

Article

Dynamics of Vertical Distribution of Soil Organic Carbon in Black Soil Profile of Northeast China in Response to Changes in Land Cover and Land Use

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Abstract

Anthropogenic land-use change influences soil organic carbon (SOC) dynamics by altering both biotic and abiotic soil factors. The carbon stable isotope ratio of SOC ($\delta^{13}\text{C}$) indicates the vegetation sources of organic carbon and legacy effects of historical land use, providing important information for carbon dynamics. However, the mechanisms driving SOC dynamics in deep soils (>100 cm) under different land cover and land-use types remain poorly understood. Here, we analyzed the SOC content and $\delta^{13}\text{C}$ in thick soil profiles (a thickness of 160 cm or 200 cm) under different land cover/land-use types in the typical black soil region of the Songnen Plain, Northeast China. The results showed that the average SOC content at 0–30 cm depth in natural forest land (38.87 g kg^{-1}) was higher than that in the forest land converted to cultivated land (31.66 g kg^{-1}), artificial forest land (22.63 g kg^{-1}), and perennial cultivated land (18.16 g kg^{-1}). Similarly, the average SOC content below 100 cm depth was higher in natural forest land (7.99 g kg^{-1}) than in artificial forest land (6.90 g kg^{-1}), the conversion of natural forest to cropland (6.59 g kg^{-1}), and perennial cultivated land (4.39 g kg^{-1}). Notably, significant positive correlations between $\delta^{13}\text{C}$ and SOC were observed in both natural forest land and perennial cultivated land, presenting the synergistic effects on SOC probably influenced by carbon input, microbial communities, and environmental conditions. Further investigation revealed that soil moisture content and pH significantly influenced SOC content, probably by regulating organic matter decomposition rates. The natural forest land with high moisture content and low pH conditions created favorable environments for carbon preservation, whereas long-term cultivated cropland with low moisture content and high pH conditions accelerated carbon mineralization processes. These results indicate that land cover and land-use change not only significantly alter surface SOC content but also drive deep soil carbon cycling dynamics by regulating soil moisture content, pH and $\delta^{13}\text{C}$ values. This study elucidates the intrinsic relationships between SOC content, $\delta^{13}\text{C}$, pH, and moisture content under land-use change, providing scientific support for land use-aware carbon management strategies in black soil regions.



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Keywords: soil organic carbon; carbon stable isotope; black soil; land use; Songnen Plain

1. Introduction

Soils constitute the largest terrestrial reservoir of carbon, storing approximately twice the amount held within the atmosphere [1–3]. The annual CO₂ emissions from global soil heterotrophic respiration amount to as high as 39 PgC [4]. Greenhouse gases are a primary driver of global warming [5,6]. The resulting warming, in turn, has the potential to further accelerate soil organic carbon (SOC) decomposition, creating a critical positive feedback loop [7,8]. Beyond its pivotal role in climate regulation, SOC profoundly influences soil fertility and nutrient cycling, directly governing agricultural productivity [9]. Therefore, a deeper understanding of SOC distribution patterns and their driving mechanisms is critically important for global carbon cycle management and sustainable agricultural development.

Contemporary research has predominantly focused on SOC dynamics within the surface soil layer [10,11], while SOC stocks below 100 cm of depth remain insufficient. The organic matter in deeper soil horizons does not solely originate from surface inputs. Instead, it arises from prolonged carbon accumulation and stabilization processes, forming persistent subsurface and deep carbon pools [12–14]. Furthermore, emerging evidence suggests that deep soil carbon sequestration potential may far exceed that of surface soils, owing to their lower disturbance regimes and enhanced stabilization mechanisms [15,16].

Land cover/land use represents a primary determinant of SOC content across both surface and subsurface soil horizons [17,18]. In different ecosystems, surface soils (0–20 cm) in forest, grassland, and shrublands contain 50%, 42%, and 33%, respectively, of total profile SOC stocks at 0–100 cm depths [19], highlighting the regulatory role of land cover/land use in carbon stratification. Agricultural practices, particularly tillage regimes, significantly alter SOC storage; no-till systems exhibit SOC enrichment in surface layers, while conventional tillage promotes SOC accumulation within compacted plough pans [13,20,21], demonstrating the complex interactions between mechanical disturbance and organic matter inputs on carbon dynamics. Vertical SOC distribution patterns are jointly governed by bioturbation, dissolved organic matter transport, and topographic controls [22–24]. Biological activity facilitates carbon translocation and redistribution, while dissolved organic compounds participate in subsurface carbon pool formation through vertical leaching processes. Concurrently, topographic variations indirectly modulate carbon distribution via differential hydrothermal conditions across landscapes. Plant community composition and cultivation duration have long-term impacts on SOC, as evidenced by the higher SOC depletion rates in oil palm plantations compared to rubber tree systems [25,26], reflecting functional group-specific carbon sequestration capacities. Notably, long-term afforestation programs have proven effective in restoring soil carbon stocks [27], underscoring the ecological benefits of vegetation restoration in carbon management strategies.

Land cover/land use critically regulates SOC stocks and their spatial distribution, while concurrently modifying key physicochemical parameters such as $\delta^{13}\text{C}$ isotopic signatures, moisture content, and pH [17,28]. These variables collectively shape soil carbon cycling dynamics through synergistic interactions with SOC. The $\delta^{13}\text{C}$ value can reveal the biological source and decomposition path of SOC, and the ratio difference (such as C₃/C₄ plant input ratio) affects the stability and turnover rate of SOC [29,30]. Soil pH value influences SOC mineralization through biotic regulation, primarily by governing microbial community structure and metabolic activity [28,31]. Soil moisture exerts a dual regulatory effect on SOC: high moisture content inhibits the activity of aerobic microor-

ganisms and slows down the decomposition of organic matter [32], whereas periodic flooding environments may enhance SOC accumulation through anaerobic preservation mechanisms [33].

Deep SOC is susceptible to various disturbances, particularly in soils with high organic matter content and fertility, such as black soil. The black soil of Northeast China represents one of the world's major black soil regions [34]. This area is also a key agricultural zone, accounting for 25% of China's total grain production [35]. However, prolonged and intensive agricultural activity has led to significant losses of surface SOC. Since the 1860s, large-scale conversion of original forests and grassland to cropland has occurred, and the advent of mechanized farming in the 1950s has further accelerated surface soil erosion, resulting in a massive reduction in surface SOC content [36,37]. Although changes in surface SOC have received considerable attention, the mechanisms driving SOC dynamics in deep soils (>100 cm) under land-use transformation remain insufficiently studied. In particular, the stability, carbon sequestration potential, and climate sensitivity of deep SOC in black soil regions require further research.

The simultaneous effects of land-use change on SOC, $\delta^{13}\text{C}$, and soil physicochemical properties remain rarely examined in an integrated manner. This study addresses these gaps by investigating the vertical differentiation of SOC, $\delta^{13}\text{C}$, pH, and moisture across 13 profiles under four contrasting land cover/use types in a typical black soil catchment. In this study, we investigated the vertical distribution of SOC, $\delta^{13}\text{C}$, and key physicochemical indicators (moisture, pH) in thick black soil profiles from different land cover/use types. The aim of the study is to determine the characteristics of the vertical distribution of SOC, the carbon isotopic composition of SOC, moisture, and pH in the black soils of Northeastern China under different types of vegetation cover and land uses to analyze their relationships with soil physicochemical properties and to substantiate approaches for sustainable land management.

2. Materials and Methods

2.1. Study Area

The study area is located in Hailun County, Heilongjiang Province, Northeast China (46.58–47.52° N, 126.14–127.45° E). It is a typical black soil area in the Songnen Plain of Northeast China (Figure 1). The terrain of Hailun County gradually decreases from northeast to southwest, with an altitude range of 147–471 m (average about 200 m). The landform types include low hills, high plains, river terraces and alluvial plains. This area belongs to the temperate continental monsoon climate, with an average annual temperature of 1.5 °C and an annual precipitation of 500–600 mm [36]. The area is rich in surface water resources. The Zhaiyin River is the largest river in this area. The parent material of black soil in this area is probably dominated by fluvial deposition and loess-like deposits. The early vegetation types were mainly forests, shrubs, and meadows. Over the past 200 years, uncultivated land and forests have been steadily converted into cropland for corn, soybeans, and rice, leading to a gradual decrease in the thickness of the black soil layer and SOC content [38].

