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Vertical Variation in Temperature Sensitivity of Soil Organic Carbon Mineralization in Changbai Mountain, China: A Microcosm Study

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Abstract: Global warming may have a complex effect on soil carbon mineralization across mountain elevations. Elevational zonation governs the soil natural composition of mountain ecosystems due to different temperature conditions. Understanding the response of carbon mineralization to climate change, particularly the temperature sensitivity (Q_{10}), is crucial for assessing the effects within mountain vertical zones. Despite this, the spatial variation and influencing factors of organic carbon mineralization at these zones remain unclear. We conducted a microcosm study in Changbai Mountain, Northeast China, to examine the response of soil carbon mineralization to warming across six different elevations (1000, 1400, 1600, 1800, 2000, and 2200 m). The soil samples were incubated at 5 °C, 15 °C, and 25 °C for 71 days. The results showed a significant elevation-dependent increase in the rate of soil organic carbon mineralization (C_{min}), with the birch forest exhibiting the highest values. Q_{10} varied across elevations, with the highest value (1.57) in the coniferous forest (1400 m), and the lowest (1.32) in the tundra (2200 m). The potential of organic carbon mineralization (C_0) demonstrated an increasing trend from 5 °C to 25 °C across the six elevations. Elevation and soil properties, especially pH, bulk density (BD), and dissolved organic carbon (DOC), emerged as critical factors influencing organic carbon mineralization; notably, elevation played a crucial role. In summary, our findings highlight the common regulatory role of elevation and soil properties in soil carbon mineralization dynamics within the vertical zones. Future research should pay attention to the distinctive features of vegetation zones to analyze how mountain carbon pool function responds to global climate change.

Keywords: carbon mineralization; elevational zonation; soil properties; temperature sensitivity

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1. Introduction

Since the Industrial Revolution, human activities have significantly affected greenhouse gas emissions, ultimately leading to global warming. It is estimated that the global temperature will increase by 1.5 °C from 2021 to 2040 [1]. Temperature, a crucial environmental factor, profoundly impacts the carbon cycle, with global warming expected to stimulate organic carbon mineralization, potentially triggering potential positive feedback [2,3]. Some studies have demonstrated that warming may promote soil microbial activity, accelerate organic decomposition, and lead to a decline in soil carbon storage [4,5]. Notably, a mere 1 °C temperature rise could result in an approximately 6% reduction in soil organic carbon across the global surface (0–30 cm) [6]. This complex interaction results in multi-level and regional differences in carbon mineralization, significantly impacting the global carbon cycle. In the meantime, warming may also change the distribution of vegetation and the growing season, which in turn affects the carbon absorption capacity of global vegetation [7]. Forest soils, serving as an important organic carbon pool within the global ecosystems, play a crucial role in regulating the carbon balance and preserving climate stability [8,9]. However, carbon stored in forest soil has the potential to re-release into the atmosphere as CO_2 and CH_4, thus contributing to greenhouse gas emissions. Consequently, the process of soil organic carbon mineralization in response to warming is believed to be a key mechanism influencing the carbon cycle and the overall carbon pool function in forest ecosystems.

Temperature sensitivity (Q_{10}) is crucial to assess the impact of warming on soil organic carbon and to determine the gas emission rate at 10 °C warming. In mountainous ecosystems, Q_{10} may be regulated by the elevation and vegetation type [10–12]. Warming can potentially alter soil properties, such as nutrition, texture, and mineral content, significantly affecting the quantity and quality of organic carbon. These changes lead to various responses in the rate of carbon mineralization and Q_{10} across the different vertical zones [13,14]. Current evidence indicates that the Q_{10} of organic carbon mineralization exhibits temperature dependence, showing variability at different temperatures [15,16]. Generally, Q_{10} tends to increase with an elevated temperature. Furthermore, it has been observed that low-temperature warming induces a higher Q_{10} compared to high-temperature warming for the same temperature increase [17,18].

The sustainable management of the carbon pool in mountain soil is a central and challenging focus of current research. The elevational zonation of mountains exerts a significant influence on the spatial distribution of organic carbon [19], displaying an extreme sensitivity to climate change [20,21]. The mountain ecosystem exhibits distinct vertical gradients in vegetation and soil properties, with the stability of the mountain carbon pool influenced by factors such as vegetation and soil properties [22,23]. The vertical zonal vegetation pattern of Changbai Mountain is typical in northern China, including four vegetation zones: coniferous and broad-leaved forests, coniferous forests, birch forests, and tundra. Elevation induces variations in environmental factors, resulting in a natural diversity in organic carbon distribution [24]. Our previous research found an initial increase in soil carbon storage with elevation, reaching its peak in coniferous forests before declining [25]. However, the temperature sensitivity of soil organic carbon mineralization and its vertical zonal variation under warm conditions remain unclear. We conducted a warming incubation experiment using soil samples of six elevation gradients in Changbai Mountain to examine the vertical distribution of organic carbon mineralization and its temperature sensitivity. Our hypotheses were as follows: (i) the rate of soil carbon mineralization decreases with increasing elevation; (ii) the change in the soil carbon mineralization rate was the most significant in birch forests under an increasing temperature; and (iii) soil properties regulate soil carbon mineralization.

2. Materials and Methods

2.1. Study Area

The study area is located on the northern slope of Changbai Mountain (Figure 1), which belongs to a continental mountain climate with cold–dry weather in winter and warm–rainy weather in summer. The temperature on Changbai Mountain varies with the elevation gradient. The mean annual temperature ranges from −4.17 to 3.15 °C and mean annual precipitation ranges from 655 mm to 955 mm. More than 60% of the precipitation is concentrated during the period from June to September. The vertical variation in vegetation across Changbai Mountains is distinct (Table 1); from top to bottom, the vegetables are found in the tundra (>2000 m), birch forest (1700–2000 m), coniferous forest (1100–1700 m), and coniferous and broad-leaved mixed forest (500–1100 m), respectively.

