forests

Article

The Role of Stand Age in Soil Carbon Dynamics in Afforested Post-Agricultural Ecosystems: The Case of Scots Pine Forests in Dfb-Climate Zone

Paweł Dłużewski [1,*], Katarzyna Wiatrowska [1] and Sebastian Kuśmierz [2,3,*]

[1] Department of Soil Science, Land Reclamation and Geodesy, Faculty of Environmental Engineering and Mechanical Engineering, Poznań University of Life Sciences, Piątkowska 94, 60-649 Poznań, Poland
[2] Institute of Soil Science, Environmental Engineering and Management, University of Life Sciences in Lublin, Leszczyńskiego 7, 20-069 Lublin, Poland
[3] Department of Soil and Environment, Swedish University of Agricultural Sciences, Lennart Hjelms väg 9, 75007 Uppsala, Sweden
* Correspondence: pawel.dluzewski@up.poznan.pl (P.D.); sebastian.kusmierz@slu.se (S.K.)

Abstract: Land use changes inevitably lead to changes in the carbon stocks stored in the soil. However, despite numerous studies investigating soil organic carbon (SOC) dynamics following the afforestation of post-agricultural lands, findings remain diverse and often inconclusive. In this study, the effect of stand age on the carbon content and stock in Scots pine (Pinus sylvestris) stands located in the Dfb-climate zone was investigated. Five research plots, characterized by similar soil types, geological structures, and tree cover, but differing in stand age (14-, 27-, 37-, 55-, 90-year-old stands), were selected. Additionally, one plot was located at arable soil as a reference. The soil was sampled from both organic and mineral horizons. The content of organic carbon in the organic horizion increased with years that passed from afforestation and amounted to 234.0, 251.6, 255.0, 265.0 and 293.0 $g\cdot kg^{-1}$ in 14-, 27-, 37-, 55- and 90-year-old stands, respectively. Such a pattern was also observed in the upper mineral horizons where the contents of SOC gradually increased from 7.27 $g\cdot kg^{-1}$ up to 17.1 $g\cdot kg^{-1}$. In the organic horizon, the stock of OC increased significantly with stand age up to 55 years after afforestation, while in the former plough layer, SOC stocks were found to slowly increase with stand age. The afforested soils, with the organic horizon, reached levels of carbon stocks observed on arable land after 17 years. Notably, the SOC stock in the mineral A horizon reach this level after 83 years. The obtained results indicate that in the years immediately following afforestation, SOC content is notably higher in arable soils compared to forest soils. However, as stand age increases, the SOC contents of upper horizons in forest soils surpass those of comparable agricultural soils. The observed SOC variability pinpoints the necessity of long-term monitoring in forest ecosystems in order to better understand the temporal dynamics of carbon turnover and to optimize afforestation strategies for long-term carbon sequestration.

Keywords: soil organic carbon; afforestation; coniferous forests; forest stand age

check for updates

Citation: Dłużewski, P.; Wiatrowska, K.; Kuśmierz, S. The Role of Stand Age in Soil Carbon Dynamics in Afforested Post-Agricultural Ecosystems: The Case of Scots Pine Forests in Dfb-Climate Zone. *Forests* **2024**, *15*, 2127. https://doi.org/10.3390/f15122127

Academic Editors: Lei Deng, Jiwei Li and Kaibo Wang

Received: 25 October 2024
Revised: 26 November 2024
Accepted: 29 November 2024
Published: 1 December 2024

1. Introduction

Soil carbon stocks are significantly impacted by the long-standing greenhouse effect and associated climate changes, notably characterized by an increase in average annual air and soil temperatures [1–4]. Additionally, land use changes have been shown to profoundly influence soil carbon content, soil productivity, and the atmospheric concentrations of carbon dioxide and other greenhouse gases [5,6]. The conversion of green areas into farmland has resulted in a global loss of 24% of soil organic carbon (SOC) [7], indicating the crucial need to rethink the current land use and carbon sequestration strategies [8].

Globally, soils hold around 75% of the terrestrial carbon [9,10], with forest soils contributing roughly 40% to total SOC stocks [11,12]. Afforestation alters the carbon cycle by replacing annual agricultural activities with longer-term forest growth, introducing different quantities and qualities of organic matter. This transition enhances biomass production and SOC content, and additionally leads to reducing soil disturbances, thereby promoting greater carbon sequestration [13,14]. However, the literature on SOC dynamics in the afforested post-agriculture areas presents varying results. Some studies report an increase in SOC from the onset of afforestation, while others note a significant decrease compared to previous agricultural use [15–17]. Paul et al. (2002) [16] reviewed 43 studies from 204 plots, revealing significant variability, especially in young stands (<10 years old). These discrepancies were mainly associated with differences in previous land use, climatic conditions, forest type and anthropogenic activity [15]. Given that long-term sequestration occurs mainly within soil organic matter, recognizing the stand age and the timeframe over which newly afforested ecosystems surpass agroecosystems in carbon accumulation is a key factor for proper management against climate change [18].

Despite extensive global studies on the potential of and barriers to carbon sequestration practices [19–23], many questions regarding their long-term impacts remain unresolved. Particular attention must be given to the multi-scaled spatial variability. Even within the European Union (EU), which aims to achieve substantial carbon balance targets, inherent soil and climatic conditions vary significantly. This variability precludes the accurate estimation of carbon sequestration potential without site-specific experimental data [24–26]. Therefore, comprehensive, localized studies are essential to effectively assess and implement carbon sequestration strategies.

