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Variations of soil aggregates and soil organic carbon mineralization across forest types on the northern slope of Changbai Mountain

Juan Jia [a,b], Dapao Yu [a], Wangming Zhou [a], Li Zhou [a], Ye Bao [a,b], Yingying Meng [a,b], Limin Dai [a,*]

[a] State Key Laboratory of Forest and Soil Ecology, Institute of Applied Ecology, Chinese Academy of Sciences, Shenyang 110016, China
[b] University of Chinese Academy of Sciences, Beijing 100049, China

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A B S T R A C T

Soil aggregation and soil organic carbon (SOC) mineralization are affected by soil properties, microbes and litter input, all of which vary with changes in temperature, precipitation and vegetations. In order to explore SOC dynamics in natural mature forest ecosystems, this study analyzed the variation of soil aggregates and SOC mineralization along an altitudinal gradient on Changbai Mountain in northeast China. Soil samples collected at four altitudinal sites were fractionated into different size of aggregates. SOC mineralization was measured by incubating soils at constant temperature. Results revealed that proportions of macro-aggregates (5–2 mm, 2–1 mm) increased with increasing altitude, while proportions of micro-aggregates (0.25–0.053 mm, <0.053 mm) decreased, which suggest that colder and wetter condition at higher altitude benefits the formation and stability of macro-aggregates. SOC mineralization rates displayed the following order: Erman's birch forest > Korean pine and broad-leaved mixed forest > Erman's birch mixed Spruce-fir forest > Spruce-fir mixed forest. Correlation and linear regression analysis revealed that potential mineralized carbon (C_0) positively correlated with microbial biomass carbon, readily oxidizable carbon and SOC. Turnover coefficient k, which represents the turnover rates of C_0, was positively correlated with proportions of macro-aggregates and negatively correlated with proportions of aggregates 1–0.25 and 0.25–0.053 mm. In conclusion, SOC mineralization was controlled by microbial activity, quality and quantity of SOC and soil structures. Greater proportions of macro-aggregates at higher altitude suggest that SOC might turnover more quickly than that at lower altitudes. Hence more attention should be paid to soils at higher altitude in the future.

1. Introduction

Soil is the largest carbon reservoir in the terrestrial biosphere. It is estimated that 1500 Pg C is stored in soil in forms of organic matter, three times of that stored in the atmosphere or terrestrial vegetations [1]. Thus, even minor changes of SOC storage may cause a profound impact on atmosphere carbon dioxide (CO_2) concentration. In this light, research on stability of SOC becomes an important focus for scientific research. As the main reservoir of SOC, soil aggregates provide physical protection for SOC, serving as an important mechanism for carbon sequestration. It has been shown that bonding of organic carbon with minerals helps to prevent carbon from decomposing [2] and therefore benefits carbon fixation. At the same time, carbon in micro-aggregates would be physically or chemically excluded from microbial attack or enzymatic reactions within the soil environment by aggregation [3]. Recent research has revealed that soil texture could supersede temperature when there is too little silt and clay to stabilize labile soil carbon and protect it from decomposition [4]. Moreover, the formation of aggregates would improve water-holding capacity and increase soil resistance to erosion [5]. All of the above suggest that stability of soil aggregates is crucial for maintaining ecosystem functions and that continuing research on mechanisms of soil aggregation is warranted.

To date a variety of studies have focused on factors which may affect soil aggregation and stability. It has been reported that soil aggregate stability was strongly correlated with the quantity of SOC [6]. Helfrich [7] found that the formation and stability of macro-aggregates were controlled by the quality of SOC. Microorganisms, as the main biotic aggregating agents, were important in soil aggregation. It was demonstrated that a decrease in microbial diversity resulted in lower stability of aggregates [8] and that stability of aggregates increased with increasing biomass of fungi [9]. However, others have found that reducing biomass of fungi was not accompanied by a decrease in macro-aggregates [10,11]. Moreover, drying/wetting and freezing/thawing cycles, which depend mainly on water content and temperature, have also been reported to be

* Corresponding author. State Key Laboratory of Forest and Soil Ecology, Institute of Applied Ecology, Chinese Academy of Sciences, Shenyang 110016, China. Tel./fax: +86 24 83970328.
E-mail address: lmdai@iae.ac.cn (L. Dai).

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important factors that influence the process of soil aggregation and stability of soil aggregates [12,13].

While most previous studies have focused primarily on farmland [14], grassland and artificial (i.e. plantation) forest, little is known about the formation and stability of soil aggregates in natural old-growth forest undisturbed by humans for many years. Further research on the distribution of soil aggregates under such natural conditions may thus enhance our knowledge regarding the dynamics of carbon sequestration.

SOC mineralization is an important biogeochemical process occurring naturally in soils, one which is critical for maintaining soil fertility and nutrition release and helping mitigate increased greenhouse gases and their effects on global climate change. Mineralization is affected by biotic factors such as quality of SOC [15] and microorganisms [16], both of which are indirectly controlled by abiotic factors such as temperature [17] and precipitation [18]. Soil aggregation may also play a key role in SOC decomposition. Christensen [19] has pointed out that factors influencing the formation of aggregates also affect SOC mineralization, especially changes in aggregate size. The ability of aggregates to physically protect SOC varies among aggregate sizes and as affected by the binding agent between SOC and aggregates [20]. In addition, carbon incorporated with different aggregates also differs in their molecular structures [21]. This highlights the necessity of taking soil structure into consideration when predicting the future trajectory of SOC dynamics.