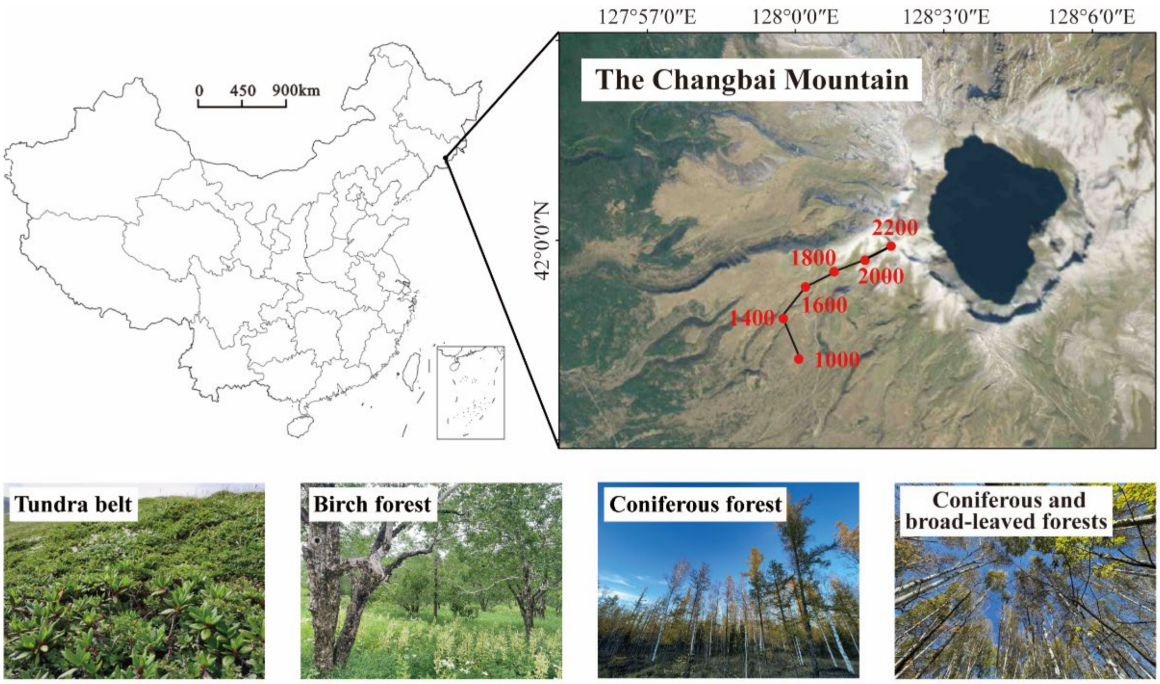

Figure 1. Distribution of sampled sites on Changbai Mountain.

Table 1. Summary of the main characteristics of sampled sites.

Elevation (m)	Latitude–Longitude	Vegetation Zone	Vegetation Type (Main Composition)
1000	128.15 E, 42.24 N	Coniferous and broad-leaved forests	*Korean pine*, *White birch*, *Quercus mongolica*, *Acer mono*, *Tilia amurensis*, *Ulmus propinoua*, and *Fraxinus mandshurica*
1400	128.13 E, 42.14 N	Coniferous forest	*Picea jezoensis*, *Abies nephrolepis*, *Pinus koraiensis*, *Korean pine*, and *Betula costata*
1600	128.07 E, 42.09 N		
1800	128.06 E, 42.06 N	Birch forest	*Betula ermanii*, and *Rhododendron aureum*
2000	128.07 E, 42.06 N		
2200	128.07 E, 42.04 N	Tundra	*Rhododendron aureum*, *Dryas octopetala*, *Vaccinum uliginosum*, and *Rhododendron redovoskianum*

2.2. Experimental Design and Soil Sampling

In July 2021, six sample sites were set at elevations of 1000, 1400, 1600, 1800, 2000, and 2200 m along the northern slope of Changbai Mountain. At each sampling point, five quadrats were established, measuring approximately 20 m × 20 m with a horizontal interval of about 50 m; there was a total of 15 samples at each elevation. From each point, three soil samples were collected using a stainless steel soil drill, ensuring representative sampling. After removing surface litter, the samples were placed into sealed bags and transported back to a laboratory. The soil samples at the same elevation were fully mixed; one portion was utilized for the incubation experiment and determination of soil water content (SWC), and the other portion was air-dried and passed through a 100-mesh sieve for a soil properties analysis.

2.3. Sample Analysis

2.3.1. Organic Carbon Mineralization

Soil organic carbon mineralization was determined with the method of a laboratory incubation–gas chromatograph. In total, 20 g soil samples were placed in a 250 mL conical bottle, and the soil was adjusted to a water holding capacity (WHC) of 60%. Pre-incubation was carried out for seven days under three temperature treatments (5 °C, 15 °C, and 25 °C, to observe the response of the carbon cycle under low-, medium-, and high-temperature conditions) to stabilize soil microorganisms. After the pre-incubation, the soils were placed in a constant-temperature incubator for 71 days (the CO_2 emission rate was constant, without significant change on the 71st day, and the experiment was terminated). The bottles were covered with sealing film with small holes to allow gas exchange while minimizing water loss. The mineralization rate was measured on days 1, 3, 5, 7, 10, 13, 16, 20, 24, 28, 33, 38, 43, 49, 55, 61, and 71 using a gas chromatograph (Agilent 7890B, Santa Clara, CA, USA). During each gas sampling event, the sealing film covering the conical bottle was removed, and a silicone plug with a three-way valve was tightly sealed in place. The gas sample was collected after 2 h. A 15 mL headspace gas sample was collected by pumping the syringe three times to mix the gas inside the conical bottle. After sampling, the plug was removed, and the conical bottle opening was covered with sealing film again [26]. Water was supplemented regularly during incubation to maintain weight conservation.

