Soil carbon quantity and form are controlled predominantly by mean annual temperature along 4000 km North-South Transect of Eastern China

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ABSTRACT

The forest ecosystem plays a key role in mitigating global climate change through carbon sequestration in its biomass and soils to limit the rising atmospheric concentration of CO_2. However, the combined overall interaction of climate and forest type on the quantities and forms of soil carbon (organic vs. inorganic) has not yet been sufficiently investigated. In this study, the contents of soil total carbon (STC), soil organic carbon (SOC) and soil inorganic carbon (SIC) were measured along the 4000 km North-South Transect of Eastern China. We sampled 252 soil samples (6 replicates for each site, 3 depths for each site) from four long-term ecosystem experimental stations in Dinghushan, Shennongjia, Beijing and Changbaishan, along the transect from south to north, including 14 different forest types. The contents of STC, SOC, and SIC in the upper 60 cm soil layer varied in different types of forest with 34 -107 g C kg^{-1}, 31-104 g C kg^{-1}, and 1.5-8 g C kg^{-1}, respectively. The northern fir and birch forest, most notably in Changbaishan, had the highest STC and SOC contents. The higher SIC contents were found in the southern evergreen broad-leaved forests in Dinghushan and Shennongjia. The contents of STC, SOC and SIC differed significantly in terms of mean annual temperature (MAT), mean annual precipitation (MAP), forest type, and soil depth. In the upper 60 cm soil layer, the most significant correlations occurred between SOC (or STC) and MAT (R^2_{SOC}= -0.62, R^2_{STC}= -0.60) when compared with the correlation between SOC (or STC) and MAP (R^2_{SOC}= -0.45, R^2_{STC}= -0.45) or elevation (R^2_{SOC}= 0.48, R^2_{STC}= 0.48). The soil stratification ratio (SR) of STC and SOC were typically ~2~3 in most forests and even reached 5~7 in Changbaishan forest, indicating a well-functioning ecosystem overall. We concluded that on

the near-continental scale (4000 km), forest soil carbon contents and forms (SOC, STC, SIC) were controlled most strongly by temperature (MAT). Therefore, an innovative selection of a specific forest type (fir or broad-leaved forest) within set temperature regimes can better contribute to maximizing soil carbon content and thus optimize its sequestration on the national to near-continental scale to mitigate climate change.

Keywords: temperature, forest type, soil carbon, North-South transect of Eastern China, climate change, stratification of soil carbon.

1. Introduction

Soil is an important sink for carbon (C). Globally, C present in terrestrial soils in the upper 100 cm layer is more than triple that of the C stored in the atmosphere (Valentini and Rebmann 2000; Rawlins et al. 2011; Lal et al. 2015; Barthès et al. 2020). Soil C sequestration is a crucial process in many climate change mitigation strategies (Amelung et al. 2020; Basile-Doelsch et al. 2020; Brodowski et al. 2006). Scientists have undertaken considerable efforts to estimate the precise global storage of soil total carbon (STC) and soil organic carbon (SOC) (Minasny et al. 2018; Djukic et al. 2010; Niwa et al. 2011) and to explain temporal SOC dynamics (Doetterl et al. 2016; Mohseni and Salar 2020; Lozano-Garcia et al. 2017; Angelopoulou et al. 2019). For example, the global amount of STC and SOC in the upper 100 cm soil layer were estimated at 2157~2293 Gt and 1462~1548 Gt, respectively (Batjes 2014). Basile-Doelsch et al. (2020) estimated that global SOC amounted to ~2400 Gt and that an annual 4 per 1000 increase in the global soil C stock can theoretically offset 9.4 Gt C of anthropogenic CO_2 emissions per year. The proposed annual sequestration of SOC in the top 30 cm layer, which is equivalent to 0.4% of current stocks, would increase the C stock annually by 1.2 Pg, partly negating the global rise in atmospheric CO_2 (Paustian et al. 2016; Marie-France et al. 2017; Rumpel et al. 2020). SOC is therefore important for ecosystems and responds sensitively to environmental changes (Sanderman 2012; Sanderman and Baldock 2010). However, substantially less attention has been paid to soil inorganic carbon (SIC) content and its changes in the forest ecosystem. Estimates of the global SIC pool vary from 695 Pg to 1738 Pg (Eswaran 1993; Schlesinger 1982) which accounts for approximately two-thirds of the global SOC pool

(Sanderman 2012; Kim et al. 2020; Chevallier et al. 2016). The global changes in SIC stocks also have significant feedback to atmospheric CO_2 contents, therefore, SIC enhancement in soils is desirable for overall C sequestration (Kim et al. 2020).

Soil C dynamics are influenced by various factors, such as mean annual temperature (MAT), mean annual precipitation (MAP) (Ngaba et al. 2019; Ngaba et al. 2020; Jobbágy 2000), clay content (Gonzalez et al. 2003; Huygens 2005; Brodowski et al. 2006), elevation (Djukic et al. 2010; Mohseni and Salar 2020), forest type (Tadesse et al. 2014; Lin et al. 2018; Kooch et al. 2017**)**, soil type (Camino-Serrano et al. 2014) and geochemistry (Feng et al. 2013; Keiluweit et al. 2015). However, there is no definitive conclusion about what is the determinant factor for forest soil C content (Davidson et al. 2000; Fissore et al. 2017; Meier and Leuschner 2010; Riahi et al. 2011). Most studies believe that MAT, MAP and vegetation species are the controlling factors (Hakkenberg et al. 2008; Conant et al.2011). In large-scale field experiment studies, vegetation has been shown to be a more important factor influencing SOC content than MAT or MAP (Doetterl et al. 2015； Zhang et al. 2015; Bardgett and Wardle 2010; Luo et al. 2015). However, MAP is recognized as a more important factor in terms of influencing SOC content (Luo et al. 2017; Campo et al. 2016). Furthermore, a number of studies have reported that forest SOC increased with increasing MAT and MAP (Zhang et al. 2015；Chen et al. 2018), while other studies have drawn the opposite conclusion (Campo et al. 2016; Zhou et al. 2016; D et al. 2016). In addition, obtaining detailed data on a continental scale concerning the distribution of C with respect to soil depth, climate gradient, and forest type would help with sustainable forest management, including C sequestration plans (Goddéris et al. 2013; Kalbitz et al. 2013).

