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Comparative Analysis of Soil Organic Carbon and Soil Oxide Minerals across Different Climates and Forest Types

Vergleich von organischem Kohlenstoff und Oxidmineralen in Böden in unterschiedlichen Klima- und Waldtypen

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analyse

Abstract

Soil organic carbon (SOC) is an important carbon stock and nutrient source. Most studies on SOC are related to climate conditions, vegetation, topography and land use, while the correlation between soil oxide minerals and SOC is still not extensively researched. Exploring the relationship between soil oxide minerals and SOC can enhance our understanding of the factors influencing SOC stocks and dynamics. We analyzed forest SOC content, employing correlation analysis to explore the relationships between SOC content and soil pH, as well as soil oxide minerals. The study utilized data from natural and planted forests in two provinces in China with distinct climates, Heilongjiang (cold and dry climate) and Anhui (warm and humid climate). In both climates, natural forests exhibited higher SOC content compared to planted forests. The difference in SOC content between natural forests and planted forests was particularly pronounced in the surface soil under cold and dry climate. In com-

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parison to forests in warm and humid climate, forests in cold and dry climate demonstrated significantly higher levels of SOC. Soils in different climates had varying levels of oxidized mineral content. In soils of cold and dry climate, the levels of Na₂O, MgO, CaO and MnO were higher, while soils in warm and humid climate had higher levels of SiO₂, Al₂O₃, Fe₂O₃, TiO₂ and K₂O. SiO₂ exhibited a close correlation with other oxide minerals in the topsoil, whereas Fe₂O₃ and Na₂O showed a strong correlation with other oxides in the subsoil. Under different climatic conditions, the same soil oxide mineral showed different correlations with SOC content. The contents of Al₂O₃, Fe₂O₃ and Na₂O were significantly and positively correlated with SOC contents in cold and dry climate, but significantly and negatively correlated in warm and humid climate. SOC and soil oxide minerals showed different characteristics under different climatic conditions and forest types. Additionally, soil oxide minerals and SOC exhibited a more significant correlation in the subsoil.

Zusammenfassung

Der organische Bodenkohlenstoff (SOC) ist ein wichtiger Kohlenstoffvorrat und eine Nährstoffquelle. Die meisten Studien zu SOC behandeln klimatische Bedingungen, Vegetation, Topografie und Landnutzung, während die Korrelation zwischen Oxidmineralen im Boden und SOC noch nicht umfassend erforscht ist. Die Erforschung der Beziehung zwischen dem Oxidmineralen und SOC kann unser Verständnis der Faktoren, die den SOC beeinflussen, vertiefen. Wir analysierten den SOC-Gehalt und verwendeten Korrelationsanalysen, um die Beziehungen zwischen SOC-Gehalt, Boden-pH und oxidierenden Mineralien im Boden zu erforschen. Die Studie nutzte Daten aus natürlichen und gepflanzten Wäldern in zwei Provinzen Chinas mit unterschiedlichen Klimazonen, Heilongjiang (kalt und trocken) und Anhui (warm und feucht). In beiden Klimaten wiesen natürliche Wälder einen höheren SOC-Gehalt im Vergleich zu gepflanzten Wäldern auf. Der Unterschied im SOC-Gehalt zwischen natürlichen Wäldern und gepflanzten Wäldern war besonders im Oberboden in der kalten und trockenen Klimazone ausgeprägt. Im Vergleich zu Wäldern in warmen und feuchten Klimazonen zeigten Wälder in kalten und trockenen Klimazonen signifikant höhere SOC-Werte. Böden in verschiedenen Klimazonen wiesen unterschiedliche Mengen an Oxidmineralen auf. In Böden mit trockenem und kaltem Klima war der Gehalt von Na₂O, MgO, CaO und MnO höher, während Böden mit heißem und feuchtem Klima einen höheren Gehalt an SiO₂, Al₂O₃, Fe₂O₃, TiO₂ und K₂O aufwiesen. SiO₂ zeigte eine enge Korrelation mit anderen Oxiden in der oberen Bodenschicht, während Fe₂O₃ und Na₂O eine starke Korrelation mit anderen Oxiden in der unteren Bodenschicht zeigten. Unter unterschiedlichen klimatischen Bedingungen zeigte dieselbe Menge Oxidminerale im Boden unterschiedliche Korrelationen mit dem SOC-Gehalt. Die Gehalte von Al₂O₃, Fe₂O₃ und Na₂O waren unter trockenen und kalten Bedingungen signifikant und korrelierten positiv mit den SOC-Gehalten, unter warm-feuchten Bedingungen waren diese jedoch signifikant und negativ. SOC und Oxidminerale im

Boden zeigten unterschiedliche Eigenschaften unter unterschiedlichen klimatischen Bedingungen und Waldtypen. Außerdem zeigten Bodenoxidmineralien und SOC eine signifikantere Korrelation im Unterboden.

1 Introduction

The natural environments and anthropogenic disturbances affect changes in soil carbon pools, which directly influence global greenhouse gases in terrestrial ecosystems and changes in the global climate. Soil organic carbon (SOC) is an active component of the soil carbon pool, and small changes in SOC stocks can lead to changes in atmospheric CO₂ concentrations (Lal 2005). In recent years, studies have also shown that SOC is affected by climatic conditions, vegetation, topography and land use (Post *et al.* 1982; Jobbágy & Jackson 2000; Zhou & Shi 2006; Mei-Yan *et al.* 2013; Waring *et al.* 2020; Jakšić *et al.* 2021; Zhou *et al.* 2023), and also studies have confirmed that soil clay minerals increase the resistance of SOC to decomposition (Churchman *et al.* 2020; Chi *et al.* 2022).