The soil organic carbon mineralization rate was expressed via the CO_2 production rate as follows:

$$C_{min} = \frac{M \cdot P \cdot T_0 \cdot V}{V_0 \cdot P_0 \cdot T \cdot M} \cdot \frac{dc}{dt} \quad (1)$$

where C_{min} is the CO_2 production rate in soil (mg·kg^{-1}·h^{-1}), M is the molar mass of CO_2 (mg·mol^{-1}), V_0 is the molar volume (22.4 L·mol^{-1}) of CO_2 in the standard state (1103 hPa, 273 K), P is the actual pressure, P_0 is the standard state pressure (1103 hPa), P/P_0 = 1 without considering the elevation, T is the actual temperature (K), T_0 is the temperature of 273 K in the standard state, V is the volume of the bottle above the liquid level (mL), m is the mass of the dry soil (kg), and dc/dt is the CO_2 concentration per hour in the bottle (mL·L^{-1}·h^{-1}).

Organic carbon cumulative mineralization was obtained using the following equation:

$$C_n = \sum_{i=2}^{n} F_i \cdot t_i \quad (2)$$

where C_n is the cumulative CO_2 mineralization (mg·kg^{-1}), F_i is the CO_2 production rate (mg·kg^{-1}·h^{-1}) at the time of the i^{th} sampling, and t_i is the time interval (h) between the i^{th} and $(i+1)^{th}$ samplings.

Temperature sensitivity (Q_{10}) of organic carbon mineralization was calculated according to the following [27]:

$$C_{min} = ae^{bT} \quad (3)$$

$$Q_{10} = e^{10b} \quad (4)$$

where C_{min} is the CO_2 production rate in soil at T (°C) temperature (mg·kg^{-1}·h^{-1}), a is the CO_2 production rate at 0 °C, and b is the temperature response coefficient.

The following first-order kinetic equation was used to simulate the mineralization process:

$$C_t = C_0 \cdot \left(1 - e^{-kt}\right) \quad (5)$$

where C_t is the cumulative CO_2 mineralization (mg·kg^{-1}), C_0 is the potential of carbon mineralization (mg·kg^{-1}, the maximum amount of mineralization in the soil under certain conditions), k is the mineralization rate constant (d^{-1}), and t is the incubation time. By fitting the measured cumulative CO_2 mineralization accumulation, the parameters C_0 and k of the first-order reaction kinetic model of soil can be obtained at different temperatures.

2.3.2. Soil Properties

Total carbon (TC) and total nitrogen (TN) in soil were determined with an elemental analyzer (Elementar, Hanau, Germany), and total phosphorus (TP) was determined with a continuous flow analyzer (Skalar Scan++, Breda, the Netherlands). Dissolved organic carbon (DOC) was determined with the elemental analyzer (Elementar, Hanau, Germany) after deionized water extraction. Microbial biomass carbon (MBC) was extracted using a 0.5 M K_2SO_4 solution (K_2SO_4:soil = 2:1) and then determined using the chloroform fumigation extraction method, and pH (water/soil = 5:1) was determined using a pH meter (Mettler Toledo, Zurich, Switzerland).

2.4. Statistical Analysis

The one-way ANOVA was employed to test the significance of the difference in the single variable, and the Tukey method was used for multiple comparisons. Two-way ANOVA was conducted to comprehensively examine the impacts of the elevation, incubation temperature, and their interactions on soil organic carbon mineralization. The 71-day incubation data were fitted and analyzed using Origin 2021 to explore kinetic characteristics and temperature sensitivity. The "Pearson correlation" was employed to analyze the relationships between soil properties and organic carbon mineralization. Furthermore, a "Random Forest analysis" and "Variance Partitioning analysis (VPA)" were performed using R 4.3.0 to elucidate the relative contributions of elevation and soil properties to organic carbon mineralization.

3. Results

3.1. Vertical Variation Characteristics of Soil Organic Carbon Mineralization

C_{min} was affected by the elevation ($p < 0.001$), incubation temperature ($p = 0.001$), and their interaction ($p < 0.001$) (Table 2). At the same incubation temperature, C_{min} varied significantly with the elevation, reaching a maximum in the birch forest (2000 m) and a minimum in coniferous and broad-leaved forests (1000 m). C_{min} exhibited an increased trend with the incubation temperature. When the temperature increased from 5 to 15 °C and from 15 to 25 °C, C_{min} increased by 12.07–65.15% and 16.23–52.48%, respectively.

Table 2. Results of two-way ANOVA for organic carbon mineralization and soil properties. C_{min}: organic carbon mineralization rate; C_n: organic carbon cumulative mineralization; C_0: carbon mineralization potential; C_0/SOC: organic carbon mineralization capacity; Q_{10}: organic carbon mineralization temperature sensitivity.