Climatic conditions, which have been extensively studied for their impact on SOC turnover [13,21,23], have been shown to influence soil susceptibility to carbon sequestration to a greater extent than previously anticipated [27–29]. The Dfb-climate zone (continental climate with a warm summer subtype) [30–32], which encompasses many EU countries, poses risks associated not only with acidification and nutrient leaching, but also with rapid soil organic matter (SOM) decomposition [33–35]. This underscores the necessity for detailed research on the site-specific impacts of carbon sequestration practices, including forest management [36,37].

In order to tackle aforementioned uncertainties, research was conducted to address gaps in current knowledge and provide a detailed analysis of SOC changes of post-arable soils—afforested with Scot pine.

2. Materials and Methods

2.1. Study Area

The research area was located in the central part of Poland, in the Wielkopolska Province, Smolniki Forest District in Skrzynka Wielka (52°25′28.8″ N; 18°00′15.4″ E, 106.82 m a.s.l). The study area represents the Dfb-climate zone's climatic conditions. The analyzed area is situated in a flat moraine plateau characterized by a composition of both till and gravelly sand formations of the Vistula glaciation. In reality, the research facility is located on a sandy terrace of a small glacial channel filled with organic soils composed of low peat contents. The terrain denivelations range from 3 to 5 m [38]. Five research plots were established in this area, each exhibiting uniform habitat conditions, including soil type and forest stand composition. The plots represent a range of forest stand ages; additionally, one plot was localized in arable land as a reference area (Figure 1 and Table 1). All plots were influenced by similar climatic conditions (Dfb-climate), water regimes (predominance of precipitation over evaporation, groundwater level over 1 m below A horizon), geological origins of parent materials (Pleistocene fluvioglacial sand deposition), grain size distributions (sand-predominant), and topographical features (plain with minimal or no elevation changes). The soils across the study area were classified as Dystric Brunic Arenosols according to the WRB classification [39].

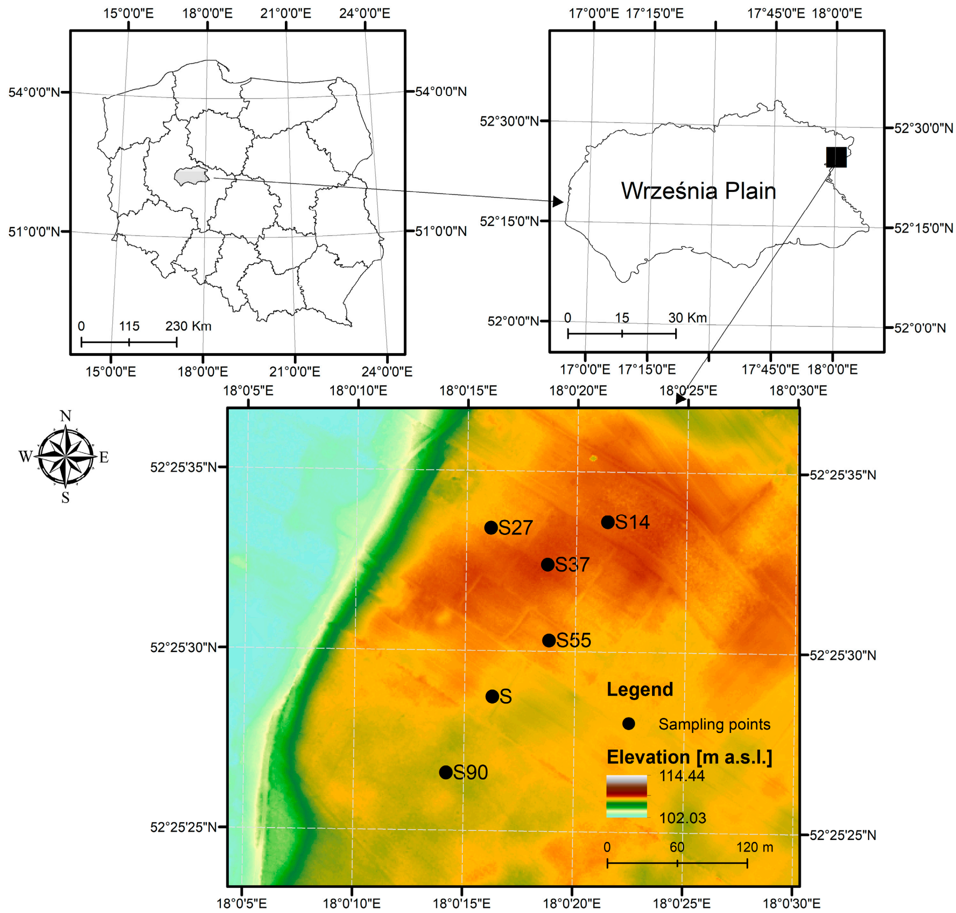

Figure 1. Location of research plots and digital terrain model (m a.s.l.—meters above sea level).

Table 1. Characteristics of the research points.

