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Case Report

Labile and Stable Fractions of Organic Carbon in a Soil Catena (the Central Forest Nature Reserve, Russia)

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Abstract: The composition of soil organic carbon (SOC) is an important soil quality indicator. We investigated the effect of site-specific soil-forming factors on plant debris and SOC properties along a soil catena with Retisols and Stagnosols in a mixed coniferous–deciduous forest. We examined sites at the summit and middle slope positions with relatively well-aerated soils and sites at footslope positions with waterlogged soils. The concentrations of labile and stable pools of SOC were determined using the method of three-stage chemodestruction. The degree of litter decomposition was calculated, and ash content was determined in the folic and histic soil horizons. The results of our study showed that SOC mostly accumulated in the forest litter and histic horizons of Stagnosols at the footslope positions. The forest litter, folic, and histic horizons were dominated by labile carbon. Equal concentrations of labile and stable carbon were typical of the mineral horizons. The location of the soil in the catena affects the partition and characteristics of SOC in umbric and albic soil horizons. SOC was found to be more stable in the soils at the footslope positions compared to the soils in other locations, because of the lower decomposition of plant remains. Larger stocks of organic carbon, including labile carbon, were restricted to the footslope catena positions.

Keywords: decomposition processes; total organic carbon; plant litter; forest soils; carbon cycling; boreal ecosystems

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1. Introduction

Soil organic matter decomposition and stabilization processes play an important role in ecosystem functioning. Numerous studies have been undertaken to evaluate turnover, stabilization, and formation of SOC using different fractionation methods. According to the stability and residence time, soil organic carbon (SOC) consisting of three main pools (labile—C_L; oxidizable—C_O; and stable—C_S) can be divided into the following fractions [1,2]:

- Physically protected (occluded within aggregates and therefore inaccessible to decomposer microorganisms);
- Chemically protected (through sorption and complexation within organomineral associations);
- Unprotected by chemical or physical mechanisms and accessible to decomposer microorganisms.

Determination of the total content of SOC and its fractions [3–5] was used to characterize soil quality associated with soil potential for optimal biological productivity and proper ecosystem services [6,7]. The characteristics of soil organic matter can serve as a sensitive indicator of the degree of changes occurring in the soil, especially under the influence of potentially toxic element pollution [8–11]. Therefore, studies of SOM composition and decomposition intensity are in demand for environmental assessment.

Many authors fractionate organic matter into labile and stable fractions. The labile pool C_L represented by the water-soluble proteins, hemicelluloses, sugars, etc. is soluble in hot and cold water and salt solutions [12] and impacts ecosystem productivity and sustainability [13]. An increased labile carbon input contributes to the formation of stable organic compounds [14] which migrate in association with soil minerals [15]. Compounds of C_L may remain in the soil for a week or longer periods of up to several years, while the compounds of stable C may remain for decades or even centuries [16]. About 70% of C_L of plant residues (Figure 1) may be brought back into the atmosphere as CO_2 [17]. The rest of the oxidizable and stable carbon experiences ongoing humification. Later, stable carbon incorporates into complexes with a soil mineral matrix [18].

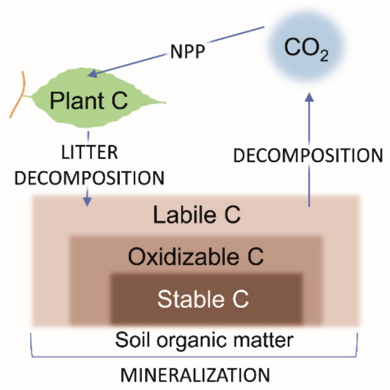

Figure 1. Diagram of a carbon cycle and SOC fractions. The oxidation resistance of SOC fractions increases from the periphery toward the center of the rectangle. NPP—net primary production.

Fractionation into labile and stable fractions of organic matter is based on different methods and may include physical separation of SOC according to particle size, density, aggregate, magnetic susceptibility, and also chemical treatment. The latter separates different SOC fractions on the basis of resistance to oxidation or by the destruction of the mineral phase, solubility, and hydrolysability [19,20]. The boundary between labile and stable SOM in many studies is given by the resistance to oxidation [21] using $K_2Cr_2O_7$ as an oxidizing agent [22,23].

The largest stock of C_L occurs in forest landscapes [24] due to active litter decomposition by the soil (micro) biota [25,26]. Since some soils in the boreal forest belt experience the most active carbon loss under rising air temperatures [27], many authors are focused on the study of the distribution and quality of soil organic carbon by forest type. In boreal forests, the total amount of SOM and the characteristics of the forest litter layer depend on the stand age [26,28]. Litter material constituents, the physical and chemical environment, and the decay entities define the organic matter conversion [29]. It is well known that in the temperate zone, moisture is an important factor that regulates the accumulation of organic carbon in the soil [30]. Wet soils in the boreal forest belt (Histosols, Stagnosols) usually have the most organic matter of all soils because the decomposition rate of fresh organic debris is inhibited by anaerobic conditions. Some studies have also confirmed the importance of soil moisture content in the fractional composition of SOM and indicated that in wetter soil, the proportion of more reactive fulvic acids increases [30]. In our study, we assume that in a soil catena limited to a single lithology, the local conditions associated with the moisture gradient have a large impact on the stocks and fractional composition of SOC both in organic (detrital) and in mineral soil horizons. The aim of our study was to assess the changes in SOC quantity and its fractional composition along a forested catena by studying stable and oxidizable fractions of organic carbon in the organic and mineral horizons of four soils, from the well-drained summit and middle slope landscapes to the poorly drained waterlogged footslope landscape. The following tasks were completed: (i) comparison of organic horizons in terms of the ash content, stocks of organic material, and quantification of the degree of litter decomposition; (ii) determination of C_L, C_O, and C_S in the organic and mineral horizons and evaluation of vertical and spatial patterns in the fractional composition of SOC; (iii) evaluation of the natural conditions affecting the vertical distribution of the SOC fractions. For the study, we chose a catena in a biosphere reserve, where plant communities represent reference vegetation typical of the southern taiga.

Studies of the spatial and vertical distribution of labile and stable fractions of SOC are mainly confined to agricultural landscapes [31,32]. Changes in the fractional composition of SOC have also been studied under conditions of landscape changes from natural ecosystems to agro-ecosystems or urban ecosystems, and from agro-ecosystems to forests, e.g., in [33–35]. Information about the spatial and vertical distribution of the labile and stable fractions of SOC in natural forest landscapes under changing conditions of soil moisture, soil type, and vegetation cover is rare. We assume that in the southern taiga landscapes, the content of the C_L fraction of SOC will increase from the summit to the slope positions. The maximum content of C_L will be observed in a waterlogged footslope position, due to the conservation of undecomposed plant residues.

2. Materials and Methods

2.1. Site Description

The field study was carried out at the Central Forest Natural Biosphere Reserve (Figure 2). The study area is situated in the southwestern part of the Valdai Hills (Tver region, Russia), which represents slightly sloping upland terrain with altitudes varying between 263 and 265 m a.s.l. The most common parent material is loess-like loam underlain at a depth of 90–190 cm by the calcareous glacial till of the Würm (MIS 2) glaciation [36]. This area is characterized by a temperate continental climate. The mean annual temperature is +3.6 °C and the mean annual precipitation is 714 mm. Representative natural mixed (spruce and deciduous) and spruce forests occupy 47% and 17% of the reserve territory, respectively [37]. The common soils of the study site are Retisols, according to the IUSS Working Group WRB [38]. However, due to high moisture, relatively flat relief, and specific lithology, the soil pattern is complex and includes large areas of boggy soils i.e., Histosols.