Index	Temperature		Elevation		Temperature × Elevation	
	F	***p***	***F***	***p***	***F***	***p***
C_{min}	15.967	<0.001	658.177	<0.001	172.309	<0.001
C_n	13.267	<0.001	750.448	<0.001	219.932	<0.001
C_0	7.450	0.002	119.077	<0.001	44.472	<0.001
C_0/SOC	3.634	0.003	72.294	<0.001	46.275	<0.001
Q_{10}	—	—	60.321	<0.001	—	—

The elevation gradient ($p < 0.001$), incubation temperature ($p < 0.001$), and their interaction ($p < 0.001$) had significant effects on C_n (Table 2). When the incubation temperature was from 5 to 15 °C and from 15 to 25 °C, C_n increased by 4.92–51.90% and 21.94–77.48%, respectively. C_n exhibited a rapid increase in the early stage of the incubation time and then gradually approached stability (Figure 2). At the same temperature, C_n had significant variations at different elevations ($p < 0.01$), with the highest value in the birch forest (2000 m) and the lowest value in the coniferous and broad-leaved forests (1000 m). The rise in C_n was lower when the incubation temperature increased from 5 to 15 °C (ΔC_n = 717.27–2382.04 mg·kg^{-1}) compared with when it increased from 15 to 25 °C (ΔC_n = 1490.08–3679.95 mg·kg^{-1}), while the greatest change was observed at 1400 m.

3.2. Vertical Variation Characteristics of Organic Carbon Mineralization Temperature Sensitivity (Q_{10})

Q_{10} was affected by different elevations ($p < 0.001$, Table 2), showing an initial rise and reaching the highest value (1.57) in the coniferous forest (1400 m). Significant variation was observed in the same vegetation (coniferous forests at 1400–1600 m, Figure 3). There is a minimum value (1.32) in the tundra (2200 m). Q_{10} in the birch forest was basically consistent with the coniferous forest.

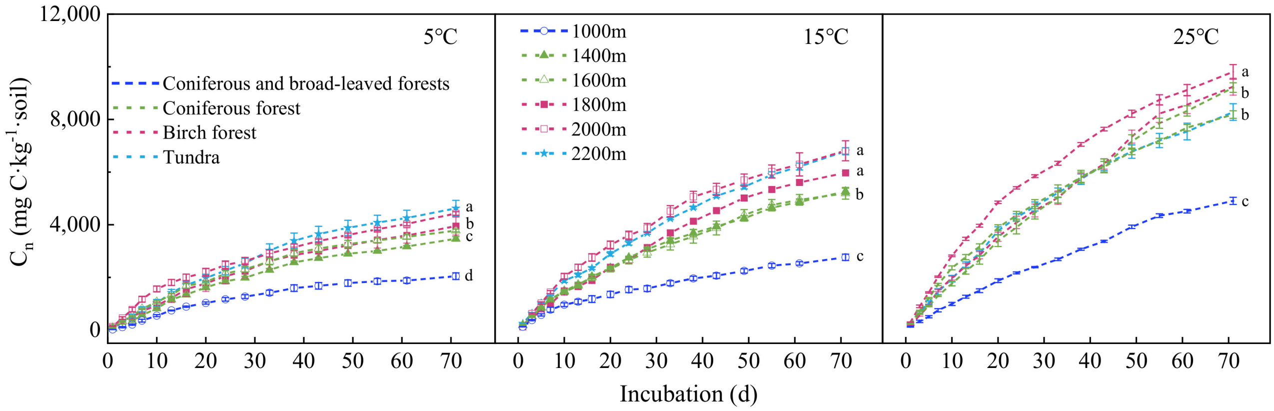

Figure 2. Dynamics of soil organic carbon cumulative mineralization at different incubation temperatures. The lowercase letters represent the difference of C_n at different vegetation zones at α = 0.05. C_n: organic carbon cumulative mineralization.

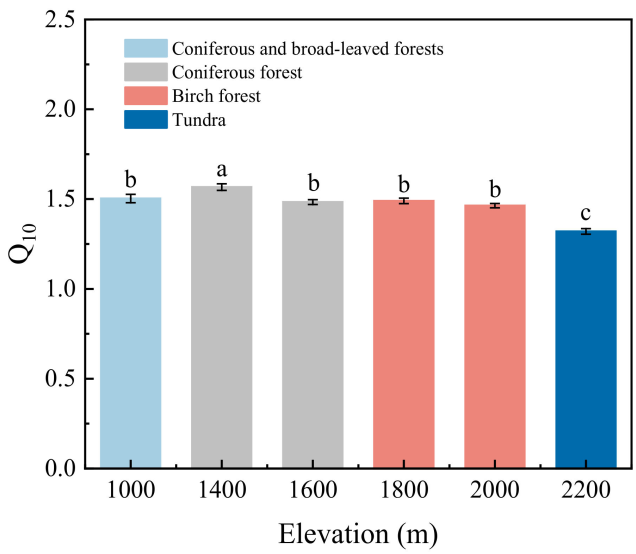

Figure 3. Dynamics of soil Q_{10} at different elevations. The lowercase letters represent the difference of Q_{10} at different elevations. Q_{10}: organic carbon mineralization temperature sensitivity.

3.3. Kinetic Characteristics of Organic Carbon Mineralization

The process of soil organic carbon mineralization followed the first-order kinetic model (Table 3). C_0 was significantly affected by the elevation ($p = 0.002$), incubation temperature ($p < 0.001$), and their interaction ($p < 0.001$) (Table 2), exhibiting an increasing trend with the incubation temperature. The change in C_0 from 15 to 25 °C was greater than that from 5 to 15 °C. The maximum of C_0 occurred at 1800 m when the temperature increased from 5 to 15 °C. However, when the temperature increased from 15 to 25 °C, C_0 at 1400 m showed the highest value, followed by 1800 m.

C_0/SOC was affected by the elevation ($p < 0.001$), incubation temperature ($p = 0.003$), and their interaction ($p < 0.001$) (Table 2). There was a gradual increase in C_0/SOC at all elevations with the incubation temperature (Figure 4). C_0/SOC increased by 1.38–90.00% (from 5 to 15 °C) and 21.25–216.02% (from 15 to 25 °C) with an increasing temperature. However, at the three incubation temperatures, C_0/SOC showed similar changes following the elevation gradient.

