soil systems

MDPI

Article

Influence of Soil Texture on Carbon Stocks in Deciduous and Coniferous Forest Biomass in the Forest-Steppe Zone of Oka–Don Plain

Sergey Sheshnitsan [1,*], Gennadiy Odnoralov [2], Elena Tikhonova [2], Nadezhda Gorbunova [1], Tatiana Sheshnitsan [1], Otilia Cristina Murariu [3] and Gianluca Caruso [4]

1 Laboratory of Forest Monitoring and Planning, Voronezh State University of Forestry and Technologies, Timiryazeva Str. 8, Voronezh 394087, Russia; vilian@list.ru (N.G.); tatianasheshnitsan@gmail.com (T.S.)
2 Faculty of Forestry, Voronezh State University of Forestry and Technologies, Timiryazeva Str. 8, Voronezh 394087, Russia; kafedra.laip@inbox.ru (G.O.); tichonova-9@mail.ru (E.T.)
3 Department of Food Technology, "Ion Ionescu de la Brad" Iasi University of Life Sciences, M. Sadoveanu Alley, 700440 Iasi, Romania; otilia.murariu@iuls.ro or otiliamurariu@uaiasi.ro
4 Department of Agricultural Sciences, University of Naples Federico II, 80055 Naples, Italy; gcaruso@unina.it
* Correspondence: sheshnitsan@gmail.com

Abstract: Forests play a crucial role in climate change mitigation by acting as a carbon sink. Understanding the influence of soil properties on carbon stocks in forests is essential for developing effective forest management strategies. The aim of the study was to assess the impact of soil texture on carbon stocks in the biomass of deciduous and coniferous tree stands of a forest-steppe ecotone. Soil samples were collected from 55 soil pits, and forest inventory data were obtained from eight permanent sample plots. The results showed that the distribution of mechanical particles in soils, particularly the stocks of silt and clay, significantly influenced the accumulation of carbon in tree stands. The stock of silt and clay was shown to increase with an increase in the diversity of tree species in forests and carbon stocks in forest stands. While soil organic carbon stocks did not exhibit a clear relationship with tree stand carbon stocks, a strong positive correlation ($r = 0.802$, $p < 0.05$) was found between the stocks of fine particles in the 2 m root-inhabited soil layer and the carbon stocks in tree biomass. The study provides a classification of forest types based on soil texture, which can facilitate differentiated forest management strategies for enhancing the carbon sequestration potential of forest ecosystems in the forest-steppe zone.

Keywords: forest type; tree stand; carbon stock; fine particles; SOC

check for updates

Citation: Sheshnitsan, S.; Odnoralov, G.; Tikhonova, E.; Gorbunova, N.; Sheshnitsan, T.; Murariu, O.C.; Caruso, G. Influence of Soil Texture on Carbon Stocks in Deciduous and Coniferous Forest Biomass in the Forest-Steppe Zone of Oka–Don Plain. *Soil Syst.* **2024**, *8*, 118. https://doi.org/10.3390/soilsystems8040118

Academic Editor: Luis Eduardo Akiyoshi Sanches Suzuki

Received: 31 July 2024
Revised: 10 November 2024
Accepted: 14 November 2024
Published: 17 November 2024

1. Introduction

Forests exert a fundamental influence on climate change mitigation. They act as an annual carbon sink, preventing the accumulation of carbon dioxide in the atmosphere at the global scale [1]. The carbon absorbed by plants is redistributed within the forest ecosystem and accumulated in plant biomass, dead organic matter, and soils. Therefore, the implementation of effective forest management and conservation strategies is essential for the enhancement of forest ecosystems as carbon sinks and the achievement of global climate goals [2–4].

Forest soils are of central importance to carbon storage in the forest ecosystem [5]. The direct and feedback relationships between forest vegetation and soils are essential for maintaining forest ecosystem functioning [6,7]. The influence of forest vegetation on soils is mediated by litterfall and root activity, which contribute to the accumulation of soil organic carbon (SOC) [8,9]. Consequently, soil properties, including soil texture, fertility and water-retention capacity, influence the growth and development of forest vegetation [10,11]. These interrelationships form a complex network that determines the productivity of forest ecosystems and their capacity to sequester carbon.

Soil texture is known to have a significant effect on the productivity of tree species, as it is a defining factor in the water regime, aeration, and nutrient availability [12,13]. In particular, it was shown that fine-textured soils with higher clay and silt content had a significant effect on the productivity of oak stands [14], and the dominance of species in a forest site can vary significantly depending on the soil texture [10].

A review of the current state of research reveals that the majority of studies have focused on individual aspects of soil–vegetation interactions, with little consideration given to the complex influence of soil texture on carbon stocks in forest stands. Furthermore, comparative studies of deciduous and coniferous forests with respect to soil texture remain relatively limited. This highlights the necessity for comprehensive studies that consider the diverse forest types and their interactions with soil properties. Thus, the study of this aspect is of particular importance in the forest-steppe zone, where climatic conditions can vary significantly, from wet to dry. This region is characterized by the dominance of drought-tolerant tree species, including oak, pine, and birch. However, the potential consequences of predicted climate change may result in shifts in vegetation composition, with a possible reduction in forest cover [15–17]. The combined effect of increases in the frequency and intensity of droughts and elevation of mean annual temperatures not only undermines soil health and productivity of forest ecosystems but also increases the vulnerability of the entire forest-steppe ecotone to further climatic stressors [18,19].

The forest-steppe zone of the Oka–Don Plain represents a distinctive ecotone, where deciduous and coniferous forests, characterized by different structural and dynamic patterns of the carbon cycle, occur in similar climatic conditions. Therefore, it is important to understand the impact of soil texture on carbon stocks in the biomass of different forest types in this region. The aim of the study was to identify patterns of influence of soil texture on carbon stocks in the biomass of deciduous and coniferous forests in the forest-steppe ecotone. The hypothesis of the study was that the distribution of mechanical particles in soils determines the differences between forest types and influences the accumulation of carbon in the tree stand.

2. Materials and Methods

2.1. Study Area

The study area is situated in the southern part of the Oka–Don plain within the typical forest-steppe zone of Russia. This study focuses on representative forests of the Voronezh region, including pine forests grown on the sands of the floodplain terraces on the watershed of the Voronezh and Usman rivers (42.2 km^2, including 21.3 km^2 of deforested lands), as well as broadleaved forests (Upland Oak Forest) developed on the highly dissected right bank of the Voronezh River (24.5 km^2) (Figure 1).

The climate is temperate continental, characterized by significant fluctuations in temperature and precipitation. The average annual air temperature is +7.6 °C. The average temperature in July and January is +21.3 °C and –6.0 °C, respectively. The average annual precipitation for the last 30 years is 586 mm, with the summer and autumn period contributing approximately 54.5% of the annual norm. From a geomorphological perspective, the study area is situated between two distinct watersheds: the Don-Voronezh and the Voronezh-Usman. The Upland Oak Forest occurs on the watershed slope, as well as partially on the Voronezh-Don watershed. The highest elevations of the watershed reach 155–165 m above sea level (asl). The topography is frequently characterized by steep and, in some instances, precipitous slopes. The right slope of the Voronezh River valley is incised by deeply eroded gullies, in some cases with their tops approaching the watershed line. The left bank of the Voronezh River is separated from the right bank by a wide floodplain with oxbow lakes and wetlands. The elevation of the Voronezh River floodplain is 92–95 m asl. The formation of small sand ramparts, with elevations reaching 90–100 m asl, has also been observed on the floodplain. The surface of the Voronezh River floodplain terraces is uneven and hilly, displaying a bumpy relief in some localities.