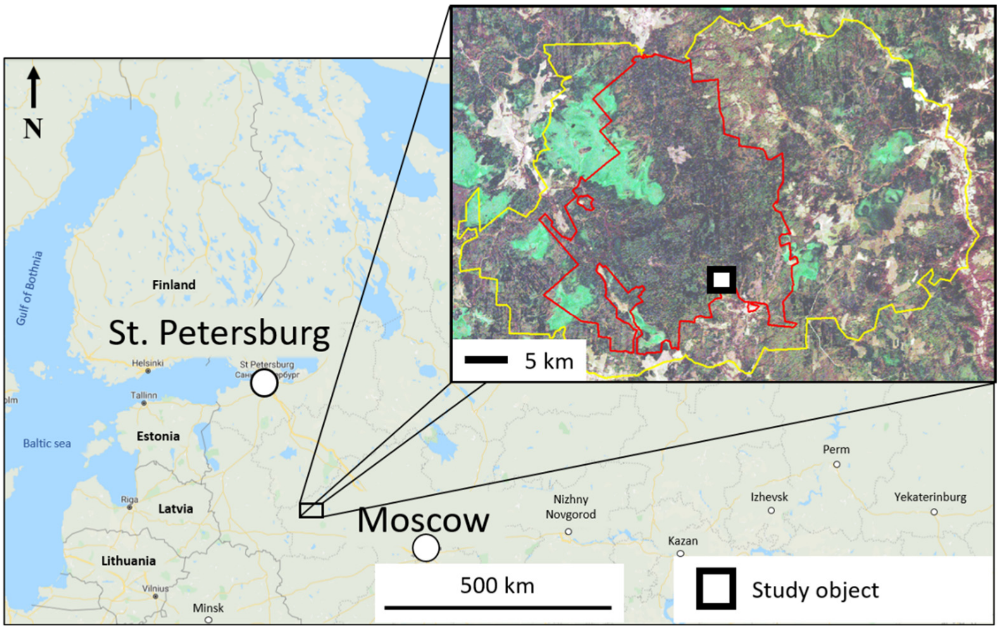

Figure 2. Location and a satellite image of the Central Forest Natural Biosphere Reserve (the yellow line indicates the boundaries of the protected area of the reserve and the red line shows its core area).

The chosen catena had a length of 190 m and was located in the southern part of the reserve. It occupied a southeast-facing gentle slope (<2°) of the interfluve area (Figure 3, Table 1). The studied segments of the catena included 4 sites: the relatively well-drained summit and upper slope with the mixed spruce and deciduous forest (sites 1 and 2), and two poorly drained sites (3 and 4) at the footslope with slightly different spruce forest communities [39].

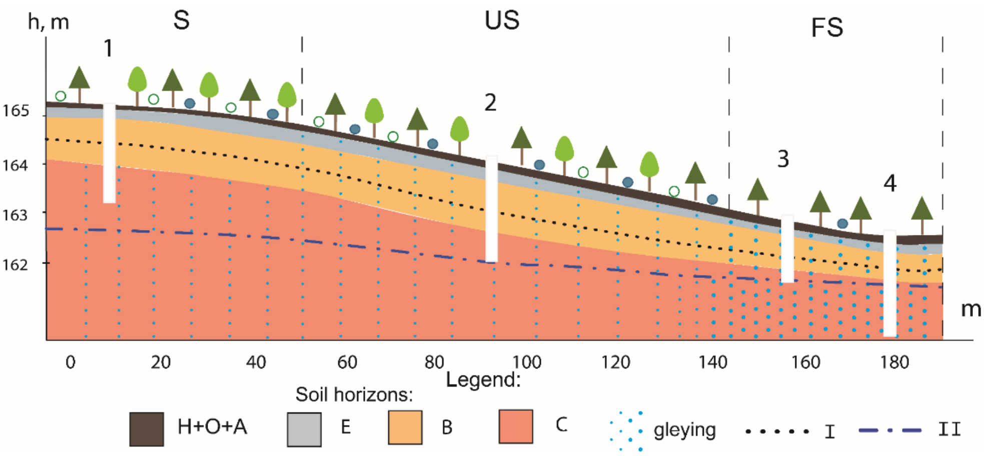

Figure 3. Schematic representation of the studied soil catena. Positions (henceforth in the figures and tables): S—summit (interfluve); US—middle slope; FS—footslope. Site 1–4 soils: 1, 2—Endocalcaric Albic Neocambic Stagnic Glossic Retisols (Geoabruptic, Chromic, Loamic); 3, 4—Endocalcaric Glossic Albic Gleyic Histic Stagnosols (Geoabruptic, Loamic). Soil horizons and materials: H—histic; O—folic and forest litter; A—umbric; E—albic; B—argic; and C—parent material. I—a boundary between loess-like loams and underlying carbonate moraine sediments. II—a groundwater level.

Table 1. Soils and plant communities along the studied catena.

Soils (WRB)		**Location * and GPS Coordinates**	**Plants**		
Name	**Horizons (ns)**		**Trees**	**Shrubs**	**Herbs and Mosses**
Endocalcaric Albic Neocambic Stagnic Glossic Retisols (Geoabruptic, Chromic, Loamic)	Oi–Oe–Oa–OAh–Ah–E–Bt/E–2Bwk–2BClk (ns = 21)	S 56°27′48.7″ N 32°57′45″ E	*Picea abies*, *Tilia cordata*, *Acer platanoides*, *Ulmus glabra*	*Corylus avellana*	*Stellaria holostea*, *Anemone nemorosa*, *Lamium galeobdolon*, *Oxalis acetosella*, *Pteridium aquilinum*, *Aegopodium podagraria*
	Oi–Oe–Oa–OAh–Ah–AhE–Escl–Bt/E–2Bwsc–2CBwsc (ns = 23)	US 56°27′47.5″ N 32°56′15.4″ E	*Picea abies*, *Tilia cordata*, *Acer platanoides*	*Corylus avellana*, *Sorbus aucuparia*, *Lonicera xylosteum*	*Hepatica nobilis*, *Galium odoratum*, *Pteridium aquilinum*, *Lamium galeobdolon*, *Asarum europaeum*, *Equisetum sylvaticum*, *Pulmonaria obscúra*, *Anemone nemorosa*, *Stellaria holostea*, *Oxalis acetosella*
Endocalcaric Glossic Albic Gleyic Histic Stagnosols (Geoabruptic, Loamic)	Oi–Oe–Ha–AhEl–Eosc–Btg (ns = 6)	FS1 56°27′47.1″ N 32°56′19.8″ E	*Picea abies*, *Tilia cordata*, *Acer platanoides*	*Sorbus aucuparia*	*Vaccinium myrtillus*
	Oi–Oe–Ha–AhE–Eg–Bt/Eg–Bg–2BC-2Crk (ns = 11)	FS2 56°27′48.0″ N 32°56′21.1″ E	*Picea abies*, *Tilia cordata*, *Acer platanoides*, *Salix caprea*	*Sorbus aucuparia*	*Pteridium aquilinum*, *Oxalis acetosella*, *Vaccinium myrtillus* *Sphagnum*

* S—summit, US—upper slope, FS—footslope; ns—the number of samples.

The degree of soil wetness increased downslope, toward the footslope position. The moisture gradient was accompanied by the change in the vegetation pattern and the composition of plant residues accumulating on the soil surface, the appearance of organic (O) and A horizons, and soil characteristics (Table 1).

