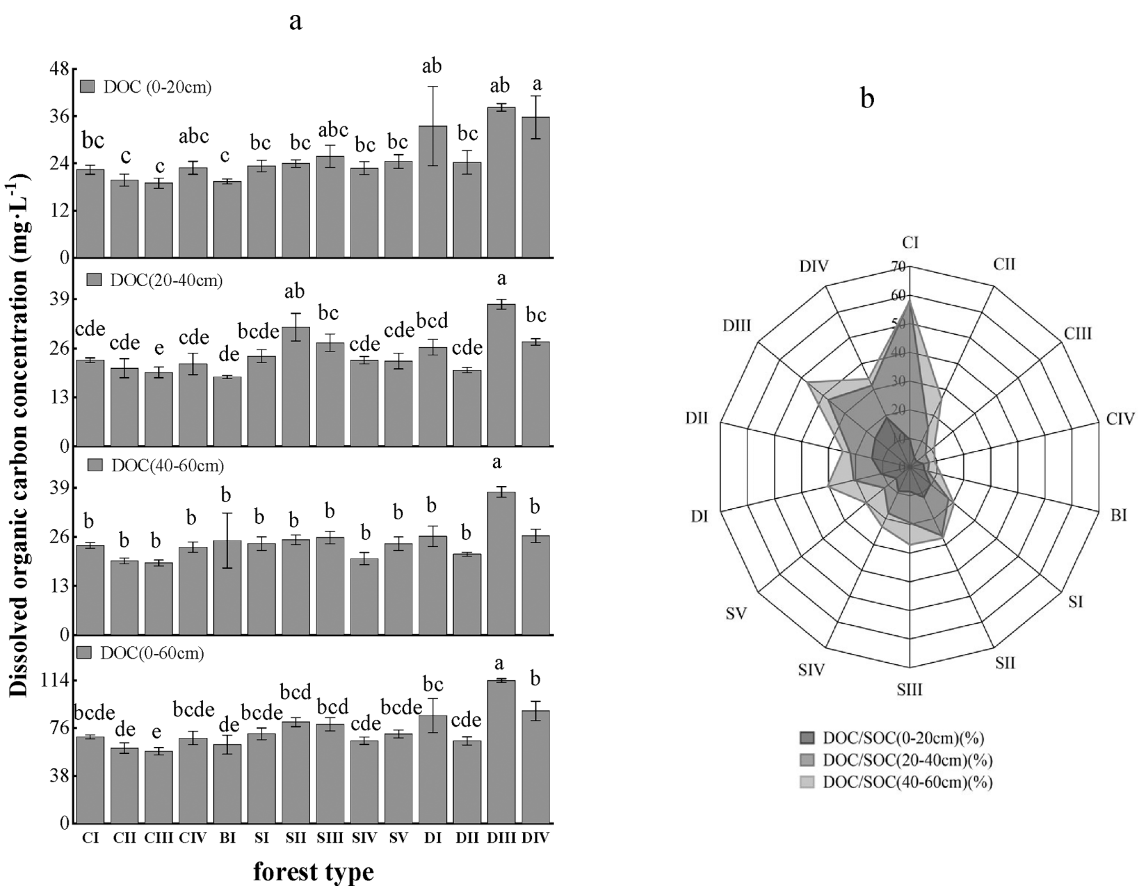

Fig. 2. Soil dissolved organic carbon concentrations at different soil depths (graph a) and the proportion of dissolved organic carbon accounting for soil organic carbon in the 14 forests (graph b) along the North-South transect of Eastern China.

concentrations in the upper 20 cm and 60 cm soil layer both occurred in the same forest at each ecosystem research station, and the lowest DOC concentrations showed the same situation (Table S1).