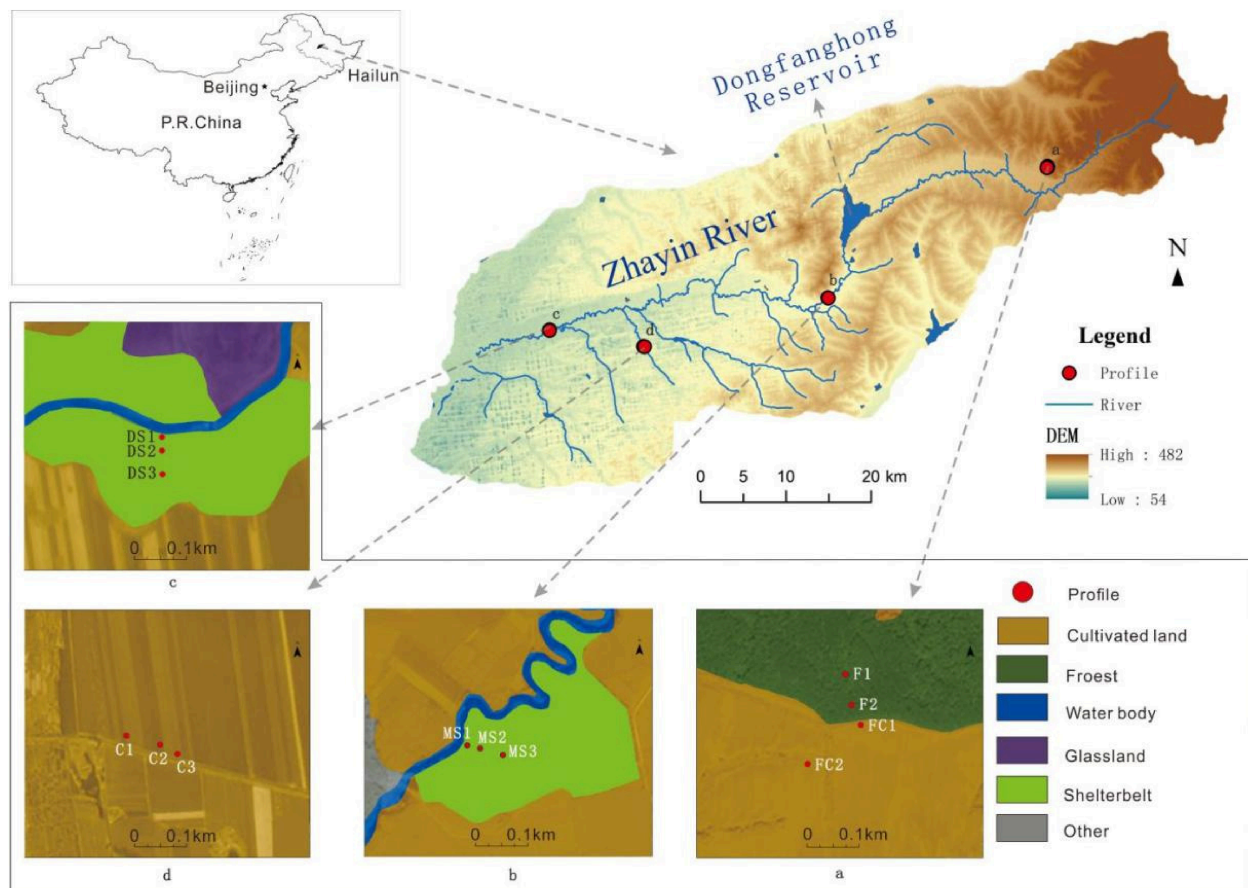


Figure 1. Location of the study area and distribution of sampling points. (a) natural forest land and forest land converted to cultivated land; (b) artificial forest land in the middle reaches of the Zhayin River; (c) artificial forest land in the lower reaches of the Zhayin River; (d) perennial cultivated land.

2.2. Sampling and Preparation of Experimental Samples

To study the effects of land cover/land use on the vertical distribution of organic carbon in black soil, we selected the Zhayin River catchment, where well-developed black soil and diverse land use types provide ideal research materials. Samples were collected from 13 soil profiles in this area at four sites (Figure 1). The catchment covers four land cover/land use types: natural forest land, artificial forest land, forest land converted to cultivated land and perennial cultivated land. Land use history for each sampling site was mainly verified using historical remote sensing imagery spanning the past several decades.

Site a is located in the upper reaches of the Zhayin River, including natural forest land (F1, F2), as well as land that was converted from forest to cropland 25 years ago. During the sampling period, forest land converted to cultivated land was planted with corn (FC1) and soybean (FC2).

Sites b and c are located in the artificial forests in the middle and lower reaches of the Zhayin River, respectively. The history of the artificial forests in the middle reaches is more than 50 years, while that in the lower reaches is only about 20 years. Three profiles with different distances from the river were selected. The 10 m site from the riverbank is the near-bank zone, which is most strongly influenced by fluvial processes such as flooding, erosion, and sediment deposition. The 35 m site from the river falls within the transitional buffer zone, while the 80 m site from the river represents the upland zone, where the direct influence of the river is minimal. Thus, site b and site c were sampled at distances of 10 m, 35 m and 80 m from the riverbank, and the profiles are named MS1, MS2, MS3, and DS1, DS2, DS3, respectively.

Site d is situated in the middle reaches of the plain farming area, with a farming history of more than 160 years. At the time of sampling, the cultivated land was primarily planted with soybean (C1), sesame (C2) and corn (C3).

In July 2018, 13 soil profiles (36 mm in diameter) were collected using a soil sampling rig (Rhino S1). Regarding the vertical distributions of SOC and $\delta^{13}\text{C}$, these patterns have accumulated over centennial to millennial timescales and are not expected to change significantly within a few years. Therefore, the sampling period of our collected profiles is reasonably representative. Except for the F1, F2, and C2 profiles, which were terminated at a 160 cm depth due to the presence of bedrock, the remaining 10 profiles all reach a depth of 200 cm. The 13 black soil profiles are classified as Phaeozems (or Chernozems, depending on the base saturation and calcareous nature of the parent material) according to the IUSS Working Group WRB [39]. Generally, the sampling depths correspond to the following master horizons: 0–30 cm: Ah horizon (mollic/epimollic horizon), characterized by dark color and high organic matter content; 30–100 cm: transitional AB or Bw horizon (cambic horizon), with decreasing organic matter and lighter color; >100 cm: C horizon, composed predominantly of fluvial or loess-like parent material with minimal pedogenic alteration. Continuous sampling was conducted at 10 cm intervals between 0 and 100 cm, and at 20 cm intervals between 100 and 200 cm. Each core was carefully sectioned into depth-specific segments approximately 1 cm thick using a stainless-steel knife. The segmented samples were immediately sealed in labeled polyethylene ziplock bags and transported to the laboratory for subsequent analysis. When sampling, impurities such as plant residues and stones were removed. Fresh soil samples were divided into two parts and wrapped in aluminum foil. One part was used for the determination of soil moisture content, and the other part was dried at room temperature and sieved through a 2 mm sieve, bagged, and sent to the laboratory for pH, SOC and carbon stable isotope measurements.

2.3. Analytical Testing

Soil organic carbon content was determined using the potassium dichromate oxidation method described in reference [40]. $\text{K}_2\text{Cr}_2\text{O}_7$ solution was used to oxidize SOC in acidic conditions under external heating conditions. The remaining $\text{K}_2\text{Cr}_2\text{O}_7$ was titrated with FeSO_4 . The SOC content was calculated according to the amount of FeSO_4 consumed, and the relative deviation (RD) of duplicate determinations was within 10%.

Soil pH (soil:water = 1:2.5) was measured in suspension [41] using a pH meter with a precision of ± 0.05 pH units for replicate measurements. The soil moisture content was determined by the drying method. The soil moisture content was determined by the weight difference after drying at 105 °C for 24 h [42]. The relative deviation between replicate determinations was within 10%.