Climatic (rainfall) and geological–geomorphological factors affect drainage. The territory of the reserve is characterized by the low permeability of the moraine sediments [36], waterlogged conditions, and a temporary watercourse after heavy rains at the lower footslope position (soil profile 4). At the summit and upper slope positions with more favorable conditions for the decomposition and transformation of organic residues, the soils had "moder" type topsoil [40]. At the upper segment of the footslope (soil profile no. 3), the topsoil was represented by a mor-like moder formed due to soil waterlogging after a snowmelt period in spring and heavy rains in summer.

2.2. Sampling

The soils of the catena were described according to the FAO guidelines and identified using the World Reference Base [38]. Soil samples were taken in September 2016 from each of the four sites from all soil genetic horizons (Table 1). During the sampling campaign, 25 samples of soil mineral horizons were collected. In September 2016, before leaf fall, we sampled the forest litter layer (O horizons) represented by semi-decomposed (fermented) remains of leaves and needles and a slightly decomposed fraction of cones and thin tree branches. The forest litter layer in the upper part of the catena (site 1 and site 2), was collected from five 50 × 50 cm plots located in the closest vicinity of the soil pits. The O horizon, according to [41], was subdivided into the Oe horizon made of a semi-decomposed (fermented) organic material and the Oa horizon with highly decomposed organic matter. At the footslope positions, where wetter soils were developed, the samples of the organic horizons were collected from five plots (20 × 20 cm) near each soil peat. The organic horizons at these positions were represented by the Oe and Ha horizons. At the beginning of November 2016, the Oi layer was collected to define the mass and stock of freshly fallen leaves on the soil surface. During the sampling campaign, 30 samples of the forest litter layer and organic horizons were taken from the upper part of the catena and six samples were collected from footslope positions of the catena.

2.3. Laboratory Analysis and Data Treatment

All samples were dried at 40 °C. The samples of the forest litter layer were then weighed to determine the reserves of detrital mass (Table A1).

During the laboratory studies of all samples (organic and mineral), pH values were measured in the soil:water suspension (1:2.5) at static conditions using a pH meter ("Expert–pH", Saint Petersburg, Russia). In 29 samples from the mineral horizons, the content of total organic carbon was analyzed using a $K_2Cr_2O_7$ wet-combustion method [22]. Organic carbon stocks were calculated using the data on the carbon content, the thickness of the studied horizons, and their bulk density determined on the basis of the volumetric cylinder method. (Table A1).

In 17 samples from Ah, Ha, and E horizons at each of the 4 sites, three SOC fractions (C_L, C_O, and C_S) were determined in five replicates (255 measurements in total). The labile and stable SOC fractions were determined using solutions of 0.8 M $K_2Cr_2O_7$ with different oxidative capacities depending on the concentration of H_2SO_4, as described in detail by Popov and Rusakov [22]. The C_L, C_O, and C_S were oxidized using solutions with low (30% H_2SO_4), middle (60% H_2SO_4), and high oxidizing capacity (concentrated H_2SO_4), respectively. The volume of oxidized organic matter was determined by titration with $Fe(NH_4)_2(SO_4)_2$ solution on a Biotrate digital burette (Helsinki, Finland). All used reagents were manufactured by Chimmed Group (Moscow, Russia).

The ash content (%) and SOM content in 36 samples of organic horizons (litter layer samples and histic horizons) were also measured. For the determination of these parameters, the conventional loss-on-ignition method using a muffle furnace (heating at 250 °C for 3 h and gradually heating up to 500 °C for 3 h) was used. Evaluation of litter decay was based on the calculation of the coefficient k which was the ratio of the mass of freshly fallen leaves accumulated in the Oi horizon to the detrital mass in the Oa + Oe horizons [42].

SOC stocks were calculated for the mineral A horizons and for the deeper strata, which included the E, B, and C horizons (up to 150 cm depth) (Table A1). Student's *t*-test was used to compare the means of two subsets separated on the basis of soil drainage conditions. The first subset included the soil data for the summit and middle slope, where relatively well-aerated soils (Retisols) were developed, and the second subset represented the data on the wetter soils (Stagnosols) at the footslope positions. The differences between Retisols and Stagnosols were significant with a p-value < 0.05. The strength of the association between the amount of SOC and organic carbon fractions was determined by Spearman's correlation analysis. All statistical analyses, including the calculation of mean and standard deviation (STD), were performed using the Statistica package.

3. Results

The forest litter layers accumulated on the soil surface in the summit and middle slope positions have higher ash content than the organic Oa and Ha horizons in the downslope positions (Figure 4A).

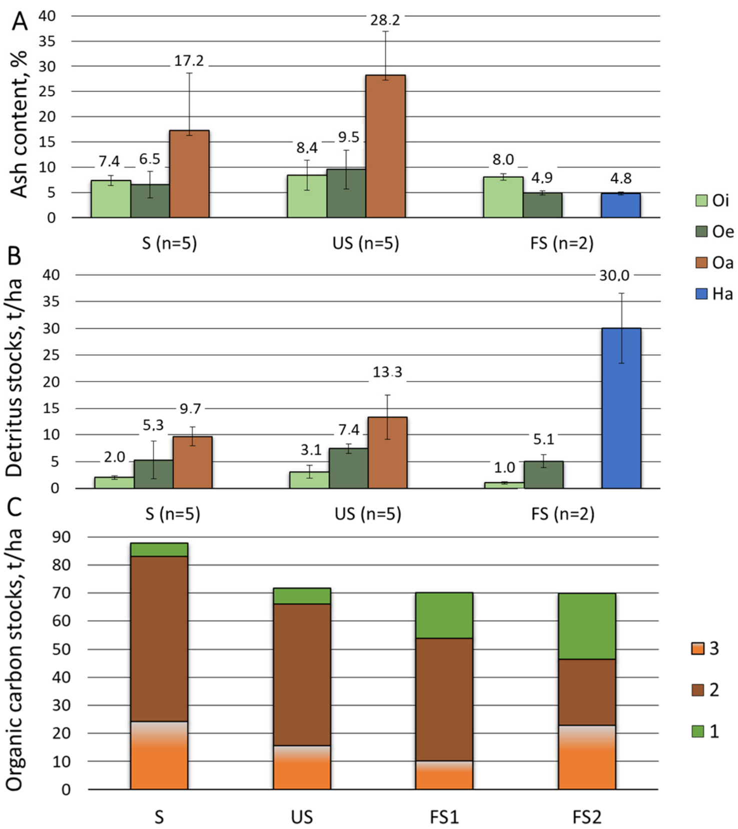

Figure 4. (**A**) Ash content in the forest litter layer, n—32; whiskers—confidence interval, 5%. (**B**) Litter stocks in the forest litter layer. (**C**) SOC stocks: 1—H and O horizons; 2—A horizon; 3—subsoil stratum (E, B, and C horizons) to the depth of 150 cm.

Detritus stocks correlated with the soil position within the catena (Figure 4B). The largest amount of plant residues was stored in the Ha horizon of Stagnosols, at the footslope position (30 t/ha), and the smallest amount was accumulated in the Oa horizon of Retisols at the summit position (9.7 t/ha). The difference between the two groups of soils (Retisols and Stagnosols) in terms of detritus stocks was statistically significant ($p < 0.001$).