We found that the highest DOC concentration in the upper 20 cm soil layer with 33.5 mg C/L occurred in Haplic Acrisol, while the lowest one with 19.0 mg C/L was found in Haplic Andosol. However, there appeared different trends in the upper 60 cm soil layer. Among all of soil types, in the upper 60 cm soil layer, Haplic ferralsol had the highest DOC concentration with 89.7 mg C/L and the second highest DOC concentration measured at 85.9 mg C/L occurred in Haplic Acrisol, while the lowest DOC concentration was found in Haplic Andosol with 57.6 mg C/L (Fig. 3).

The DOC concentrations was higer in 0–20 cm depth than in 40–60 cm depth in southern areas with MAP $\geq$ 1500 mm over the North-South transect, but there did not appeared a regular trend about DOC concentration at the depth of 20–40 cm, namely it was higher or lower than that at the depths of 0–20 cm or 40–60 cm. In these areas (MAP $\geq$ 1500 mm) there contained all of forest types in DF and part of forest types in SF, i.e. mountain evergreen broadleaved forest (DI), conifer-broadleaved mixed forest (DII), monsoon evergreen broadleaved forest (DIII), warm coniferous forest (DIV), subalpine coniferous-broadleaved mixed forest (SIV), and subalpine coniferous forest (SV). In contrast, in the northern regions with MAP < 1500 mm over the transect, the DOC concentrations were slight lower in 0–20 cm depth than in 40–60 cm depth (Fig. 4). Most of forests in CF, BF and SF research stations were included in the areas with MAP < 1500 mm, i.e. Korean pine broadleaved forest (CI), Yue birch forest (CIV), warm temperate deciduous broadleaved forest (BI), evergreen broadleaved forest (SI), evergreen deciduous broadleaved mixed forest (SII), deciduous broadleaved forest (SIII). In a word, there exhibited an opposite trend on DOC concentrations from surface soil to subsoil in all the 14 forests along the North-South transect, however, the DOC concentration at the depth of 20–40 cm did not show a regular trend (Fig. 4, Table S1).

3.2. The proportion of DOC in SOC

The highest proportion of DOC accounting for SOC (19.09 %) in the upper 20 cm soil layer was observed in warm coniferous forest (DIV) whilst the lowest proportion value (3.16 %) occurred in Yue spruce-fir forest (CIII). Similarly, the highest proportion of DOC (0–60 cm) accounting for SOC (27.15 %) occurred in DIII while the lowest one (5.54 %) was observed in CIII. The proportion of DOC accounting for SOC at the depth of 40–60 cm was far higher than that at the depth of 0–20 cm in each forest and the ratio of DOC in SOC increased with increasing soil depth (Fig. 2b, Table S3).

3.3. Correlation between soil dissolved organic carbon and influencing factors

The DOC concentrations at any soil depth differed significantly between the 14 forests, MAT, MAP, soil type ($p < 0.01$), and showed different levels of correlation with the influencing factors (Fig. 5, Table S2).

The DOC concentrations at the depth of 0–20 cm strongly positively correlated with MAP, MAT, forest type, soil type and weakly positively correlated with slope, while strongly negatively correlated with ALT, pH (Fig. 5, Table S2). Forest type ($R^2 = 0.48$) most correlated with DOC concentrations in the upper 20 cm soil layer, followed by MAP ($R^2 = 0.46$), MAT ($R^2 = 0.45$). At the depth of 20–40 cm, the DOC concentrations most correlated with MAT ($R^2 = 0.43$), followed by forest type