Both the mineral type and the physicochemical properties of the minerals have been shown to influence the mechanism of interaction between minerals and organic matter to varying degrees (Kalbitz et al. 2005; Lumsdon et al. 2005; Jardine et al. 2006; Gjettermann et al. 2008; Kothawala et al. 2009). Previous research has indicated that the stability of SOC is affected not only by clay minerals but also by oxides of Iron (Fe) and Aluminum (Al) (Baldock & Skjemstad 2000; Kaiser & Guggenberger 2003; Schneider et al. 2010), as well as by multivalent cations (Baldock & Skjemstad 2000). Soil oxide minerals, comprising oxides and hydrates of Fe, Al, Magnesium (Mg), Titanium (Ti), Silicon (Si), etc., are an integral component of soil clay minerals alongside layered silica-aluminates. Although quantitatively a minor component of clays, soil oxides, with small particles and large surface area, play a crucial role as the main components of soil inorganic colloids, exhibiting high sorption affinity and reactivity with SOC (Gu et al. 1995; Weng et al. 2005; Wagai & Mayer 2007; Schneider et al. 2010; Chen et al. 2014). Oxide minerals in soil, such as Fe and Al, have been demonstrated to strongly adsorb to SOC (Jardine et al. 2006; Gjettermann et al. 2008). These interactions occur through processes such as ligand exchange, multivalent cation bond bridges, complexation, and relatively weak van der Waals forces (Lützow et al. 2006), contributing not only to the stability of the SOC structure but also to increased SOC stability in soil micropores (Baldock & Skjemstad 2000). In addition, intermolecular interactions between SOC and Fe and Al oxides on the surface of clay particles that improves the stability of SOC (Oades et al. 1989; Basile-Doelsch et al. 2007), prolonging the SOC cycle in the ecosystem, and reducing the loss of soil nutrients (Xu & Zhu 2009). Among the former studies, it has been shown that the protective effect of different types of minerals on SOC varies (Herrick & Wander 2018), and also that SOC stability was significantly affected by the nature of clay minerals, but not by the content of clay minerals (Bruun et al. 2010).

Climate variables, especially temperature and rainfall, profoundly influence soil development processes in terms of thermodynamic dynamics and hydrological cycling, as identified by Velde (1992). In warm and humid climates, water availability enhances chemical weathering, facilitating soil development and affecting the formation and transformation of oxide minerals such as Fe and Al oxides (Deepthy & Balakrishnan 2005). Climate also impacts the interaction between SOC and clay minerals. In warm, humid conditions, the ratio of Fe oxides to aluminous clays strongly controls the storage and stability of SOC (Kirsten et al. 2021). Singh et al. (Singh et al. 2017) revealed a negative correlation between Fe and AI sesquioxide sand soil respiration, playing a crucial role in enhancing the ability of layered silicate aluminosilicates to stabilize SOC. In addition, human activities alter the original physical structure and chemical properties of soil, which is particularly evident in the soils of planted and natural forests. Numerous studies suggest that the SOC content in planted forests is often found to be lower than in natural forests (Wang et al. 2020; Dong et al. 2023). Dong et al. (2023) found that lower SOC content in planted forests is significantly related to the length of soil mycelium and aggregate stability. Mechanical disturbance during the establishment and management of planted forests may damage soil fine root status, fungal structure, and soil aggregate structure, leading to reduced SOC content (Sapsford et al. 2021). However, some studies suggest that mechanical soil cultivation might help soil acquire active mineral surfaces and strengthen the persistence of SOC and mineral binding (Kirsten et al. 2021). Existing research mainly focuses on exploring the relationship between oxide minerals and SOC under specific climates and forest types. The variability and correlation between SOC content and oxide minerals under various climatic conditions, as well as the differences across different forest types and soil depths, remain underexplored areas in current research.

2 Materials and Methods

2.1 Overview of the study sites

Study Area I is situated in the Monsoon-influenced warm-summer humid continental climate zone, located in the central part of Heilongjiang Province. The average annual temperature in the study area is 2.8 ± 1.5 °C, with an average annual precipitation of 575 ± 173 mm. In winter average temperature is -17.9 ± 2.5 °C, while the summer average temperature is 20.6 ± 1.4 °C. Approximately 65% of the annual rainfall is concentrated in the summer season. The region encounters around 200 days per year with daily minimum temperatures below 0 °C, around 1 day per year with daily maximum temperatures exceeding 35 °C. The soil in Study Area I originates primarily from granite, the soil type is classified as Cryumbrept according to the USDA, or as Humic Cambisol in the WRB scheme (Staff 2022; WRB 2022). The main understory shrubs include *Rhododendron sp., Rosa dahurica*, and *Spiraea salicifolia*. The main understory herbaceous plants include *Carex sp., Carex lanceolata*, and *Calamagrositis langsdorffi*.

Study Area II is situated in the Monsoon-influenced humid subtropical climate zone, located in southern Anhui Province. The average annual temperature in the study area is 17.3 ± 0.8 °C, with an average annual precipitation of 1551 ± 378 mm. Winter experiences an average temperature of 6.0 ± 1.2 °C, while the summer average temperature is 27.8 ± 0.9 °C. Approximately 40% of the annual rainfall is concentrated during the summer season. The region experiences approximately 30 days per year with daily minimum temperatures below 0 °C and around 30 days per year with daily maximum temperatures exceeding 35 °C. The soil in Study Area II primarily originates from granite, the soil type is classified as Hapludalf according to the USDA, or as Haplic Alisol in the WRB scheme (Staff 2022; WRB 2022). The main understory shrubs include *Quercus glauca*, *Dicranopteris dichotoma*, and *Spiraea salicifolia*. The main understory herbaceous plants include *Carex sp., Carex lanceolata*, and *Calamagrositis langsdorffii*. The natural forests in Study Area I and Study Area II are typically mixed coniferous and broad-leaved forests.

The climate data was derived from the daily land surface observational data collected by meteorological stations within each study area. We averaged the daily and monthly temperature and precipitation data over a thirty-year period (1991-2021). The dataset was sourced from the Climate Data Online (CDO) by the National Oceanic and Atmospheric Administration (NOAA), and could be downloaded from https:// www.ncdc.noaa.gov/cdo-web/datasets. We classified the climates of the two study areas based on map derived from the Köppen-Geiger climate classification method, as presented by Beck et al. (2018), and illustrated in Fig 1. Although both climate names of the study areas include the term 'humid,' this terminology primarily describes the distribution of precipitation and temperature, along with other related factors. Compared to Study Area II, Study Area I has significantly lower annual precipitation. Therefore, in the subsequent content, to clearly differentiate the hydrothermal conditions of the two study areas, we describe Study Area I as 'cold and dry,' while Study Area II is characterized as 'warm and humid.' Such a distinction helps to more accurately reflect the fundamental differences in the hydrothermal characteristics of the two regions.