Plot Abbreviation	Characteristic
Forest 14-year-old stand (S14)	A 14-year-old stand dominated by Scots pine (*Pinus sylvestris*, 70%), with silver birch (*Betula pendula*, 20%), European beech (*Fagus sylvatica*, 10%), and occasional European larch (*Larix decidua*).
Forest 27-year-old stand (S27)	A 27-year-old stand with a predominance of Scots pine (80%), silver birch (20%), and occasional small-leaved linden (*Tilia cordata*) and black locust (*Robinia pseudoacacia*).
Forest 37-year-old stand (S37)	A 37-year-old stand primarily composed of Scots pine (100%), with occasional silver birch.
Forest 55-year-old stand (S55)	A 55-year-old stand consisting almost entirely of Scots pine (100%), with occasional silver birch.
Forest 90-year-old stand (S90)	A 90-year-old stand predominantly of Scots pine (100%), with occasional silver birch, sessile oak (*Quercus petraea*), and black alder (*Alnus glutinosa*).
Arable land (S)	An arable land control area for comparative purposes.

2.2. Sampling and Preparation

Before the localization of the research plots, preliminary studies were carried out to assess the spatial variability of the study site to ensure representativeness and minimize variability in the study design. Subsequently, six research plots with a 5 × 5 m size were designated, and further plots were subdivided into 25 1 m-square subplots. For the analysis, composite soil samples (in tripplicate) from the mineral horizon were collected monthly for 2 years, as were samples from the organic horizon and samples to assess bulk density (in duplicate).

2.3. Analyses

The samples taken were air-dried at a temperature of 21 °C and then sieved through a 2 mm sieve. For the analyses, only the fraction consisting of soil particles smaller than 2 mm in diameter was used. Coarse material, constituting less than 0.5% by weight, was excluded to ensure compliance with the standard criteria for soil analysis.

The following soil properties were determined: soil texture by the hydrometric method [40], pH by the potentiometric method in 1M KCl solution and in H_2O in the ratio 1:2.5 m:v [41], organic carbon content by the dry combustion method using an Multi N/C 3100 TC–TN analyzer (Analytik Jena, Germany). Due to the lack of carbonate salts in the tested samples, total carbon was considered to be organic carbon [42]. Nitrogen was assessed by the Kjeldahl method, and exchangeable forms of Ca, Mg, K and Na were determined by the atomic absorption technique in an extract of 1 M ammonium acetate at pH 7.0. The bulk density was determined using the gravimetric method as the ratio of soil core mass dried at 105 °C to its volume (100 cm^3) (ISO 11272) [43]. The density of the organic horizon was determined by cutting squares with a size of 20 cm from the O horizon. The samples were taken in duplicate, transported to the laboratory at 4 °C, and dried for 72 h ay 70 °C [44].

An internal laboratory reference material and reagent blank were used in order to control the accuracy of soil analyses. The values obtained fall in the required range of the reference content. The instrument detection limit for SOC in the samples was 0.03 $mg \cdot kg^{-1}$.

Organic carbon stock ($kg \cdot m^{-2}$) was calculated on the basis of its total content, soil density and horizon thickness, according to the formula

$$\text{Cstock} = (\%\ \text{SOC} \times \cdot \rho\text{c} \times \text{m})/10$$

where % SOC—organic carbon content in the analyzed soil horizon (%), ρc—soil bulk density in the given soil horizon ($g \cdot cm^{-3}$), m—thickness of a given soil horizon (cm).

2.4. Statistical Methods

Descriptive statistics, including measures of central tendency and dispersion, were calculated to summarize the data prior to further analysis. Differences in mean soil organic carbon (SOC) contents among forest stands were evaluated using Tukey's Honestly Significant Difference (HSD) test. Further variations in SOC content were assessed using the non-parametric Friedman analysis of variance due to the non-normal distribution of the data. Interrelationships among soil parameters were analyzed using Principal Component Analysis (PCA), which reduces data dimensionality by identifying principal components that account for the maximum variance in the dataset. To achieve the requirement of variable comparability, PCA was computed after standardizing the data with the formula

$$x_{sc} = \frac{x_i - mean(x)}{sd(x)}$$

where x_{sc} is the scaled variable, x_i is the individual variable, $mean(x)$ is the mean of x values, and $sd(x)$ is the standard deviation of x values. To further examine and better visualize pairwise relationships between variables, matrix correlation was computed using the Performance Analytics version 2.0.4 R-package. The quantitative influence of forest stand age on SOC stock in the mineral horizon was evaluated using exponential regression analysis with polynomial degrees up to the second order. In addition, to further elaborate on obtained data, dendrogram hierarchical clustering utilizing the complete linkage method was performed to examine the grouping patterns among the forest stands based on their SOC accumulation. All statistical computations were carried out using Statistica 13.01

software (TIBCO Software Inc., Palo Alto, CA, USA) and RStudio (Posit PBC, Boston, MA, USA).

3. Results

3.1. Bulk Density

Bulk density measurements were conducted separately for the litter layer and mineral horizon. The litter density in the organic horizon decreased with the age of the stand, and ranged from 0.319 g·cm^{-3} in the S90 forest stand to 0.392 g·cm^{-3} in the S14. The results indicate that the bulk density was relatively consistent across the individual profiles. At the ochric level, bulk density ranged from 1.39 g·cm^{-3} in the S90 forest stand to 1.50 g·cm^{-3} in the arable land (Table 2). A similar trend was observed for the organic horizon, whereby density decreases with the increase in the age of the stand.

Table 2. Summary of soil physical properties of the plots studied.

Reference Area	Litter Density (g·cm^{-3})	Bulk Density (g·cm^{-3})	Particle Density (g·cm^{-3})	Porosity (cm^{-3}·cm^{-3})
		ρc	ρs	fc
S90	0.319	1.39	2.59	0.46
S55	0.352	1.40	2.61	0.47
S37	0.364	1.43	2.62	0.46
S27	0.368	1.45	2.63	0.45
S14	0.392	1.48	2.63	0.45
S	-	1.50	2.62	0.44

ρc—mass of soil per unit volume, including the pore spaces; ρs—density of the solid particles of the soil, excluding pore spaces; fc—the fraction of the soil's total volume that is occupied by pore spaces.