Table 3. First-order kinetic equations for organic carbon mineralization.

Temperature (°C)	Elevation (m)	$C_t = C_0(1-e^{-kt})$	R^2
5	1000	$Ct = 2378.52(1-e^{-0.03t})$	0.996
	1400	$Ct = 4277.07(1-e^{-0.02t})$	0.996
	1600	$C_t = 4349.18(1-e^{-0.03t})$	0.998
	1800	$C_t = 4895.36(1-e^{-0.02t})$	0.998
	2000	$Ct = 4605.27(1-e^{-0.03t})$	0.998
	2200	$Ct = 6232.53(1-e^{-0.02t})$	0.999
15	1000	$Ct = 2919.59(1-e^{-0.03t})$	0.997
	1400	$Ct = 6300.08(1-e^{-0.02t})$	0.997
	1600	$C_t = 6537.09(1-e^{-0.02t})$	0.994
	1800	$C_t = 9314.89(1-e^{-0.02t})$	0.997
	2000	$Ct = 7978.83(1-e^{-0.03t})$	0.980
	2200	$Ct = 8730.68(1-e^{-0.02t})$	0.993
25	1000	$Ct = 7314.00(1-e^{-0.01t})$	0.998
	1400	$Ct = 18,121.29(1-e^{-0.03t})$	0.997
	1600	$C_t = 9707.66(1-e^{-0.02t})$	0.997
	1800	$C_t = 17,412.72(1-e^{-0.01t})$	0.999
	2000	$Ct = 11,357.59(1-e^{-0.03t})$	0.997
	2200	$Ct = 10,583.67(1-e^{-0.02t})$	0.993

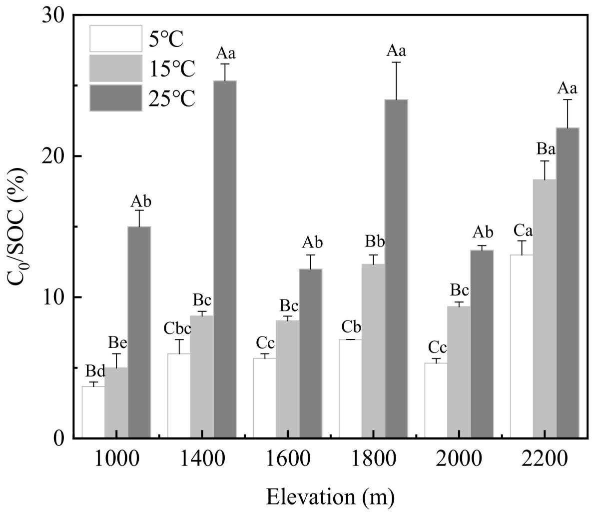

Figure 4. Dynamics of soil C_0/SOC at different elevations. The lowercase letters represent the difference of C_0/SOC at different elevations under the same incubation temperature, and the capital letters represent the difference of C_0/SOC at different incubation temperatures at the same elevation. C_0/SOC: organic carbon mineralization capacity.

3.4. Influence Factors of Organic Carbon Mineralization

Elevation significantly affected soil properties ($p < 0.01$), while the incubation temperature had no significant impact on soil properties. pH, BD, TN, TP, and MBC showed a decreasing trend with increasing elevation, while TC and DOC exhibited an increased trend.

The VPA analysis (Figure 5) indicated that the elevation and soil properties explained 79.00% of the total variation of organic carbon mineralization, showing a positive influence on the soil organic carbon mineralization, and the effect of elevation (69.00%) was the most significant. The Random Forest analysis results (Figure 6) demonstrated that soil C_{min}, C_n, C_0, and C_0/SOC were markedly explained by elevation and soil properties, explaining 67.94%, 70.42%, 58.15%, and 63.87%, respectively. The elevation gradient was identified as the primary variable for organic carbon mineralization. In addition to the elevation, DOC, pH, and BD are also important explanatory variables for C_{min} and C_n. TP, DOC, and pH have significant impacts on C_0, and MBC, TP, and BD are important indicators for C_0/SOC.

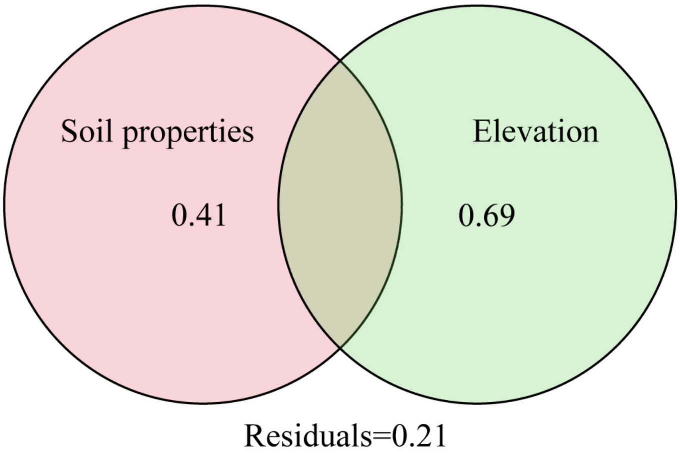

Figure 5. VPA of the contribution of elevation and environmental factors to soil carbon mineralization. The residuals reflect unexplained variance.