In order to examine the overall functionality of the soil ecosystem, the stratification ratio (SR) was determined (López-Fando and Pardo 2011). The stratification ratio (SR) is defined as the SOC (and similarly the STC) content in a surface divided by the deeper layer in the soil profile (Ma et al. 2016). Soil surfaces are vital interfaces that receive and process the intense impact of rainfall and control the gas flux partitioning into and out of the soil (Franzluebbers 2002). A value of SR≥2 signals good soil quality and functionality, with a high SOC content reflecting a relatively undisturbed soil surface with better water infiltration, and more stable aggregates, etc. However, under degraded soil conditions of SR>2 are not commonly found (Franzluebbers 2002; Crespo 2021; De Moraes Sa, 2009). To investigate the SR indicator of SOC (or STC) along a large spatial gradient would provide valuable information that would help in understanding climate effects and the forest ecosystem response to its soil C sequestration.

In this study, we therefore sampled soils from four long-term experimental research sites (including 14 forest types) along the 4000 km North-South transect of Eastern China, recognized as the 15th International Geosphere Biosphere Programme standard transect (Zhang 1995; Xu et al. 2017). Along this transect, the present study examined: (1) the spatial distribution of variation in STC, SOC, and SIC contents, and (2) the relative importance of key factors (e.g. forest type-MAT-MAP and elevation) on the forms (STC, SOC, and SIC) and amounts of C present in soil. We assumed that temperature and forest type would be the key factors influencing soil C content and form.

2. Materials and Methods

2.1 Study site

The study was conducted in the North-South Transect of Eastern China (109.5°E to 128° E, 18.73°N to 53°N) which is the 15th transect of the International Geosphere Biosphere Programme (IGBP). The transect is more than 4000 km from north to south, with the MAT and MAP ranging from -4~24℃ and 420~1750 mm, respectively, and covering soil types from tropical Rhodic Ferralsol, and subtropical Haplic Acrisol to cold temperate Haplic Podzol (Fig. 1, Table 1). The transect contains most of the Northern Hemisphere forest types from tropical rain forests to cold temperate coniferous forests, which are mainly controlled by the East Asian summer monsoon (Zhang 1995).

2.2 Soil sampling

Soil samples were collected from four long-term forest ecosystem research sites: Dinghushan Forest (DF, 112.5°~112.55°E, 23.15°~23.18°N), Shennongjia Forest (SF, 110.05°~110.57°E, 31.32°~31.6°N), Beijing Donlingshan Forest (BF, 115.43° E, 39.97° N) and Changbaishan Forest (CF, 128.47°E, 42.4°N) ecosystem stations in September-October 2019 and June 2020. The four stations represent four key climate zones (cold temperate, warm temperate, north subtropical, south subtropical), are evenly distributed across the North-South transect, and are almost all included in China's national nature reserves. At each station, soil samples were collected from different natural forests with different elevations from foot slope to summit (Fig. 1, Table 1). In DF, we selected mountain evergreen broad-leaved, conifer-broad-leaved mixed, monsoon evergreen broad-leaved, and warm coniferous forest. In SF evergreen broad-leaved, evergreen deciduous broad-leaved mixed, deciduous broad-leaved, subalpine coniferous-broad-leaved mixed and subalpine coniferous were selected. For BF, only a warm temperate deciduous broad-leaved forest was selected, while for CF we selected Korean pine broad-leaved, Korean pine spruce-fir, Yue spruce-fir, and Yue birch forest (Table 1). These forests all belong to natural forests that are not subject to any harvesting, logging, or the addition of fertilizer. For each forest type, we selected six representative plots (six replicates), which were measured as 20 m×20 m plots with a distance of at least 15 m between each plot. The three subplots were randomly chosen using the S-shaped sampling method in each plot and within each subplot the fresh, green undecomposed litter material (~0.5 cm), small pebbles or stones were removed. We sampled three soil layers (0-20 cm, 20-40 cm, 40-60 cm) using a stainless-steel corer with a diameter of 5 centimeters and thoroughly mixed the corresponding layer to prepare a representative sample of the whole plot. At the same time, soil samples were collected using a ring knife with a volume of 100 cm^3 to calculate the soil bulk density (Blake 1965). Information on positional data including longitude, latitude, and elevation were recorded by a GPS device. The soil samples were air-dried, and homogenized by sieving (<0.149 mm) to determine the physical and chemical parameters. The soil samples were then sealed in polyethylene bags prior to use.

2.3 Soil properties and statistical analysis

Soil total carbon (STC) was analyzed using an elemental analyzer (PerkinElmer 2400 II, USA), while SOC content was measured using the dichromate oxidation method (Jones 2001). The soil bulk density was determined using the drying method under laboratory conditions (Blake 1965), and complemented with existing bulk density records of the four forest ecosystem stations. The content of SIC is given as the difference between STC and SOC.