The soil samples were dried at room temperature, crushed to pass through a 75 μm sieve, oven dried at 50 °C for 24 h, and treated with 10% HCl for 48 h to remove carbonate in the soils [43]. The samples were then washed with distilled water and oven dried at 40 °C for 24 h. The composition of carbon isotopes of soil organic carbon (denoted as $\delta^{13}\text{C}$) was measured by a stable isotope mass spectrometer (Delta V Advantage, Bremen, Germany). The $\delta^{13}\text{C}$ values were calculated using the Pee Dee Belemnite (PDB) international standard as a reference standard. The calculation formula is as follows: $\delta^{13}\text{C}(\text{‰}) = (R_{\text{sample}}/R_{\text{PDB}} - 1) \times 1000$, where R_{sample} is the $^{13}\text{C}/^{12}\text{C}$ ratio of the sample to be tested; R_{PDB} is the $^{13}\text{C}/^{12}\text{C}$ ratio of the international standard substance PDB. Repeated measurements of a laboratory standard sample yielded a standard deviation (SD) better than 1.0‰ for $\delta^{13}\text{C}$.

2.4. Statistical Analysis

The Bartlett's test of sphericity yielded a significant result ($p < 0.05$), indicating that there was common variance among the variables, satisfying the prerequisites for principal component analysis (PCA) [44]. Statistical analysis was conducted using SPSS 18.0 software (IBM Corp., New York, NY, USA) [45]. Principal component analysis biplots, line charts, and correlation plots were plotted using Origin Pro 2024 software (OriginLab Corporation, Northampton, MA, USA. <https://www.originlab.com>, accessed on 1 January 2025).

R packages lavaan (version 0.6–21) and plspm (version 0.6.0) were used to construct a structural equation model (SEM) to analyze the path and intensity of each factor's impact on SOC [46,47]. The goodness of fit of the model was evaluated using chi-squared (χ^2), degrees of freedom (df), comparative fit index (CFI), Tucker–Lewis index (TLI), standardized residual mean root (SRMR), and root mean square error of approximation (RMSEA). The criteria for evaluation were: $\chi^2/\text{df} < 5$, CFI > 0.95 , TLI > 0.9 , RMSEA < 0.06 , and SRMR < 0.08 .

3. Results and Discussion

3.1. Vertical Differentiation and Heterogeneity of SOC: Impacts of Land Cover/Use Change

The results of the vertical distribution of SOC content in 13 profiles are shown in Figure 2. In the upper reaches of the Zhayin River, SOC content in natural forest land (F1, F2), forest land converted to cultivated land (FC1, FC2), and perennial cultivated land (C1, C2, and C3) was predominantly concentrated in the surface layer (at a depth of 0–30 cm) of black soil (Figure 2a,b). In the middle layer (30–100 cm), SOC content of all land cover/land use types displayed a gradual decreasing trend. In the deep soil layers (100–200 cm), SOC content stabilized, varying between 2.01 and 10.31 g kg^{−1}. Particularly, different crop types planted in perennial cultivated land did not lead to significant differences in SOC content among the three profiles.

In the artificial forest land in the middle reaches of the Zhayin River, the MS1 profile showed predominant SOC accumulation in the surface layer and upper part of the middle layers (0–60 cm) with an average content of 27.02 g kg^{−1}, while MS2 and MS3 exhibited SOC enrichment in the 0–90 cm depth interval, averaging 30.55 g kg^{−1} and 26.16 g kg^{−1}, respectively (Figure 2c). Deeper in the soil profile, SOC content decreased sharply and then stabilized.

In downstream artificial forest land profiles (DS1–DS3), SOC content in the soil layer at a depth of 0–90 cm was lower than in midstream artificial forest land (MS1–MS3), while the 90–200 cm layers showed comparable SOC contents between downstream and midstream sites (Figure 2c,d).

The average SOC content in the surface layer (0–30 cm) in profile samples under different land cover/land use types in the black soil region follows a descending order: natural forest land (38.87 g kg^{−1}), natural forest land converted to cultivated land (31.66 g kg^{−1}), artificial forest land (22.63 g kg^{−1}), and perennial cultivated land (18.16 g kg^{−1}). The average SOC content in the middle layer (30–100 cm) in profile samples under different land cover/land use types in the black soil region follows a descending order: artificial forest land (17.70 g kg^{−1}), natural forest land (13.09 g kg^{−1}), perennial cultivated land (9.94 g kg^{−1}), and forest land converted to cultivated land (8.68 g kg^{−1}). The average SOC content in the deep layer (>100 cm) in profile samples under different land cover/land use types in the black soil region follows a descending order: natural forest land (7.99 g kg^{−1}), artificial forest land (6.90 g kg^{−1}), forest land converted to cultivated land (6.59 g kg^{−1}), and perennial cultivated land (4.39 g kg^{−1}). This result is consistent with the general understanding of the carbon sequestration advantages of forest land systems [48,49]. Natural forests form stable carbon sources through high-lignin litter [50], whereas carbon input in

artificial forests is comparatively lower due to their simplified structure and management practice. Perennial cultivated land has a carbon deficit due to the removal of most of the aboveground biomass. Particularly, qualitative differences in carbon inputs exacerbate vertical stratification. The hard-to-decompose components of forest land form an organic–mineral complex in deep soil, while the stubble of cultivated land induces a “priming effect” and accelerates the mineralization of historical carbon pools [51,52].

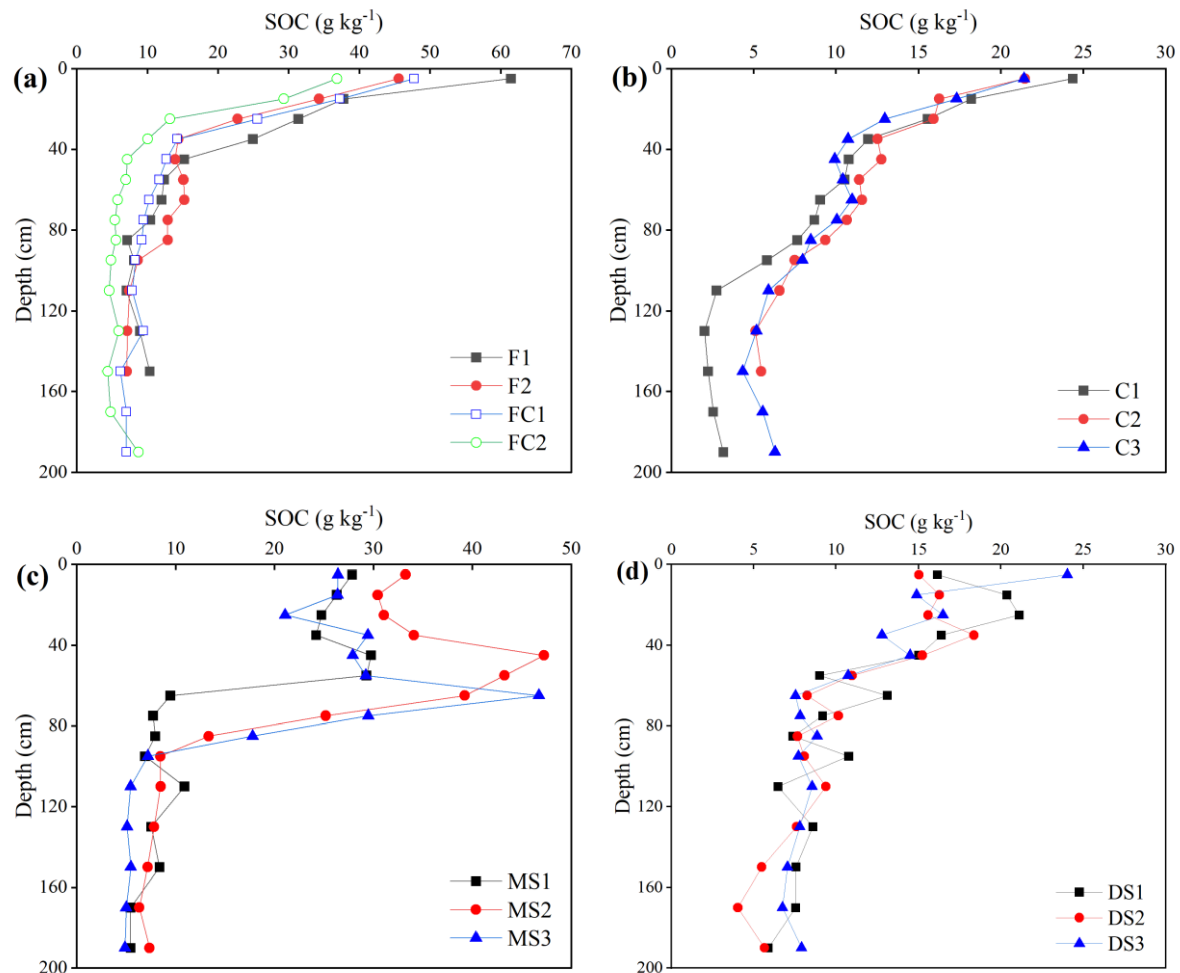


Figure 2. Vertical distribution of SOC content in each profile sample in Hailun County, Northeast China. (a) natural forest land and forest land converted to cultivated land; (b) perennial cultivated land; (c) artificial forest land in the middle reaches of the Zhayin River; (d) artificial forest land in the lower reaches of the Zhayin River.