3.2. Soil Organic Carbon

The contents of SOC in the organic horizon increased with the age of the stand, and amounted to 234.0, 251.6, 255.0, 265.0 and 293.0 g·kg^{-1} in the 14-, 27-, 37-, 55- and 90-year-old stands, respectively. The SOC contents in the A layer across all analyzed soil samples during the measurement period varied from 4.84 to 31.43 g·kg^{-1} (Figure 2). There was considerable variability in the SOC content in the soil upper horizon among the research plots, as indicated by a coefficient of variation (CV) of 49.1%.

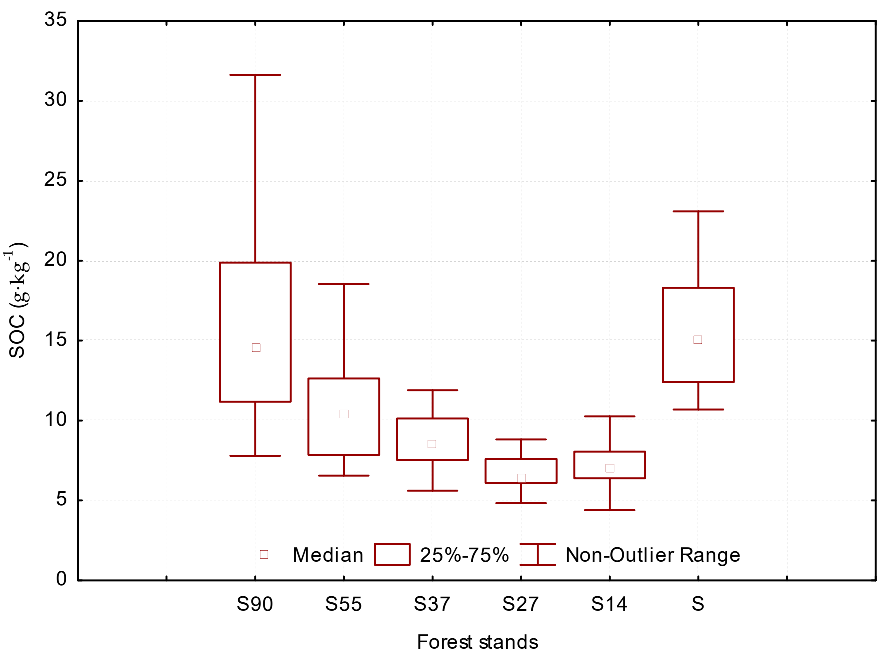

Figure 2. Variation of SOC contents in soils (0–23 cm depth) on the Skrzynka Wielka test plot.

The oldest forest stands (S90 and S55) demonstrated markedly higher SOC contents, with values of 17.10 g·kg^{-1} and 11.30 g·kg^{-1}, respectively. In contrast, younger forest stands exhibited significantly lower SOC contents, with average values ranging from 8.84 g·kg^{-1} (S37) to 7.02 g·kg^{-1} (S27) and 7.27 g·kg^{-1} (S14). The SOC content in the agriculturally managed soil was 15.34 g·kg^{-1} (Figure 2).

The analysis of SOC content in the deeper soil horizons indicated the gradual decrease in SOC with soil depth among all analyzed stands (Figure 3). The S90 stand was characterized by the steepest rate of decline in the upper horizons, yet was found to be the most rich in SOC among all of the tested forest stands, particularly in the horizons deeper than described in the previous section. Notably, the agriculturally managed soil was characterized by a substantially higher carbon content in the deeper soil horizons compared to the forest stands.

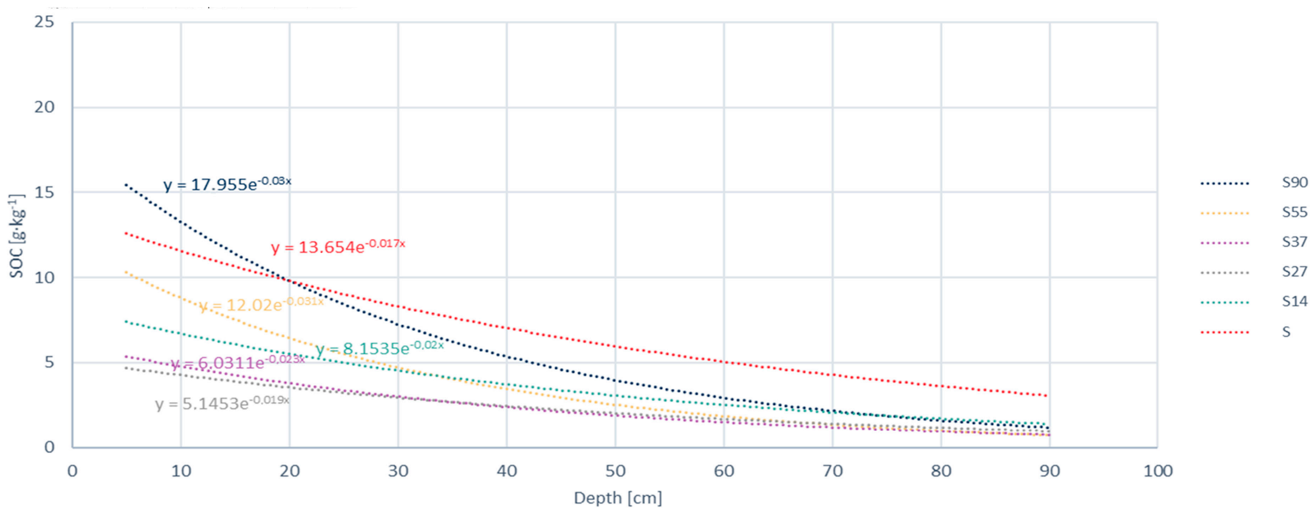

Figure 3. Rates of SOC content reduction with soil depths (exponential fitting was employed to highlight the trends).