The amount of carbon stored in the Ha and Oa horizons showed the same pattern: the organic carbon stock increased down the catena (Figure 4C). The amount of carbon stored in the Ha horizon (24 t/ha) of the waterlogged soils was nearly five times as high as in the Oa horizon of the well-drained soils (5 t/ha). However, in the A horizons, organic carbon stocks were generally higher than in the organic horizons and showed a different trend: the amount of organic carbon decreased down the slope from 59 to 24 t/ha. In the subsoil (the strata incorporating E, B, and C horizons), the smallest total organic carbon stock (10 t/ha) was found in the Retisols of the upper footslope position, while the highest organic carbon stock (24 t/ha) occurred in the Retisols of the summit position.

Litter decomposition (k, evaluated as fresh litter to detrital mass ratio) was relatively low, but at the well-drained sites with Retisols (k = 0.14), it was nearly five times as high as at the lowest catenary positions with Stagnosols (k = 0.03).

Labile organic carbon C_L exhibited the highest concentrations in the superficial Oa and Ha horizons (Figure 5). The calculation of the carbon lability index (Table 2), which is the ratio of labile to non-labile carbon, showed that this fraction predominated in all organic horizons. They contained 2.0–3.7 times as much C_L as C_O and C_S (Table 2). The Co fraction was not sensitive to the position within the catena: it was distributed rather evenly in the O horizon (henceforth in the text: mean ± SD = 50 ± 26 mg/g). The low variability range in the O horizon had C_S (Cv = 22%) and C_L (20%). In the A horizons, C_S (96%), C_O (88%), and C_L (82%) had significantly larger variability compared to the forest litter horizons.

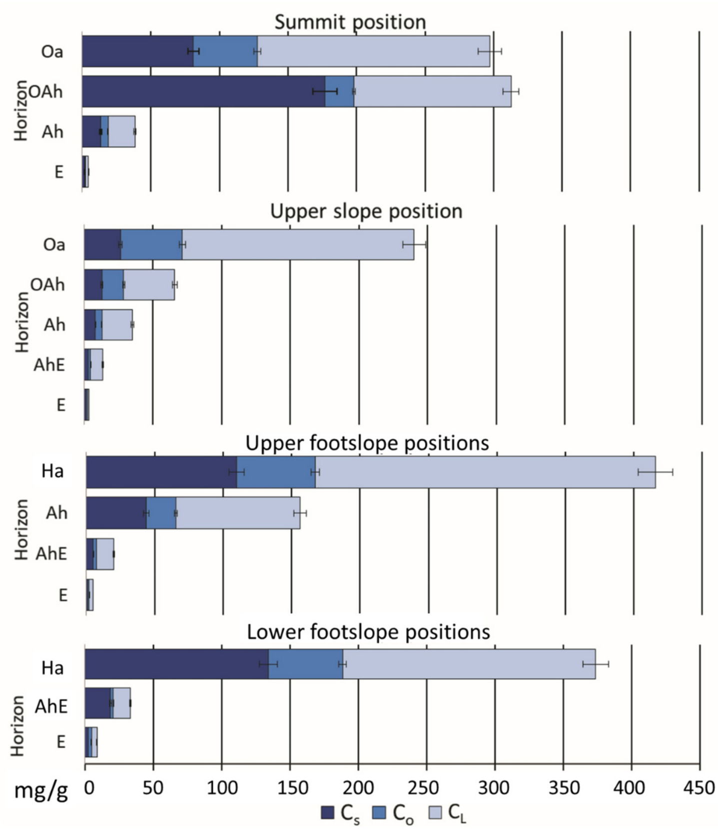

Figure 5. Organic carbon fractions in the soil horizons: C_L—labile; C_O—oxidizable; C_S—stable.

The Oa horizon of Stagnosols at the footslope position had relatively high C_L concentrations (217 mg/g) compared to the similar horizons in the well-drained Retisoils of the upper parts of the catena (185 mg/g). However, the difference between the two groups of soils (Retisols and Stagnosols) in terms of the C_L concentrations in the O horizons was insignificant ($p = 0.07$, Figure 6).

In the A horizons, the highest C_L concentrations were registered in Stagnosols (138 mg/g). The difference between the two groups of soils (Retisols and Stagnosols) in terms of the C_S, C_O, and C_L concentrations in the Ah horizons was significant ($p < 0.00002$, Figure 6).

Table 2. Carbon lability indexes calculated for the soils of the catena.

Location	Horizon (ns/nm)	Lability Indexes	
		C_L/C_S	$C_L/(C_S + C_O)$
Summit and upper slope	Oa (2/10)	3.7 ± 2.4	2.0 ± 1.2
	OAh (2/10)	2.1 ± 2.1	1.1 ± 0.8
	Ah (2/10)	5.9 ± 6.0	2.3 ± 1.7
	AhE (1/5)	8.3 ± 9.0	2.1 ± 0.5
	E (2/10)	1.5 ± 1.2	0.8 ± 0.5
Footslope	Ha (1/5)	2.4 ± 0.6	1.5 ± 0.3
	Ah (2/10)	1.8 ± 0.7	1.2 ± 0.5
	AhEtoscl (2/10)	2.2 ± 2.6	1.3 ± 1.5
	Et (3/15)	2.0 ± 1.6	0.9 ± 0.5

(ns)—the number of samples; (nm)—the number of measurements. SOC fractions: C_L—labile; C_O—oxidizable; C_S—stable.

Compared to the E horizons of the Retisols in the upper catenary positions, Stagnsols also displayed the highest C_L (3 mg/g) and C_O (4 mg/g) concentrations. The difference between the two groups of soils (Retisols and Stagnosols) in terms of the C_L and C_O concentrations was significant (p = 0.03 and 0.01, Figure 6). The Cs fraction did not show any significant differentiation (p = 0.06, Figure 6) along the catena.

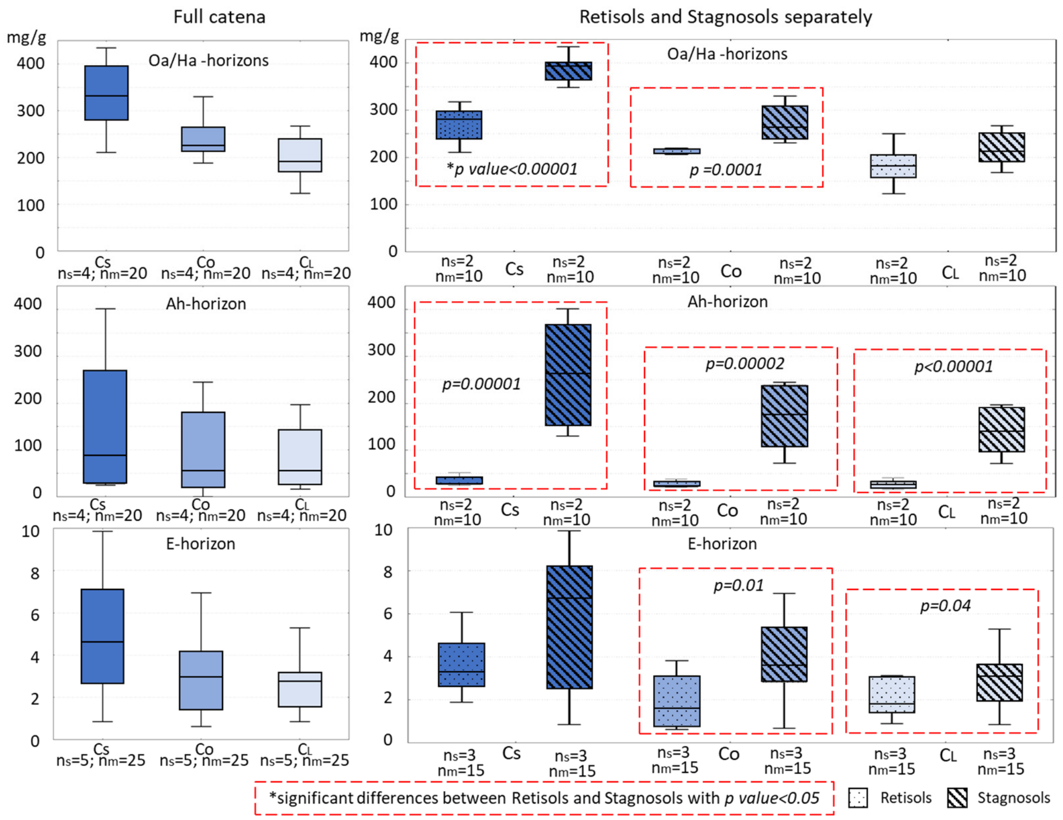

Figure 6. Concentrations of soil carbon fractions in soil horizons in the studied catena: ns—the number of samples; nm—the number of measurements. SOC fractions: C_L—labile; C_O—oxidizable; C_S—stable.