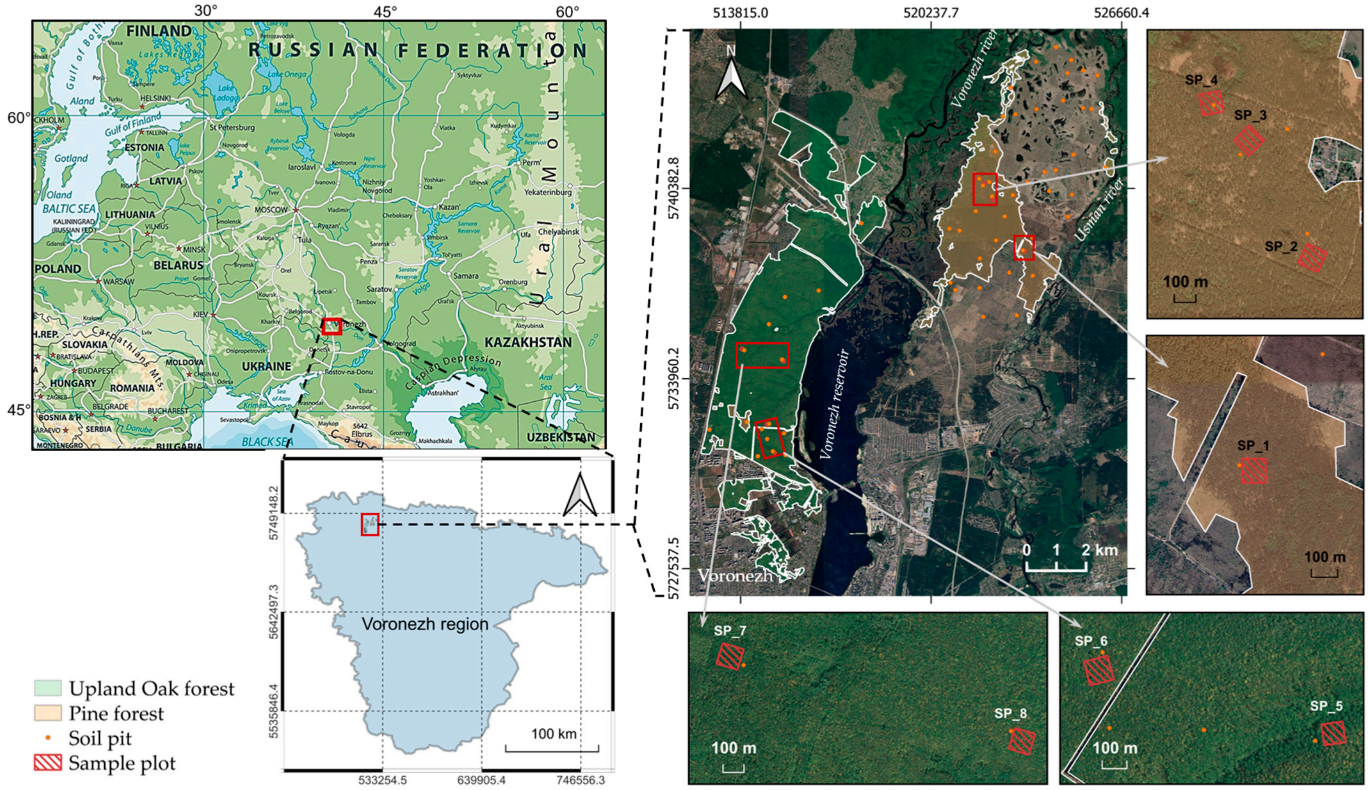


Figure 1. The geographical location of the study area.

Middle Quaternary deposits occur within the Upland Oak Forest and are represented by cover, alluvial, alluvial-fluvioglacial, deluvial, and alluvial-deluvial deposits. They are characterized by the presence of dusty loess-like porous loams. The right bank of the Voronezh River, together with the gully and gully complex, is covered by a series of diluvial and alluvial-fluvioglacial deposits. These deposits are represented by a variety of sedimentary materials, including sand, loam, and clay, which occur in different combinations. The sands are typically fine- to medium-textured, frequently exhibiting clay content, and often interlayered with clays.

The modern Quaternary deposits are associated with the broad floodplains of the Voronezh and Usman rivers. In general, the upper part of the floodplain is composed of dark-colored clays and their mixtures, while the lower part is composed of finely and unevenly grained sands. In some instances, the sands, particularly in the channel floodplain, emerge from the underlying deposits and exhibit distinct layers. The ancient alluvial sediments of Upper Quaternary age are represented by loose, rarely cohesive sands or sandy loam.

The Mollic Leptosols that are predominant within the pine forest on the left bank of the Voronezh River are situated on alluvial sandy deposits. The soils' texture on the left bank is determined by the presence of different fractions of sands composing the terraces. The soils of the upland oak forest exhibit a more diverse morphological profile, with enhanced illuvial processes and a less uniform texture. The soil types present at this site are identified as Mollic Leptosols and Grey-Luvic Phaozems (WRB, 2022 [20]).

2.2. Soil Sampling and Sample Plot Descriptions

A total of 55 full-profile soil pits, excavated to a depth of up to 2 m, were dug during the study of soil cover in different forest types. The pits were dug not only on areas covered with forest vegetation but also on deforested lands (the Voronezh-Usman interfluve) with known characteristics of the forest types that existed in this area in the recent past. In order to ensure the most comprehensive data set was obtained, a minimum of one soil pit was established for every 15 hectares for a total study area of about 850 ha. After a morphological description of the soil profile, a series of soil samples were collected from each pit by genetic soil horizons for subsequent analysis (total $N = 310$).

This study adopted a widely used forest typology according to the classification of Alekseev and Pogrebnyak [21]. This classification scheme uses an edaphic grid to define forest types that are distinguished by specific soil nutrient content (trophotope) and moisture content (hygrotope); all established soil profiles were clustered within the trophogenic series (Table 1). The forest ecosystems of the study area encompass the full spectrum of recognized forest types. These conditions are favorable for the growth of 18 species of forest-forming species, among which the dominant species are Scots pine (*Pinus sylvestris* L.), common oak (*Quercus robur* L.), Norway maple (*Acer platanoides* L.), small-leaved linden (*Tilia cordata* Mill.), common ash (*Fraxinus excelsior* L.), wych elm (*Ulmus glabra* Huds.), and aspen (*Populus tremula* L.).

Table 1. Forest types in the study area (according to Alekseev and Pogrebnyak's classification).

Forest Type (Trophotope)		Abbreviation in This Study
Index	**Name**	
A	Pine forest	Pf
B	Pine–oak forest	POf
C	Pine forest with birch, aspen and oak participation	PfBAOp
D	Oak grove	Og

Eight permanent sample plots (100 × 100 m^2) were established in different old-growth forests in the vicinity of soil pits. A census-based forest inventory was performed within these plots, and the main characteristics of the tree stands were determined (Table 2).

Table 2. Sample plot characteristics.

Sample Plot	Elevation (m asl)	Forest Type	Tree Stands Variables							Soil Type (WRB, 2022 [20])
			Tree Species Composition		Site Index	Age, Years	DBH, cm	H, m	Volume, $m^3 \cdot ha^{-1}$	
			Tree Species	RC *, %						
SP_1	120	Pf	*Pinus sylvestris* L.	100	3	130	30.7	24.2	327	Mollic Leptosols
SP_2	118	POf	*Pinus sylvestris* L.	100	1	140	42.2	29.6	451	Mollic Leptosols
SP_3	115	POf	*Pinus sylvestris* L.	100	1	110	39.2	28.6	424	Mollic Leptosols
SP_4	113	POf	*Pinus sylvestris* L.	100	1	100	43.0	32.6	493	Gleyic Phaozems
SP_5	178	PfBAOp	*Quercus robur* L. *Tilia cordata* Mill. *Populus tremula* L.	80 10 10	3	100 80 80	26.2 28.0 20.0	23.4 24.2 19.1	167 41 35	Mollic Leptosols
SP_6	180	PfBAOp	*Quercus robur* L. *Tilia cordata* Mill. *Acer platanoides* L.	30 50 20	3	100 75 85	33.4 22.3 23.3	22.6 19.6 18.6	86 120 63	Mollic Leptosols
SP_7	183	PfBAOp	*Quercus robur* L. *Populus tremula* L. *Acer platanoides* L. *Tilia cordata* Mill.	50 30 10 10	3	110 70 50 50	34.7 24.3 13.5 18.4	24.1 27.5 14.5 16.2	169 88 32 18	Mollic Leptosols
SP_8	174	Og	*Quercus robur* L. *Acer platanoides* L. *Tilia cordata* Mill.	60 20 20	2	105 80 70	38.4 23.5 18.9	26.0 18.9 17.2	216 73 66	Grey-Luvic Phaozems

* RC—relative composition, DBH—stem diameter at breast height, H—tree height.