The intensification of land use (forest land converted into cultivated land) leads to the breakdown of the soil’s physical protection mechanisms. Soil aggregates in natural forest land provide physical protection to maintain and stabilize the soil [53,54], while cultivated land tillage increases the proportion of microaggregates, increases oxygen permeability, and promotes protected carbon mineralization [55]. This explains the phenomenon wherein the surface layer (0–30 cm) of natural forest land has the best carbon preservation, in contrast to the low carbon content of cultivated soils in the surface layer.

Variations in soil moisture content and aeration status reshape the carbon turnover rate by regulating microbial community functions [56]. The canopy of natural forest maintains a cool and humid soil environment, which inhibits the activity of aerobic microorganisms. As a result, the decomposition rate of SOC is lower than in cultivated land. Vertically, the natural forest land preserved the historical carbon pools in the soil layer (approximately

> 40 cm), likely due to an anaerobic environment (Figure 2a). In contrast, the perennial cultivated land experienced continuous carbon loss in the 30–100 cm layer, driven by root depletion and the leaching of dissolved organic carbon (Figure 2b). The artificial forest land, meanwhile, exhibited characteristics of a transitional state (Figure 2c,d).

3.2. Vertical Variation Characteristics of $\delta^{13}\text{C}$ and Its Effect on SOC Content

The vertical profiles of soil $\delta^{13}\text{C}$ suggest that depth-dependent variations can indicate organic carbon sources [43,57,58]. Carbon isotopes of black soil profiles have been analyzed in previous studies. The $\delta^{13}\text{C}$ range (−28‰ to −26‰) of black soil profiles in Northeast China [59] is generally consistent with carbon isotope results of artificial forests in the lower reaches of the Zhaiyin River (DS1, DS2 and DS3 profiles) (Figure 3d). In the natural forest profiles, the average $\delta^{13}\text{C}$ values for F1 and F2 were −23.37‰ and −24.87‰ in the surface layer (0–30 cm), −24.61‰ and −23.80‰ in the middle layer (30–100 cm), and −26.58‰ and −26.17‰ in the deep layer (below 100 cm), respectively (Figure 3a). Among them, profile F1 exhibited higher $\delta^{13}\text{C}$ values in the surface layer and lower values in the deeper layer, whereas profile F2 showed an increasing trend from 0 to 70 cm depth, followed by a decreasing trend below 70 cm. The relatively enriched surface $\delta^{13}\text{C}$ values in the natural forest F1 profile, compared to typical temperate C_3 forest soils, may reflect legacy contributions from historical C_4 vegetation. In the forest land converted to cultivated land, the $\delta^{13}\text{C}$ value of the FC1 profile increased from the surface to 50 cm depth and then declined continuously, whereas the $\delta^{13}\text{C}$ value of the FC2 profile increased from the surface to a 40 cm depth and then declined. Notably, the $\delta^{13}\text{C}$ value of FC2 in the deep layer (>170 cm) increased sharply to −22.98‰, while the $\delta^{13}\text{C}$ values of FC1 remained consistently lower than those of FC2 below 100 cm (Figure 3a).

The $\delta^{13}\text{C}$ values of the perennial cultivated land profiles C1, C2, and C3 are shown in Figure 3b. In general, the $\delta^{13}\text{C}$ values of the three profiles at 0–90 cm depth showed a small change, while the $\delta^{13}\text{C}$ value decreased below 90 cm depth (Figure 3b). The spatial differentiation of $\delta^{13}\text{C}$ values in the profile of artificial forest land (MS1, MS2, and MS3) was obvious. In the middle reaches, $\delta^{13}\text{C}$ values of the MS1 profile peaked at 60 cm depth (−23.44‰) and then decreased sharply, while the $\delta^{13}\text{C}$ values of MS2 and MS3 profiles increased slowly after four large rises and falls at 0–80 cm depth (Figure 3c). In the artificial forest soil profile of the lower river reaches, the amplitude of $\delta^{13}\text{C}$ variation is relatively small below a depth of 30 cm (Figure 3d).

The $\delta^{13}\text{C}$ values of SOC observed in soil profiles are not a simple, direct reflection of the overlying vegetation [60]. Instead, they integrate multiple processes along the plant–litter–soil continuum. First, the initial carbon isotopic signal is determined by the composition of plant litter, which differs among vegetation types (e.g., forest, grassland and cropland) and even among plant tissues (e.g., leaves and roots) [61,62]. Second, during litter decomposition, preferential mineralization of ^{13}C -enriched cellulose components and the relative accumulation of ^{13}C -depleted lignin [63] can shift the isotopic signature of the remaining organic matter. Third, and importantly, soil microorganisms further modify the $\delta^{13}\text{C}$ signal through selective substrate utilization and the production of microbial necromass [64]. The vertical differentiation of $\delta^{13}\text{C}$ in black soil profiles in this study should therefore be interpreted as a combined consequence of historical vegetation inputs, depth-dependent decomposition, and microbial carbon turnover, rather than as a direct proxy of land-cover change alone. Further compound-specific isotope analyses or biomarker approaches would help to disentangle the relative contributions of plant-derived versus microbial-derived carbon to the bulk $\delta^{13}\text{C}$ signal.