The content of SIC (g kg^{-1}) was calculated using the following equation:

$$SIC_C = STC_C - SOC_C \qquad (1)$$

where SIC_C, STC_C, and SOC_C represent the contents of SIC, STC, and SOC.

The stock of soil carbon (Mg ha^{-1}) at each depth was calculated according to the following equation:

$$STC_t/SOC_t/\ SIC_t = C \times D \times BD/10 \qquad (2)$$

where C, D, and BD represent the STC/SOC/SIC content (g kg^{-1}), the thickness of the soil layer (cm), and the bulk density (g cm^{-3}).

A stratification ratio (SR) of soil carbon was calculated as the SOC/STC content in a surface divided by that one deeper in the soil profile（Eq.(3)）.

$$SR_{SOC/STC} = \frac{SOC/STC_{C\ 0-20cm}}{SOC/STC_{C\ 20-40cm/40-60cm}} \qquad (3)$$

The differences between the soil carbon contents were evaluated according to the ANOVA method with post hoc multiple comparisons using a least significance difference (LSD) test with $p < 0.05$ as the cut-off value to indicate statistical significance in SPSS 26.0. Correlation measures how closely related two sets of multivariate data are (soil carbon contents vs influencing factors) by calculating the correlation coefficient (Pearson and Spearman) between all elements. Linear regression was performed with SPSS 26.0 and Origin 2021.

3. Results

3.1 Transect STC, SOC, and SIC content

The highest STC contents (107.1± 9.2 g C kg^{-1} and 102.7±3.0 g C kg^{-1} ; 0-60 cm) were found in CIII (Yue spruce-fir forest) and CIV (Yue birch forest) in CF, while the lowest STC contents (36.6 ±2.6 g C kg^{-1} and 38.8±2.4 g C kg^{-1}) were observed in DII (conifer-broad-leaved mixed forest) and DIV (warm coniferous forests) in DF. The STC contents in other forests had intermediate values, with the largest (88.0±5.1 g C kg^{-1}) found in BI (in BF). The variation in terms of SOC contents roughly followed that of STC contents, with the highest and the lowest values measured at 104.0±11.9 g C kg^{-1} and 31.4±4.4 g C kg^{-1}, respectively, since SOC contents account for 80% or more of the measured STC contents (Fig. 2). The SIC contents were always less than 10%, with the highest values measured at 8.41±1.0 g C kg^{-1} and 7.99±1.3 g C kg^{-1} in the upper 60 cm layer for SI (in SF) and DI (in DF), respectively (Table S1).

In general, the contents of STC (or SOC) decreased with depth in all forests, with more than 50% concentrated in the upper 0-20 cm layer (Fig. 2). In the CII forest (Korean pine spruce-fir forest) (in CF), the STC contents decreased drastically (> 80%) from a depth of 0-20 cm to 40-60 cm, while the smallest decrease (~40%) was observed in the warm temperate deciduous broad-leaved forest in BI (Fig. 2, Table 2). In contrast, the decrease related to depth in the SIC content was much less pronounced. Overall, the variations in SOC and STC contents were particularly pronounced in the upper soil layer, while the variation in SIC content was more significant in the subsoil (Fig. 2, Table S1).

3.2 Soil carbon stock

In our study, the stocks of STC and SOC (0-60 cm) were significantly higher in northern temperate zones with a lower temperature than in southern subtropical areas. For example, the highest stocks of STC and SOC were measured at 591.2 Mg C ha^{-1} and 566.6 Mg C ha^{-1}, respectively, in the BF ecosystem station in temperate regions. However, the lowest STC and SOC stocks (316 Mg C ha^{-1} and 287.4 Mg C ha^{-1}) were observed in the DF ecosystem station in subtropical areas (Table 2). The SIC stock (0-60 cm) did not show a regular trend with latitude, but a higher stock of SIC was generally found in the southern part rather than in the northern part of the 4000 km transect. Overall, the highest STC or SOC stock (0-60 cm) occurred in the warm temperate deciduous broad-leaved forest in BF.

Among the 14 forests, in the upper 20 cm soil layer, we found the highest stocks of SOC (71.4±10.3 Mg C ha^{-1}) and STC (70.9±7.8 Mg C ha^{-1}) in the Yue spruce-fir forest (CIII). In contrast, in the upper 20 cm soil layer, the lowest stocks of SOC (29.8±1.2 Mg C ha^{-1}) and STC (31.5±1.3 Mg C ha^{-1}) were found in the subalpine coniferous-broad-leaved mixed forest (SIV) (Table 3). In general, the trends of soil C content and stocks matched each other along the transect.

3.3 Stratification ratio of soil carbon

The SR of STC and SOC differed significantly ($p < 0.01$) in the 14 forests along the transect. The highest SR_{STC} and SR_{SOC} were observed in CF, followed by DF and SF. The lowest SR_{STC} and SR_{SOC} were found in BF. Most forests had SR values greater than 2 and even up to 7.06 in CII (Korean pine spruce-fir forest), while only two forests (BI and CIV) were found to have SR<2 (Fig. S3). The SR value generally increased with increasing depth, i.e. the SR value of 0-20/40-60 cm was higher than the SR value of 0-20/20-40 cm. The SR_{STC} and also the SR_{SOC} correlated significantly with slope, followed by MAP and MAT, respectively (Table S2).

3.4 Soil carbon content correlation with other key parameters

The depth-based SOC and STC values correlated significantly with each other ($p < 0.01$) in all of the14 forests along the transect, but there was no correlation between the SIC and SOC or STC.