4. Discussions

The difference in the ash content registered in the organic horizons along the catena is derived from the forest litter layer origin and composition and can be explained by the predominant accumulation of deciduous plant residues on the soil surface at the summit and upper slope position, and the input of low-ash coniferous plant residues at the footslope. As our previous studies revealed [43], the foliage of the dominating deciduous tree species (*Tilia cordata* and *Acer platanoides)* is richer in mineral components (the average ash contents are 6.9% and 5.2%, respectively) than the foliage of the predominant coniferous species (*Picea abies*) containing fewer mineral compounds (the ash content is 3.7%). Similar differences in the ash content between the aboveground tissues of deciduous and coniferous plant species were reported in Ghana [44].

Forest litter decomposition is essential for carbon cycling in forest and waterlogged ecosystems [45,46] and is closely related not only to its composition but also to microbial activities and soil characteristics, including texture, pH, cation exchange capacity, the content of organic matter, and nutrients [29,47]. Within the studied catena, the decomposition ratio varied greatly and showed a statistically significant difference between the two groups of soils ($p = 0.0008$). The soils at the footslope had a much lower degree of forest litter decomposition compared to the soil at the summit and upper slope positions. The lower values of the coefficient k (more than five times) evaluating forest litter decomposition can be related to the increasing soil moisture in the waterlogged soils, which controls the characteristics of microorganism populations [48]. The litter type also plays a significant role. At the footslope positions, litter material was composed mainly of coniferous residues and mosses (sphagnum). The coniferous needle litter is characterized by less microbial activity compared to the deciduous leaf litter [49,50]. Branches, stems, and tree cones generally decompose slower than leaves [51], contributing to detrital litter mass accumulation [52]. The presence of boreal mosses such as sphagnum in the plant communities is another important factor contributing to the accumulation of organic material on the soil surfaces. Boreal mosses are frequently observed to degrade slowly compared to vascular plants due to their specific chemical composition and cellular structure [53]. According to Bazilevich and Titljanova [42], mosses contain up to 25% of cellulose and 15–20% of tannins and flavonoids. In the humid climate of the Central Forest Natural Reserve, the low litter decomposition at the waterlogged footslope leads to the accumulation of large SOC reserves [54]. Variations in the litter stocks and SOC content within the catena may result from water redistribution processes [55–60].

In the forest litter layer of the studied southern taiga catena, the concentrations of labile organic carbon fraction C_L (540–700 mg/g) were higher than in the soils of the Šumava forest in the Czech Republic (350–440 mg/g). However, the C_L contents in the moder-type humus horizons (220–250 mg/g) were much lower [12]. High concentrations of C_L in the O horizons indicate its input with plant residues and active participation in a soil–plant interaction. The fraction C_L, containing bioavailable and easily decomposable organic compounds, is subject to a faster turnover [61]. Accordingly, chemical elements bonded to the organic matter in the studied soils are mobile and available for plants [43].

The lability index of organic carbon is in accordance with the change in the hydrological conditions in the soil [62]. The Oa horizons at the footslope positions of the catena had lower lability indexes, indicating that organic carbon was more stable than in other positions. The concentration of C_S in the studied Oa horizon was lower than the concentrations of C_L and C_O. It corresponds to the soil data [12] on the Šumava forest (120–220 mg/g). The content of C_S in the waterlogged footslope positions increased along with the SOC content because of the low litter decomposition [63].

In the AhE horizon, the high concentration of C_L also confirms the data obtained by Bazilevich and Titljanova [42] on specific decaying mosses and may be a sign of SOC conservation as well as of more durable accumulation of mineral compounds involved in biogeochemical cycles in this horizon.

In the E horizon, larger concentrations of C_S appear as far as these are signs of SOC influence on the physical and chemical properties of the mineral soil horizons. Persistent organic compounds linger in the soil for long periods and can bind to minerals [64].

5. Conclusions

The study evaluated the role of different soils and soil horizons in organic carbon storage. In all studied soils, regardless of their positions within the catena, the contents of SOC and its labile and stable fractions showed vertical variation with depth, with higher contents in the surface detrital horizons and a significant decrease toward the E horizons, within 20–25 cm. The contribution of the labile fraction to SOC content showed the same pattern: it was larger in the organic and humus horizons and significantly lower in the eluvial E horizons, where the stable fraction makes up 40% of the organic carbon pools.

The study also revealed that changes in forest type and soil moisture regime along the catena have a significant influence on the features of the detrital horizons and organic carbon stocks. Due to unfavorable conditions for plant residue decay, the histic horizon of Stagnosols formed at the footslope positions stores the highest amount of organic carbon compared to the detrital litter horizons. The input of higher quality litter to Retisols occupying the uppermost well-drained positions is accompanied by better decay of plant residues and the formation of humus horizons with higher storage of organic carbon compared to both the organic and mineral horizons in Stagnosols.

The results of the present study can contribute to a better understanding and the filling of the gaps in the field of the spatial and vertical distribution of SOC fractions in the soils of natural forest landscapes. The results obtained can be used as a background to monitor the transformation of SOC properties and SOC storage that occurs under various types of anthropogenic impact and might be useful for developing soil management strategies in the forest zone.

Author Contributions: P.E.: formal analysis, investigation, field and laboratory work, data curation, writing—original draft preparation, visualization; E.A.: conceptualization, investigation, fieldwork, writing—original draft preparation, writing—review and editing; I.S.: investigation, fieldwork, resources, writing—review and editing. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. Properties of soil horizons in the studied catena.