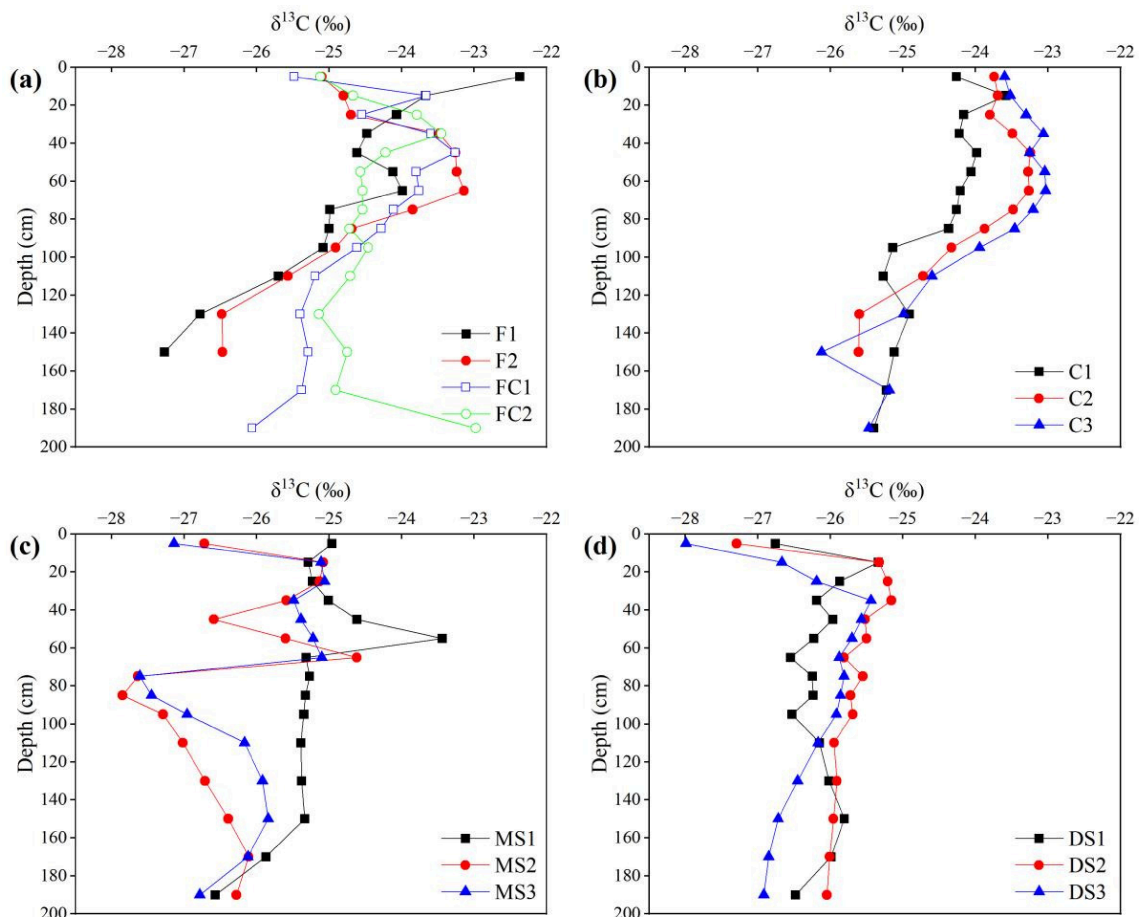


Figure 3. Vertical variation of $\delta^{13}\text{C}$ values in different soil profiles in Hailun County, Northeast China. (a) natural forest land and forest land converted to cultivated land; (b) perennial cultivated land; (c) artificial forest land in the middle reaches of the Zhayin River; (d) artificial forest land in the lower reaches of the Zhayin River.

Pearson correlation analysis revealed relationships between $\delta^{13}\text{C}$ and SOC content across different land cover/land use types (Figure 4). Natural forest land showed a significant positive correlation between $\delta^{13}\text{C}$ and SOC ($r = 0.48$, $p < 0.05$), and perennial cultivated land exhibited an even stronger positive correlation ($r = 0.63$, $p < 0.01$), indicating SOC accumulation accompanied by $\delta^{13}\text{C}$ enrichment. Additionally, artificial forest land showed a statistically significant correlation ($r = 0.25$, $p < 0.05$), indicating the joint regulation of natural and human factors.

Although the F2 profile in the natural forest land and the C2 and C3 profiles in perennial cultivated land from the surface to 70 cm deep exhibited increasing $\delta^{13}\text{C}$ (Figure 3a,b) and decreasing SOC (Figure 2a,b), a positive correlation between $\delta^{13}\text{C}$ value and SOC content in the vertical profile of natural forest land and perennial cultivated land was significant (Figure 4). Consistent with previous findings that microorganisms preferentially utilize ^{12}C -enriched components [65], we speculate that in the surface layer (0–30 cm), microorganisms preferentially consumed ^{12}C -enriched components, leaving behind ^{13}C -enriched residues. For the C2 and C3 profiles in perennial cultivated land, isotope fractionation drove a gradual increase in $\delta^{13}\text{C}$ from 40 cm to 70 cm depth (Figure 3b), which may be related to the accelerated loss of light carbon through mineralization caused by tillage disturbance. The carbon pools were formed due to the input of C₃ (soybean and sesame) and C₄ (corn) crop residues in perennial cultivated land. $\delta^{13}\text{C}$ displayed an obvious maximum point (Figure 3a,b) at approximately 70 cm depth, while SOC decreased only slightly (Figure 2a,b).

This may be attributed to the heterogeneity of deep carbon sources and the possibility that deep soil has sealed organic matter inherited from historical vegetation succession. The lower $\delta^{13}\text{C}$ values in deep layers of natural forest land showed the dominant input of C_3 plants.

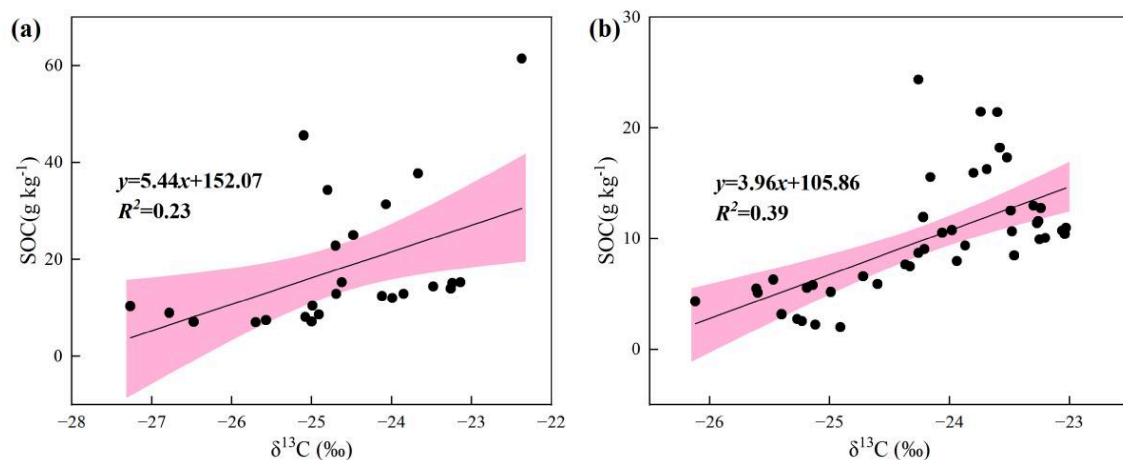


Figure 4. Correlation between $\delta^{13}\text{C}$ and SOC content: (a) natural forest land; (b) perennial cultivated land. The shaded area indicates the 95% regression confidence interval.

3.3. Vertical Variation Characteristics of Soil Moisture and pH, and Their Correlations with SOC and $\delta^{13}\text{C}$

The results of soil moisture and pH value are presented in Figures 5 and 6, respectively. The average soil moisture contents in the surface layer (0–30 cm) of natural forest F1 and F2 in the upper reaches of the Zhayin River are 46.97% and 37.53%, respectively. The average soil moisture content in the surface layer (0–30 cm) of forest land converted to cultivated land FC1 and FC2 in the upper reaches of the Zhayin River are 34.62% to 23.92%, respectively. Overall, the moisture content in natural forest and cropland converted from forest land was higher in the surface layer than in the middle and deep layers (Figure 5a). Notably, natural forest land (F1 and F2) showed a significant decrease in moisture content with depth (sharp decline below 30 cm), but the vertical fluctuation of forest land converted to cultivated land was small. The soil moisture of perennial cultivated land (C1, C2 and C3) decreased with increasing depth (Figure 5b). The moisture content of artificial forest land showed spatial differentiation, with large values in the middle reaches (MS1, MS2 and MS3), significantly higher than those in the lower reaches (DS1, DS2 and DS3) (Figure 5c,d). The overall performance is that the soil moisture content of forest land is higher than that of cultivated land, with the difference primarily reflected in the surface layer.

The soil pH values of 13 soil profiles were significantly different. In the surface layer (0–30 cm depth), the pH values of the natural forest land and forest land converted to cultivated land samples in the upstream natural and artificial forest samples in the middle reaches were the lowest (Figure 6). The pH value of forest land converted to cultivated land is roughly the same as that of natural forest land (Figure 6a). This phenomenon shows that due to the relatively short farming time of forest land converted to cultivated land, some characteristics of natural forest land are still retained to a certain extent. The soil pH value of the artificial forest in the middle reaches was lower than that of the artificial forest in the lower reaches (Figure 6c,d). The soil pH value of cultivated land under long-term tillage is higher than that of natural forest land and forest land converted to cultivated land. The higher soil pH observed in long-term cultivated land compared to natural forest land and converted forest land may be attributed to several factors. Long-term tillage can promote the mixing and homogenization of surface and subsurface horizons, potentially

bringing base cations from deeper, calcareous parent material to the surface. Additionally, the application of fertilizers in agricultural management, as well as the removal of base cations by crop harvest and subsequent return through crop residues, can alter the soil acid–base balance. However, the regulation of soil pH involves complex interactions among parent material, land use history, and management practices.