We conducted field surveys to assess the forest stands in the two study areas and evaluated the key forest attributes (tree height, diameter at breast height, forest density, and successional stage) and topographic features (elevation, slope, and aspect) of the forests within the study areas. For both natural and planted forests within the same study area, we selected plots with fundamentally consistently matched key forest attributes and topographic features, where the primary distinction was the forest type. The criteria for site selection across different study areas were grounded in ensuring that the forests exhibited typical vegetation and soil types characteristic of each respective region. Moreover, efforts were made to maximize comparability by seeking consistency in key forest attributes and topographic features whenever feasible. Using a 40-meter measuring tape, we delineated three plots of $10m \times 10m$ in each forest stand. Subsequently, we measured the tree height and diameter at breast

height of trees with a diameter at breast height \geq 5 cm within each plot. The forest basic properties in different study areas were recorded in Table 1.

Table 1: Forest properties in the two study areas. Presented are means ± standard deviation (n = 3). Symbols: "H" for Heilongjiang, "A" for Anhui, "nf" for natural forest, "pf" for planted forest. For example, "Hnf" refers to the natural forest in Heilongjiang.

Tabelle 1: Waldeigenschaften in den zwei Untersuchungsgebieten. Angegeben sind Mittelwerte ± Standardabweichung (n = 3). Symbole: "H" für Heilongjiang, "A" für Anhui, "nf" für Naturwald, "pf" für gepflanzter Wald. Zum Beispiel bezieht sich "Hnf" auf den Naturwald in Heilongjiang.

Target	Forest	Forest	Forest	Diameter at	Tree Height	Basal Area	Density	True Consider	
Region	Туре	Code	Age (a)	Breast Height (cm)	(m)	(m²/ha)	(trees/ha)		
Heilong jiang	Natural forest	Hnf	~35	13.21±5.11	12.61±1.50	18.38±6.05	1167±208	Larix dahurica, Pinus sylvestris, Betula platyphylla, Poulus davidiana	
	Planted forest	Hpf	30	12.50±2.97	12.42±1.41	17.72±3.04	1367±153	Larix olgensis, Pinus sylvestris, Betula platyphylla	
Anhui	Natural forest	Anf	~20	15.17±5.43	12.74±2.92	27.21±5.88	1333±231	Pinus massoniana, Cunninghamia lanceolata, Salix babylonica, Robinia pseudoacacia	
	Planted forest	Apf	17	14.27±3.55	11.68±1.33	22.65±3.14	1367±252	Pinus massoniana, Eucalyptus robusta, Populus davidiana	



Figure 1: Map illustrating the location of the study areas and sampling sites. The map shows climate zones using different colors and forest locations with triangular icons. Climate zones are identified by a unique three-letter code in parentheses, indicating classifications based on climate, precipitation, and temperature. Specifically, Study Area I is classified under climate type Dwb, while Study Area II falls under Cfa.

Abbildung 1: Karte zur Lage der Untersuchungsgebiete und Probenahmenstellen. Die Karte unterscheidet Klimazonen mittels Farben und Waldstandorte mit Dreiecksymbolen. Klimazonen werden durch einen einzigartigen dreibuchstabigen Code in Klammern gekennzeichnet, der Klassifizierungen basierend auf Klima, Niederschlag und Temperatur angibt. Speziell ist das Untersuchungsgebiet I unter dem Klimatyp Dwb klassifiziert, während das Untersuchungsgebiet II unter Cfa fällt.

2.2 Field sampling

Samples were collected from both natural and planted forests within two designated study areas. To reduce variability associated with environmental factors and ensure comparability of our research findings, all sampling sites were selected to maintain consistency in elevation, aspect, slope, canopy closure (Wang *et al.* 2012; Oueslati *et al.* 2013; Rooney *et al.* 2023). Five sampling sites were arranged in a "W" pattern, with each site spaced more than 20 m apart. At each sampling site, soil samples were collected from both the topsoil (0-20 cm) and subsoil (20-40 cm) layers. Stones, grass roots and tree roots were removed from the soil samples. Additionally, using 100 cm³

soil core samplers, soil core samples were collected from both the top and bottom layers at each sampling point. All collected soil samples were then transported to the laboratory for testing. Characteristics of soil properties at sampling sites can be found in Table 2.

Table 2: Soil properties at the four sampling sites. Presented are means \pm standard error (n = 5). Symbols: "H" for Heilongjiang, "A" for Anhui, "nf" for natural forest, "pf" for planted forest, "1" for 0-20 cm soil layer, and "2" for 20-40 cm soil layer. For example, "Hnf1" refers to the 0-20 cm soil layer of natural forest in Heilongjiang.

Tabelle 2: Bodeneigenschaften an den vier Probenahmestellen. Angegeben sind Mittelwerte \pm Standardfehler (n = 5). Symbole: "H" für Heilongjiang, "A" für Anhui, "nf" für Naturwald, "pf" für Plantagenwald, "1" für eine Bodentiefe von 0–20 cm und "2" für eine Bodentiefe von 20–40 cm. Zum Beispiel bezieht sich "Hnf1" auf den Bodenbereich von 0-20 cm im Naturwald von Heilongjiang.