Position	Horizon	Depth, cm	pH	Ash Content, %	Bulk Density, g/cm^3	SOC Stocks, t/ha	Detritus Stocks, t/ha	C_L, mg/g					C_O, mg/g					C_S, mg/g				
Summit	Oi	surface	-	7.4 *	-	-	2.0 *	-														
	Oe	surface	-	6.5 *	-	-	5.3 *															
	Oa	surface	5.1	17.3 *	0.1	4.8	9.7 *	192	123	185	184	165	26	97	32	34	44	67	79	78	100	81
	OAh	2–6	4.6	-	1.3	58.7	-	110	121	125	113	105	12	17	9	22	45	189	172	193	165	166
	Ah	11–20	4.4	-	1.4	47.9	-	16	25	21	24	11	7.0	1.5	0.6	8.3	10	29	2.3	7.0	3.0	26
	E	20–30	4.9	-	1.4	8.8	-	1.8	3.1	3.1	1.4	1.0	1.1	0.7	0.6	1.7	0.0	4.1	2.2	0.9	0.4	1.0
	Bt/E	45–55	5.2	-	1.6	5.7	-	-														
	2B	70–90	5.6	-	1.7	5.9	-															
	2BC	110–130	7.2	-	1.7	3.3	-															
Upper slope	Oi	surface	-	8.3 *	-		3.1 *	-														
	Oe	surface	-	9.5 *	-		7.4 *															
	Oa	surface	4.7	28.2 *	0.1	5.8	13.3 *	153	161	200	210	120	62	44	20	9	90	25	40	21	61	40
	OAh	2,5–4	4.6	-	0.3	15.3	-	50	40	30	46	20	5,4	10	24	11	30	12	10	4	19	30
	Ah	5–10	4.3	-	0.6	15.3	-	29	20	19	19	25	10	2.6	4.0	2.1	5.0	1.4	3.3	3.5	22	10
	AhE	12–18	4.4	-	1.2	19.9	-	9.0	8.4	8.6	10	7.0	2.9	2.0	1.7	0.6	2.0	0.3	2.4	2.3	7.5	1.0
	E	30–40	4.9	-	1.6	12.5	-	1.0	1.0	1.0	1.5	1.0	1.0	1.0	1.0	0.5	1.0	1.2	2.0	0.7	0.9	2.0
	Bt/E	52–62	4.9	-	1.6	1.1	-	-														
	Bt/Eg	75–85	5.8	-	1.6	0.2	-															
	2B	104–114	6.5	-	1.8	0	-															
	2BC	140–150	6.9	-	1.8	1.8	-															

Table A1. *Cont.*

Position	Horizon	Depth, cm	pH	Ash Content, %	Bulk Density, g/cm^3	SOC Stocks, t/ha	Detritus Stocks, t/ha	C_L, mg/g					C_O, mg/g					C_S, mg/g				
Upper footslope	Oi	surface	-	8.5	-		1.2								-							
	Oe	surface	4.0	5.2	0.0	16.2	7.0	267	240	262	224	250	39	78	29	61	80	89	117	167	97	80
	Ha	9–14	4.0	5.0	0.5	40.0	35.3	110	71	96	97	80	10	35	18	25	20	33	32	69	53	30
	AhE	17–20	4.7		1.3	3.8		11	13	14	14	12	2.1	2.3	2.7	3.0	2.0	7.9	5.8	5.7	1.4	4.0
	Eg	25–35	6.2	-	1.6	2.4	-	2.3	3.1	3.2	3.2	2.0	0.5	1.1	1.2	2.2	1.0	1.2	0.8	0.6	0.6	1.0
	Btg	48–58	6.6		1.6	7.8									-							
Lower footslope	Oi	surface		7.5			0.9															
	Oe	surface	-	2.1	-	-	5.1								-							
	Sphagnum	surface		4.1			4.4															
	Ha	0–8	4.0	4.6	0.1	23.7	24.8	195	197	176	168	190	50	43	55	69	55	156	152	135	111	115
	AhE	8–12	4.4		1.4	23.5		12	11	10	20	10	0.8	2.5	2.6	4.0	0.0	21	23	23	16	10
	Eg	17–23	4.9		1.6	14.6		5.3	5.3	3.7	2.8	3.0	0.7	1.7	2.6	4.1	2.0	3.8	2.9	2.8	1.3	3.0
	Eg	28–35	5.4		1.6	2.7		0.9	2.0	3.2	3.9	1.0	0.0	1.0	0.8	1.1	1.0	5.9	4.5	4.2	1.3	4.0
	Bt/Eg	39–45	5.5	-	1.6	0.3	-															
	Bg	60–70	6.0		1.6	2.3																
	2BC	80–90	5.7		1.7	2.9									-							
	2C	110–120	6.1		1.8	1.4																

* Average of five measurements.