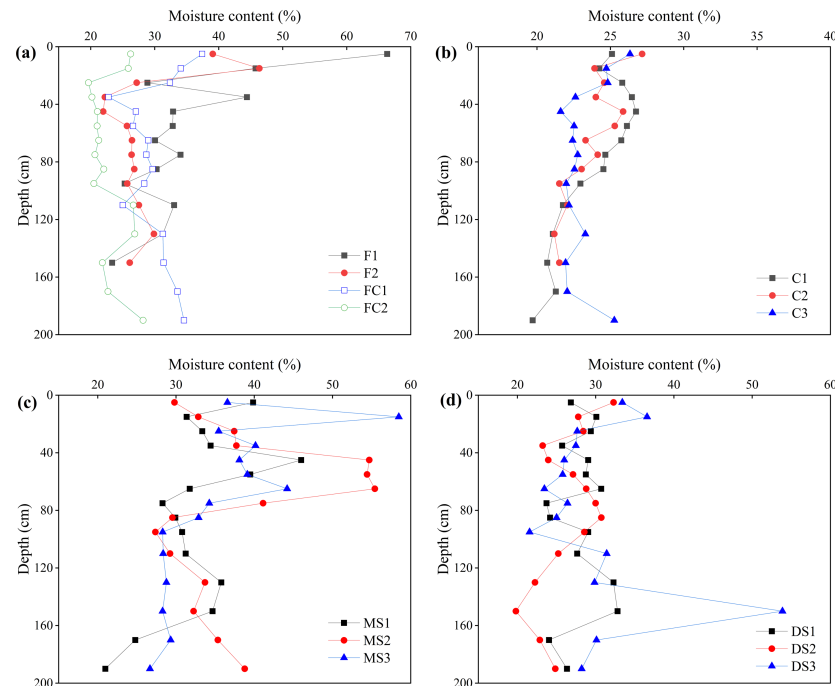


Figure 5. Vertical variation of moisture values in different soil profiles in Hailun County, Northeast China. (a) natural forest land and forest land converted to cultivated land; (b) perennial cultivated land; (c) artificial forest land in the middle reaches of the Zhayin River; (d) artificial forest land in the lower reaches of the Zhayin River.

Correlation analysis revealed that the soil moisture content was significantly positively correlated with SOC content in all four land cover/land use types ($p < 0.01$). The correlation coefficients were as follows: natural forest land, $r = 0.81$; artificial forest land, $r = 0.68$; forest land converted to cultivated land, $r = 0.47$; and perennial cultivated land, $r = 0.70$ (Figure 7). The correlation between soil pH and SOC is more complex. There was a significant negative correlation between soil pH and SOC in artificial forest land and perennial cultivated land ($p < 0.01$), and the correlation coefficients were -0.67 and -0.55 , respectively (Figure 8). There was also a significant negative correlation between soil pH and SOC content in natural forest land ($r = -0.40$, $p < 0.05$).

Different land cover/land use types significantly changed the relationship between soil moisture, pH, $\delta^{13}\text{C}$ and SOC. The high moisture content of natural forest forms an anaerobic environment, inhibits SOC decomposition, and makes its SOC content (especially in the surface layer) higher than other types. SOC was significantly positively correlated with $\delta^{13}\text{C}$ and soil moisture content in perennial cultivated land (Figures 4b and 7d), indicating that long-term tillage reduced soil moisture and accelerated organic carbon mineralization with ^{13}C enrichment [66]. In addition, canopy interception in forest land promoted microbe-mediated SOC stabilization [67], while frequent dry-wet alternation in cultivated land accelerated SOC mineralization, resulting in a significant decrease in SOC content in the 0–30 cm layer compared to natural forest land. These differences indicate that land cover/land use type is a key regulator of regional moisture–carbon balance.

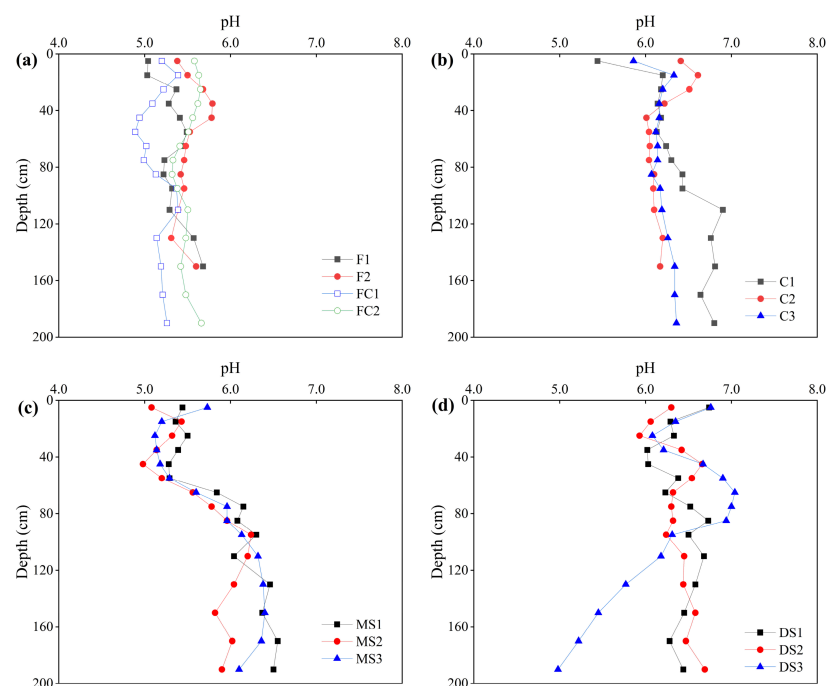


Figure 6. Vertical variation of pH values in different soil profiles in Hailun County, Northeast China. (a) natural forest land and forest land converted to cultivated land; (b) perennial cultivated land; (c) artificial forest land in the middle reaches of the Zhayin River; (d) artificial forest land in the lower reaches of the Zhayin River.

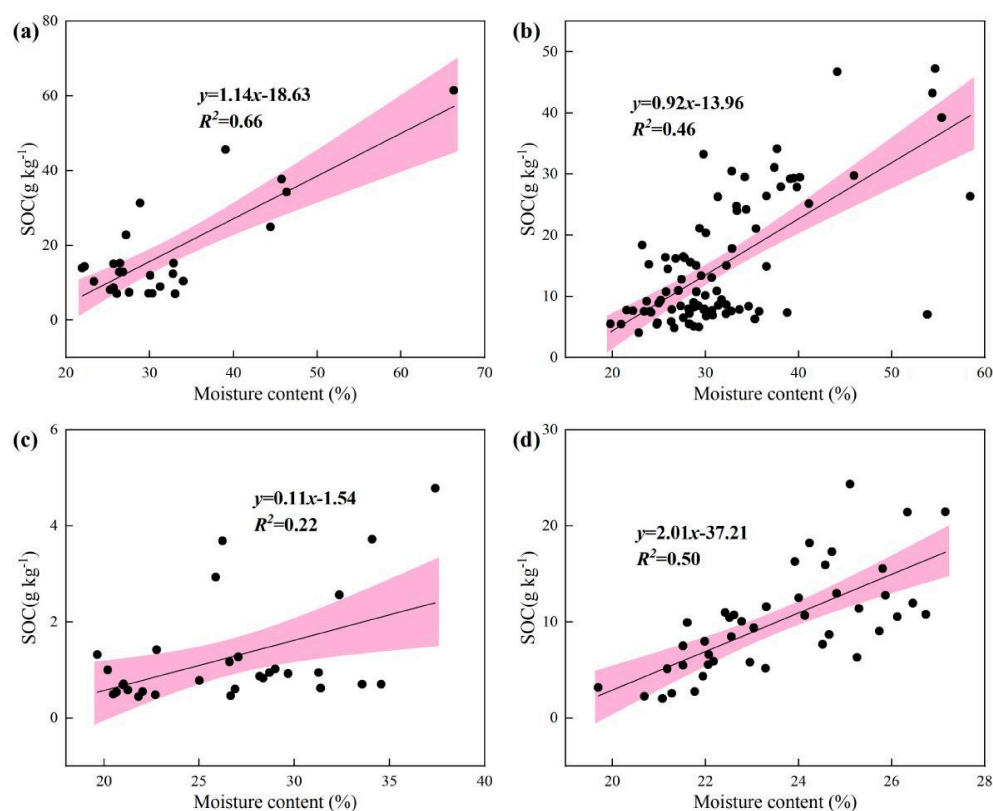


Figure 7. Correlation between soil moisture content and SOC: (a) natural forest land; (b) artificial forest land; (c) forest land converted to cultivated land; (d) perennial cultivated land. The shaded area indicates the 95% regression confidence interval.