At different soil depths (0-20 cm, 20-40 cm, 40-60 cm), both the SOC and STC showed a significant negative correlation ($p < 0.01$) with MAT and MAP, and a positive correlation ($p < 0.01$) with elevation (Fig. 3, Fig. S4). However, only the SOC content correlated negatively with slope in the 0-20 cm depth (Fig. 3). Additionally, the SIC content in the 0-20 cm and 40-60 cm depths positively correlated ($p < 0.01$) with MAT, slope, and elevation, slope, respectively (Fig. 4).

The best correlations were found between MAT and the contents of SOC or STC in all soil depths (Table S2). Soil and forest type were the second and third factors that correlated best with the contents of SOC and STC in the upper 20 cm layer, but elevation and MAP were more closely associated with the contents of SOC and STC in the 20-40 cm and 40-60 cm depths

(Table S2). In the upper 20 cm layer, the SIC content correlated best with MAT, followed by soil type and forest type, but elevation and slope provided the best correlation with SIC content in the 20-40 cm and 40-60 cm depths, respectively (Table S2).

4. Discussion

4.1 Distribution of soil carbon along the transect

The transect-based trends in SOC matched those of STC, although those of SIC were different. Higher SOC and STC contents were observed in both CF and BF, i.e. the northern high latitude sites with low MAT and MAP (Fig. 2, Table S1). The low temperature reducing the activity of microorganisms and slowing down C decomposition (Cesarz et al 2013; Keith et al. 2009; Ainsworth and Long 2005) ultimately resulted in more soil C accumulation in northern temperate deciduous broad-leaved and coniferous forests. In contrast, a higher SIC content was observed in southern low latitudes of the transect (Fig. 2, Table S1). SIC is classified as lithogenic inorganic carbon (LIC) and pedogenic inorganic carbon (PIC), which is carbonate inherited from the parent material of the soil and is formed through a dissolution and precipitation process of the carbonate parent material. Among the forms, PIC forms with the weathering of Ca/Mg-bearing silicates and then results in the C sequestration (Emmerich 2003), but a great deal of uncertainty remains with respect to the actual quantities involved and produced (Lal et al. 2015). Moreover, soil parent materials are quite different due to the geological process leading to the different formation of LIC or PIC with various ions, which may or may not easily combine with carbonate ions. In the southern part of the transect, the dominant rock type is sandstone or dolomite which contains more Ca/Mg-bearing silicates than the basalts of the northern part (Xu et al. 2020). In addition to the difference in MAT and MAP, this may lead to the higher SIC content in the southern forests of the transect. The SIC content in our study accounted for around 10% (and even up to 20%) of the STC content. However, the issue of how variable amounts of SIC interact with SOC sequestration in forest ecosystems required investigating in more detail (Mohseni and Salar 2020).

The measured SOC and STC contents generally decreased with increasing slope, but did not follow a strictly linear trend (Table 1, Table S1). More soil C content was found in depositional areas within the forest landscapes, i.e. arears with a moderate slope < 20°, which was similar to findings in other studies (Berhe and Kleber, 2013; Doetterl et al., 2016). In contrast, in more steep sloping areas there was less soil C content (Table 1, Table S1). Such areas are known to be more prone to erosion and loss of C, thus leading to a lower SOC (and STC) content (Berhe et al., 2008). However, in our study a higher soil C content was also found at sites with steeper slope areas, for example the subalpine coniferous forest, which proved that SOC (and STC) were not solely governed by the steepness of slopes in various forests.

We observed that transect-based SOC and STC contents decreased with increasing soil depth, which was consistent with previous studies (Harper and Tibbett 2013; Franzluebbers 2002; Yang et al. 2015). The decreasing trends with increasing depth, which we observed in all forests, is likely driven by the fact that plant litter fall and subsequent decomposition mainly occur at the soil surface. The C in the subsoil may be derived from root exudates, dead roots (Kell 2012), or dissolved C leaching down (Harper and Tibbett 2013), which enter in smaller amounts (Berger 2002). The SOC (or STC) content is therefore high in the surface soil, as has been commonly reported (Jobbágy 2000，Koarashi 2012).

4.2 Carbon stratification ratio and overall soil storage

In our transect, the Korean pine spruce-fir forest in CF had the highest SR_{SOC} (7.1) and the warm temperate deciduous broad-leaved forest in BF had the lowest SR_{SOC} (1.3) (Fig. S3). More than 60% of the 14 natural forest ecosystems had SR_{SOC} values of more than 2, which suggested overall a well-functioning forest ecosystem on the whole, since SR >2 is not common in under degraded soil（Franzluebbers 2002). We can therefore conclude that natural growth forests in our study of the transect had a well-functioning ecosystem and may have great potential for soil C sequestration.

The value of SR_{SOC} was most negatively correlated with slope (Table S2) in the investigated transect, which indicated that more C accumulated in the surface soil. From another perspective, the region with a gentle slope means that less soil and water is lost, while more stable soil aggregates, and more organic matter could accumulate (Fissore et al. 2017). The SR_{SOC} in correlation with slope could indicate a well-functioning forest ecosystem, which provides an interesting direction for forest management on the near continental scale. However, sampled soil depths should be standardized and evaluated for future comparisons between various global ecosystems using the SR approach (Fernández-Romero et al.2016; De Moraes Sa and Lal 2009; Causarano et al. 2008).