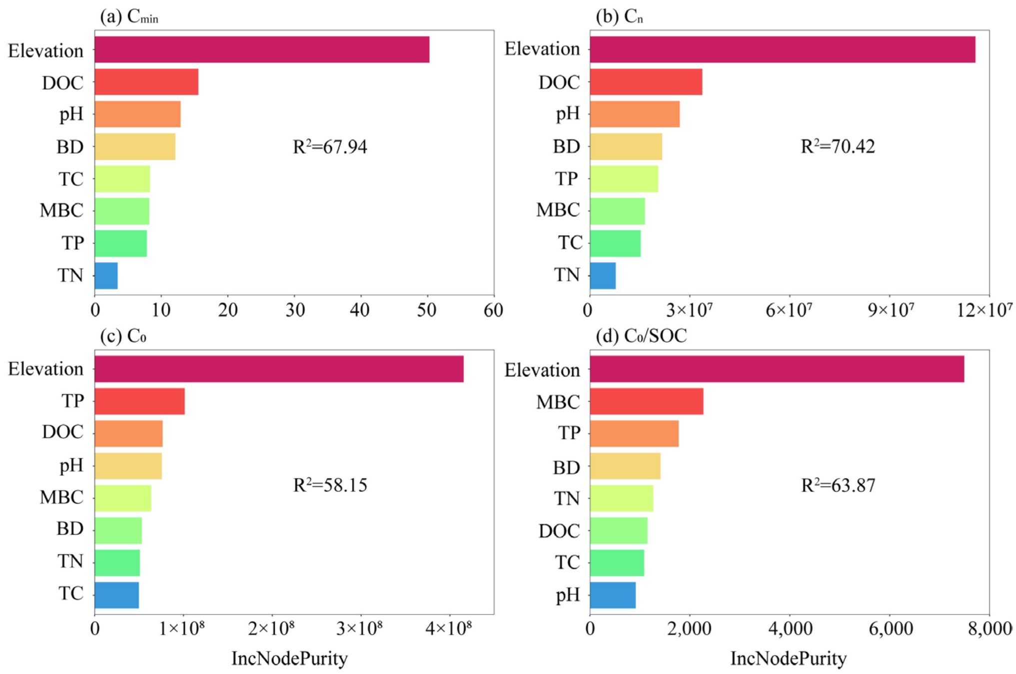

Figure 6. Random Forest analysis of relative effects of soil properties on carbon mineralization. C_{min}: organic carbon mineralization rate; C_0: carbon mineralization potential; BD: bulk density; TC: total carbon; TN: total nitrogen; TP: total phosphorus; DOC: dissolved organic carbon; MBC: microbial carbon. The color is used to characterize the scores of different indicators in the Random Forest analysis.

Pearson correlation analysis results showed that C_{min} was significantly negatively correlated with pH, BD, and MBC, while significantly positively correlated with DOC (Figure 7). pH, BD, TP, and MBC had a negative effect on C_n, while DOC had a positive effect on it. C_0 was negatively correlated with pH, TN, TP, and MBC, and positively correlated with DOC. pH, BD, TN, TP, and MBC had significantly negative effects on C_0/SOC.