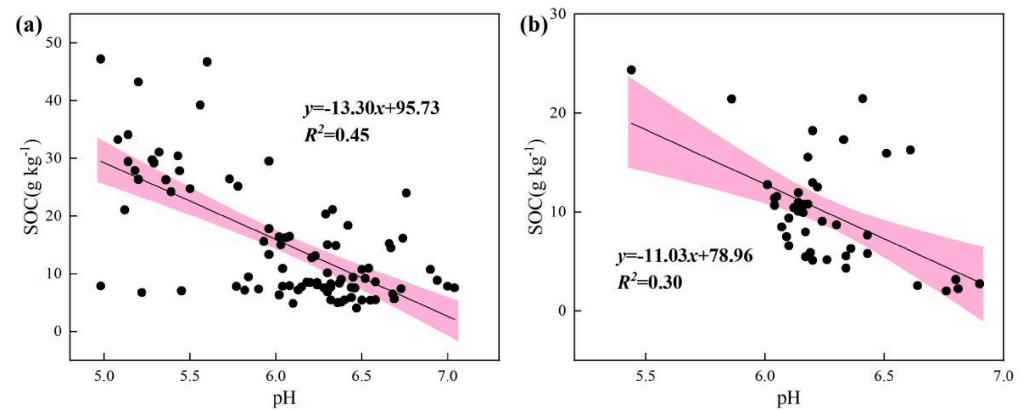


Figure 8. Correlation between pH and SOC: (a) artificial forest land; (b) perennial cultivated land. The shaded area indicates the 95% regression confidence interval.

3.4. PCA and SEM Reveal the Moisture–pH Coupling as a Core Driver of SOC Dynamics

The results of principal component analysis (PCA) revealed the intrinsic relationship between SOC and pH, moisture content and $\delta^{13}\text{C}$ in the four land cover/land use types (Figure 9). The results showed that the contribution rates of the first two principal components to the variance were 51.5% and 28.2%, respectively, and the cumulative contribution rate was 79.7%. PC1 was composed of pH, SOC and moisture content, and its rotational loads were -0.52 , 0.61 and 0.60 , respectively. It is speculated that PC1 mainly revealed the effects of soil pH and moisture content on SOC content in the profile. PC2 was mainly composed of a variable of $\delta^{13}\text{C}$, and its rotational load was 0.89 . It was speculated that PC2 revealed the historical evolution characteristics of C_3/C_4 vegetation types in soil profile samples. Land cover/land use affects SOC by altering the moisture–pH balance. The natural forest land maintained high moisture content and low pH conditions that inhibited decomposition and retained C_3 vegetation signals with depleted $\delta^{13}\text{C}$, while the low moisture content and high pH combinations of perennial cultivated land simultaneously reduced SOC and enriched $\delta^{13}\text{C}$. Therefore, the moisture–pH coupling constitutes a core hub for isotopic fractionation and carbon preservation.

The structural equation modeling (SEM) quantified the direct and indirect effects of moisture, pH, and $\delta^{13}\text{C}$ on SOC (Figure 10). Specifically, the sample size (N) for each land use type was as follows: natural forest land, $N = 26$; artificial forest land, $N = 90$; converted forest-to-cropland, $N = 30$; and perennial cultivated land, $N = 43$. These sample sizes meet or exceed the commonly recommended minimum of 10 observations per estimated parameter for SEM analysis. The results showed that soil moisture content was the most important positive driving factor for SOC content. In artificial forest land, the indirect effect (0.25) was mainly derived from the pathway of “moisture affected SOC through pH”, indicating that pH was a key mediator variable. Interestingly, the negative effect of moisture on pH (-0.68) interacted with the negative effect of pH on SOC (-0.37), eventually forming a positive indirect effect. This suggested that soil moisture may activate specific microbial communities by regulating pH [68], thereby indirectly affecting SOC dynamics. In perennial cultivated land, the indirect effect was mainly achieved through the two paths of “moisture affected SOC through $\delta^{13}\text{C}$ ” and “moisture affected $\delta^{13}\text{C}$ through pH, ultimately affecting SOC”, highlighting the core intermediary position of $\delta^{13}\text{C}$. Soil moisture content may affect the vertical distribution pattern of SOC by promoting microbial activity and enhancing $\delta^{13}\text{C}$ fractionation during decomposition.

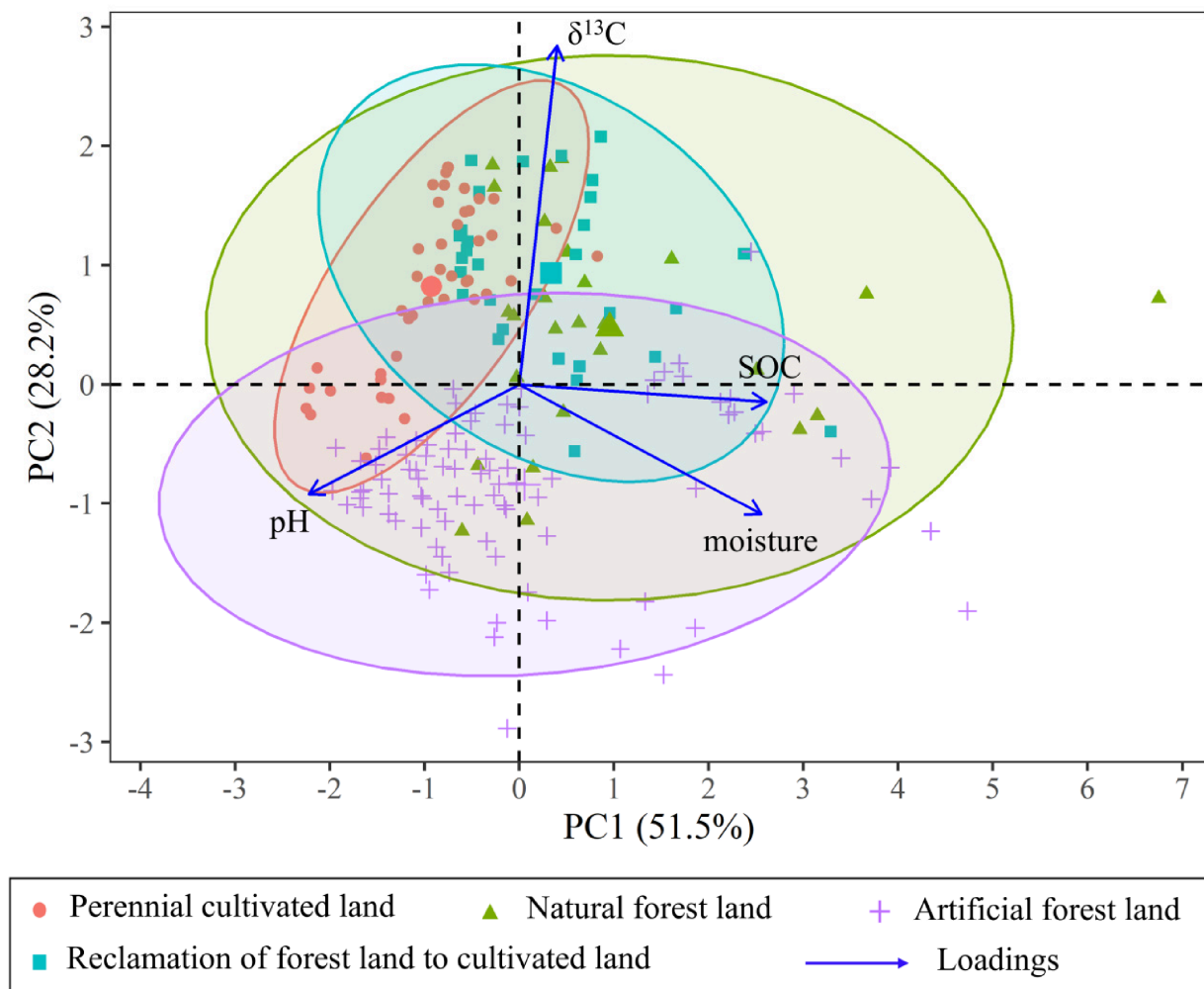


Figure 9. Principal component analysis biplots of all samples. PC1 and PC2 refer to the first and second principal components, respectively; the shaded areas of different colors represent the 95% confidence ellipse.