In terms of the stocks of soil C, we found that more soil C stocks accumulated in northern temperate zones than in southern subtropical forests along the transect, namely CF and BF have more C stock in the forest soil (Table 3). This result was consistent with a previous study (Franzluebbers 2001), which showed that soil C stock increased with increasing latitude. However, there is more litter fall input in subtropical areas than in temperate regions (Fantappiè et al. 2008), for example in our transect study the mean annual litter biomass of evergreen broad-leaved forest (SF) and Korean pine broad-leaved forest (CF) were about 7 Mg·ha^{-1} and 5 Mg·ha^{-1} , respectively (Liu et al. 2012; Liu et al. 2009; Fang 2006; Weng 1993), with the higher temperature and precipitation leading to a higher decomposition ratio and ultimately resulting in lower C accumulation in subtropical areas (Oades 1988). Climate factors dominated by MAT and MAP (especially MAT) affected soil C content more significantly than other influencing factors (Table S2). However, we found that in the same temperate zone the highest soil C stock occurred in broad-leaved forest (BF) whereas the highest soil C content occurred in coniferous forest (CF), which suggests that soil C formation, decomposition, and accumulation are affected by multiple factors. To understand what and how various factors affect soil C is of urgent importance.

4.3 Correlations between soil carbon and potential influencing factors

In this study, MAT was found to be the most important factor influencing soil C quantity and forms (SOC, STC, SIC) (Table S2). This differed from previous studies suggesting that MAP (Luo et al. 2017) or vegetation species (Gartzia-Bengoetxea et al. 2016; Guendehou et al. 2014) are the most important factors influencing soil C. MAT has received considerable attention and been the subject of controversy as one of the crucial environmental driving factors for soil C content (Conen et al. 2006; Knorr et al. 2005; Davidson et al. 2006). This is because

MAT not only controls vegetation species and quantity, but also affects the timing of leaf fall and associated C input into the forest litter layer (Boča et al. 2014). Furthermore, MAT also influences the structure and functioning of microbial communities, thus affecting the speed of soil C decay (Pare et al. 2006; Cesarz et al 2013; Keith et al. 2009).

Aside from MAT, there are other influencing factors for C. Soil type and forest type (especially for 0-20 cm soil), MAP and elevation (especially for 20-60 cm soil) were also found to be key factors directly or indirectly determining the quantity, turnover, and distribution of C in soils (Fig. 3, Fig. 4, Fig. S4, Table S2). On the one hand, soil type can indirectly influence the accumulation of C through its different clays, and porosity structure (Zhou 2005) or pH and forest type may control SOC content by controlling the amount or quality of litter input (Studdert and Echeverría 2000, Zhou 2014). On the other hand, MAP may influence soil C via water leaching or changing microbial biomass and elevation may be an indirect factor for soil C through changing MAP (Mohseni and Salar 2020).

Overall, this study provided us with information for a theoretical framework on how to overcome the complex relation between soil C and controlling factors. This large-scale (4000 km transect) study indicated that temperature is extremely important for soil C. This enables us to better weigh the various factors and thus build more accurate soil C dynamic models, which in turn may prove helpful in developing mitigation options to limit global climate change. Additionally, forest type was an important factor for soil C in the study, which suggests that more fir forests or broad-leaved forests can be planted to enhance soil C sequestration and thus mitigate climate change.

5. Conclusion

As expected, the distribution of soil C content (STC, SOC, SIC) varied significantly along the North-South transect of Eastern China. The northern fir forest (CF) had the largest STC and SOC contents, but the highest SIC content was observed in the southern evergreen broad-leaved forests. Overall, the soil C content in the forest ecosystems was more strongly controlled by MAT than MAP, forest or soil type, elevation, or slope. Northern fir and broad-leaved forests in temperate zones of the transect are likely to make the biggest contribution to maximizing soil forest C content.

6. Contributions

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

Acknowledgements

The authors would like to thank the members of staff at the Forest Ecosystem Research Stations of the Chinese Academy of Science. We would particularly like to thank Zhoude Ma, Xiao Ye, Xuan Mei, Yujin Zhu and Yang Wang, Guanhua Dai, Wenting Xu, Guowei Chu, and Dingsheng Mo for their support with the forest soil sampling. We would like to thank Yuxia Tang and Huayang Hong for assisting with the laboratory analysis. We would also like to thank the Priority Academic Program Development of Jiangsu Higher Education Institutions (Grant No.164010595) who funded this research.