2.3. Soil Analysis

The bulk density (BD) was determined using the excavation method. Soil samples were collected in triplicate without loosening or disturbing the soil at different depths, using steel rings of known volume. Subsequently, the soil samples were dried in an oven at 103 ± 2 °C until a constant weight was achieved, and the dry weight per unit volume ($g \cdot cm^{-3}$) was calculated. SOC content in soil samples was obtained from the dichromate oxidation method using N-phenanthranilic acid as an indicator [22]. Samples were also dried in a heating oven at 103 ± 2 °C to a constant weight for conversion to dry weight. Soil particle size distribution was obtained from a pipette-sieving method, and the USDA soil texture classification system was adopted [23].

2.4. Calculation of Particle Stocks in Soils and Carbon Stocks in Soils and Forest Biomass

SOC and particle stocks were based on the soil BD and the thickness of the soil layers and were computed with the following Equation (1):

$$S = \sum_{i=1}^{n} (C \times BD \times H \times 10) \quad (1)$$

where S is the sum of SOC or particle stock for the different layers, Mg·ha^{-1}; C is the content of SOC or mechanical particles in soil layer, %; BD is the soil bulk density, g·cm^{-3}; H is the thickness of the soil layer, m; and n is the number of soil layers.

Estimation of tree biomass stocks was conducted using single-tree allometric Equation (2) based on data on a stem diameter of 1.3 m and tree height [24]:

$$\ln P_i = a_0 + a_1 \ln H + a_2 \ln DBH \quad (2)$$

where P_i is the biomass stock, kg dry weight; H is the tree height, m; DBH is the stem diameter of 1.3 m, cm; a_0, a_1, and a_2 are species-specific coefficients of allometric equation.

Biomass-to-carbon conversion factors were used according to IPCC guidelines [25]: 0.51 for conifers and 0.48 for broadleaved tree species.

2.5. Statistical Analyses

Descriptive statistics and a correlation analysis among various sample groups were carried out using STATISTICA 12.0 software (StatSoft Inc., Tulsa, OK, USA, 2014). The statistical significance of the differences between variables was assessed according to the distribution patterns of the sample data, using parametric methods (pairwise Student's *t*-test for independent variables). Pearson correlation coefficients were calculated, and a regression analysis was performed to examine the tightness and type of relationship between the two variables. All statistical calculations were performed at a significance level of $p < 0.05$.

3. Results

3.1. SOC Content and Soil Texture in Forest Types

Table 3 presents the results of statistical analyses of SOC content and soil texture in different forest soil layers clustered according to the forest types in which soil pits were established.

Although in some cases the total SOC content exhibited significant differences between forest types, in the majority of cases such differences were not apparent. Notably, the minimum mean values of SOC content in the Pf forest type, ranging from 0.24% to 0.54%, are significantly distinct from those observed in other soil types within the 0–50 cm layer across different forest types. Conversely, the soil types of POf, PfBAOp, and Og exhibit comparable mean SOC levels, which are similar to those observed in the poorly fertile Pf soils. Consequently, regardless of the forest type, SOC contents are higher in the upper soil layer than in the deeper layers. This can be attributed to the elevated biological activity and the presence of plant residues in the upper soil horizon.

The soil texture exhibits more substantial distinctions between the various forest types. The sand content of layers 0–50 cm and 0–100 cm is greater in the Pf and POf forest types than in other forest types, with the highest proportion of sand particles typically observed in Pf forests. In contrast, the proportion of silt and clay is greater in forest types PfBAOp and Og. It should be noted that the soils in the Og forest type have a particularly high clay content, reaching a maximum mean value of 19.7% in the 0–200 cm layer, ranging from

18.3 to 21.5%. This indicates a particularly heavy soil texture in this forest type. The analysis of the coefficients of variation for each soil texture component demonstrated substantial variability in the distribution of silt-sized and clay-sized particles. The particularly high CV values for clay, ranging from 8.8% to 156.2%, indicate significant variability in clay content between forest types. Furthermore, the variability of sand content is smaller (CVs varied from 1.1% to 12.9%). This suggests a more homogeneous distribution of sand in the different forest soil profiles. The high variability of clay-sized particles suggests the potential for diverse processes of soil formation and heterogeneity in the parent rocks from which forest soils were formed.

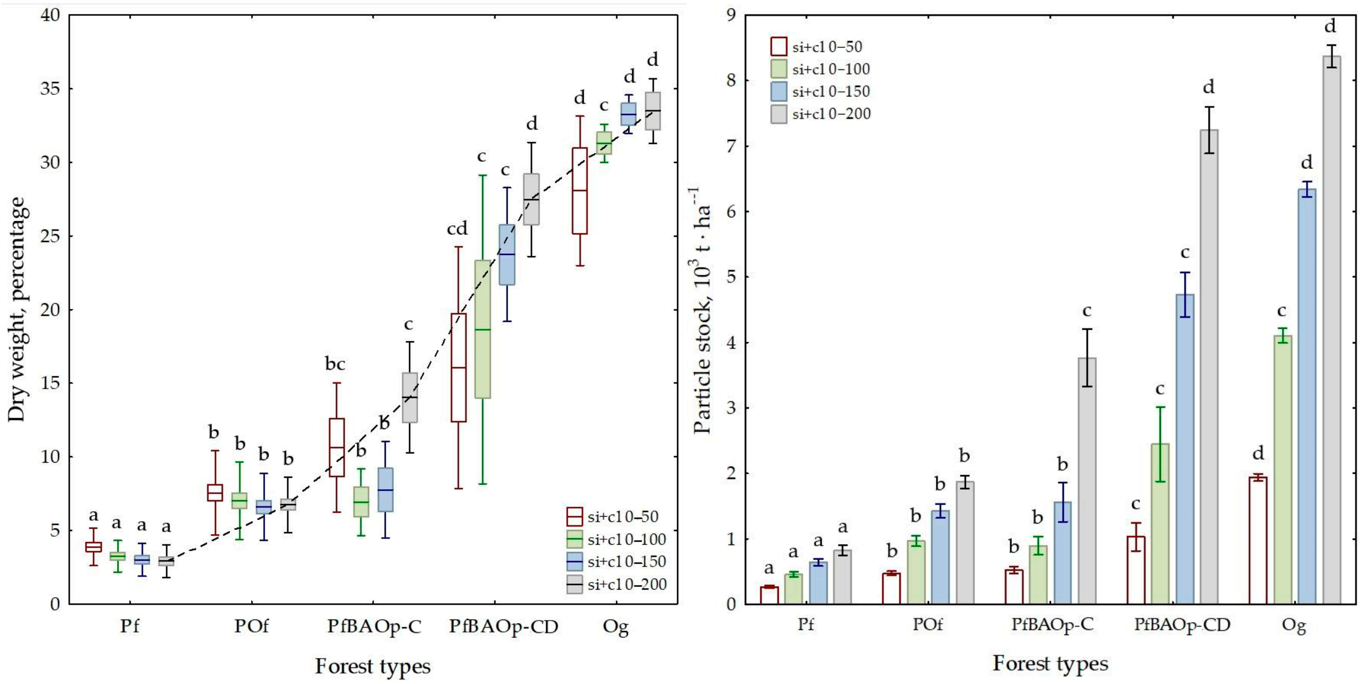
Table 3. SOC content and soil texture in different soil layers of forest types.