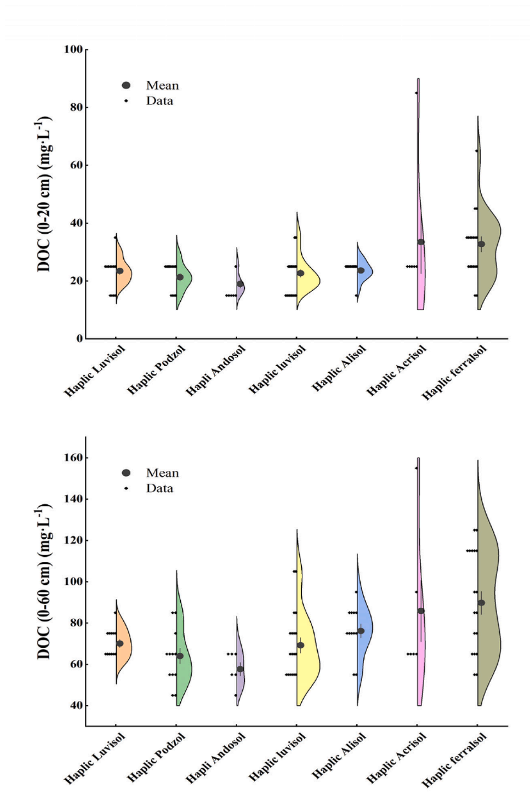

Fig. 3. The distribution of soil dissolved organic carbon concentration at the depths of 0–20 cm and 0–60 cm in different soil types along the North-South transect of Eastern China.

(R^2 = 0.41) and MAP (R^2 = 0.38). Similarly, the DOC concentrations at the depth of 40–60 cm significantly correlated most with forest type (R^2 = 0.37), followed by MAT (R^2 = 0.32) and soil type (R^2 = 0.31). In the upper 60 cm soil layer, the DOC concentrations most correlated with MAT(R^2 = 0.50), followed by MAP (R^2 = 0.46) and forest type (R^2 = 0.45) (Table S2). At any soil depth, slope was the weakest correlation factor with DOC concentrations and soil pH only correlated with DOC concentrations at the depth of 0–20 cm (Table S2).

Whatever at any soil layer, MAT, MAP and forest type were the most correlation large-scale factors for DOC concentrations.

4. Discussion

4.1. Distribution of DOC concentration along the North-South transect

In this study, we found an opposite trend on DOC concentrations from the depth of 0–20 cm to 40–60 cm in all the 14 forests (Fig. 4). In these forests with MAP $\geq$ 1500 mm in Dinghushan and Shennongjia, DOC concentrations appeared an apparently decreasing trend from surface soil to subsoil, which was an identical result with previous studies (Camino-Serrano et al.2014; Michalzik et al. 2001). The high MAP can enhance plant material decomposition rates (Zhou 2015), and then result in DOC derived from fresh litterfall being largely retained in surface soil and small fraction of litter-derived DOC moving into subsoil by leaching (Fröberg et al. 2007). Moreover, the DOC in surface soil may be run off into rivers by the high rainfall intensity in the areas with high MAP (Herbrich 2017), which lead to less DOC moving into subsoil. However, in the forests of Changbaishan and Beijing Donglingshan with MAP < 1500 mm, the DOC concentrations slightly increased from 0 to 20 cm to 40–60 cm depth (Table 1, Table S1), which was different from previous studies (Leinemann et al. 2018). As we known, the quantities of DOC in forest soils was regulated by a suit of complex physiochemical process that retain, transport or release (Scott and Rothstein 2014). Some complex compounds from litter inputs onto soil surfaces, while more easily soluble compounds continue into subsoils (Guggenberger and Kaiser 2003; Kaiser and Kalbitz 2012), which may lead to large quantities of DOC into subsoil. Sanderman et al. pointed that some litter-derived compounds with previously absorbed into surface soil or microbially-altered having a lower affinity for soil surfaces dissolved and migrated deeper into soil, or older DOC into deep soil could be remobilized by input of fresh highly surface-reactive, which result in more DOC observed in greater soil depth (Sanderman 2008; Kaiser and Kalbit 2012). Even more, some researches indicated that DOC in deep soil is not directly derived from topsoil (Hagedorn 2004) due to that DOC may be consumed in the upper soil layer (Fröberg et al. 2007).