Target	Forest	Lawar (cm)	Soil Codo	Soil Bulk Density	Soil Porosity	Soil Texture (mm) (%)			
Region	Туре	Layer (CIII)	5011 COUE	(g/cm³)	(%)	2-0.02	0.02-0.002	<0.002	
	Natural	0-20	Hnf1	0.74±0.12	69.54±3.95	58.96±3.89	28.98±3.26	12.06±0.90	
	forest	20-40	Hnf2	1.39±0.19 47.60±6.		61.58±5.63	27.90±7.43	10.23±2.88	
Hellongjiang		0-20	Hpf1	0.97±0.11 64.21±4.15		40.96±2.75	35.02±4.71	24.02±2.77	
	Planted forest	20-40	Hpf2	1.16±0.07	55.35±1.97	47.47±7.29	32.03±4.72	20.51±4.85	
	Matural	0-20	Anf1	1.19±0.10	49.42±2.35	47.73±2.49	36.35±3.47	15.72±3.18	
Archart	forest	20-40	Anf2	1.45±0.04	42.99±1.32	42.70±2.72	36.36±3.39	20.93±1.90	
Annui	Disated	0-20	Apf1	1.22±0.06	49.78±2.77	48.55±4.76	34.65±3.42	17.00±3.46	
	forest	20-40	Apf2	1.38±0.11	44.85±3.05	46.24±3.15	33.24±4.56	18.12±2.64	

2.3 Laboratory analysis

Soil bulk density was determined using the core method, soil texture was conducted using the pipette method, and soil porosity was calculated by computational method (Lu 2000). Soil (air-dried and sieved through a 2 mm mesh) pH was measured in a distilled water suspension at a soil-solution ratio of 1/2.5. The SOC content was determined using the potassium dichromate dilution heat method (Bao 2000), 0.5 g soil sample (air-dried and sieved through a 0.149 mm mesh) was mixed with 10 mL of 1 mol/L potassium dichromate (K₂Cr₂O₇) solution prepared in a 1/6 ratio and 4 mL of concentrated Sulfuric acid (H₂SO₄) in a 500 mL triangular flask. After 1 minute of stirring and 30 minutes of setting, adding water and diluting it to 250 mL. Adding 3-4 drops of o-phenanthroline indicator, the solution was titrated with 0.5 mol/L FeSO₄ standard solution until a color change from green to dark green, resulting in a brick-red hue.

Determination of oxide minerals in soils by X-ray fluorescence spectrometry. The soil samples were crushed and ground to less than 200 mesh (74 μ m) using a pulverizer. Subsequently, the samples were thoroughly mixed and precisely weighed to 4.00 g. The samples were pressed into 40 mm diameter pieces under 30 MPa pressure using a boric acid bedding, and then tested by X-ray fluorescence spectrometer.

2.4 Data processing and statistical methods

The data were statistically analyzed using SPSS 24.0 software with MANOVA and multiple comparisons (LSD) to analyze the significant differences (P = 0.05) in SOC content in soil between different study areas and between natural and planted forests. Correlation between SOC contents and pH and soil oxide mineral contents were investigated using Origin 2022.

3 Results

3.1 Variability analysis of SOC content

The SOC content in the study areas was characterized (Fig. 2A). The content of SOC varied significantly among different climates, natural and planted forests, and different soil layers. In Study Area I, the SOC content in natural forest was significantly higher than that in planted forest (P < 0.05). Additionally, the SOC content in the topsoil was significantly higher than that in the subsoil (P < 0.01), with SOC contents of 157.7 g/kg and 41.8 g/kg, respectively. In Study Area II, while the SOC content was slightly higher in the topsoil of the natural forest, there were no significant differences in SOC content between the natural and planted forests and different soil layers (P > 0.05).

The C/N ratio of the soil in Study Area I was higher than that in Study Area II (Fig. 2B). Specifically, in Study Area I, the C/N ratio of soils in natural forest was significantly higher than that in planted forest (P < 0.05). Conversely, in Study Area II, there was no significant difference in the C/N ratio between soils in natural and planted forests (P > 0.05).

The C/N ratio generally exhibited a pattern where the topsoil had a higher ratio than the subsoil. Notably, in Study Area I, the C/N ratio of the subsoil in the planted forest was higher than that of the topsoil.



Figure 2: SOC content and C/N ratio in different climate zones, forest types and soil layers (n = 5). Whiskers show standard error. Lowercase letters indicate significant differences at P < 0.05 level. The color of the bars corresponds to the climate zone colors in Fig. 1.

Abbildung 2: SOC-Gehalt und C/N-Verhältnis in verschiedenen Klimazonen, Waldtypen und Bodenschichten (n = 5), Vertikale Balken zeigen Standardfehler. Unterschiedliche Kleinbuchstaben zeigen signifikante Unterschiede zwischen den Gruppen bei P < 0,05 an. Die Farbe der Balken entspricht den Farben der Klimazonen in Abb. 1.

3.2 Characteristics and variability analysis of soil pH and soil oxide mineral content

The soil pH and the contents of soil oxide minerals at the sampling sites in the study areas showed a certain pattern of variation. It was discerned that in Study Area I, the surface soil exhibited a significantly lower pH value (P < 0.05), whereas in Study Area II, there were no significant differences in the pH values between the surface and subsoil layers (P > 0.05).

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Table 3: Characterization of pH and oxidized mineral contents in different climate zones (CL), forest types (FT), and soil layers (SL). Presented are means \pm standard error (n = 5). Different letters indicate significant differences between groups at P < 0.05, where uppercase letters indicate comparisons within the same climatic zone, and lowercase letters denote comparisons among the same forest type. The interactions of factors are indicated by asterisks, with * representing a significance level of P < 0.05, ** for P < 0.01, and *** for P<0.001.

Tabelle 3: Charakterisierung des pH-Wertes und des Gehalts an oxidierten Mineralien in verschiedenen Klimazonen (CL), Waldtypen (FT) und Bodenschichten (SL). Dargestellt sind Mittelwerte \pm Standardfehler (n = 5). Verschiedene Buchstaben kennzeichnen signifikante Unterschiede zwischen den Gruppen bei P < 0,05, wobei Großbuchstaben Vergleiche innerhalb derselben Klimazone und Kleinbuchstaben Vergleiche zwischen gleichen Waldtypen anzeigen. Die Wechselwirkungen von Faktoren werden durch Sternchen angezeigt, wobei * ein Signifikanzniveau von P < 0,05, ** für P < 0,01 und *** für P < 0,001 darstellt.