Soil Properties	Soil Layer, cm	Forest Types (Trophotopes)				
		Pf (*n* = 16)	POf (*n* = 26)	PfBAOp-C (*n* = 5)	PfBAOp-CD (*n* = 5)	Og (*n* = 3)
SOC, %	0–50	0.54 ± 0.22 [a]	0.86 ± 0.38 [b]	0.84 ± 0.41 [b]	0.82 ± 0.37 [b]	0.93 ± 0.26 [b]
	0–100	0.36 ± 0.14 [a]	0.57 ± 0.26 [b]	0.50 ± 0.28 [ab]	0.51 ± 0.21 [ab]	0.54 ± 0.27 [ab]
	0–150	0.29 ± 0.12 [a]	0.43 ± 0.19 [b]	0.38 ± 0.23 [ab]	0.36 ± 0.14 [ab]	0.45 ± 0.16 [ab]
	0–200	0.24 ± 0.10 [a]	0.34 ± 0.16 [b]	0.30 ± 0.20 [ab]	0.28 ± 0.10 [ab]	0.37 ± 0.13 [ab]
Sand, %	0–50	96.1 ± 1.3 [a]	92.3 ± 2.8 [b]	87.2 ± 5.8 [c]	83.9 ± 8.2 [cd]	73.4 ± 3.6 [d]
	0–100	96.7 ± 1.1 [a]	92.9 ± 2.6 [b]	91.0 ± 3.0 [bc]	81.3 ± 10.5 [cd]	70.5 ± 2.2 [d]
	0–150	96.9 ± 1.1 [a]	93.3 ± 2.3 [a]	90.8 ± 2.6 [a]	76.2 ± 4.5 [b]	68.7 ± 4.8 [b]
	0–200	97.0 ± 1.2 [a]	92.5 ± 3.3 [a]	84.9 ± 3.6 [a]	72.5 ± 3.8 [b]	67.7 ± 6.4 [b]
Silt, %	0–50	2.8 ± 1.4 [a]	5.7 ± 2.7 [b]	6.4 ± 1.1 [b]	8.4 ± 4.3 [bc]	12.4 ± 3.3 [c]
	0–100	2.4 ± 1.4 [a]	5.5 ± 2.4 [b]	5.2 ± 2.3 [bc]	8.5 ± 4.6 [cd]	12.9 ± 0.6 [d]
	0–150	2.2 ± 1.4 [a]	5.4 ± 2.2 [b]	5.5 ± 2.5 [b]	12.0 ± 3.0 [c]	13.6 ± 0.7 [c]
	0–200	2.2 ± 1.3 [a]	5.6 ± 2.1 [b]	9.4 ± 2.6 [c]	14.3 ± 4.1 [cd]	14.0 ± 0.9 [d]
Clay, %	0–50	1.1 ± 1.1 [a]	1.8 ± 1.2 [a]	4.2 ± 3.5 [b]	7.7 ± 4.6 [bc]	15.6 ± 4.7 [c]
	0–100	0.9 ± 1.1 [a]	1.5 ± 1.2 [a]	1.7 ± 1.2 [a]	10.2 ± 5.9 [b]	18.4 ± 1.9 [b]
	0–150	0.8 ± 1.2 [a]	1.2 ± 0.9 [a]	2.3 ± 1.4 [b]	11.8 ± 3.2 [c]	19.7 ± 0.8 [d]
	0–200	0.7 ± 1.1 [a]	1.2 ± 0.8 [a]	4.7 ± 2.6 [b]	13.2 ± 2.8 [c]	19.5 ± 1.7 [d]

Data are presented as mean ± standard deviation. Within each string, values with similar letters do not differ statistically according to Student's *t*-test at $p < 0.05$.

It is evident that the majority of studied soil characteristics demonstrate substantial variability within certain layers of each trophotope. To prove the reliability of the gradient by forest types, it is necessary to select one or several parameters in the soil layers of all trophotopes that exhibit a sufficiently low degree of variability and significant differences of mean values. The analysis was conducted on fine particles (less than 0.02 mm) comprising total silt-sized and clay-sized particles within the corresponding soil layers. The data on the particle content in soils of different forest types are presented in Figure 2a.

The mean fine particle content of less developed forest soils of pine forests was minimal, ranging from 3.9% in the top layer to 2.9% in the two-meter soil profile. The highest particle content was observed in the oak forest, reaching 28.1% in the 0–50 cm layer and increasing to 33.5% of the total dry weight in the 0–200 cm layer. The fine particle content exhibited significant variation between forest types at different depths, with the greatest differences observed in the 0–150 and 0–200 cm layers. Therefore, in forest soils of 150 cm thickness, a reliable and consistent increase in fine particle content can be observed in the sequence of forest types: Pf < POf ≈ PfBAOp-C < PfBAOp-CD < Og. In soil profiles of 200 cm depth, the pattern is even more evident, with the exception of the absence of differences between the last two forest types. The particle content was found to be increasing in the following order: Pf < POf < PfBAOp-C < PfBAOp-CD ≈ Og.



(**a**) (**b**)

Figure 2. Fine particle (silt + clay) contents (**a**) and stocks (**b**) in the soils of different forest types. Box plot graph: the central line represents the mean value; the box indicates the standard error; and the whiskers denote the standard deviation. The dotted curve connects the mean values of fine particle content in the 0–200 cm soil layer, demonstrating a reliable increase in this parameter in accordance with the gradient of forest types. Histogram graph: columns—mean values, whiskers—standard errors. Similar letters in both graphs show the absence of differences between forest types according to Student's *t*-test at $p < 0.05$.

3.2. SOC and Particle Stocks in Soils of Different Forest Types

Based on the data on percentages of soil mechanical fractions and SOC by increasing layers, the mean stocks of mechanical particles and SOC in the same layers were calculated. Table 4 presents a summary of the statistical analysis of SOC stocks, as well as sand, silt, and clay particle stocks across different forest types and soil layers.

Table 4. SOC and soil mechanical particle stocks ($Mg \cdot ha^{-1}$) in different soil layers of forest types.