In addition, the depth and thickness of soil horizons differ in different forest soil due to the variation of landscape position, vegetation, parent material and processing time (Hartemink et al.2020). The depth of 0–20 cm may contain the whole O horizon which is mainly made from plant residue and other organic matter, and/or part of A horizon. Similarly, the depth of 20–40 cm may contain part of A horizon which mainly occurs leaching process, and part of B horizon which occurs illuviation process and concentrates silicates, clay content, other carbonates. Similar situation is also at the depth of 40–60 cm that may contain part of A and B horizon or only contain B horizon. In the studied 14 forests along the North-South transect, the distribution discrepancy of DOC concentrations in soil depth resulted from the various soil pH, soil clay content, water holding capacity, leaching rates, porosity in different soil horizons (Alway and Trumbull 1912; Purvis and Davidson 1948; Vazhenin et al.1969). More important, these different soil characteristics combined with climate conditions and microbial processing can affect the production, sorption, desorption, migration, decomposition of DOC (Saidy et al. 2013; Kaiser and kalbitz 2012). The approach of mechanical sampling and invisible boundaries of soil horizon (Hartemink and Minasny 2014) intensified this kind of difference on DOC changing with soil depth. In our study we found relative consistent changing trend on DOC concentrations from the depth of 0–20 cm (main O horizon) to the depth of 40–60 cm (main B horizon), namely, DOC concentrations from surface soil to subsoil decreased in the forests with MAP $\geq$ 1500 mm while increased in the forests with MAP < 1500 mm (Fig. 4). However, due to the complex formation, migration of DOC, to acquire more information about the vertical distribution of soil DOC in a large scale and what the relation between soil depth, MAP and DOC concentration, more research work needs to be explored.

In the North-South transect study, we found that the highest DOC concentration was observed in monsoon evergreen broadleaved forest (DIII) and the lowest DOC concentration occurred in Yue spruce-fir forest (CIII) (Fig. 2), which is consistent with previous studies (Wang et al. 2016; Michalzik et al. 2001) that higher DOC concentrations were observed in Dinghushan forests along the North-South transect. Broadleaved forests in subtropical areas have greater amount and higher quality litters, thereby resulting in more DOC production (Cotrufo 2013) and increasing the probability for soil organic molecules to dissolve into water (Borken et al. 2011). However, our result differed from these studies that lower DOC concentration was observed in broadleaved forests than in coniferous forests (Camino-Serrano et al. 2014; Fröberg et al. 2011; Kalbit et al. 2000a, 2000b; Smolander 2002). Compared to the early studies that focus mainly on temperate forests, we complemented subtropical forests to explore the variation of soil DOC and found that higher DOC concentration was observed in subtropical broadleaved forests (Fig. 2, Table S1). In addition, albeit the similar types of forests, i.e. deciduous broadleaved forest and monsoon evergreen broad-leaved forest, or warm coniferous forest and subalpine coniferous forest, there was still discrepancy on the quantity of DOC concentration (Fig. 2, Table S1). The differences suggest that the accumulation of DOC is affected by not only forest type but also other variables such as soil type, climate parameters (Roth et al. 2015; Camino-Serrano 2014).