SEM analysis showed that the driving mechanism of SOC content changes in different land cover/land use types was distinct. In natural forest land, the total effect of soil moisture on SOC was 0.74, of which the direct effect (0.91) was the main contribution and had a significant positive effect (Figure 10a). In artificial forest land, soil moisture content indirectly affects SOC mainly by changing pH, and all paths have a positive net effect (total effect 0.66), of which direct contribution accounts for 62.12% and indirect contribution accounts for 37.88% (Figure 10b). In newly cultivated land, the total effect of soil moisture on SOC is 0.49, with a significant direct effect (0.69), while the indirect path correlation coefficient was not significant (Figure 10c). Although there was an inhibitory indirect path, soil moisture still had a net positive effect on SOC. In perennial cultivated land, soil moisture had a strong positive effect on SOC (total effect 0.71), of which the direct effect (0.54) was dominant, and the indirect effect (0.17) was mainly mediated by $\delta^{13}\text{C}$ (Figure 10d).

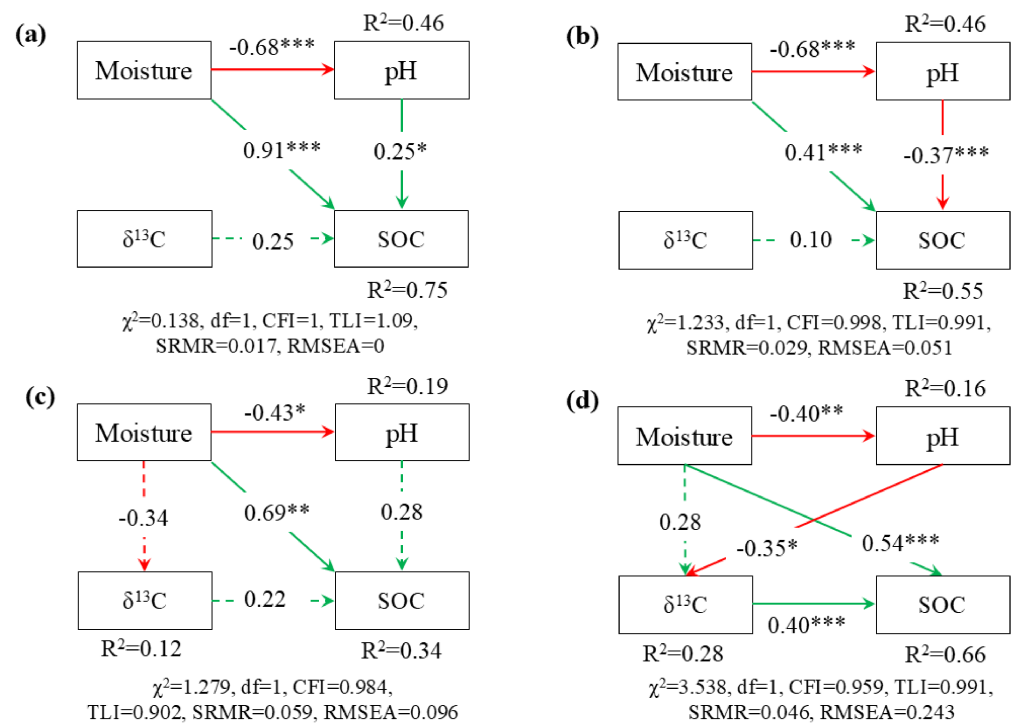


Figure 10. Structural equation modeling analysis of SOC content dynamics across land use types: (a) natural forest land; (b) artificial forest land; (c) forest land converted to cultivated land; (d) perennial cultivated land. Note: Green lines indicate positive effects, red lines denote negative effects; solid lines represent significant paths, dashed lines indicate non-significant paths. * denotes $p < 0.05$, ** denotes $p < 0.01$, *** denotes $p < 0.001$.

3.5. Implications for Sustainable Management of Black Soil, and Future Research Directions

The forest land converted to cultivated land (approximately 25 years since conversion) exhibited lower SOC content in vertical profiles compared to adjacent natural forest land profiles with a distance of about 50 m (Figure 2a). Compared to natural forests, artificial forests with monoculture vegetation and shorter growth cycles suggested reduced SOC accumulation. The lower SOC content in downstream artificial forest lands versus mid-stream counterparts may reflect their shorter land use history. Perennial cultivated lands displayed the lowest SOC levels, predominantly driven by farming activities. Soil moisture emerged as the major driver of vertical SOC distribution. This study indicates that land use intensification (natural forest land converted into perennial cultivated land) induces irreversible depletion of black soil carbon stocks, with subsoil carbon loss lagging behind surface depletion. These findings provide useful scientific basis for black soil conservation: (1) prioritize maintaining natural forest vegetation cover to benefit from its high carbon input and low disturbance for enhanced carbon sequestration; (2) reform artificial forest management by introducing deep-rooted tree species and diversifying litter inputs to mimic natural forest carbon cycling mechanisms; (3) optimize cropland moisture management through no-till practices and deep straw incorporation (≥ 30 cm depth) to suppress SOC mineralization via physical coverage while augmenting subsoil carbon inputs.

The findings of this study show some future research directions. Firstly, the investigation relied on spatial sequence data from representative sampling points. Although this method can indirectly infer the temporal effects of land use change, long-term fixed-point observations are needed to directly verify the temporal accumulation effects and evolutionary trajectories of SOC dynamics. Secondly, this study focuses on a typical black soil region in the Songnen Plain, and future research could further verify the regional representativeness of the conclusions in black soil subtypes under different climatic conditions and soil

textures. Thirdly, the stability of SOC is controlled by multiple mechanisms, such as mineral protection and physical isolation within aggregates. Future research could consider further exploring key processes such as soil microstructure and mineral–organic interactions.

A limitation of this study is that soil organic carbon was measured as concentration (g kg^{-1}) rather than as stock (kg m^{-2}), because bulk density data were not collected. Forest soils typically have lower bulk density than cultivated soils, meaning that the SOC concentration advantage of natural forest observed here may overestimate the corresponding stock advantage. Future studies incorporating bulk density measurements would allow a more quantitative assessment of carbon sequestration potential.

4. Conclusions

This study presents a preliminary analysis of the vertical differentiation of SOC, carbon isotope composition, pH and moisture content in the typical black soil of Northeast China under varying land cover and land use conditions. The mean SOC contents in the surface layer (0–30 cm) for each land use type were measured (natural forest land: 38.87 g/kg; artificial forest land: 22.63 g/kg; converted forest land: 31.66 g/kg; perennial cultivated land: 18.16 g/kg). Long-term tillage results in the loss of soil organic carbon. The findings suggest that changes in land cover and land use can profoundly influence SOC content in black soil profiles, primarily through their effects on soil moisture, pH, and $\delta^{13}\text{C}$, with particularly pronounced impacts observed in surface SOC concentrations.

The effect of $\delta^{13}\text{C}$ vertical differentiation on SOC stability exhibits significant variations across different land cover and land use types. In the soil profiles of natural forest land and perennial cultivated land, $\delta^{13}\text{C}$ values and SOC content display significant concurrent variation, which may be attributed to isotope fractionation induced by microbial decomposition, differences in deep carbon inputs, and the regulatory influence of environmental factors. Soil moisture emerges as a key driver of the vertical distribution of organic carbon, indirectly modulating $\delta^{13}\text{C}$ fractionation by affecting microbial activity. Moreover, the interaction between soil moisture and pH plays a dominant role in SOC stability, particularly in deeper soil layers.

These findings enhance our understanding of the mechanisms governing the stability of deep carbon pools in black soil and provide practical management strategies and theoretical support for carbon sequestration in black soil. A key pathway to effectively protecting the black soil carbon pools and ensuring the sustainable development of the black soil ecosystem in the future lies in a suite of measures: maintaining natural forest cover, expanding artificial forests, optimizing cropland moisture management, and promoting no-tillage techniques combined with deep straw incorporation into the soil.

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