Hierarchical classification (Figure 4) illustrates that soils with the lowest SOC content (S27 and S14) were the most similar, forming a distinct group. Another group included soils of the older stands (S37 and S55), while the most divergent soils were those from S90 and S. This indicates a significant impact of forest stand age on SOC accumulation, with older stands accumulating substantially more SOC.

Table 3. SOC stocks (kg·m^{-2}) in the horizons of the topsoil.

Forest Stand	Sum of O + A	O Horizon	A Horizon
S90	8.47	3.74	4.72
S55	9.68	6.52	3.16
S37	7.25	4.64	2.61
S27	6.58	4.63	1.95
S14	3.97	1.83	2.14
S	4.51	-	4.51

Variables derived from the S stand with Ap horizon corresponding to depth (0—23 cm).

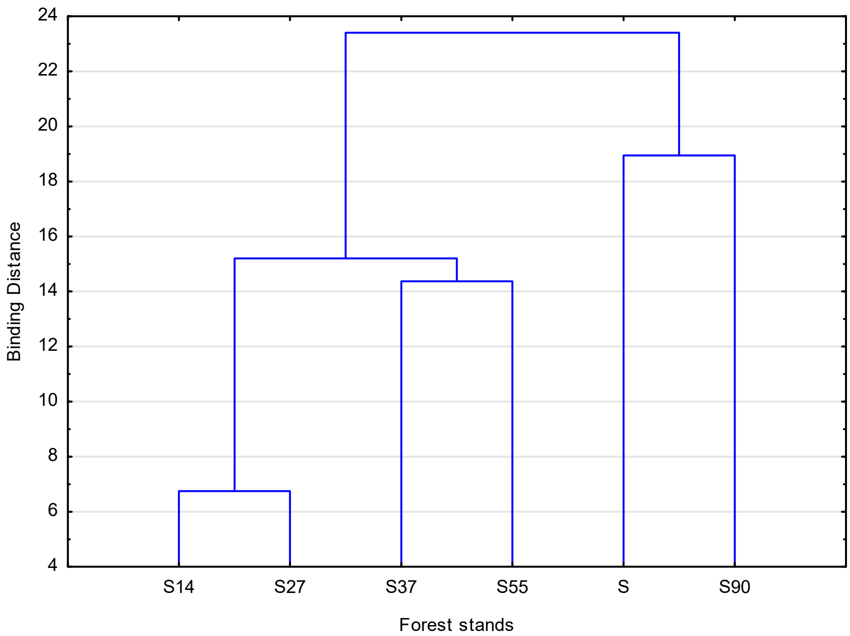

Figure 4. Hierarchical classification of SOC content for analyzed forest stands.The lowest stock of SOC in the organic horizon of the afforested soils was recorded in S14 (1.83 kg·m^{-2} on average), and this increased with stand age up to 6.52 kg·m^{-2} in the S55 (Tab.3). The SOC stock in the mineral horizon also increased with the age of the stand and ranged from 1.95 kg·m^{-2} in S27 to 4.72 kg·m^{-2} in S90, while in the arable land (S), it was 4.51 kg·m^{-2} (Table 3). An important observation regarding all test stands is that the stocks of SOC in the sum of organic and mineral horizons were notably higher in afforested soils than in the arable land, and, furthermore, the difference increased with stand age (Table 3).

Polynomial regression analysis further demonstrated that SOC stock is significantly influenced by forest stand age. Notably, model fitting revealed that the observed impact was most pronounced in the A horizon ($R^2 > 95\%$), whereas the O horizon and the combined organic and mineral horizons exhibited a comparatively lower degree of fit ($R^2 < 50\%$) (Table 4). The obtained model allowed the estimation of the time required for SOC stock in the A horizon of afforested soil to reach levels corresponding to those of arable soil, which was calculated to be approximately 83 years.

Table 4. Regression model for SOC stock as a function of forest stand age.

	Quadratic Coefficient	**Linear Coefficient**	**Intercept**	**R^2**
A horizon	0.0003	0.0073	1.8501	0.9746
O horizon	−0.0023	0.2652	−1.3427	0.3412
A + O horizons	−0.0021	0.2727	0.4994	0.4914

3.3. Soil Physicochemical Properties

Across the pedogenic horizons (Supplement Table S1), substantial heterogeneity of other soil properties was observed (Supplement Table S2). The upper horizons exhibited higher concentrations of SOC, nitrogen and CEC compared to the deeper horizons. However, an exception was noted in the S55 soil profile, where the AE horizon had a slightly lower SOC content than the underlying A-horizon. The concentrations of analyzed exchangeable cations associated with the soil's sorption complex also diminished progressively with depth. Principal Component Analysis revealed significant relationships between soil organic carbon and other measured soil properties (Figure 5). The first principal component explained 56.1% of the total variance in the dataset, while the second principal component accounted for an additional 13.6%, resulting in a cumulative explained variance of 69.7%, making them suitable for interpreting key trends among the variables. In the SOC cosine squared, 67% of variance was effectively captured by both the first- and second-dimension plains.