We found that the highest DOC concentration in the upper 60 cm soil

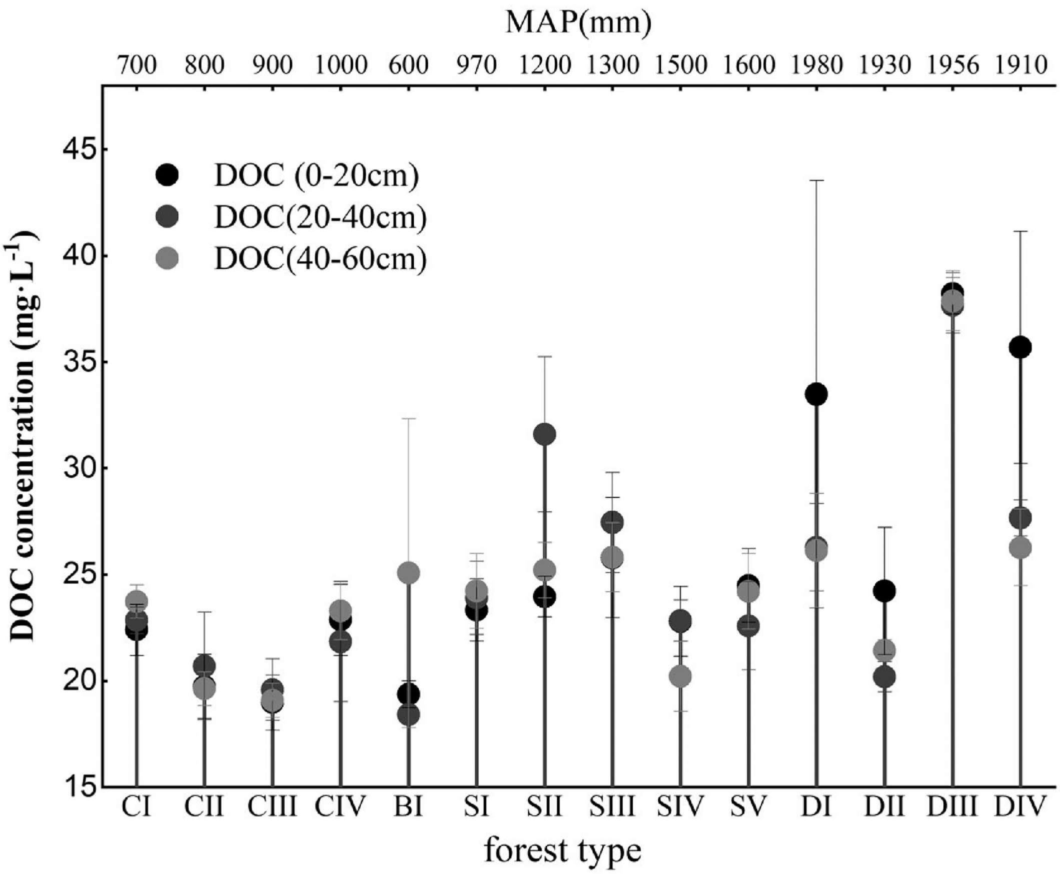

Fig. 4. The soil dissolved organic carbon concentrations in different forests at different soil depths along the North-South transect of Eastern China.

layer was observed in Haplic ferralsol (Fig. 3), which is developed in subtropical areas with abundant annual precipitation. Also, Haplic ferralsol has a low pH (~3.9) which may enhance dissolution of DOC due to its acid-base properties (Kalbit et al. 2000a, 2000b; Hruska et al. 2003). However, the highest DOC concentration in the upper 20 cm soil layer was observed in Haplic Acrisol (Fig. 3), which is developed in the same subtropical areas with Haplic ferralsol. However, Haplic Acrisol has a higher organic carbon which could convert into more DOC than Haplic ferralsol in the upper 20 cm soil layer (Fig. 3, Table S4). In addition, the soil texture of Haplic Acrisol is more clayey than Haplic ferralsol, such that much water can be sustained in the upper soil layer and result in more buildup of DOC (Camino-Serrano et al. 2014).

On the contrary, we found that the lowest DOC concentration at the depths of 0–20 cm or 0–60 cm were both observed in Haplic Andosol (Fig. 3). Typically, SOC content in Haplic Andosol is protected against decomposition by sorption to the volcanic mineral, so that more SOC content is stabilized resulting in low DOC concentrations production (Óskarsson et al. 2004).

In a word, soil type affects DOC concentrations through soil texture, pH or particles, further to determines the stabilization degree of SOC (Schwendenmann 2005) and the amount of emissions of CO_2 to atmosphere.

4.2. Proportion of DOC accounting for SOC in forests

In all the 14 forests, the proportions of DOC accounting for SOC increased with increasing depth (Fig. 2b, Table S3), which suggested that larger DOC in subsoil contributed to the C stabilization. Some scientists believed that DOC was a potential source of stabilized C in subsoil through C redistribution in deeper soil layers (Fröberg et al. 2007; Kalbitz and Kaiser 2008), therefore, more SOC was accumulated (Schneider et al. 2010; Saidy 2015) rather than loss by CO_2 form (Smith 2004), finally led to C sequestration in subsoil. Therefore, the 14 natural forest ecosystems along the North-South transect possessed a large potential capacity for soil C sequestration.