To date, relatively few studies have focused on variation of soil aggregates and its correlation with SOC mineralization in old-growth forests, which have been reported to accumulate carbon in soils and act as a global carbon sink [22]. Understanding factors that affect soil aggregation and carbon dynamics along an altitudinal gradient in natural old-growth forests is important for understanding carbon balance in forest ecosystems and making more precise prediction of the response of these forests to climate change in the future. With this in mind, the objective of this study are: (i) to investigate variation of soil aggregates and SOC mineralization across four forest types along an altitudinal gradients in the Changbai Mountain, region of Northeast China; (ii) to analyze factors that affect soil aggregation and SOC mineralization; (iii) to better assess the relationship between SOC mineralization and soil structures.

2. Materials and methods

2.1. Study area

The study was conducted on the northern slope of Changbai Mountain Nature Reserve in Northeast China (41°42′45″–42°45′18″N, 127°33′30″–128°16′48″), which is situated on the border between China and North Korea. Elevation of the northern slope ranges from 740–2691 m. With increasing altitude, mean annual temperature (MAT) decreased from 3 °C to −5 °C, while mean annual precipitation (MAP) increased from 680 to 1100 mm. Influenced by the climatic gradient, clear altitudinal vegetation zones occur from the base to the top including: (1) Korean pine and broad-leaved mixed forest (KBF) (740–1100 m), dominated by *Pinus koraiensis*, *Tilia amurensis*, and *Fraxinus mandshurica*, with dark brown forest soil of loess parent material; (2) spruce-fir mixed forest (SFF) (1100–1600 m), dominated by *Picea jezoensis*, *Picea koyamai var. koraiensis*, and *Abies neephrolepis*, with brown coniferous forest soils of ash sand parent material; (3) Erman's birch and spruce-fir mixed forest (EBSF) (1600–1800 m), dominated by *Betula ermanni*, *P. koyamai var. koraiensis*, *A. neephrolepis* and *P. jezoensis*, with mountain grass forest soil; and (4) Erman's birch forest (EBF), ranging from 1800 to 2000 m, with vegetation a mix of *B. ermanni* and *Larix olgensis* and *Sorbus amurensis* and mountain grass forest soil [23]. In effect, changes in vegetation and environmental factors along the altitudinal gradient of Changbai Mountain provide a living laboratory for studying soil aggregation and its relationship with SOC mineralization under natural environmental conditions.

2.2. Field sampling

Sampling locations were chosen along an altitudinal gradient on northern slope of Changbai Mountain for forest types KBF, SFF, EBSF and EBF. For each type, three 20 m × 20 m sampling plots were established; the distance between two plots was no less than 5 m. After removal of above-ground plant debris, three undisturbed soil blocks (20 cm × 10 cm × 10 cm) were randomly taken from the 0 to 20 cm layer of each plot. Then soil blocks were placed in plastic container and immediately transported to laboratory. At the same time, soil cores were collected and taken to laboratory for analysis of bulk density, pH, SOC, microbial biomass carbon (MBC) and readily oxidizable carbon (ROC). The main characteristics are summarized in Table 1.

2.3. Sample preparation and analyses

Soil samples were air-dried after removal of visible plant residues and stones. Distribution of aggregates was determined by dry-sieving and subsequently wet-sieving. Air-dried soil that had passed through an 8 mm sieve was weighed (500 g), and then further sieved sequentially through five sieves with 5, 2, 1, 0.25 and 0.053 mm, respectively. In this way, structural-aggregate units of >5, 5–2, 2–1, 1–0.25, 0.25–0.053 and <0.053 mm in size were separated. After each of these fractions was weighed, their fractions of the total weight of dried soil sample were determined. The fractionated samples were combined to make recombined soil. Fifty grams of recombined soil was placed in a 1000 mL container and was immersed in distilled water for 10 minutes. Containers were re-filled with distilled water and set aside for additional 10 minutes, and then sealed with plastic wrap and been flipped up and down for 10 times. Samples were then poured onto five screens (5, 2, 1, 0.25 and 0.053 mm mesh, respectively) and all of the sieves were flipped up and down under water for another 10 times. After the sieving process was completed, stable aggregates remaining on sieves of different sizes were transferred to labeled containers and oven-dried at 65°. All fractions were then weighed to calculate their proportions relative to bulk soil. The bulk soil and soil aggregates were then finely ground and analyzed for total organic carbon [24]. MBC was analyzed via the chloroform fumigation and extraction method [25]. ROC was oxidized by 333 mmol L^{-1} $KMnO_4$ [26]. Three replicates of each sample were analyzed.

Table 1
Profile of sample plots.

Sample plots	Altitude (m)	MAT (°C)	MAP (mm)	Stand volume (m^3/ha)	Stand density (trees/ha)	pH	BD (g/cm^3)	SOC (g/kg)	MBC (mg/kg)	ROC (g/kg)
KBF	790	2.6	691	503	630	5.13	0.84	65.43	1550.4	27.63
SFF	1350	−0.5	855	610	1010	4.64	0.84	34.86	492.37	12.79
EBSF	1700	−2.3	967	439	970	4.85	0.81	55.32	522.74	16.84
EBF	1910	−3.3	1038	106	1030	4.75	0.98	52.49	659.8	17.06

KBF: Korean pine and broad-leaved mixed forest; SFF: Spruce-fir mixed forest; EBSF: Erman's birch and spruce-fir mixed forest; EBF: Erman's birch forest; MAT: mean annual temperature; MAP: mean annual precipitation; BD: bulk density; SOC: soil organic carbon; MBC: microbial biomass carbon; ROC: readily oxidizable carbon.