References

1. Duddigan, S.; Shaw, L.J.; Alexander, P.D.; Collins, C.D. A Comparison of Physical Soil Organic Matter Fractionation Methods for Amended Soils. *Appl. Environ. Soil Sci.* **2019**, *2019*, 3831241. [CrossRef]
2. Wambsganss, J.; Stutz, K.P.; Lang, F. European beech deadwood can increase soil organic carbon sequestration in forest topsoils. *For. Ecol. Manag.* **2017**, *405*, 200–209. [CrossRef]
3. Pham, T.G.; Nguyen, H.T.; Kappas, M. Assessment of soil quality indicators under different agricultural land uses and topographic aspects in Central Vietnam. *Int. Soil Water Conserv. Res.* **2018**, *6*, 280–288. [CrossRef]
4. Muñoz-Rojas, M. Soil quality indicators: Critical tools in ecosystem restoration. *Curr. Opin. Environ. Sci. Health* **2018**, *5*, 47–52. [CrossRef]
5. Valle, S.R.; Carrasco, J. Soil quality indicator selection in Chilean volcanic soils formed under temperate and humid conditions. *Catena* **2018**, *162*, 386–395. [CrossRef]
6. Bünemann, E.K.; Bongiorno, G.; Bai, Z.; Creamer, R.E.; De Deyn, G.; de Goede, R.; Fleskens, L.; Geissen, V.; Kuyper, T.W.; Mäder, P.; et al. Soil Quality—A Critical Review. *Soil Biol. Biochem.* **2018**, *120*, 105–125. [CrossRef]
7. De, P.; Deb, S.; Deb, D.; Chakraborty, S.; Santra, P.; Dutta, P.; Hoque, A.; Choudhury, A. Soil quality under different land uses in eastern India: Evaluation by using soil indicators and quality index. *PLoS ONE* **2022**, *17*, e0275062. [CrossRef]
8. Zamulina, I.V.; Gorovtsov, A.V.; Minkina, T.M.; Mandzhieva, S.S.; Bauer, T.V.; Burachevskaya, M.V. The influence of long-term Zn and Cu contamination in Spolic Technosols on water-soluble organic matter and soil biological activity. *Ecotoxicol. Environ. Saf.* **2021**, *208*, 111471. [CrossRef]
9. Kebonye, N.M.; Eze, P.N.; Ahado, S.K.; John, K. Structural equation modeling of the interactions between trace elements and soil organic matter in semiarid soils. *Int. J. Environ. Sci. Technol.* **2020**, *17*, 2205–2214. [CrossRef]
10. Gangloff, S.; Stille, P.; Pierret, M.-C.; Weber, T.; Chabaux, F. Characterization and evolution of dissolved organic matter in acidic forest soil and its impact on the mobility of major and trace elements (case of the Strengbach watershed). *Geochim. Cosmochim. Acta* **2014**, *130*, 21–41. [CrossRef]
11. Basta, N.T.; Ryan, J.A.; Chaney, R.L. Trace Element Chemistry in Residual-Treated Soil: Key Concepts and Metal Bioavailability. *J. Environ. Qual.* **2005**, *34*, 49–63. [CrossRef]
12. Kolář, L.; Kužel, S.; Horáček, J.; Čechová, V.; Borová-Batt, J.; Peterka, J. Labile fractions of soil organic matter, their quantity and quality. *Plant Soil Environ.* **2009**, *55*, 245–251. [CrossRef]
13. Bongiorno, G.; Bünemann, E.K.; Oguejiofor, C.U.; Meier, J.; Gort, G.; Comans, R.; Mäder, P.; Brussaard, L.; de Goede, R. Sensitivity of labile carbon fractions to tillage and organic matter management and their potential as comprehensive soil quality indicators across pedoclimatic conditions in Europe. *Ecol. Indic.* **2021**, *99*, 38–50, Erratum in *Ecol. Indic.* **2021**, *121*, 107093. [CrossRef]
14. Cotrufo, M.F.; Wallenstein, M.D.; Boot, C.M.; Denef, K.; Paul, E. The Microbial Efficiency-Matrix Stabilization (MEMS) framework integrates plant litter decomposition with soil organic matter stabilization: Do labile plant inputs form stable soil organic matter? *Glob. Chang. Biol.* **2013**, *19*, 988–995. [CrossRef] [PubMed]
15. Błońska, E.; Lasota, J.; Gruba, P. Enzymatic activity and stabilization of organic matter in soil with different detritus inputs. *J. Soil Sci. Plant Nutr.* **2017**, *63*, 242–247.
16. Lasota, J.; Błońska, E.; Łyszczarz, S.; Tibbett, M. Forest Humus Type Governs Heavy Metal Accumulation in Specific Organic Matter Fractions. *Water Air Soil Pollut.* **2020**, *231*, 80. [CrossRef]
17. Jenkinson, D.S.; Adams, D.E.; Wild, A. Model estimates of CO_2 emissions from soil in response to global warming. *Nature* **1991**, *351*, 304–306. [CrossRef]
18. Sollins, P.; Homann, P.; Caldwell, B.A. Stabilization and destabilization of soil organic matter: Mechanisms and controls. *Geoderma* **1996**, *74*, 65–105. [CrossRef]
19. Mustafa, A.; Saeed, Q.; Karimi Nezhad, M.T.; Mohammad, T.; Nan, S.; Hongjun, G.; Ping, Z.; Naveed, M.; Minggang, X.; Nú nez-Delgado, A. Physically separated soil organic matter pools as indicators of carbon and nitrogen change under long-term fertilization in a Chinese Mollisol. *Environ. Res.* **2023**, *216*, 114626. [CrossRef]
20. Kholodov, V.A.; Farkhodov, Y.R.; Yaroslavtseva, N.V.; Ziganshina, A.R.; Maksimovich, S.V. Heterogeneity of Organic Matter of Aggregates of Protocalcic Chernozems. *Eurasian Soil Sci.* **2022**, *55*, 998–1004. [CrossRef]
21. Kopecký, M.; Kolář, L.; Perná, K.; Váchalová, R.; Mráz, P.; Konvalina, P.; Murindangabo, Y.T.; Ghorbani, M.; Menšík, L.; Dumbrovský, M. Fractionation of Soil Organic Matter into Labile and Stable Fractions. *Agronomy* **2021**, *12*, 73. [CrossRef]
22. Popov, A.I.; Rusakov, A.V. Chemodestructive fractionation of soil organic matter. *Eurasian Soil Sci.* **2016**, *49*, 606–612. [CrossRef]
23. Partyka, T.; Hamkalo, Z. Estimation of Oxidizing Ability of Organic Matter of Forest and Arable Soil. *Zemdirb.-Agric.* **2010**, *97*, 33–40.
24. Geraei, D.S.; Hojati, S.; Landi, A.; Cano, A.F. Total and labile forms of soil organic carbon as affected by land use change in southwestern Iran. *Geoderma Reg.* **2016**, *7*, 29–37. [CrossRef]
25. Feng, W.; Zou, X.; Schaefer, D. Above- and belowground carbon inputs affect seasonal variations of soil microbial biomass in a subtropical monsoon forest of southwest China. *Soil Biol. Biochem.* **2009**, *41*, 978–983. [CrossRef]
26. Kuznetsova, A.I.; Geraskina, A.P.; Lukina, N.V.; Smirnov, V.E.; Tikhonova, E.V.; Shevchenko, N.E.; Gornov, A.V.; Ruchinskaya, E.V.; Tebenkova, D.N. Linking Vegetation, Soil Carbon Stocks, and Earthworms in Upland Coniferous–Broadleaf Forests. *Forests* **2021**, *12*, 1179. [CrossRef]
27. Schlesinger, W.H.; Bernhardt, E. *Biogeochemistry: An Analysis of Global Change*; Academic Press: Cambridge, MA, USA, 2020; ISBN 9780128146088.