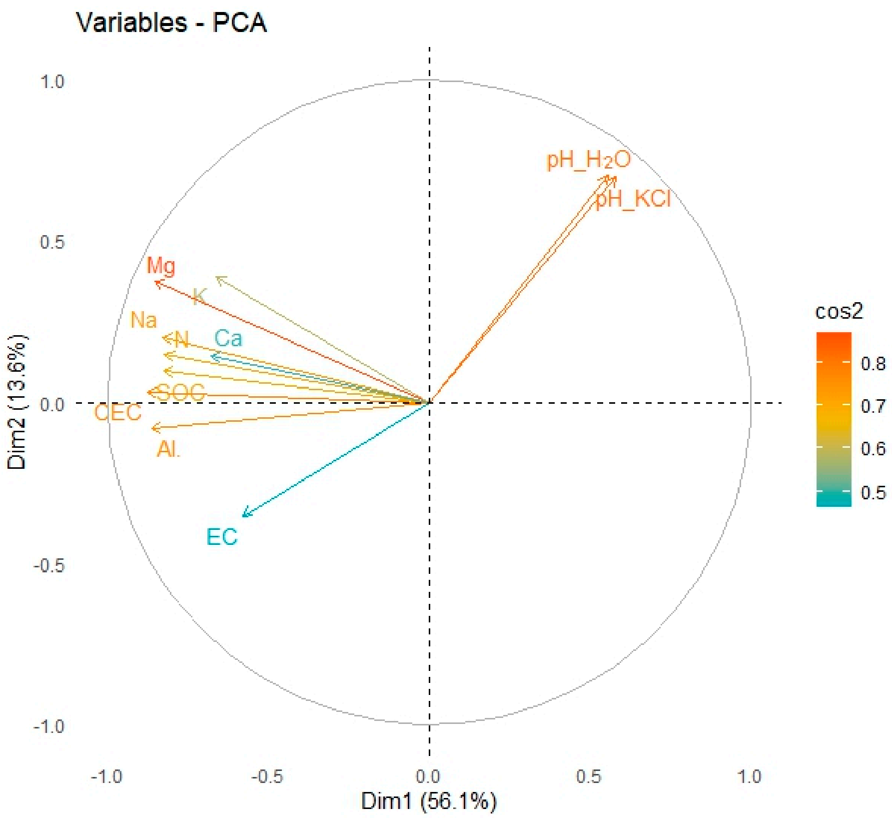

Figure 5. Principal Component Analysis correlation circle. Each vector's length represents the contribution of a variable to PC1 (Dim1) and PC2 (Dim2) principal components. The angle between the vectors indicates the correlation between the given variables: close to 0 degrees for strong positive correlation, close to 180 degrees for strong negative correlation, and close to 90 degrees for weak or near-zero correlation. A color scale based on cosine squared (cos2) was added to better visualize the variable's total variance, as explained by PC1 and PC2.

Notable interrelations were observed among analyzed soils' chemical parameters (Figure 5, Supplement Figure S1). The SOC content was significantly ($p < 0.01$) correlated with each measured parameter except for pH measured in H_2O solution. However, pH measured in the KCl solution showed a negative significant correlation with SOC on tested soils. Positive correlations were noted between SOC, N and CEC, as well as all analyzed exchangeable cations. The pH measured in KCl solutions showed a significant negative correlation with SOC on tested soils.

4. Discussion

The analysis of grain size characteristics revealed that the average contents of soil particles were as follows: very coarse sand 3%, coarse sand 24%, medium sand 34%, fine sand 31%, and very fine sand 4%. This distribution corroborates Krygowski's (1953) [38] observations of well-washed sandy sediments in a Dfb-climate, which were reported as indicative of soil-forming processes. Despite the availability of rigorous methods for selecting research plots and ensuring comparability, the study areas exhibited considerable soil and habitat micro-variability. This variability is likely attributable to historical land treatments and other factors affecting carbon input and accumulation. These factors were challenging to identify and control within the short timeframe of the research program.

Nonetheless, the criteria for selecting research plots, such as similar soil cover, climatic and meteorological conditions and topography, enabled the acquisition of a comprehensive chrono-sequence.

The analyzed soils exhibited comparable pedogenic structures, though the depths of individual horizons varied notably (Supplement Table S1). Interestingly, the AE horizon was present only in the S55 stand. This observation aligns with previous studies, which indicate that afforestation, particularly in coniferous stands, promotes the accumulation of forest litter, leading to changes in soil properties. In humid climates, like the analyzed Dfb-climatic zone, where precipitation exceeds evapotranspiration, such accumulation can enhance the leaching of labile organic compounds and contribute to progressive acidification. Despite a clear decrease in pH with increasing soil depth (Table 4, Supplement Table S2), no distinct eluvial horizon was observed in either the younger stands or the older S90 stand. This absence may be related to the dynamics of organic matter accumulation and mineralization in afforested soils. While forest litter accumulation tends to increase with stand age [45,46], this process eventually reaches a threshold where increased rates of mineralization limit further organic matter buildup, potentially reducing the thickness of the organic horizon. Our findings support this interpretation, as the thickness of the O horizon increased with stand age up to the S55 stage, but decreased notably in the S90 stand (Supplement Table S1), suggesting a shift in organic matter dynamics as the forest matures.