Soil Properties	Soil Layer, cm	Forest Types (Trophotopes)				
		Pf (*n* = 16)	POf (*n* = 26)	PfBAOp-C (*n* = 5)	PfBAOp-CD (*n* = 5)	Og (*n* = 3)
SOC	0–50	36.8 ± 14.6 (39.6) * ^{a}	57.4 ± 24.7 (43.1) ^{bc}	52.3 ± 23.9 (45.7) ^{ab}	53.7 ± 24.6 (45.8) ^{ab}	61.8 ± 15.2 (24.7) ^{c}
	0–100	50.8 ± 19.3 (37.9) ^{a}	77.0 ± 34.7 (45.1) ^{b}	64.3 ± 33.8 (52.6) ^{ab}	66.6 ± 26.8 (40.2) ^{ab}	75.7 ± 28.2 (37.2) ^{ab}
	0–150	61.6 ± 25.0 (40.6) ^{a}	88.8 ± 40.7 (45.9) ^{b}	80.2 ± 44.0 (54.8) ^{ab}	71.9 ± 28.0 (38.9) ^{ab}	88.7 ± 32.2 (36.3) ^{ab}
	0–200	68.3 ± 28.3 (41.4) ^{a}	96.1 ± 45.5 (47.3) ^{b}	81.9 ± 53.6 (65.4) ^{ab}	74.0 ± 27.0 (36.5) ^{ab}	95.5 ± 33.8 (35.4) ^{ab}
Sand	0–50	6612 ± 216 (3.3) ^{a}	6078 ± 630 (10.4) ^{b}	5445 ± 449 (8.3) ^{c}	4974 ± 1935 (38.9) ^{cd}	4499 ± 51 (1.1) ^{d}
	0–100	13,600 ± 415 (3.1) ^{a}	12,695 ± 627 (4.9) ^{b}	12,034 ± 314 (2.6) ^{c}	10,869 ± 1872 (17.2) ^{cd}	8657 ± 164 (1.9) ^{d}
	0–150	20,146 ± 1576 (7.8) ^{a}	19,272 ± 804 (4.2) ^{a}	18,306 ± 525 (2.9) ^{a}	15,341 ± 1378 (9.0) ^{b}	13,761 ± 756 (5.5) ^{b}
	0–200	27,571 ± 906 (3.3) ^{a}	25,637 ± 1277 (5.0) ^{a}	22,223 ± 714 (3.2) ^{a}	19,391 ± 1692 (8.7) ^{b}	18,135 ± 1609 (8.9) ^{b}
Silt	0–50	189 ± 93 (48.9) ^{a}	357 ± 158 (44.4) ^{b}	399 ± 71 (17.8) ^{bc}	538 ± 255 (47.3) ^{cd}	960 ± 226 (23.5) ^{d}
	0–100	334 ± 184 (55.2) ^{a}	729 ± 341 (46.7) ^{b}	675 ± 330 (48.9) ^{bc}	1115 ± 558 (50.0) ^{cd}	1815 ± 282 (15.5) ^{d}
	0–150	468 ± 279 (59.6) ^{a}	1106 ± 445 (40.2) ^{b}	1100 ± 507 (46.1) ^{b}	2387 ± 557 (23.3) ^{c}	2709 ± 176 (6.5) ^{c}
	0–200	618 ± 372 (60.2) ^{a}	1542 ± 565 (36.7) ^{a}	2514 ± 667 (26.5) ^{a}	3802 ± 1048 (27.6) ^{b}	3614 ± 196 (5.4) ^{b}
Clay	0–50	79 ± 76 (95.7) ^{a}	119 ± 81 (68.2) ^{a}	127 ± 121 (95.7) ^{a}	493 ± 271 (54.9) ^{b}	981 ± 303 (30.9) ^{b}
	0–100	125 ± 157 (125.5) ^{a}	241 ± 231 (95.7) ^{a}	221 ± 154 (69.8) ^{a}	1335 ± 717 (53.7) ^{b}	2293 ± 273 (11.9) ^{b}
	0–150	172 ± 240 (139.5) ^{a}	321 ± 353 (109.9) ^{ab}	463 ± 283 (61.2) ^{b}	2346 ± 599 (25.5) ^{c}	3632 ± 256 (7.1) ^{d}
	0–200	209 ± 320 (152.8) ^{a}	327 ± 206 (63.1) ^{a}	1254 ± 706 (56.3) ^{b}	3444 ± 615 (17.9) ^{c}	4757 ± 181 (3.8) ^{d}

* Data are presented as mean ± standard deviation, and coefficient of variation is given in brackets. Within each string, values with similar letters do not differ statistically according to Student's *t*-test at $p < 0.05$.

The analysis of these data generally supports the hypothesis that there are significant differences between forest types and their dependence on the distribution of soil characteristics. Furthermore, relatively high SOC stocks are observed in the 0–200 cm layer for the POf and Og forest types, reaching 96.1 Mg·ha^{-1} and 95.5 Mg·ha^{-1}, respectively. These values are significantly higher than those observed for Pf (68.3 Mg·ha^{-1}). Furthermore, the SOC stock in the 0–50 cm layer for Og is also significantly higher, reaching 61.8 Mg·ha^{-1}, than in other forest types, indicating greater organic carbon accumulation in the upper soil layers for this forest type.

As anticipated, the highest sand fraction stocks are observed in all Pf soil layers in comparison to other forest types. For example, the sand stock in the 0–200 cm layer of Pf is 25.7 × 10^3 Mg·ha^{-1}, whereas that of Og is significantly lower at 18.1 × 10^3 Mg·ha^{-1}. This trend is also evident in other layers. Conversely, the Og forest type exhibits notably elevated silt and clay stocks, with significantly higher values observed across all soil layers, including a maximum of 4.8 × 10^3 Mg·ha^{-1} in the 0–200 cm layer.

The total silt and clay stocks in soils of different forest types (Figure 2b) exhibit analogous patterns, reflecting their distribution by layers. Furthermore, the variability observed in these stocks across different soil layers is significantly lower than that observed in the coefficients of variation obtained for silt and clay stocks in some layers. Thus, CV values for the 0–200 cm layer of soils in different forest types do not exceed 36.5%, and for the 0–150 cm layer, they reach 42.6%. For comparison, CVs for clay stocks exceeded 152%, while that for silt stocks reached 60% (Table 4).

It is noteworthy that a clear relationship between SOC stocks and stocks of silt- and clay-sized particles is observed only in the upper 50 cm layer (Figure 3).

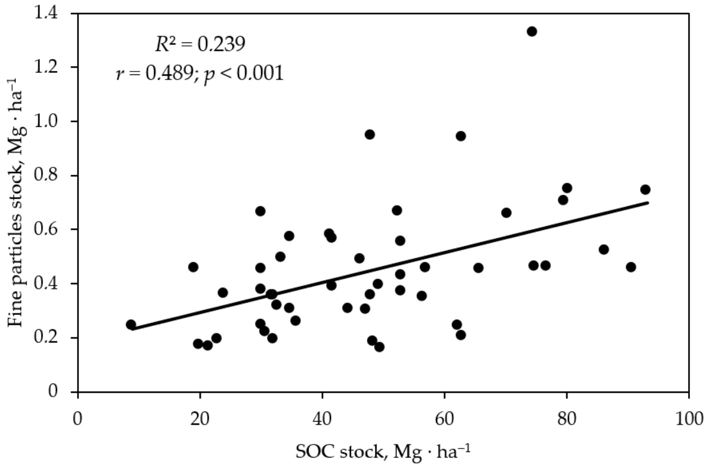


Figure 3. The relationship between SOC stock and fine particle (silt + clay) stock in the 0–50 cm soil layer.

Although the determination coefficient is not high and indicates that approximately 23.9% of the variance in SOC stocks is explained by variations in fine particle stocks, the moderately positive correlation coefficient and high statistical significance nonetheless confirm the existence of a stable trend of increasing carbon stocks in the upper horizons of forest soils with increasing mechanical structure. This relationship becomes less evident in the 0–100 cm layer ($r = 0.312$; $p < 0.05$) and is almost entirely absent in deeper layers.

3.3. *Assessment of the Dependence of Tree Stand Carbon Stocks on Soil Texture*

Table 5 provides comparative data on carbon stocks in stand biomass, organic carbon stocks, and fine particle stocks in soils to a depth of the 2 m root-inhabited soil layer.

Table 5. Comparison of carbon stocks in tree biomass and soil and fine particle stocks across forest types.

Sample Plot	Forest Type (Trophotope)	Tree Stand Carbon Stock, Mg·ha^{-1}	SOC Stock in the Layer, Mg·ha^{-1}		Fine Particle Stock in 0–200 cm of Soil, Mg·ha^{-1}
			0–50 cm	0–200 cm	
SP_1	Pf	99.9	31.9	38.3	696
SP_2	POf	129.1	47.9	110.2	1428
SP_3	POf	131.0	70.2	135.7	2026
SP_4	POf	132.4	93.1	141.5	2494
SP_5	PfBAOp-C	136.1	52.8	74.2	3944
SP_6	PfBAOp-CD	124.9	80.3	91.4	5852
SP_7	PfBAOp-CD	147.0	47.9	56.8	7758
SP_8	Og	180.7	77.1	131.1	8710

Analysis of the data in Table 5 shows that there is no obvious relationship between tree stand carbon stocks and SOC stocks both in the upper horizons and down to a 2 m depth. For example, the tree stands at SP_5 and SP_6 have similar carbon stocks at 136.1 and 124.9 Mg·ha^{-1}, respectively, while SOC stocks differ significantly at 52.8 and 80.3 Mg·ha^{-1}, respectively. A similar trend can be observed at sites SP_3 and SP_4.