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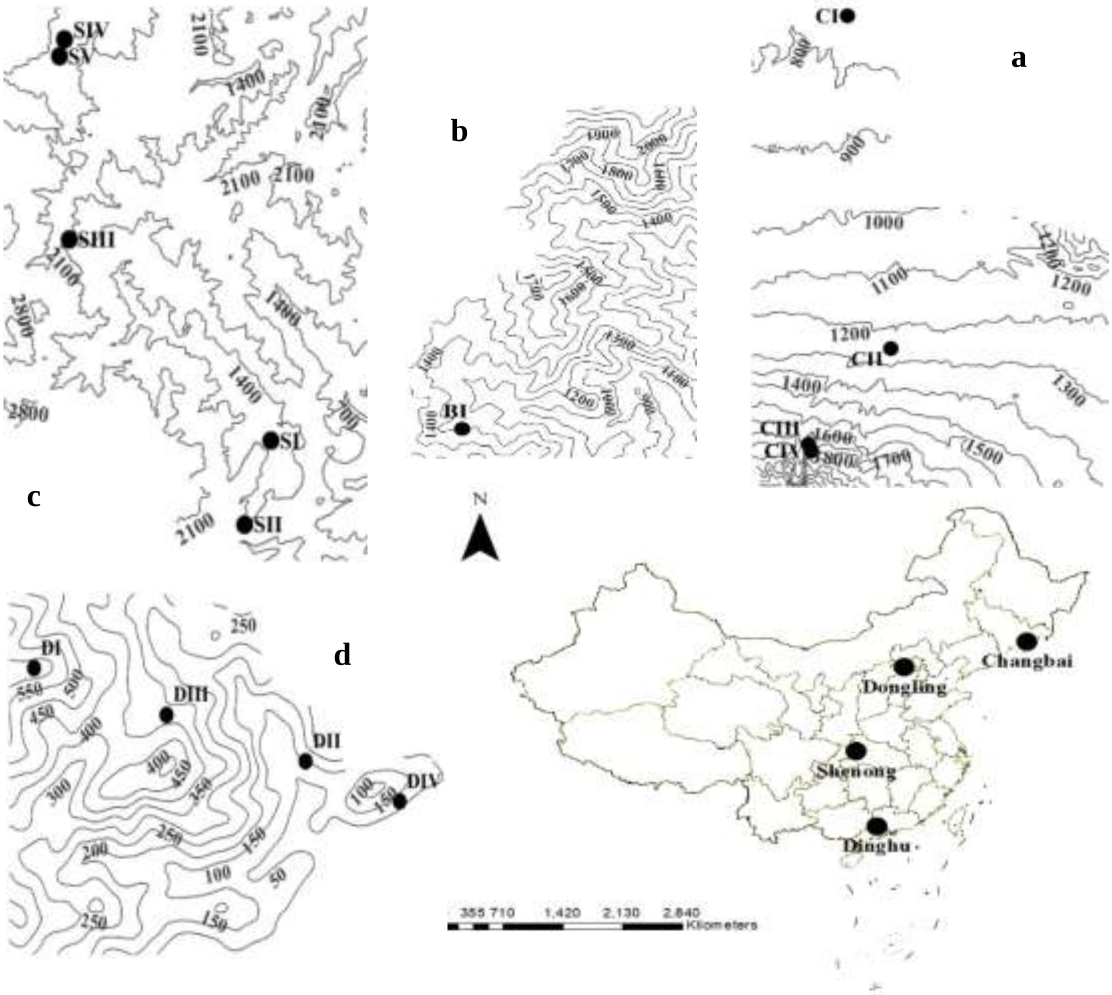

Fig. 1. Map of study area and distribution of soil sampling sites along the North-South transect of Eastern China. Graphs a-d were different forest ecosystems of Changbai, Beijing Doling, Shennong, and Dinghu, respectively. The abbreviations are as follows:

DI, mountain evergreen broad-leaved forest; DII, conifer-broad-leaved mixed forest; DIII, monsoon evergreen broad-leaved forest; DIV, warm coniferous forest; SI, evergreen broad-leaved forest; SII, evergreendeciduous broad-leaved mixed forest; SIII, deciduous broad-leaved forest; SIV, subalpine coniferous-broad-leaved mixed forest; SV, subalpine coniferous forest; BI, warm temperate deciduous broad-leaved forest; CI, Korean pine broad-leaved forest; CII, Korean pine spruce-fir forest; CIII, Yue spruce-fir forest; CIV, Yue birch forest.