When analyzing mineral surface horizons, the results obtained align with the documented changes in soil organic carbon content with forest stand age [47–49]. The lower SOC content observed in younger forest stands (S14 and S27) may be attributed to the intensive oxidation of organic compounds resulting from mechanical soil preparation for afforestation. This disturbance likely increased soil oxygen diffusion and accelerated organic matter mineralization. Additionally, the lower input of forest litter in these younger stands could have contributed to the reduced SOC content in the upper horizons (Figure 2). Notably, the highest SOC content in the upper mineral horizons was found in the soils of the oldest stands, with contents of 11.3 $g \cdot kg^{-1}$ (S55) and 17.1 $g \cdot kg^{-1}$ (S90). Such values, which are higher than those reported in young forests soils [50], further support our findings.

Interestingly, the variance of SOC content in the analyzed horizons was strongest in older stands (S55, S90), indicating higher heterogeneity, which may be attributed to the diverse nature of the forest litter and plant debris, including both conifers and deciduous trees, and its varying susceptibility to microbial decomposition [51,52]. The SOC heterogeneity in arable land was slightly higher than that seen in younger forest stands, with a CV of 22.45%, which may reflect cyclical fluctuations in SOC content due to variations in crop residue input and organic fertilizer applications, followed by periods of intense mineralization. Such potential explanations have often been given in agroforestry- and carbon farming-related studies, indicating that, in addition to local variables [53], environmental management can disrupt soil SOC variability [54,55]. Additionally, the observed variability in SOC stocks may reflect the uneven organic matter input into the soil. In older forest stands, forest litter production, driven by factors such as species composition, stand age, canopy density, and tree health [18,56], play a crucial role in soil formation.

Both the O and A horizons exhibited similar patterns regarding the dependence of SOC on stand age. Including the organic horizon in assessments underscores the benefits of afforestation for carbon accumulation. Nevertheless, due to its long-term stability, the mineral soil horizon is considered a more reliable indicator of long-term carbon sequestration potential [57]. Interestingly, a notable decline in SOC stocks was observed shortly after afforestation when forest litter was excluded from consideration (Table 3), and the underlying mechanisms remain unclear. The observed decrease in SOC stocks after afforestation compared to reference arable land may be attributed to pre-planting soil preparation activities that promote oxidizing conditions, which may enhance organic matter mineralization. Additionally, the absence of tree cover during early afforestation stages increases soil exposure to solar radiation, further accelerating decomposition processes. Regression analysis (Table 4) suggests that SOC stocks in the

A horizon will recover to levels comparable to arable soils approximately 83 years post-afforestation. This finding underscores the necessity of long-term monitoring to elucidate carbon dynamics in post-agricultural afforested soils, as highlighted by the review study performed by Mäkipää et al. (2023) [4].

The SOC stock in the O horizon of afforested soils ranged from 46% in 14-year-old stands to 67% in 57-year-old stands. These proportions exceed those reported by Laganière et al. (2010) [58], where the organic horizon accounted for 17% of the total SOC stock. Similarly, the SOC stocks observed in our study were higher than those reported by Shi et al. (2013) [59]. Interestingly, though, the variabilities registered by us in some SOC contents and stocks were comparable to ones shown in the study of Hooker and Compton (2003) [60], who investigated afforested post-agricultural soils in the United States. Such resemblance may indicate that the observed stand age has similar effect patterns to SOC, regardless of climate zone.

SOC's dependence on stand age (Figures 2 and 3), as observed in our study, is consistent with the results of Laganiere et al. (2010) [58], Kang et al. (2018) [61] and Smal et al. (2019) [62], who also reported elevations in carbon accumulation in the post-agricultural afforested soils with forest stand age. However, in our study, interesting patterns were also observed across soil depths (Figure 3), indicating that the observed phenomena occur regardless of forest soil depths. Similarly to SOC, other analyzed soil parameters also elucidated a gradual decline with the soil depth (Supplement Table S2).

Close interrelations between SOC content and he analyzed soil characteristic variables (Supplement Figure S1) further pinpoint the complexity of carbon turnover in afforested soils. In our case study, the notable inter-effects between variations in SOC, pH and exchangeable cations seem to shape the PC1 and PC2 plains when depicted in reduced dimensions (Figure 5). It could be theorized that the process of soil acidification, which progresses with stand age (Supplement Table S2), affects the transformation of organic carbon in the soil environment. An increase in the soil concentration of hydrogen ions may slow down the rate of organic matter mineralization [63], promoting the condition required for its accumulation in forest soils.

Along with the observed intercorrelations (Figure 5, Supplement Figure S1), the aforementioned SOC–forest stand age dependence indicates the potential to develop explanatory and predictive Dfb-climate-specific SOC model derivations, the need for which has been highlighted in the European Union Agenda for climate neutrality [64]. However, it has to be noted that the observed SOC–stand age dependence has to be taken into account when validating such models for forest soils.