Moreover, in our study, we found that the proportions of DOC accounting for SOC in the upper 20 cm soil layer were larger in subtropical forests than in temperate forests, and exhibited a contrary situation at the depth of 20–60 cm over the North-South transect, which meant that long-term soil C sequestration potential in temperate forests is larger than in subtropical forest ecosystems. DOC is an indicator of SOC stability due to its characteristics such as easily being oxidized to CO_2 or dissolved into water (Kalbitz et al. 2003) or being utilized by microorganism (Schwesig et al. 2003, Barnes et al. 2018; Mann et al. 2015; Hood et al. 2009). High proportion of DOC in SOC means increasing probabilities of CO_2 release into atmosphere, soil C loss and inferior C sequestration capacity. Consequently, the lower and higher proportion of DOC/SOC in the surface soil and subsoil, respectively, implicates that the more stabilization of soil C in temperate forests over the North-South transect.

4.3. DOC concentrations in relation to various parameters

In our study, we found that DOC concentrations significantly correlated most with forest type, MAP, MAT at any soil depth (Fig. 2, Table S2). Bantle et al. pointed that DOC release was determined by tree species in surface soil (Bantle et al. 2014). Different forests can affect DOC concentrations by different C/N ratio (Weedon et al. 2009) or lignin content (Kuehne et al.2008) or litter fresh degree (Don and Kalbitz 2005). DOC release from plant leaves is much more from fresh than decomposed litter (Don and Kalbitz 2005). In our study, larger DOC concentrations were observed in Dinghushan forests than in