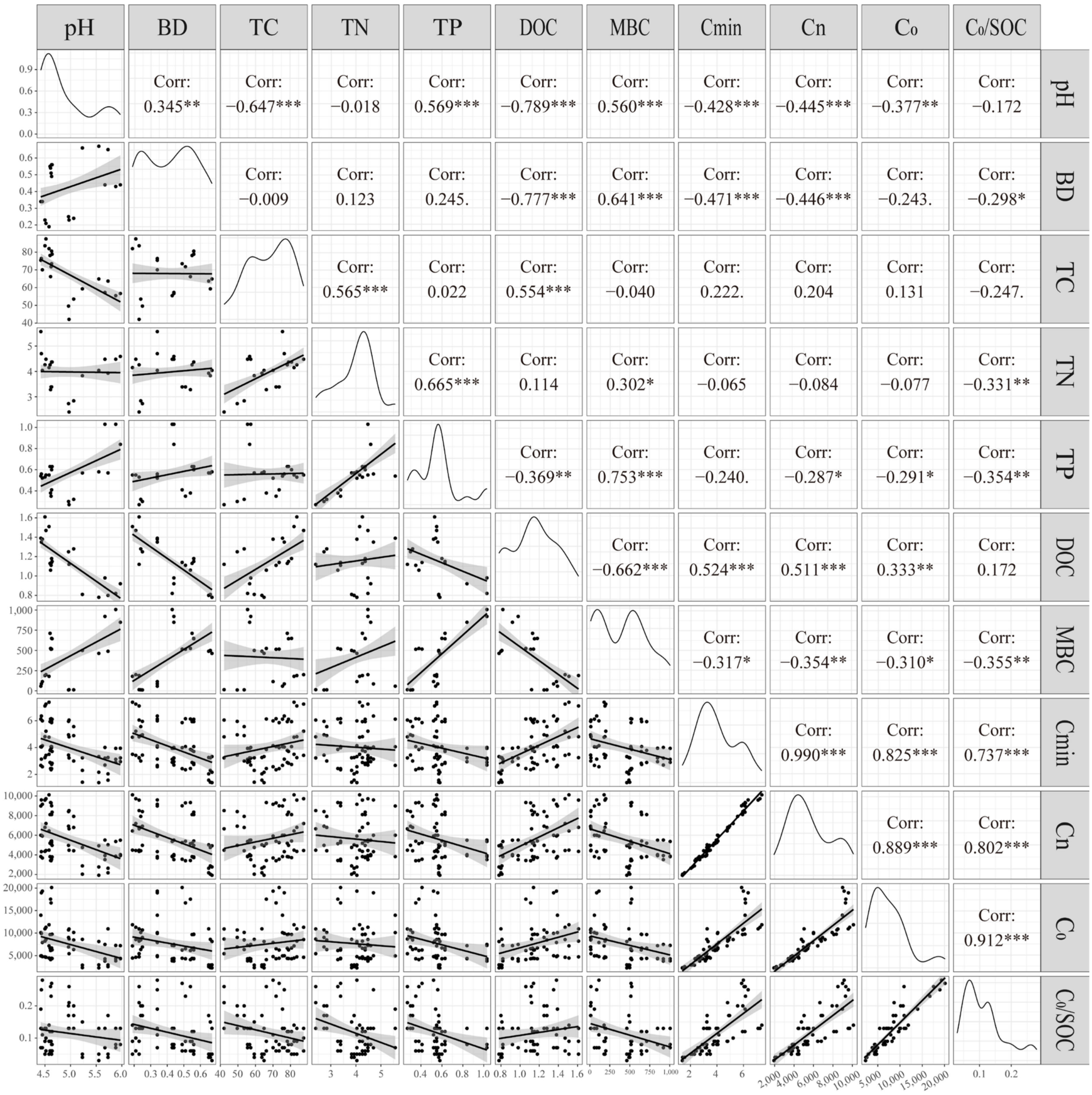

Figure 7. Random Forest analysis of relative effects of soil properties on carbon mineralization. *, **, *** represent statistical significance at the level of $p < 0.05$, $p < 0.01$ and $p < 0.001$, respectively. BD: bulk density; TC: total carbon; TN: total nitrogen; TP: total phosphorus; DOC: dissolved organic carbon; MBC: microbial carbon.

4. Discussion

The results showed that Q_{10} had a significant difference across elevations and was regulated by elevation, incubation temperatures, and their interaction. With increasing elevation, C_{min} first increased and then decreased, and C_n showed the largest value in the birch forest (2000 m) and the lowest value in the coniferous and broad-leaved forests (1000 m). Meanwhile, C_{min} and C_n exhibited an increasing trend with the incubation temperature. Q_{10} reached its peak (1.57) in the coniferous forest (Figure 3), indicating more sensitivity to warming. Furthermore, significant differences in Q_{10} were observed in the same vegetation zone ($p < 0.01$, between coniferous forests at 1400 m and 1600 m, Figure 3).

4.1. Responses of Soil Organic Carbon Mineralization to Warming in Vertical Zones

A significant increase in C_{min} and C_n was observed at all elevations in response to warming. Additionally, the results of the Random Forest analysis (Figure 6) showed that elevation is the most crucial factor for organic carbon mineralization. The alterations in soil factors caused by elevation, with the temperature being the most prominent factor, could influence carbon mineralization. Previous research has indicated that the temperature has a direct impact on soil microorganisms, leading to an increase in the microbial respiratory quotient and the subsequent release of more CO_2 [28]. Significant differences were found in the response of soil organic carbon mineralization to the temperature along the different elevations. Q_{10} in the tundra was the lowest (Figure 3), possibly related to the lower microbiological activity. The varying responses at each elevation to the temperature may stem from differences in microbial community composition [29,30]. Soil microorganisms, serving as primary catalysts for soil mineralization, could influence the underground carbon mineralization process through organic carbon decomposition [31,32]. In a low-temperature environment, the metabolic process of microorganisms is slow, and low temperatures may affect the soil enzyme activity, further limiting the carbon mineralization process [33]. This phenomenon is especially significant at high altitudes and latitudes in cold regions. In a previous study, Kang et al. (2023) [34] found that compared to other vegetation zones, the tundra has a greater peat soil content and exhibits a less sensitive response to temperature changes due to lower microbial diversity resulting from the colder temperatures in the tundra.

C_n exhibited a rapid increase in the initial phase, eventually reaching a state of stability (Figure 2). This finding is likely attributed to the higher organic carbon content and the introduction of water into the soil during the initial incubation period, which increases microbial activity and leads to an increase in CO_2 release [35]. Previous research has shown that in the early stages of a warming incubation, the active substrate in the soil is rapidly utilized without the introduction of external organic carbon. Excessive substrate consumption may lead to insufficient carbon sources in the soil, which becomes a critical limiting factor for microbial activity, limiting the growth and metabolic activities of microorganisms, and resulting in a decline in the mineralization rate [36–38]. Over time, the mineralization rate stabilizes at a lower level. It is noteworthy that during this process, the absence of additional organic carbon hinders microbial activity and contributes to the observed stabilization of CO_2 release.

At the same incubation temperature, C_{min} showed an initial decline followed by an increase as elevation increased. Additionally, C_n exhibited a notable elevation-dependent pattern, with higher values observed at higher elevations compared to lower elevations (Figure 2). Notably, C_{min} and C_n in the coniferous forest (1400 m) changed more significantly in response to the temperature shifting from 5 to 25 °C. Q_{10} reached its highest value in coniferous forests, suggesting a greater sensitivity to temperature changes. This increased sensitivity may be attributed to the abundance of soil fauna, known contributors to organic carbon mineralization. Soil fauna plays a crucial role in enhancing soil carbon decline through ecological processes such as organic matter decomposition, excreta decomposition, and respiration [39]. In our previous studies, Liu et al. (2023) [40] found a significant decrease in both the abundance and diversity of soil oribatid mites with increasing elevation in Changbai Mountain. The abundance displayed a hump-shaped distribution along the elevational gradient, peaking in the coniferous forest. This finding highlights the interaction between elevation, temperature, and soil fauna dynamics, shaping carbon dynamics in Changbai Mountain ecosystems.