Concurrently, a distinct positive correlation is evident between the stocks of fine particles (comprising total clay and silt stocks) in soil at depths of up to 2 m and carbon stocks in tree phytomass (Figure 4).

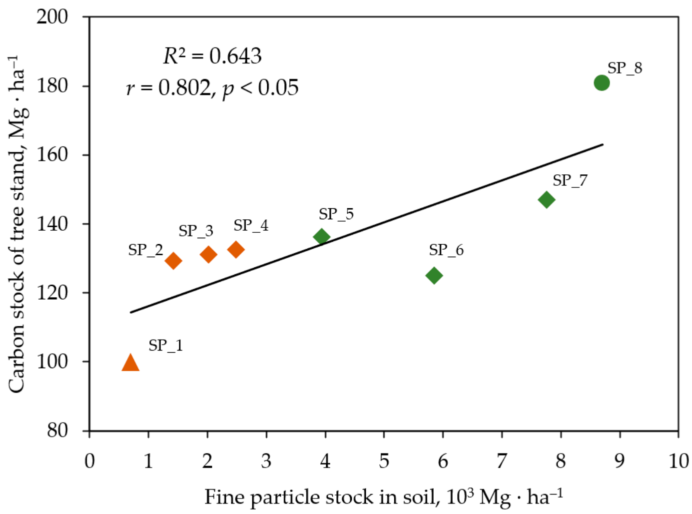


Figure 4. The relationship between carbon stock of tree stands and fine particle (silt + clay) contents in the 2 m root-inhabited soil layer. Orange markers denote coniferous tree stands, and green markers represent broadleaved tree stands. Triangle—pine forest (Pf), diamonds—forests with possible dominance of coniferous and deciduous tree species (POf, PfBAOp), circle—deciduous forests (Og).

The value of the coefficient of determination indicates that 64.3% of the observed variation in the carbon stock of tree cover can be explained by changes in the soil content of fine particles. The correlation coefficient (r = 0.802) indicates a strong positive relationship between the two variables. It is evident that elevated concentrations of fine particles within the 2 m root-inhabited soil layer contribute to an enhancement in carbon stocks in tree phytomass.

4. Discussion

The disparate age of the left-bank and right-bank landscapes of the Voronezh River valley, coupled with the unequal soil texture of their deposits, has resulted in the accumulation of the major chemical constituents in soils exhibiting marked differences. Consequently, the same soil types give rise to a wide variety of forest types.

The findings of this study indicate that SOC stocks are not a primary factor in distinguishing between different forest types and that they do not have a significant impact on the carbon stocks of tree stands. Soil chemical parameters alone are known to be poor predictors of tree productivity [26]. Apparently, this indicator is of secondary importance to the tree stand and can be determined by the influence of stand composition and the characteristics of the parent rocks on which forest soils were formed [27,28]. The observed positive correlation between soil carbon stocks and clay and silt stocks in the topsoil is in accordance with the findings of previous studies, which also identified a correlation between SOC stocks and the content of fine particles in soil [29–31]. The same positive relationship of SOC content with clay plus silt content in soils under tree stands was found by Riestra et al. (2012) [32]. Silt- and clay-sized particles are known to provide an enhanced capacity for organic carbon sorption [33].

The soil particle size distribution of the upper soil horizon and the nature of the parent rock are the primary factors influencing the formation of a forest type (trophotope). A significant degree of variation was observed in numerous soil characteristics across the various layers of each forest type. In order to substantiate the reliability of the gradation by trophotopes, it was determined that the clay and silt stocks in soil layers 0–200 cm serve as the determining indicators.

The stock of fine particles smaller than 0.02 mm in the 0–200 cm soil layer is distinguished by relatively low variability in the distribution of aggregates across the entire trophogenic series. This factor is of particular significance in differentiating between forest types. Furthermore, the high significance of these differences provides additional evidence.

The topsoil of the PfBAOp-CD forest type usually has a sandy texture, sometimes changing to sandy loam within the 0–100 cm layer. At depths greater than 1 m, the parent rock is replaced by sandy loam. Such a difference in the composition of the soil profile according to the mechanical composition results in some difference in the fine particle stock, which is more pronounced in the 0–50 cm layer and to a lesser extent in the 0–200 cm layer, thus the mean stock of particles smaller than 0.02 mm in the 0–200 cm layer of soils of PfBAOp-CD is $(27.5 \pm 3.9) \times 10^3$ Mg·ha^{-1} and in Og conditions—$(33.5 \pm 2.2) \times 10^3$ Mg·ha^{-1}. In comparison, under C conditions, this value was lower $(14.0 \pm 3.8) \times 10^3$ Mg·ha^{-1}. Obviously, the PfBAOp-CD trophotope differs significantly from the PfBAOp-C conditions despite the similar texture of their topsoils. At the same time, the PfBAOp-CD and Og conditions, despite the differences in mechanical composition from the surface, are close to each other by their soil texture in the 0–200 cm layer. All these factors make it legitimate to divide the PfBAOp forest type into two subgroups and to identify the intermediate forest type (trophotope).

The results of this study permit the identification of gradations in the total silt and clay particle content in the two-meter root-inhabited soil layer of different forest types (Table A1). The classification system comprises five groups of forest types according to trophotope. For each forest type, the minimum and maximum values of silt and clay stocks, expressed in tons per hectare, are indicated. The data in the table indicate that the stocks of silt and clay naturally increase with an increase in the diversity of tree species in forests and vice versa. Obviously, the differentiation of forest management should be determined by the classification of forest types or groups of forest types with similar soil-typological conditions. Accordingly, the most appropriate composition of tree species for reforestation can be selected, and areas for the conservation of existing forest stands can be identified using the developed gradation.

The relationship between fine particle stocks in forest soils and tree stand carbon stocks, supported by data showing an increase in tree productivity with higher clay content, indicates the significant influence of soil texture on forest productivity. The findings of earlier studies indicated that soil quality has a significant impact on forest ecosystem productivity [34]. Soil texture can be considered the most fundamental qualitative soil physical characteristic, exerting a significant influence on the exchange, retention, and uptake of water, nutrients, and oxygen. It is a primary soil property that affects a number of other properties and processes [35]. The stock of silt and clay particles in the soil is a critical factor in the water-holding capacity of the soil [36,37], the availability of nutrients [31], the root growth rate [38,39], the level of soil microbial activity [40], as well as the rate of nutrient cycling [41], all of which are essential for maintaining a healthy forest ecosystem.

Devi (2021) [42] suggested that loamy soils, comprising 40% sand, 40% silt, and 20% clay, are conducive to tree growth due to the favorable properties of these mineral particles. The growth rates of trees on loam soils are typically higher than those on sandy loam or clay soils. These observations reflect the enhanced fertility and moisture retention capacity of loam [43]. Additionally, a study of mixed-species plantations on loam soils demonstrated superior survival rates of trees compared to other soil types [44].

The results of these studies demonstrated that forests with sandy soils had lower carbon stocks than those with loamy soils [42]. However, other studies indicated that the influence of tree diversity on forest productivity was more amplified in sandy soils, where resources are limited, and greater species diversity can more effectively occupy different niches than in loamy soils, where competition for resources may be less intense due to the higher availability of nutrients [45,46]. This indicates that the interrelationship between soil texture, tree diversity, and productivity may be dependent on the specific characteristics of the forest ecosystem. Although the present study results demonstrate that soil texture predicts forest productivity in forest-steppe regions, additional factors such as climate, topography, and management practices that may also affect forest carbon stocks need to be considered.

5. Conclusions

This study demonstrated that soil texture, particularly total stock of silt and clay, is a key factor influencing the carbon stocks in the biomass of coniferous and deciduous forest stands in the forest-steppe zone. It is noteworthy that SOC stocks in these conditions do not significantly affect carbon stocks in stands. The data obtained provide a foundation for classifying forest types based on soil characteristics for facilitating differentiated forest management strategies. This enables the optimal selection of tree species composition for the purpose of reforestation as well as the delineation of areas conducive to the continued maintenance of existing forests. In particular, developing methods to improve the quality of soils with low silt and clay content will increase the potential for forest growth on these soils.