28. Shrestha, B.M.; Chen, H.Y.H. Effects of stand age, wildfire and clearcut harvesting on forest floor in boreal mixedwood forests. *Plant Soil* **2010**, *336*, 267–277. [CrossRef]
29. Krishna, M.P.; Mohan, M. Litter decomposition in forest ecosystems: A review. *Energy Ecol. Environ.* **2017**, *2*, 236–249. [CrossRef]
30. Błońska, E.; Lasota, J. Soil Organic Matter Accumulation and Carbon Fractions along a Moisture Gradient of Forest Soils. *Forests* **2017**, *8*, 448. [CrossRef]
31. Hu, W.; Shen, Q.; Zhai, X.; Du, S.; Zhang, X. Impact of environmental factors on the spatiotemporal variability of soil organic matter: A case study in a typical small Mollisol watershed of Northeast China. *J. Soils Sediments* **2021**, *21*, 736–747. [CrossRef]
32. Qin, Z.; Yang, X.; Song, Z.; Peng, B.; Van Zwieten, L.; Yu, C.; Wu, S.; Mohammad, M.; Wang, H. Vertical distributions of organic carbon fractions under paddy and forest soils derived from black shales: Implications for potential of long-term carbon storage. *Catena* **2021**, *198*, 105056. [CrossRef]
33. Pollakova, N.; Jonczak, J.; Szlováková, T.; Kolenčík, M. Soil organic matter quantity and quality of land transformed from arable to forest. *J. Cent. Eur. Agric.* **2016**, *17*, 661–674. [CrossRef]
34. Toenshoff, C.; Joergensen, R.G.; Stuelpnagel, R.; Wachendorf, C. Dynamics of soil organic carbon fractions one year after the re-conversion of poplar and willow plantations to arable use and perennial grassland. *Agric. Ecosyst. Environ.* **2013**, *174*, 21–27. [CrossRef]
35. De Lucia, B.; Cristiano, G.; Vecchietti, L.; Bruno, L. Effect of different rates of composted organic amendment on urban soil properties, growth and nutrient status of three Mediterranean native hedge species. *Urban For. Urban Green.* **2013**, *12*, 537–545. [CrossRef]
36. Puzachenko, Y.G.; Kozlov, D.N.; Siunova, E.V.; Sankovskii, A.G. Assessment of the reserves of organic matter in the world's soils: Methodology and results. *Eurasian Soil Sci.* **2006**, *39*, 1284–1296. [CrossRef]
37. Smirnova, O.V.; Zaugolnova, L.B.; Evstigneev, O.I.; Korotkov, V.N.; Khanina, L.G. *Succession Processes in the Reserves of Russia and the Problems of Conservation of Biological Diversity*; Smirnova, O.V., Shaposhnikov, E.S., Eds.; Rossijskoe Botanicheskoe Obshhestvo: Saint Petersburg, Russia, 1999; ISBN 5-86871-030-4.
38. IUSS Working Group WRB. *World Reference Base for Soil Resources. International Soil Classification System for Naming Soils and Creating Legends for Soil Maps*, 4th ed.; International Union of Soil Sciences: Vienna, Austria, 2022.
39. Schaetzl, R.J. 4.9 Catenas and Soils. In *Treatise on Geomorphology*; Elsevier: Amsterdam, The Netherlands, 2013; pp. 145–158; ISBN 978-0-08-088522-3.
40. Regmi, B.; Rengel, Z.; Shaberi-Khabaz, H. Fractionation and Distribution of Zinc in Soils of Biologically and Conventionally Managed Farming Systems, Western Australia. In Proceedings of the 19th World Congress of Soil Science, Soil Solutions for Changing the World, Brisbane, Australia, 1–6 August 2010; pp. 105–108.
41. Jabiol, B.; Zanella, A.; Ponge, J.-F.; Sartori, G.; Englisch, M.; van Delft, B.; de Waal, R.; Le Bayon, R.-C. A proposal for including humus forms in the World Reference Base for Soil Resources (WRB-FAO). *Geoderma* **2013**, *192*, 286–294. [CrossRef]
42. Bazilevich, N.I.; Titlyanova, A.A. *Biotic Turnover on Five Continents: Element Exchange Processes in Terrestrial Natural Ecosystems*; Tishkov, A.A., Ed.; Nauka: Novosibirsk, Russia, 2008; ISBN 978-5-7692-0941-3.
43. Enchilik, P.R.; Semenkov, I.N.; Aseeva, E.N.; Samonova, O.A.; Iovcheva, A.D.; Terskaya, E.V. Catenary Biogeochemical Differentiation in the Southern Taiga Landscapes (Central Forest Reserve, Tver Oblast). *Vestn. Mosk. Univ. Seriya 5 Geogr.* **2020**, *6*, 121–133.
44. Asare, M.O.; Afriyie, J.O.; Hejcman, M.; Krbová, M.J. Can Wood Ashes of Commonly Planted Tree Species in Ghana be Applied as Fertilizers? *Waste Biomass-Valorization* **2022**, *13*, 1043–1058. [CrossRef]
45. Chen, M.; Zhu, X.; Zhao, C.; Yu, P.; Abulaizi, M.; Jia, H. Rapid microbial community evolution in initial Carex litter decomposition stages in Bayinbuluk alpine wetland during the freeze–thaw period. *Ecol. Indic.* **2020**, *121*, 107180. [CrossRef]
46. Li, F.; Hu, J.; Xie, Y.; Yang, G.; Hu, C.; Chen, X.; Deng, Z. Foliar stoichiometry of carbon, nitrogen, and phosphorus in wetland sedge Carex brevicuspis along a small-scale elevation gradient. *Ecol. Indic.* **2018**, *92*, 322–329. [CrossRef]
47. Coleman, D.; Cole, E.; Elliott, C. Decomposition, Organic Matter Turnover and Nutrient Dynamics in Agroecosystems. In *Agricultural Ecosystems—Unifying Concepts*; Lowrance, R., Stinner, B.R., House, G.J., Eds.; Wiley-Interscience: New York, NY, USA, 1984; pp. 83–104.
48. Xu, C.; Yu, X.; Duan, H.; Li, J.; Xia, S.; Zhang, Q.; Li, C. The decomposition processes and return of carbon, nitrogen, and phosphorus of Phragmites australis litter with different detritus amount. *Hydrobiologia* **2022**, in press. [CrossRef]
49. Hansson, K.; Olsson, B.A.; Olsson, M.; Johansson, U.; Kleja, D.B. Differences in soil properties in adjacent stands of Scots pine, Norway spruce and silver birch in SW Sweden. *For. Ecol. Manag.* **2011**, *262*, 522–530. [CrossRef]
50. Vesterdal, L.; Clarke, N.; Sigurdsson, B.D.; Gundersen, P. Do tree species influence soil carbon stocks in temperate and boreal forests? *For. Ecol. Manag.* **2013**, *309*, 4–18. [CrossRef]
51. Hobbie, S.E.; Schimel, J.P.; Trumbore, S.E.; Randerson, J.R. Controls over carbon storage and turnover in high-latitude soils. *Glob. Chang. Biol.* **2000**, *6*, 196–210. [CrossRef] [PubMed]
52. Weintraub, M.; Schimel, J.P. Nitrogen Cycling and the Spread of Shrubs Control Changes in the Carbon Balance of Arctic Tundra Ecosystems. *Bioscience* **2005**, *55*, 408–415. [CrossRef]
53. Philben, M.; Butler, S.; Billings, S.A.; Benner, R.; Edwards, K.A.; Ziegler, S.E. Biochemical and structural controls on the decomposition dynamics of boreal upland forest moss tissues. *Biogeosciences* **2018**, *15*, 6731–6746. [CrossRef]

54. Peel, M.C.; Finlayson, B.L.; McMahon, T.A. Updated world map of the Köppen-Geiger climate classification. *Hydrol. Earth Syst. Sci.* **2007**, *11*, 1633–1644. [CrossRef]
55. Huang, W.; Xu, W.; Wang, S.; Yuan, Y.; Wang, C. Extraction of Knowledge about Soil-Environment Relationship Based on an Uncertainty Model. *Acta Pedol. Sin.* **2018**, *55*, 54–63. [CrossRef]
56. Wang, Z.; Liu, B.; Wang, X.; Gao, X.; Liu, G. Erosion effect on the productivity of black soil in Northeast China. *Sci. China Ser. D Earth Sci.* **2009**, *52*, 1005–1021. [CrossRef]
57. Błońska, E.; Lasota, J.; Piaszczyk, W.; Wiecheć, M.; Klamerus-Iwan, A. The effect of landslide on soil organic carbon stock and biochemical properties of soil. *J. Soils Sediments* **2018**, *18*, 2727–2737. [CrossRef]
58. Jandl, R.; Lindner, M.; Vesterdal, L.; Bauwens, B.; Baritz, R.; Hagedorn, F.; Johnson, D.W.; Minkkinen, K.; Byrne, K.A. How Strongly Can Forest Management Influence Soil Carbon Sequestration? *Geoderma* **2007**, *137*, 253–268. [CrossRef]
59. Stendahl, J.; Johansson, M.-B.; Eriksson, E.; Nilsson, Å.; Langvall, O. Soil organic carbon in Swedish spruce and pine forests—Differences in stock levels and regional patterns. *Silva Fenn.* **2010**, *44*, 5–21. [CrossRef]
60. Walz, J.; Knoblauch, C.; Böhme, L.; Pfeiffer, E.-M. Regulation of soil organic matter decomposition in permafrost-affected Siberian tundra soils—Impact of oxygen availability, freezing and thawing, temperature, and labile organic matter. *Soil Biol. Biochem.* **2017**, *110*, 34–43. [CrossRef]
61. Lorenz, M.; Hofmann, D.; Steffen, B.; Fischer, K.; Thiele-Bruhn, S. The molecular composition of extractable soil microbial compounds and their contribution to soil organic matter vary with soil depth and tree species. *Sci. Total. Environ.* **2021**, *781*, 146732. [CrossRef]
62. Prescott, C.E. Litter decomposition: What controls it and how can we alter it to sequester more carbon in forest soils? *Biogeochemistry* **2010**, *101*, 133–149. [CrossRef]
63. Xu, C.; Chen, Z.; Xia, S.; Zhao, W.; Zhang, Q.; Teng, J.; Yu, X. The initial mass of residue can regulate the impact of *Phragmites australis* decomposition on water quality: A case study of a mesocosm experiment in a wetland of North China. *J. Freshw. Ecol.* **2021**, *36*, 49–62. [CrossRef]
64. Lehmann, J.; Solomon, D.; Kinyangi, J.; Dathe, L.; Wirick, S.; Jacobsen, C. Spatial complexity of soil organic matter forms at nanometre scales. *Nat. Geosci.* **2008**, *1*, 238–242. [CrossRef]