C_0 serves as an indicator of the soil's organic carbon mineralization potential, reflecting the capacity of microorganisms to utilize organic carbon. In our study, C_0 exhibited a response to the temperature akin to that of C_n. Across all elevations, C_0 displayed an upward trend as the temperature increased (Table 3), suggesting that higher temperatures could enhance the potential for carbon mineralization. Previous research has indicated that the increase in the temperature stimulates microbial metabolic activity, thereby promoting carbon utilization efficiency by microorganisms and accelerating the process of organic carbon turnover in soil, which may not be beneficial for carbon sequestration [18]. The C_0/SOC ratio is the standard to measure the capacity of soil mineralization and carbon sequestration, with a higher C_0/SOC ratio indicating greater soil mineralization ability [41]. Our findings showed a steady increase in organic carbon mineralization capacity in Changbai Mountain in response to warming (Figure 4). This trend is consistent with the elevation-dependent pattern observed for DOC. It implies that soil microorganisms in Changbai Mountain could more efficiently decompose organic carbon in response to warming. Notably, the coniferous forest exhibited the highest values for both C_0 and C_0/SOC at 25 °C (Table 3 and Figure 4), underscoring its higher sensitivity to warming.

4.2. Analysis of Driving Factors of Soil Organic Carbon Mineralization

Mountain forest soil is an important component and nutrient pool of terrestrial ecosystems, and alterations in soil nutrient elements along elevation gradients mirror diverse ecological strategies in mountain systems. The biogeochemical process of organic carbon mineralization is intricately influenced by numerous factors, with nutrient availability emerging as a critical determinant affecting the quantity and quality of organic carbon, as well as the efficacy of microbial substrate utilization [42,43]. Our investigation in Changbai Mountain revealed varying degrees of an increase or decrease in soil properties corresponding to changes in elevation. VPA (Figure 5) showed that soil properties account for 41% of the variability in organic carbon mineralization, underscoring the direct/indirect effects of elevation-induced changes in soil properties on carbon mineralization. These findings emphasize the dynamic interaction between soil properties and organic carbon mineralization in the unique context of mountainous terrain in Changbai Mountain. A study has shown that an ample supply of nutrients essential for microorganisms can substantially enhance their biological activity, thereby promoting the mineralization of organic carbon [44].

In our study, carbon mineralization ability could be attributed to the availability of organic carbon. According to the kinetic theory, the "carbon quality-temperature" hypothesis predicts that the decomposition of low-quality organic carbon in soil demands more activation energy and is more temperature-sensitive [45]. Higher organic carbon content is expected to increase microbial metabolism, thereby enhancing the process of carbon mineralization [46,47]. It is generally believed that soils with higher C/N exhibit lower organic carbon quality and need greater activation energy for organic carbon mineralization, with more temperature sensitivity [9,48]. In our study area, the soil with higher C/N demonstrated a higher Q_{10}, aligning with established research conclusions. This relationship reinforces the idea that the quality of organic carbon serves as a valuable indicator of soil organic carbon mineralization, influencing the sensitivity of the soil microbial community to temperature variations.

A significant positive correlation ($p < 0.01$, Figure 7) was observed between DOC and C_{min}, C_n, and C_0. This correlation underscores the vital role of DOC as an easily decomposed source for organic carbon mineralization, given the variability in bioavailability among soil organic carbon components. Solid organic carbon, being less bioavailable, should be dissolved before it can undergo mineralization into CO_2 and CH_4 [49]. According to kinetic theory, the temperature sensitivity of soil organic carbon increases with higher activation energy and lower solubility of organic matter [50–52]. However, our study did not find a significant correlation between DOC and Q_{10}. This observation may be attributed to the inherent complexity of organic carbon mineralization, which is subject to be limited by various environmental factors.

Soil pH and BD are important factors affecting soil organic carbon mineralization. pH plays a crucial role in affecting the soil redox status and creating an environment that influences substrates, microorganisms, and enzyme activities of organic carbon mineralization [53,54]. In the present study, soil pH had a significantly negative effect on C_{min}, C_n, and C_0 ($p < 0.01$, Figure 7). Laboratory measurements indicated that soils at different elevations in Changbai Mountain are weakly acidic (pH range: 4.53–5.45) with relatively minor fluctuations. Further incubation experiments are needed to explore the coupling relationship between pH and soil carbon mineralization, revealing the underlying mechanisms. BD influences soil organic carbon mineralization primarily through its impact on soil aeration; the increased soil compaction may hinder microbial activity. The correlation analysis showed that C_{min} and C_n were significantly negatively correlated with BD ($p < 0.01$, Figure 7). Previous research has reported a substantial decrease in organic carbon mineralization with rising BD. This decline could be attributed to the increase in soil compaction, leading to reduced soil aeration and consequently inhibiting the decomposition of soil organic carbon by microorganisms [55,56], consistent with our research. Nevertheless, the effect of BD on carbon mineralization is largely reflected in soil aeration and its impact may vary under the combined influence of different soil textures and water conditions [57]. Hence, further investigations are necessary to verify this complex mechanism.

5. Conclusions

Our results showed significant differences in the rate of organic carbon mineralization and temperature sensitivity across the elevational zonation of Changbai Mountain. Contrary to our hypothesis, C_{min} generally tended to increase and then decrease with increasing elevation. C_n demonstrated higher values at higher elevations, both C_{min} and C_n increased with a rising incubation temperature, and the highest Q_{10} was observed in the coniferous forest. Additionally, during the warming incubation, C_0 was higher at 1800–2200 m. C_0 and C_0/SOC gradually increase due to warming. Our findings indicated the critical influence of elevation on soil organic carbon mineralization, with other factors such as pH, BD, and DOC acting as significant regulators. These results highlighted that global climate change induces positive carbon–climate feedback through the accelerated mineralization of organic carbon. Elevation played a pivotal role in affecting matrix availability and the intricate process of organic carbon turnover by impacting soil properties. Our research contributes essential insights for comprehending the temperature sensitivity of soil organic carbon mineralization and understanding the potential impacts of climate change on soil carbon dynamics in mountain ecosystems.

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