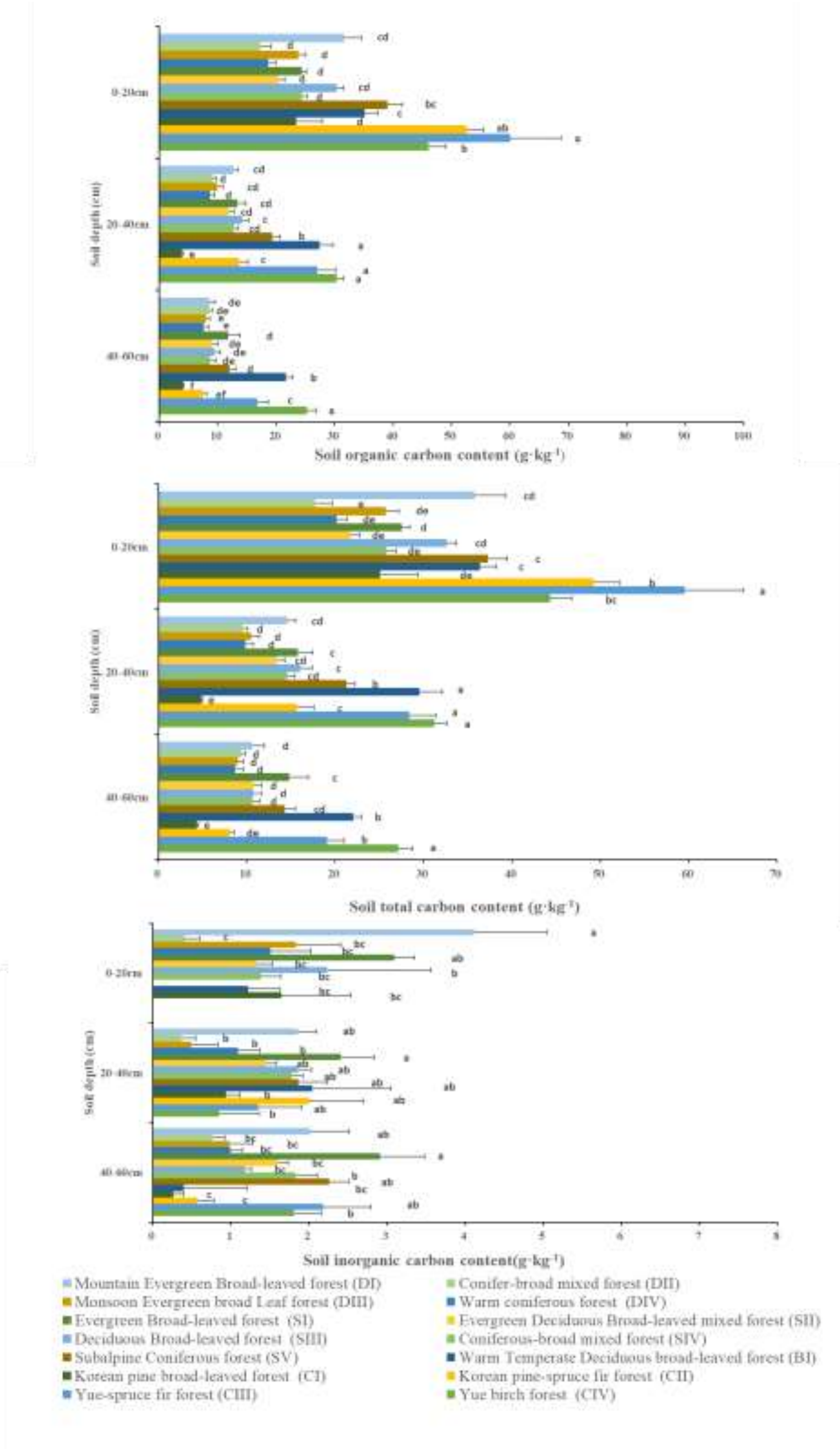

Fig.2. The distribution of soil carbon at various depths in 14 different forests along the transect. Different letters indicate the significant ($p < 0.05$) differences between the forest types. Short lines indicate the standard error.

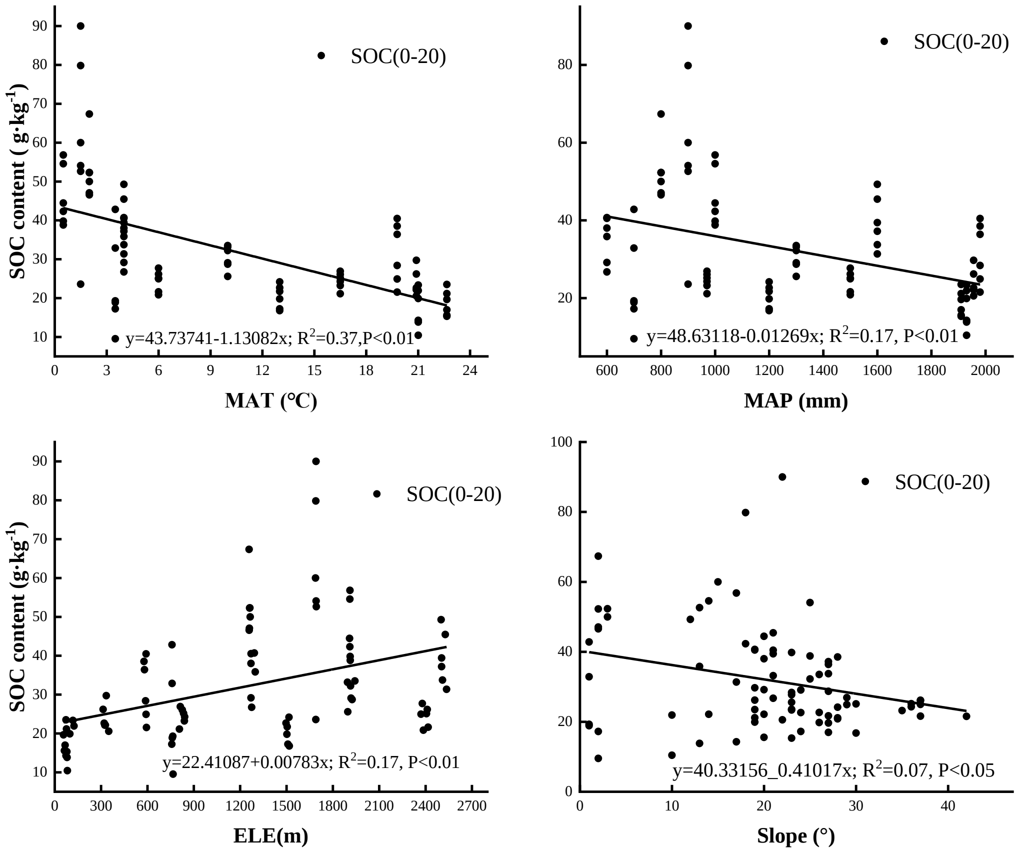

Fig. 3. Soil organic carbon at a depth of 0-20 cm for different forest types along the North-South transect in relation to MAT, MAP, ELE and slope (n=6).