Soil code	рН	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	Na ₂ O	MgO	CaO	K ₂ O	TiO ₂	MnO
	P					(%)				
Hnf1	4.55±0.24 ^{Ba}	27.38±3.39 Ab	7.96±1.07 ^{вс}	2.52±0.34 ^{Bc}	2.00±0.35 ^{Bb}	1.79±0.14 ^{Ba}	0.92±0.13 ABb	0.61±0.25 Ab	0.34±0.05 Ab	0.07±0.01 Aa
Hnf2	5.43±0.29 Aa	28.10±1.95 Ab	13.06±2.03 Ab	5.00±0.67 Aa	2.95±0.26 Aa	2.05±0.22 Aa	1.10±0.19 ^{Aa}	0.75±0.12 Ab	0.48±0.12 Ab	0.07±0.01 Aa
Hpf1	4.79±0.30 ^{Ba}	28.56±0.80 Ab	8.21±0.38 ^{Bb}	2.27±0.20 ^{Bb}	1.93±0.15 ^{Ba}	1.76±0.03 ^{Ba}	0.87±0.08 ^{Ba}	0.79±0.13 Ac	0.38±0.02 Ab	0.07±0.01 Aab
Hpf2	5.44±0.27 Aa	29.46±1.23 Ab	8.68±0.39 ^{Bb}	2.49±0.21 ^{Bb}	1.87±0.16 ^{Ba}	1.79±0.06 ^{ва}	0.89±0.13 ^{Ba}	0.64±0.16 Ac	0.38±0.03 Ab	0.09±0.02 Aa
Anf1	5.24±0.26 Aa	64.84±3.69 Aa	17.86±1.49 ^{Ba}	3.76±0.39 Ab	0.67±0.10 ^{Bc}	1.14±0.08 Ab	0.41±0.04 Ac	1.92±0.22 Aa	0.64±0.13 Aa	0.04±0.01 ^{Bb}
Anf2	5.30±0.28 Aa	65.46±4.47 Aa	18.09±1.00 ^{Ba}	2.66±0.29 ^{Bc}	0.80±0.20 Bc	1.18±0.20 Ab	0.33±0.09 Ac	2.00±0.26 Aa	0.60±0.11 Aa	0.04±0.01 ^{Bb}
Apf1	5.28±0.26 Aa	58.10±4.95 ^{Ba}	23.85±3.57 Aa	3.47±0.29 Aa	0.74±0.16 ^{Bb}	0.70±0.10 ^{Bc}	0.18±0.04 ^{Bc}	1.55±0.12 ^{Bb}	0.55±0.06 Aa	0.05±0.01 ^{Bb}
Apf2	5.53±0.20 Aa	60.49±4.92 ^{ABa}	22.67±3.15 Aa	3.62±0.37 Aa	1.32±0.17 ^{Ab}	1.23±0.17 Ab	0.47±0.08 Ab	2.18±0.17 Aa	0.53±0.08 Aab	0.07±0.02 Aab
CZ	-	***	***	*	***	***	***	***	***	***
FT	-		•	***	*	*	*	-	-	***
SL	*	-	-	***	***	***	*	**	-	***
CZ * FT	-	**	***	***	***	-	-	-	-	***
CZ * SL	-	-	**	***	-	-	-	**	-	***
FT * SL	-	-	-	-	*	-	-	-	-	***
CZ*FT*SL	-	-	-	***	***	**	**	***	-	***

Within the same study area, the subsoil of natural forest in Study Area I had significantly higher levels of Silicon dioxide (SiO₂), Iron(III) oxide or Ferric oxide (Fe₂O₃), Sodium oxide (Na₂O) and Manganese oxide (MnO) than the topsoil of natural forest and both the subsoil of planted forest (P < 0.05). There was no significant difference in the mineral oxide contents between the subsoil and topsoil of planted forest in Study Area I (P > 0.05).

In Study Area II, the topsoil of natural forest had a significantly higher Fe₂O₃ content than the subsoil (P < 0.05), with no other significant variation between layers (P > 0.05). The topsoil of planted forest in Study Area II had significantly lower SiO₂ and lower levels of Magnesium oxide (MgO), Calcium oxide (CaO), and Potassium oxide (K₂O) compared to both the subsoil of planted forest and the soils of natural forest (P < 0.05). Compared to other soils in Study Area II, the subsoil of planted forest had significantly higher contents of Na₂O and MnO, and the Al₂O₃ content was significantly higher in planted forest than in natural forest (P < 0.05). When comparing the same forest types, soils in Study Area I had significantly lower contents of SiO₂, Al₂O₃, K₂O, and Titanium dioxide (TiO₂) than the forest soils in Study Area II (P < 0.05), while the contents of Na₂O, MgO, CaO, and MnO were significantly higher (P < 0.05). The subsoil of natural forest in Study Area I had significantly higher Fe₂O₃ contents within the natural forest soils, and for planted forest soils, those in Study Area II had significantly higher Fe₂O₃ (P < 0.05).

Climatic zone had a significant impact on the contents of SiO₂, Al₂O₃, Na₂O, and TiO₂, reaching a significant level of P < 0.001. The impact of climatic zone on MgO and K₂O was also significant, with a significance level of P < 0.01. Forest type had a significant effect on the contents of SiO₂ and K6O at the P < 0.05 level. However, soil layer did not significantly affect the content of oxide minerals (P > 0.05).

In the analysis of interactions between factors, the interaction between climatic zone and forest type significantly influenced the contents of Fe₂O₃ (P < 0.05), with the impact on SiO₂ being more significant at the P < 0.01 level. The interaction between climatic zone and soil layer only showed a significant effect on the content of Fe₂O₃ (P < 0.05). The interaction between soil layer and forest type did not have a significant impact on oxide minerals (P > 0.05). Notably, the triple interaction among climatic zone, soil layer, and forest type showed a significant effect on the content of Fe₂O₃ (P < 0.05).