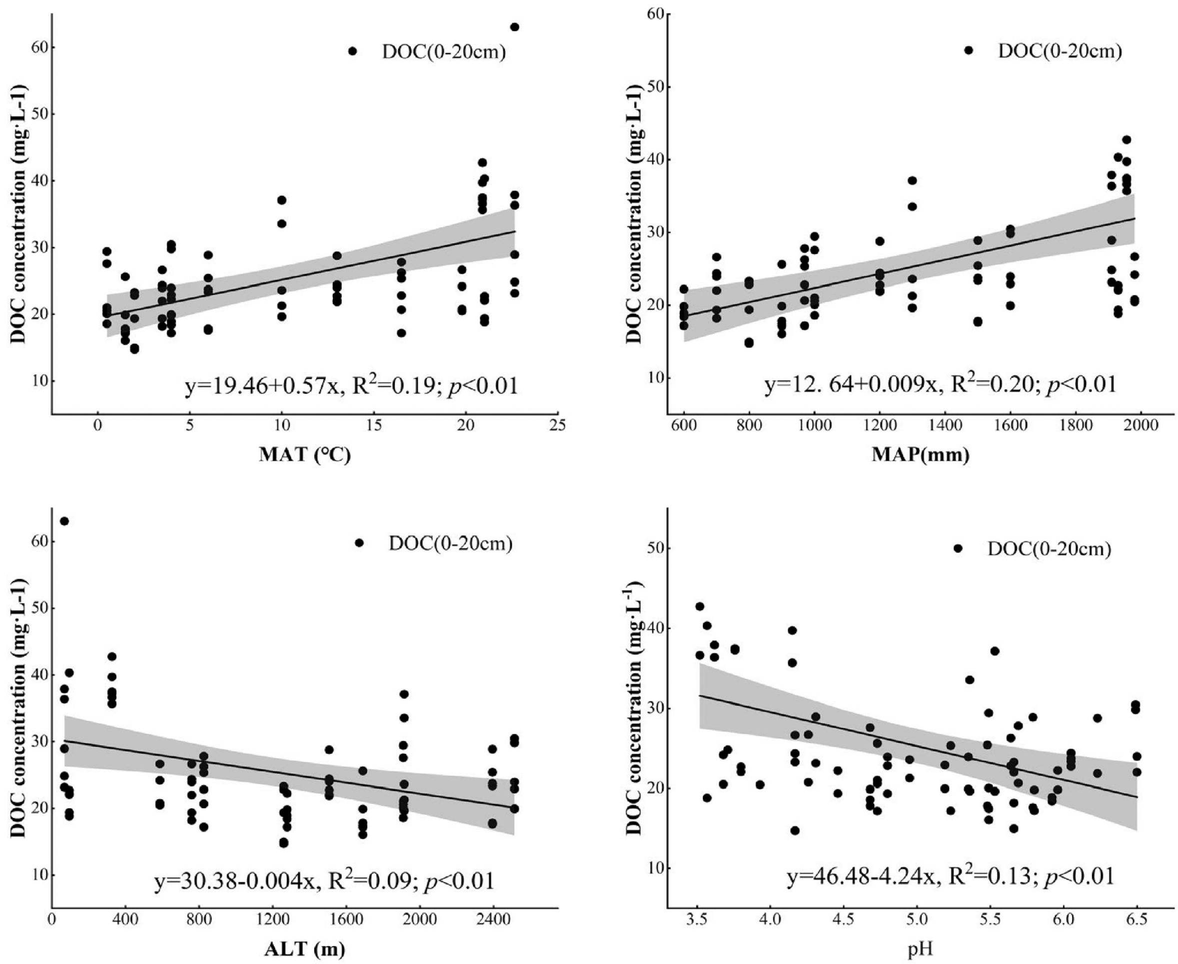

Fig. 5. The DOC concentrations at a depth of 0–20 cm in different forest types along the North-South transect in relation to MAT, MAP, ALT and soil pH (n = 6).

Table 1
Main characteristics of the soil sampling sites along the North-South transect.

Sampling sties		LON (E)	LAT(N)	ALT (m)	Slope	MAT (℃)	MAP (mm)	Soil type	Forest type
Changbai (CF)	CI	128.0953°	42.4018°	761	1°	3.5	700	Haplic Luvisol	Korean pine broadleaved forest
	CII	128.1284°	42.1414°	1261	2°	2	800	Haplic Podzol	Korean pine spruce-fir forest
	CIII	128.0659°	42.0667°	1691	19°	1.5	900	Haplic Podzol	Yue spruce-fir forest
	CIV	128.0680°	42.0610°	1911	20°	0.5	1000	Haplic Andosol	Yue birch forest
Dongling (BF)	BI	115.4256°	39.9580°	1279	19°	4	600	Haplic luvisol	Warm temperate deciduous broadleaved forest
Shennong (SF)	SI	110.4988°	31.3689°	827	34°	16.5	970	Haplic Alisol	Evergreen broadleaved forest
	SII	110.4777°	31.3086°	1508	27°	13	1200	Haplic Alisol	Evergreen deciduous broadleaved mixed forest
	SIII	110.3413°	31.5139°	1916	24°	10	1300	Haplic luvisol	Deciduous broadleaved forest
	SIV	110.3374°	31.6576°	2395	32°	6	1500	Haplic luvisol	Subalpine coniferous-broadleaved mixed
	SV	110.3337°	31.6454°	2514	21°	4	1600	Haplic Luvisol	Subalpine coniferous forest
Dinghu (CF)	DI	112.5235°	23.1759°	587	28°	19.79	1980	Haplic Acrisol	Mountain evergreen broadleaved forest
	DII	112.5483°	23.1687°	96	15°	21.01	1930	Haplic ferralsol	Conifer-broadleaved mixed forest
	DIII	112.5356°	23.1723°	328	20°	20.9	1956	Haplic ferralsol	Monsoon evergreen broadleaved forest
	DIV	112.5570°	23.1657°	70	23°	22.66	1910	Haplic ferralsol	Warm coniferous forest

The abbreviations are as follows: LON, longitude; LAT, latitude; ALT, altitude; MAT, mean annual temperature; MAP, mean annual precipitation. These climate data were collected from the literature about the four long-term ecosystem stations and soil types according to FAO/UNESCO, and the slope value was analyzed using the Arcgis 10.4 software.