Further research could focus on detailed studies of the relationship between different soil types and tree species. Other research must be carried out to examine the influence of climate change on alterations to forest productivity, with specific reference to soil physico-chemical characteristics. An understanding of these aspects will facilitate the development of more effective forest management strategies in the forest-steppe zone, ensuring the long-term sustainability and productivity of forest ecosystems.

Author Contributions: Conceptualization, S.S. and G.O.; methodology, G.O. and S.S.; software, S.S.; validation, E.T., S.S. and N.G.; formal analysis, E.T., G.C. and O.C.M.; investigation, G.O., S.S., T.S. and N.G.; resources, G.O. and S.S.; data curation, E.T. and S.S.; writing—original draft preparation, S.S. and E.T.; writing—review and editing, E.T., O.C.M. and G.C.; visualization, S.S. and T.S.; supervision, O.C.M. and G.C.; project administration, S.S.; funding acquisition, S.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Ministry of Science and Higher Education of the Russian Federation (theme No. 1023013000012-7) "Biogeochemical monitoring of the carbon cycle in natural and anthropogenic ecosystems of the Voronezh region under conditions of global climate change (FZUR-2023-0001)".

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The original contributions presented in the study are included in the article. Further inquiries can be directed to the corresponding author.

Conflicts of Interest: The authors declare no conflicts of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

Appendix A

Table A1. Gradations of total silt and clay particles in the 2 m root-inhabited soil layer of different forest types.

Forest Types (Trophotopes)	Range of Total Silt and Clay Particle Stock (t·ha^{-1})	
	Minimum	Maximum
Pine forest (A)	0	1000
Pine–oak forest (B)	1001	2500
Pine forest with birch, aspen, and oak participation (C)	2501	5000
Pine forest with birch, aspen, and oak participation (CD)	5001	8000
Oak grove (D)	8001	>8001

References

1. Bonan, G. *Seeing the Forest for the Trees: Forests, Climate Change, and Our Future*, 1st ed.; Cambridge University Press: Cambridge, UK, 2023. [CrossRef]
2. United Nations Economic Commission for Europe. *The Outlook for the UNECE Forest Sector in a Changing Climate: A Contribution to the Forest Sector Outlook Study 2020–2040*; Geneva Timber and Forest Discussion Papers; United Nations: New York, NY, USA, 2023. [CrossRef]
3. Noormets, A.; Miao, G.; Kim, D.; Ono, M.; McNulty, S.G. Mitigation Potential of Forests: Challenges to Carbon Accrual in the Ecosystem. In *Future Forests*; Elsevier: Amsterdam, The Netherlands, 2024; pp. 75–94. [CrossRef]
4. Landry, G.; Thiffault, E.; Cyr, D.; Moreau, L.; Boulanger, Y.; Dymond, C. Mitigation Potential of Ecosystem-Based Forest Management under Climate Change: A Case Study in the Boreal-Temperate Forest Ecotone. *Forests* **2021**, *12*, 1667. [CrossRef]
5. Zhang, Y.; Guo, X.; Chen, L.; Kuzyakov, Y.; Wang, R.; Zhang, H.; Han, X.; Jiang, Y.; Sun, O.J. Global Pattern of Organic Carbon Pools in Forest Soils. *Glob. Chang. Biol.* **2024**, *30*, e17386. [CrossRef] [PubMed]
6. Van Der Putten, W.H.; Bardgett, R.D.; Bever, J.D.; Bezemer, T.M.; Casper, B.B.; Fukami, T.; Kardol, P.; Klironomos, J.N.; Kulmatiski, A.; Schweitzer, J.A.; et al. Plant–Soil Feedbacks: The Past, the Present and Future Challenges. *J. Ecol.* **2013**, *101*, 265–276. [CrossRef]
7. Shen, Y.; Li, J.; Chen, F.; Cheng, R.; Xiao, W.; Wu, L.; Zeng, L. Correlations between Forest Soil Quality and Aboveground Vegetation Characteristics in Hunan Province, China. *Front. Plant Sci.* **2022**, *13*, 1009109. [CrossRef]
8. Feng, J.; He, K.; Zhang, Q.; Han, M.; Zhu, B. Changes in Plant Inputs Alter Soil Carbon and Microbial Communities in Forest Ecosystems. *Glob. Chang. Biol.* **2022**, *28*, 3426–3440. [CrossRef] [PubMed]
9. Cao, J.; He, X.; Chen, Y.; Chen, Y.; Zhang, Y.; Yu, S.; Zhou, L.; Liu, Z.; Zhang, C.; Fu, S. Leaf Litter Contributes More to Soil Organic Carbon than Fine Roots in Two 10-Year-Old Subtropical Plantations. *Sci. Total Environ.* **2020**, *704*, 135341. [CrossRef]
10. Heiskanen, J.; Hallikainen, V.; Uusitalo, J.; Ilvesniemi, H. Co-Variation Relations of Physical Soil Properties and Site Characteristics of Finnish Upland Forests. *Silva Fenn.* **2018**, *52*, 18. [CrossRef]
11. Launiainen, S.; Kieloaho, A.-J.; Lindroos, A.-J.; Salmivaara, A.; Ilvesniemi, H.; Heiskanen, J. Water Retention Characteristics of Mineral Forest Soils in Finland: Impacts for Modeling Soil Moisture. *Forests* **2022**, *13*, 1797. [CrossRef]
12. Gomez, A.; Powers, R.F.; Singer, M.J.; Horwath, W.R. Soil Compaction Effects on Growth of Young Ponderosa Pine Following Litter Removal in California's Sierra Nevada. *Soil Sci. Soc. Am. J.* **2002**, *66*, 1334–1343. [CrossRef]
13. Slesak, R.A.; Palik, B.J.; D'Amato, A.W.; Kurth, V.J. Changes in Soil Physical and Chemical Properties Following Organic Matter Removal and Compaction: 20-Year Response of the Aspen Lake-States Long Term Soil Productivity Installations. *For. Ecol. Manag.* **2017**, *392*, 68–77. [CrossRef]
14. McFadden, J.P.; MacDonald, N.W.; Witter, J.A.; Zak, D.R. Fine-Textured Soil Bands and Oak Forest Productivity in Northwestern Lower Michigan, U.S.A. *Can. J. For. Res.* **1994**, *24*, 928–933. [CrossRef]
15. Bede-Fazekas, Á.; Török, P.; Erdős, L. Empirical Delineation of the Forest-Steppe Zone Is Supported by Macroclimate. *Sci. Rep.* **2023**, *13*, 17379. [CrossRef] [PubMed]
16. Chytrý, K.; Willner, W.; Chytrý, M.; Divíšek, J.; Dullinger, S. Central European Forest–Steppe: An Ecosystem Shaped by Climate, Topography and Disturbances. *J. Biogeogr.* **2022**, *49*, 1006–1020. [CrossRef]
17. Han, Q.; Keeffe, G.; Cullen, S. Climate Connectivity of European Forests for Species Range Shifts. *Forests* **2021**, *12*, 940. [CrossRef]