The climatic zero factor showed a significant impact on Fe₂O₃ at the *P* < 0.05 level and exerted a highly significant influence on all other oxidized minerals except Fe₂O₃ (*P* < 0.001), marking it as the most influential factor on soil oxidized minerals. Forest type had a highly significant effect on Fe₂O₃ and MnO (*P* < 0.001), and a significant impact on SiO₂, Al₂O₃, Na₂O, MgO, and CaO (*P* < 0.05). Soil layer demonstrated a highly significant effect on Fe₂O₃, and MnO, with K₂O showing significance at the *P* < 0.01 level and CaO at the *P* < 0.05 level.

In the analysis of interactions between factors, the interaction between climate zone and forest type had a highly significant effect on the contents of Al_2O_3 , Fe_2O_3 , Na_2O_3 , and MnO (P < 0.001), and a significant effect on SiO₂ at the P < 0.01 level. The interaction between climate and soil layer showed a highly significant impact on Fe_2O_3 and MnO (P < 0.001), and a significant impact on Al_2O_3 and K_2O at the P < 0.01 level. The interaction between soil layer and forest type only showed an extremely significant effect on MnO (P < 0.001), with no significant effect on other oxidized minerals (P > 0.001). Notably, the three-factor interaction among climate zero, soil layer, and forest type presented a highly significant effect on the contents of Fe₂O₃, Na₂O, K₂O, and MnO (P < 0.001), and a significant effect on MgO and CaO at the P < 0.01 level.

3.3 SOC content in relation to pH and mineral elements characteristics and variability analysis

There were significant differences in the content of soil oxide minerals between the study areas and soil layers, and the content of SOC varied with the study areas and soil depth. Therefore, a correlation analysis of soil oxide and SOC contents in different study areas and soil layers was conducted. Fig. 3A and B present the correlation analysis between the contents of soil oxidized minerals and SOC in the topsoil and subsoil of Study Area I, respectively. From Fig. 3A, it was observed that the contents of Fe₂O₃, CaO, and K_2O showed stronger correlations with SOC content in the topsoil. However, these correlations were not significant correlation (P > 0.05). Fig. 3B indicated that in the subsoil of Study Area I, the correlation between SOC content and the contents of various oxide minerals became stronger with increasing soil depth. Specifically, SiO2 content showed a significant negative correlation with SOC content (P < 0.05), while Al₂O₃, Fe₂O₃, MgO, CaO, TiO₂ contents showed a significant positive correlation with SOC content (P < 0.05). The contents of Na₂O and K₂O exhibited a highly significant positive correlation with SOC content (P < 0.01). Fig. 3C and D showed the correlation analysis between the oxidized mineral contents and SOC content in the topsoil and subsoil of Study Area II, respectively. Fig. 3C illustrated that in Study Area II's topsoil, both CaO and SiO₂ contents significantly positively correlated with SOC content (P < 0.05), along with a positive correlation observed for Fe₂O₃, MgO, and TiO₂ with SOC. From Fig. 4D, it was evident that in the Study Area II, there was a significant positive correlation between the contents of Al_2O_3 and Fe_2O_3 and SOC in the subsoil (P < 0.05), and a highly significant positive correlation between the contents of Na₂O and SOC (*P* < 0.01).

There was a correlation not only between SOC content and soil oxide minerals contents but also among different soil oxide mineral contents. Between the two different study areas, there was a strong correlation for the oxidized mineral contents in the subsoil of Study Area I, but not in the topsoil of Study Area II. The content of SiO₂ showed a strong correlation with other oxide minerals in the topsoil, while the contents of Fe₂O₃ and Na₂O exhibited a strong correlation with other oxide minerals in the subsoil. Al₂O₃ showed a strong correlation with other oxide minerals in the subsoil of Study Area I and in the topsoil of Study Area II. In addition, the content of K₂O exhibited a stronger correlation with the content of other oxide minerals in the subsoil, whereas the content of TiO₂ in the soil of Study Area I and the content of CaO in the soil of Study Area II showed a better correlation with the contents of other oxide minerals.



Figure 3: Correlation Analysis of Soil Oxide Minerals Content and SOC in Soils. Figure A presents the correlation analysis between soil oxide mineral and SOC contents in the topsoil of Study Area I. Figure B illustrates the correlation analysis in the subsoil of Study Area I. Figure C depicts the correlation between soil oxide mineral and SOC contents in the topsoil of Study Area I. Figure D demonstrates the correlation analysis in the topsoil of Study Area II. Figure D demonstrates the correlation analysis in the subsoil of Study Area II. Figure D demonstrates the correlation analysis in the subsoil of Study Area II. Correlation ellipses in the upper half of the matrix indicate the strength and direction of relationships, with more elongated ellipses reflecting stronger correlations. The lower half of the matrix displays numerical correlation coefficients, with color coding from blue (negative correlation) to red (positive correlation). Significance is denoted by asterisks, with "*" indicating $P \le 0.05$ and "**" indicating $P \le 0.01$.

Abbildung 3: Korrelationsanalyse des Gehalts an Bodenoxidmineralen und SOC-Gehalt im Boden. Abbildung A zeigt die Korrelationsanalyse zwischen Bodenoxidmineralen und SOC-Gehalt im Oberboden des Untersuchungsgebiets I. Abbildung B zeigt die Korrelationsanalyse im Unterboden des Untersuchungsgebiets I. Abbildung C zeigt die Korrelation zwischen Bodenoxidmineralen und SOC-Gehalt im Oberboden des Untersuchungsgebiets II. Abbildung D zeigt die Korrelationsanalyse im Unterboden des Untersuchungsgebiets II. Die Korrelationsellipsen im oberen Teil der Matrix zeigen die Stärke und Richtung der Beziehungen an, wobei länglichere Ellipsen stärkere Korrelationen widerspiegeln. Der untere Teil der Matrix zeigt numerische Korrelationskoeffizienten an mit einer Farbkodierung von Blau (negative Korrelation) bis Rot (positive Korrelation). Die Signifikanz wird durch Sterne angezeigt, wobei "*" $P \le 0,05$ und "**" $P \le 0,01$ bedeutet.