Changbaishan forests, due to the more quantities of fresh litter (∼9 Mg·ha^{-1}) in Dinghushan forests. More information about the correlation between C/N ratio and DOC concentrations in the 14 forests will be explored in future.

In our study, DOC concentrations in the upper 60 cm soil layer correlated most with MAT and MAP (Fig. 5, Table S2), which was consistent with the previous studies that DOC concentrations increased with increasing MAT (Fröberg et al. 2006; Liechty et al.1995). The DOC from plant litter (Scott and Rothstein 2014), microbial decomposition or root exudates (Jílková et al. 2019; Kalbitz and Kaiser 2008) easily dissolve into water or leach into subsoil (Schulze et al. 2011) or migrate into aquatic system (Scott and Rothstein 2014), thus, the accumulation of DOC in forest soil is the balance between production and decomposition (mainly driven by biological activity) or adsorption and desorption (largely controlled by soil type) (Bolan et al. 2011). These processes share a dependency of climate parameters, such as MAT, MAP. Higher MAT can improve the production of DOC by enhancing the activity of microorganism that can make more large carbon molecules decompose into small ones (Fröberg et al. 2006; Liechty et al. 1995; Andersson et al. 2000), and then enhance the production of DOC, but at the same time the decomposition rate of DOC could be also improved. In addition, higher MAP can reduce mineralization rates of SOC (Blodau, 2002), and lead undecomposed plant residues remaining as a source of DOC in soil (Camino-Serrano 2014). Also, the high precipitation level can increase the connectivity between SOC and soil water (Borken et al. 2011), and thus enhance the dissolution of SOC, finally result in more DOC accumulation.

The DOC concentrations at the depth of 0–20 cm had a significant negative correlation with soil pH (Fig. 5, Table S2). Higher DOC concentration was observed in the soils with lower pH (pH (H_2O) < 4.0) than in those with higher pH (pH (H_2O) greater than 4.0). The conclusion was similar with previous studies that larger DOC concentrations were found in acid soils than in basic soils (Clarke et al. 2005; Löfgren and Zetterberg 2011). Soil pH not only has a strong direct effect on solubility of DOC (Hruska 2003), but also indirectly changes the microbial activities to affect DOC concentrations (Camino-Serrano et al. 2014). The low pH can enhance the dissolution of organometal complexes to produce more DOC (Kalbit et al. 2000a, 2000b).

The variable altitudes exhibited a significant negative correlation with DOC concentration at any soil depth (Fig. 5, Fig. S1). Altitudes indirectly affect the DOC concentrations by altering the MAT or MAP, namely higher altitude signifies definite lower temperature. The DOC concentrations decreased with increasing altitude, which was consistent with the trend that less DOC concentration accumulated in forests with lower MAT along the North-South transect. In a word, the altitude correlated the DOC concentrations, but the level of correlation was inferior to that between climate factors (MAT and MAP) and DOC concentrations.

5. Conclusion

We estimated the distribution of DOC concentrations along the North-South transect and assessed its relation with different controlling factors. We found that higher soil DOC concentrations were observed in subtropical forests over the North-South transect. The highest and lowest DOC concentrations were found in monsoon evergreen broad-leaved forest, Haplic Acrisol and Yue spruce-fir forest, Haplic Andosol, respectively. The DOC concentrations decreased with soil depth in the forests with MAP $\geq$ 1500 mm. Temperate forests (especially Yue spruce-fir forest) possessed a larger potential for long-term soil C sequestration. MAT, MAP and forest type were the most large-scale controlling factors for DOC concentration over the North-South transect.

6. Contributions

Jie Gu performed experiment design, soil sampling, data collection, data analyses and wrote the manuscript. Roland Bol performed data analyses and helped to write the manuscript. Yang Wang helped to write the manuscript. Huanchao Zhang acquired funding for soil sampling and data collection. The authors declared that there is no conflict of interest.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that has been used is confidential.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.catena.2022.106691.

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