18. Mansilla, C.A.; McCulloch, R.D.; Morello, F. The Vulnerability of the Nothofagus Forest-Steppe Ecotone to Climate Change: Palaeoecological Evidence from Tierra Del Fuego (~53°S). *Palaeogeogr. Palaeoclimatol. Palaeoecol.* **2018**, *508*, 59–70. [CrossRef]
19. Shvidenko, A.; Buksha, I.; Krakovska, S.; Lakyda, P. Vulnerability of Ukrainian Forests to Climate Change. *Sustainability* **2017**, *9*, 1152. [CrossRef]
20. Schad, P. World Reference Base for Soil Resources—Its Fourth Edition and Its History. *J. Plant Nutr. Soil Sci.* **2023**, *186*, 151–163. [CrossRef]
21. Fomin, V.V.; Zalesov, S.V.; Popov, A.S.; Mikhailovich, A.P. Historical Avenues of Research in Russian Forest Typology: Ecological, Phytocoenotic, Genetic, and Dynamic Classifications. *Can. J. For. Res.* **2017**, *47*, 849–860. [CrossRef]
22. Skjemstad, J.; Baldock, J. Total and Organic Carbon. In *Soil Sampling and Methods of Analysis*, 2nd ed.; Carter, M., Gregorich, E., Eds.; CRC Press: Boca Raton, FL, USA, 2007. [CrossRef]
23. Kroetsch, D.; Wang, C. Particle Size Distribution. In *Soil Sampling and Methods of Analysis*, 2nd ed.; Carter, M., Gregorich, E., Eds.; CRC Press: Boca Raton, FL, USA, 2007. [CrossRef]
24. Usoltsev, V.A.; Shobairi, S.O.R.; Chasovskikh, V.P. Comparing of Allometric Models of Single-tree Biomass Intended for Airborne Laser Sensing and Terrestrial Taxation of Carbon Pool in the Forests of Eurasia. *Nat. Resour. Model.* **2019**, *32*, e12187. [CrossRef]
25. Paustian, K.; Ravindranath, N.H.; van Amstel, A.R. *2006 IPCC Guidelines for National Greenhouse Gas InventoriesLand Use, Land-Use Change, and Forestry. A Special Report of the IPCC*; Environmental Systems Analysis WIMEK: Wageningen, The Netherlands, 2006; Volume 4, Agriculture, Forestry and Other Land Use.
26. Hansson, K.; Laclau, J.-P.; Saint-André, L.; Mareschal, L.; Van Der Heijden, G.; Nys, C.; Nicolas, M.; Ranger, J.; Legout, A. Chemical Fertility of Forest Ecosystems. Part 1: Common Soil Chemical Analyses Were Poor Predictors of Stand Productivity across a Wide Range of Acidic Forest Soils. *For. Ecol. Manag.* **2020**, *461*, 117843. [CrossRef]
27. Osei, R.; Titeux, H.; Bielak, K.; Bravo, F.; Collet, C.; Cools, C.; Cornelis, J.-T.; Heym, M.; Korboulewsky, N.; Löf, M.; et al. Tree Species Identity Drives Soil Organic Carbon Storage More than Species Mixing in Major Two-Species Mixtures (Pine, Oak, Beech) in Europe. *For. Ecol. Manag.* **2021**, *481*, 118752. [CrossRef]
28. Diers, M.; Weigel, R.; Culmsee, H.; Leuschner, C. Soil Carbon and Nutrient Stocks under Scots Pine Plantations in Comparison to European Beech Forests: A Paired-Plot Study across Forests with Different Management History and Precipitation Regimes. *For. Ecosyst.* **2021**, *8*, 47. [CrossRef]
29. Zeng, R.; Wei, Y.; Huang, J.; Chen, X.; Cai, C. Soil Organic Carbon Stock and Fractional Distribution across Central-South China. *Int. Soil Water Conserv. Res.* **2021**, *9*, 620–630. [CrossRef]
30. Heger, A.; Becker, J.N.; Vásconez Navas, L.K.; Eschenbach, A. Factors Controlling Soil Organic Carbon Stocks in Hardwood Floodplain Forests of the Lower Middle Elbe River. *Geoderma* **2021**, *404*, 115389. [CrossRef]
31. Li, J.; Nie, M.; Powell, J.R.; Bissett, A.; Pendall, E. Soil Physico-Chemical Properties Are Critical for Predicting Carbon Storage and Nutrient Availability across Australia. *Environ. Res. Lett.* **2020**, *15*, 094088. [CrossRef]
32. Riestra, D.; Noellemeyer, E.; Quiroga, A. Soil Texture and Forest Species Condition the Effect of Afforestation on Soil Quality Parameters. *Soil Sci.* **2012**, *177*, 279–287. [CrossRef]
33. Matus, F.J. Fine Silt and Clay Content Is the Main Factor Defining Maximal C and N Accumulations in Soils: A Meta-Analysis. *Sci. Rep.* **2021**, *11*, 6438. [CrossRef]
34. Shao, G.; Ai, J.; Sun, Q.; Hou, L.; Dong, Y. Soil Quality Assessment under Different Forest Types in the Mount Tai, Central Eastern China. *Ecol. Indic.* **2020**, *115*, 106439. [CrossRef]
35. Schoenholtz, S.H.; Miegroet, H.V.; Burger, J.A. A Review of Chemical and Physical Properties as Indicators of Forest Soil Quality: Challenges and Opportunities. *For. Ecol. Manag.* **2000**, *138*, 335–356. [CrossRef]
36. Szecsődi, O.; Makó, A.; Labancz, V.; Barna, G.; Gálos, B.; Bidló, A.; Horváth, A. Using Different Approaches of Particle Size Analysis for Estimation of Water Retention Capacity of Soils: Example of Keszthely Mountains (Hungary). *Acta Silv. Lignaria Hung.* **2021**, *17*, 37–50. [CrossRef]
37. Wang, C.; Li, S.; He, X.; Chen, Q.; Zhang, H.; Liu, X. Improved Prediction of Water Retention Characteristic Based on Soil Gradation and Clay Fraction. *Geoderma* **2021**, *404*, 115293. [CrossRef]
38. Jones, C.A. Effect of Soil Texture on Critical Bulk Densities for Root Growth. *Soil Sci. Soc. Am. J.* **1983**, *47*, 1208–1211. [CrossRef]
39. Schäffer, J. Recovery of Soil Structure and Fine Root Distribution in Compacted Forest Soils. *Soil Syst.* **2022**, *6*, 49. [CrossRef]
40. Seaton, F.M.; George, P.B.L.; Lebron, I.; Jones, D.L.; Creer, S.; Robinson, D.A. Soil Textural Heterogeneity Impacts Bacterial but Not Fungal Diversity. *Soil Biol. Biochem.* **2020**, *144*, 107766. [CrossRef]
41. Fernandes, P.; Souza, A.T.; Tanaka, M.; Sebastiani, R. Decomposition and Stabilization of the Organic Matter in an Old-Growth Tropical Riparian Forest: Effects of Soil Properties and Vegetation Structure. *For. Ecosyst.* **2021**, *8*, 13. [CrossRef]
42. Devi, A.S. Influence of Trees and Associated Variables on Soil Organic Carbon: A Review. *J. Ecol. Environ.* **2021**, *45*, 5. [CrossRef]
43. Heineman, K.D.; Jensen, E.; Shapland, A.; Bogenrief, B.; Tan, S.; Rebarber, R.; Russo, S.E. The Effects of Belowground Resources on Aboveground Allometric Growth in Bornean Tree Species. *For. Ecol. Manag.* **2011**, *261*, 1820–1832. [CrossRef]
44. Cao, S.; Chen, L.; Xu, C.; Liu, Z. Impact of Three Soil Types on Afforestation in China's Loess Plateau: Growth and Survival of Six Tree Species and Their Effects on Soil Properties. *Landsc. Urban Plan.* **2007**, *83*, 208–217. [CrossRef]

45. Huang, Y.; Ma, Y.; Zhao, K.; Niklaus, P.A.; Schmid, B.; He, J.-S. Positive Effects of Tree Species Diversity on Litterfall Quantity and Quality along a Secondary Successional Chronosequence in a Subtropical Forest. *J. Plant Ecol.* **2017**, *10*, 28–35. [CrossRef]
46. Mensah, S.; Noulèkoun, F.; Dimobe, K.; Seifert, T.; Glèlè Kakaï, R. Climate and Soil Effects on Tree Species Diversity and Aboveground Carbon Patterns in Semi-Arid Tree Savannas. *Sci. Rep.* **2023**, *13*, 11509. [CrossRef]