4 Discussion

Soil oxide minerals possess colloidal properties and can adsorb nutrients, playing a crucial role in nutrient retention and soil formation (Kome *et al.* 2019). It was observed that the contents of Na₂O, MgO, CaO and MnO were significantly higher in the soil of Study Area I compared to Study Area II (P < 0.05), while the contents of SiO₂, Al₂O₃, Fe₂O₃, TiO₂ and K₂O were significantly lower in the soil (P < 0.05). Due to intense weathering of rocks in warm and humid zone, soil development becomes more comprehensive. The climatic conditions in these areas expedite the leaching and oxidation of soil minerals. Soluble chlorides and salts were leached out, while oxides of Si, Al, Fe, *etc.*, were retained, intensifying silica-aluminization in Study Area II. Conversely, salts of Na, Mg, Ca, etc., easily dissolve and leach, resulting in a continuous decrease in their contents with soil development. The transition from cold and dry zone to warm and humid zone not only alters soil oxide minerals content but also significantly impacts the accumulation of SOC.

Our study indicated that the SOC content in Study Area I was significantly higher than in Study Area II. Within the same Study Area, natural forests exhibited higher SOC content compared to planted forests, and at the same forest, topsoil consistently had higher SOC content than subsoil. This variation in SOC content across different climates, soil layers, and forest types was consistent with many previous studies (Franzluebbers & Stuedemann 2005; Wang et al. 2012; de Blécourt et al. 2013; Ofiti et al. 2021). Multiple studies have indicated that temperature and precipitation play a crucial role in the carbon cycling of forest ecosystems (Neumann et al. 2018; Harris et al. 2021). The relatively low temperature and precipitation in Study Area I resulted in a slower rate of SOC mineralization (Kato et al. 2006; Wynn et al. 2006), which is more conducive to the preservation of fresh SOC (Pregitzer & Euskirchen 2004). In the vertical profile, as soil depth increases, the contribution of root-derived litter and exudates to SOC gradually increases, while the contribution from leaf-derived litter decreases (Ofiti et al. 2021). Plant organic matter is the primary source of SOC. The topsoil contains more roots, root exudates, and soil microorganisms as sources of SOC. Additionally, a significant amount of aboveground plant organic carbon, such as bark, dead branches, and surface litter, also initially accumulates and decomposes in the topsoil (Franzluebbers & Stuedemann 2005; Angst et al. 2016). Overall, SOC tends to decrease with increasing depth.

In our study, significant differences in SOC between the topsoil and subsoil were observed under cold and dry climatic condition (P < 0.05), whereas in warm and humid climate, despite higher SOC content in the topsoil, the difference with the subsoil was not significant (P > 0.05). The topsoil contains younger unstable SOC, which decomposes faster in warm and humid climates (Jakšić *et al.* 2021). In topsoil, there is a higher concentration of fresh and unstable SOC compared to subsoil, which exhibits a more pronounced response to climatic variations. In cold and dry climates, this can result in the retention of a larger quantity of fresh SOC in the topsoil, thereby accentuating the differences between soil layers. In contrast, under warm and humid conditions, this labile SOC is likely to undergo substantial decomposition or move downward through leaching, thus contributing to the subsoil and diminishing the distinctness in SOC distribution across different soil layers (Angst *et al.* 2016; Tamene *et al.* 2020). This transfer mechanism is more pronounced in soils with higher sand content. In addition to climatic factors, vegetation can also influence soil properties through litterfall and root dynamics, thereby affecting SOC (Finzi *et al.* 1998). Compared to deciduous trees, coniferous tree litter contains a higher proportion of lignin and cellulose, resulting in slower decomposition rates (Baskaran *et al.* 2019). These characteristics of litter are particularly significant in temperate and boreal climates where coniferous forests are prevalent, as low temperatures inherently slow down the decomposition of organic matter (Augusto *et al.* 2015; Lukina *et al.* 2019).

It is important to note that despite our selection of planted and natural forests with closely matched characteristics within two study areas, minor differences were still present. For example, in both study areas, the natural forests exhibited slightly larger average tree height and diameter at breast height, along with somewhat lower stand densities. According to Cha et al.'s (2019) research, there is a significant correlation between SOC content and tree age, but this correlation is relatively weaker with vegetative attributes such as diameter at breast height and tree height. A research on beech and birch forests suggests that while vegetation properties like stand density, diameter at breast height, and tree height may not significantly correlate with SOC content, they are notably related to SOC storage (Li et al. 2010). Some studies have not found significant effects of above-ground biomass and forest age on SOC (Edmondson et al. 2014; Mathew et al. 2016). However, minor variations in continuous forest characteristic variables generally do not lead to major changes in SOC. Yet, in our study, larger differences in SOC content were observed between natural and planted forests, particularly in Study Area I, suggesting that forest type may be a more crucial factor influencing SOC content differences than variations in vegetative characteristics. We found that in Study Area I, the SOC content in natural forest was significantly higher than that in planted forest (P < 0.05), especially in the topsoil. However, in Study Area II, although the SOC content in natural forest was higher, there was no significant difference between the SOC content in natural forest and planted forest. The decrease in SOC in planted forests is hypothesized to be associated with extensive soil disturbance during afforestation, introducing substantial amounts of fresh organic matter into deeper soil layers, thus triggering a priming effect that promotes SOC decomposition and mineralization(Lü et al. 2015). Furthermore, this relationship may also be illustrated in terms of C/N ratio, as some studies have found that high soil N content inhibits the decomposition of SOC (Treseder 2008; Cusack et al. 2010; Lavoie et al. 2011). Excess N can decrease the microbial biomass in the soil (Janssens et al. 2010; Huang et al. 2011). Additionally, increased soil N inhibits the activity of soil oxidative enzymes, leading to a decrease in the mineralization rate of SOC, which is more favorable to the accumulation of SOC (Cusack et al. 2010). This explains the high SOC content in the natural forest of Study Area I. in Study Area II, there was no significant difference in SOC content between planted and natural forests (P > 0.05), and the C/N ratio exhibited same characteristics, further explaining the significant C/N ratio favoring SOC accumulation. Although there are significant differences in SOC accumulation under different climates, our study did not perform a specific quantitative analysis of climate factors. How climate factors affect SOC remains an area that requires further research in this field.