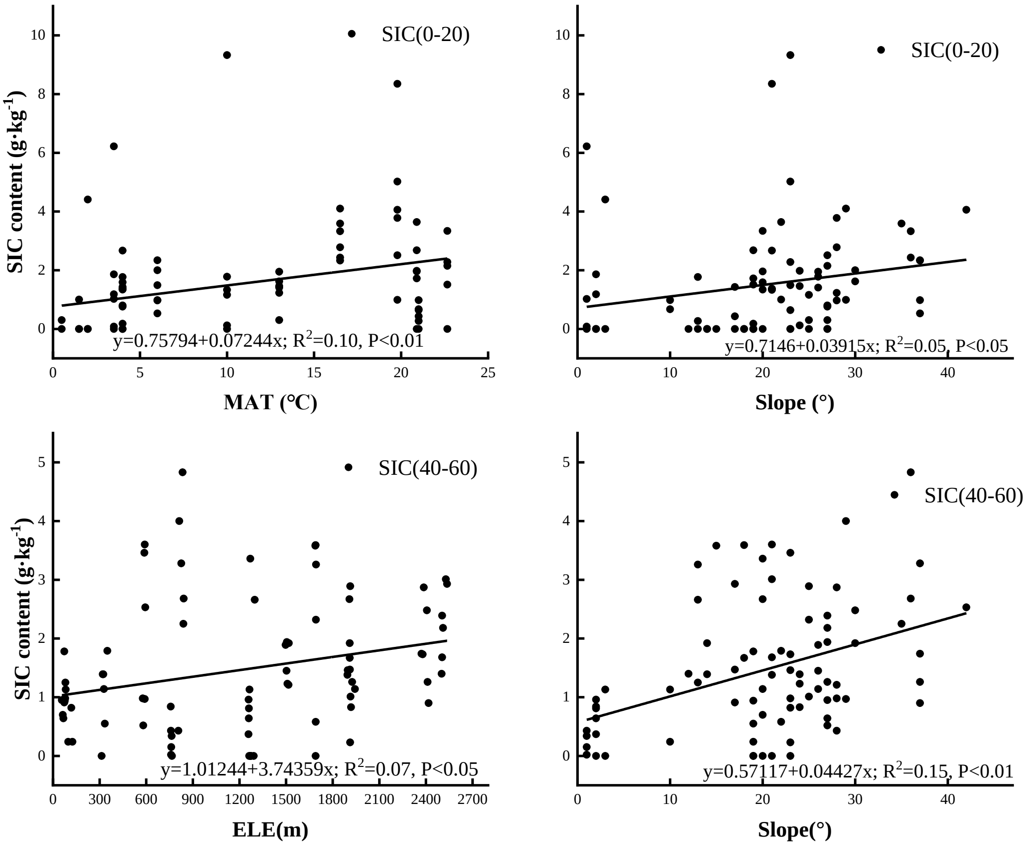

Fig. 4. Soil inorganic carbon at depths of 0-20 cm and 40-60 cm for different forest types along the North-South transect in relation to MAT, ELE and slope (n=6).

Table 1

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

Sampling sties		LON (E)	LAT(N)	ELE (m)	Slope	MAT (℃)	MAP (mm)	Soil type	Forest type
Dinghu (DF)	DI	112.5235°	23.1759°	587	28°	19.79	1980	Haplic Acrisol	Mountain evergreen broad-leaved forest
	DII	112.5483°	23.1687°	96	15°	21.01	1930	Haplic ferralsol	Conifer-broad-leaved mixed forest
	DIII	112.5356°	23.1723°	328	20°	20.9	1956	Haplic ferralsol	Monsoon evergreen broad-leaved forest
	DIV	112.5570°	23.1657°	70	23°	22.66	1910	Haplic ferralsol	Warm coniferous forest
Shennong (SF)	SI	110.4988°	31.3689°	827	34°	16.5	970	Haplic Alisol	Evergreen broad-leaved forest
	SII	110.4777°	31.3086°	1508	27°	13	1200	Haplic Alisol	Evergreen deciduous broad-leaved mixed
	SIII	110.3413°	31.5139°	1916	24°	10	1300	Haplic luvisol	Deciduous broad-leaved forest
	SIV	110.3374°	31.6576°	2395	32°	6	1500	Haplic luvisol	Subalpine coniferous-broad-leaved mixed
	SV	110.3337°	31.6454°	2514	21°	4	1600	Haplic Luvisol	Subalpine coniferous forest
Beijing Dongling (BF)	BI	115.4256°	39.9580°	1279	19°	4	600	Haplic luvisol	Warm temperate deciduous broad-leaved
Changbai (CF)	CI	128.0953°	42.4018°	761	1°	3.5	700	Haplic Luvisol	Korean pine broad-leaved 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

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

Table 2

The soil carbon stock in the upper 60 cm layer of different forest stations along the transect.

Sites	Soil carbon stock (Mg ha^{-1})		
	SOC(0-60cm)	STC(0-60cm)	SIC(0-60cm)
DF	287.4	316.0	28.6
SF	354.9	389.3	39.6
BF	566.6	591.2	24.6
CF	480.4	489.8	18.0

Table 3

The soil carbon stock in the upper 20 cm layer of different forest types along the transect.

Sites	Soil carbon stock (Mg ha^{-1})		
	SOC (0-20 cm)	STC (0-20 cm)	SIC (0-20 cm)
DI	58.7±5.4	66.3±6.4	7.6±1.7
DII	37.8±4.2	38.7±4.3	0.9±0.4
DIII	41.5±2.2	44.7±2.5	3.2±1.0
DIV	37.8±2.5	40.9±2.3	3.1±1.0
SI	39.3±1.3	44.3±1.4	5.0±0.4
SII	29.9±1.6	31.9±1.6	2.0±0.3
SIII	38.0±1.5	40.7±1.4	2.8±1.6
SIV	29.8±1.2	31.5±1.3	1.7±0.3
SV	40.4±2.6	38.5±2.3	0.0±2.8
BI	56.3±3.5	58.2±3.0	2.0±0.6
CI	40.1±7.7	42.9±7.4	2.8±1.5
CII	53.6±2.9	50.3±2.9	0.0±1.5
CIII	71.4±10.3	70.9±7.8	0.0±6.0
CIV	45.2±2.8	43.4±2.4	0.0±0.6