Our research found that, compared to surface soils, the correlation between subsoil and oxide minerals was more pronounced (Poirier et al. 2020). In Study Area I, topsoil SOC exhibits a negative correlation with pH and K₂O, while demonstrating a positive correlation with Fe₂O₃. This finding aligns with Dai et al.'s (2013) research conducted in similar climatic zones. In Study Area I, topsoil is characterized by notably lower pH levels and diminished K₂O concentrations. Under acidic conditions, the increased positive charge and abundance of adsorption sites on Fe oxides favor the formation of stable Fe-organic complexes with SOC, particularly through interactions with carboxyl and hydroxyl functional groups (Gu et al. 1994). We have observed a significant negative correlation between K_2O and Fe_2O_3 (P < 0.01), which may be related to the competition for adsorption sites among metals under acidic conditions. This competition affects the bioavailability of K₂O, making it a crucial factor influencing the microbial mineralization and decomposition of SOC (Kaspari et al. 2008). In the subsoil of Study Area I, significant positive correlations were observed between the contents of Al₂O₃, Fe₂O₃, Na₂O, MgO, CaO, K₂O, TiO₂, and SOC (P < 0.05). In the acidic environment of the topsoil, mineral oxides tend to leach along with SOC. The higher pH in the subsoil promoted the fixation of these metal oxides, which then participated collectively in the chemical reactions and mineral formation processes of the subsoil (Tombácz et al. 2004).

In the topsoil of Study Area II, Fe_2O_3 showed a positive correlation with SOC, while CaO and K_2O exhibited significant positive correlations with SOC. In the warm and humid environment, surface litter decomposes more easily, thus the biomass of fine roots and soil microbial biomass are particularly important for the accumulation of SOC. CaO improves the structure of soil aggregates and enhance soil nutrients, promoting microbial activity and root growth. In the topsoil of Study Area II and soils of Study Area I, SOC consistently showed a positive correlation with Fe_2O_3 , CaO, and MgO. Fe serves as the primary contributor of active hydroxyl groups in soil oxides, and hydroxyl groups, acting as metal ion ligands, undergo exchange with other ligands in the soil solution, functioning as flocculants (Hou *et al.* 2007). Zhang *et al.* (2013) demonstrated significant positive correlation between Fe oxide and SOC content. Wang *et al.* (2021) demonstrated the presence of Fe-OC-Ca and the interaction between them, and Sowers *et al.* (2018) showed the synergistic effect of calcium on SOC sequestration to ferrihydrite.

Percival *et al.* (2000) identified a significant linear relationship between SOC content and Al, observing an increase in SOC content in forests associated with elevated Fe and Al oxide contents. The abundant and active performance of Al oxides in soils acts as a "bridge" in the organic-inorganic composite process (Kleber *et al.* 2007). This leads to the formation of stable organic-mineral complexes, reinforcing the tensile strength and stability of aggregates (Barral et al. 1998). SOC can adhere to the surface of Fe-Al oxide precipitation products and becomes embedded in the network structure of these mineral colloids, obtaining "spatial isolation" to shield it from decomposition (Greathouse et al. 2014). Nevertheless, our findings in the subsoils of Study Area Il showed a significant negative correlation between SOC and Al₂O₃, Fe₂O₃, and Na₂O (P < 0.05), which may indicate that these metal oxides do not effectively stabilize SOC under certain conditions. The soils in Study Area II exhibited higher bulk density and lower porosity. Heavy rainfall and high humidity environments facilitate the reduction and re-oxidation of Fe (Ponnamperuma 1972). During this process, SOC previously stabilized by oxidized minerals is released (Lovley & Phillips 1986). Some microorganisms can use Fe oxides as electron acceptors, enhancing the decomposition of SOC (Lalonde et al. 2012). Nguyen et al.'s (2019) research indicates that changes in temperature may not affect the stability of Fe-bound SOC. However, in deeper soils, mineral oxides may develop different crystalline forms due to the long-term effects of temperature and moisture, influencing their capacity to bind with organic matter. Amorphous Fe oxides, with their higher specific surface area, may bind more closely with organic matter, while crystalline Fe oxides may participate less in such binding (Wiseman & Püttmann 2006). Soils in warm and humid climates tend to produce more crystalline Fe oxides (Li et al. 2012). Additionally, the influence of other soil parameters, such as pH, clay content, and soil organic matter composition, also plays a significant role in modulating the interactions between mineral oxides and SOC, further adding complexity to the understanding of SOC dynamics in varied climatic and soil conditions (Kome et al. 2019). Therefore, comprehensive studies incorporating these factors are essential for a more nuanced understanding of SOC stabilization mechanisms in relation to soil mineralogy and climatic influences.

5 Conclusions

The content of SOC in cold and dry climate zone was significantly higher than warm and humid climate zone, and there was a significant surface aggregation of SOC in cold and dry climate conditions. In the same study area and soil layer, natural forests had higher SOC content, and this difference was particularly pronounced in the surface soil under cold and dry climate. Under warm and humid climate, there was no significant difference in SOC content between natural forest and planted forest. Compared to soils in warm and humid climates, soils in cold and dry climates exhibited significantly higher levels of Na₂O, MgO, CaO and MnO, while the contents of SiO₂, Al₂O₃, Fe₂O₃, TiO₂, and K₂O were significantly lower.

We found a significant correlation between the content of oxide minerals and SOC content in the subsoil. The correlation between the oxide minerals content correlation was stronger in the subsoil under cold and dry climatic conditions as well as in

the topsoil under warm and humid climatic conditions. We also found that the same oxide minerals showed different correlations with SOC content under different climatic conditions, *e.g.*, the contents of Al_2O_3 , Fe_2O_3 and Na_2O showed a significant positive correlation with SOC content under cold and dry condition, but a significant negative correlation under warm and humid conditions. In addition, soil oxide minerals showed different characteristics under different climatic conditions and in soil layers, such as SiO₂ was strongly correlated with other oxide minerals in topsoil and Fe_2O_3 and Na2O were strongly correlated with other oxide minerals in subsoil.

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Conflicts of Interest

The authors declare no conflict of interest.

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