5. Conclusions

This study underscores the dynamic nature of soil organic carbon accumulation across different-aged Scots pine stands within the Dfb-climate zone, revealing a distinct age-dependent gradient in SOC content. The highest degree of SOC accumulation was observed in the surface mineral horizon of the oldest stands (90 years), with younger stands exhibiting reduced SOC. The upper horizons showed significant SOC stock increases with stand age, underscoring their role as a critical carbon sink in afforested soils. Notably, the SOC in afforested soils reached levels comparable to those in arable soils after approximately 83 years in the mineral horizon, reinforcing the importance of long-term afforestation practices in carbon sequestration. Our findings highlight the need for the long-term monitoring of SOC stocks in afforested post-agricultural soils. However, further research on other forest types under diverse climatic conditions is crucial to determine the specific age at which afforested soils surpass, from the global perspective, former agricultural lands in terms of carbon accumulation. Such studies will offer valuable insights that will help in optimizing site-specific afforestation strategies, ultimately enhancing carbon sequestration potential and contributing to climate change mitigation.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/f15122127/s1, Figure S1: Analyzed soil parameters' correlation matrix; Table S1: Depths of soil horizons and particle size distributions in the studied soils; Table S2: Selected soil physicochemical properties' variability across soil horizons.

Author Contributions: P.D.: conceptualization, P.D., K.W. and S.K.; data curation, P.D. and S.K.; formal analysis, P.D.; methodology, P.D. and K.W.; software, P.D.; visualization, P.D. and S.K.; writing—review and editing, P.D., K.W. and S.K. All authors have read and agreed to the published version of the manuscript.

Funding: The publication was financed by the Polish Minister of Science and Higher Education as part of the Strategy of the Poznan University of Life Sciences for 2024–2026 in the field of improving scientific research and development work in priority research areas.

Data Availability Statement: The original contributions presented in the study are included in the article, and further inquiries can be directed to the corresponding authors.

Conflicts of Interest: The authors declare that they have no known financial interests or personal relationships that could have influenced the work reported in this paper.

References

1. Xu, E.; Zhang, H.; Xu, Y. Effect of Large-Scale Cultivated Land Expansion on the Balance of Soil Carbon and Nitrogen in the Tarim Basin. *Agronomy* **2019**, *9*, 86. [CrossRef]
2. 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]
3. Gautam, M.; Agrawal, M. Greenhouse Gas Emissions from Municipal Solid Waste Management: A Review of Global Scenario. In *Carbon Footprint Case Studies*; Springer: Berlin/Heidelberg, Germany, 2021; pp. 123–160.
4. Mäkipää, R.; Abramoff, R.; Adamczyk, B.; Baldy, V.; Biryol, C.; Bosela, M.; Casals, P.; Curiel Yuste, J.; Dondini, M.; Filipek, S.; et al. How Does Management Affect Soil C Sequestration and Greenhouse Gas Fluxes in Boreal and Temperate Forests? *A Review. For. Ecol. Manag.* **2023**, *529*, 120637. [CrossRef]
5. Lal, R. Soil Conservation and Ecosystem Services. *Int. Soil Water Conserv. Res.* **2014**, *2*, 36–47. [CrossRef]
6. Yoro, K.O.; Daramola, M.O. Effect. In *Advances in Carbon Capture*; Elsevier: Amsterdam, The Netherlands, 2020; pp. 3–28.
7. Murty, D.; Kirschbaum, M.U.F.; Mcmurtrie, R.E.; Mcgilvray, H. Does Conversion of Forest to Agricultural Land Change Soil Carbon and Nitrogen? A Review of the Literature. *Glob. Chang. Biol.* **2002**, *8*, 105–123. [CrossRef]
8. Paul, C.; Bartkowski, B.; Dönmez, C.; Don, A.; Mayer, S.; Steffens, M.; Weigl, S.; Wiesmeier, M.; Wolf, A.; Helming, K. Carbon Farming: Are Soil Carbon Certificates a Suitable Tool for Climate Change Mitigation? *J. Environ. Manag.* **2023**, *330*, 117142. [CrossRef]
9. Lal, R. Forest Soils and Carbon Sequestration. *For. Ecol. Manag.* **2005**, *220*, 242–258. [CrossRef]
10. Le Quéré, C.; Andrew, R.M.; Canadell, J.G.; Sitch, S.; Korsbakken, J.I.; Peters, G.P.; Manning, A.C.; Boden, T.A.; Tans, P.P.; Houghton, R.A.; et al. Global Carbon Budget 2016. *Earth Syst. Sci. Data* **2016**, *8*, 605–649. [CrossRef]
11. Dixon, R.K.; Solomon, A.M.; Brown, S.; Houghton, R.A.; Trexier, M.C.; Wisniewski, J. Carbon Pools and Flux of Global Forest Ecosystems. *Science* **1994**, *263*, 185–190. [CrossRef]
12. Huntington, T.G. Carbon Sequestration in an Aggrading Forest Ecosystem in the Southeastern USA. *Soil Sci. Soc. Am. J.* **1995**, *59*, 1459–1467. [CrossRef]
13. Wiesmeier, M.; Prietzel, J.; Barthold, F.; Spörlein, P.; Geuß, U.; Hangen, E.; Reischl, A.; Schilling, B.; von Lützow, M.; Kögel-Knabner, I. Storage and Drivers of Organic Carbon in Forest Soils of Southeast Germany (Bavaria)—Implications for Carbon Sequestration. *For. Ecol. Manag.* **2013**, *295*, 162–172. [CrossRef]
14. Wiesmeier, M.; Urbanski, L.; Hobley, E.; Lang, B.; von Lützow, M.; Marin-Spiotta, E.; van Wesemael, B.; Rabot, E.; Ließ, M.; Garcia-Franco, N.; et al. Soil Organic Carbon Storage as a Key Function of Soils—A Review of Drivers and Indicators at Various Scales. *Geoderma* **2019**, *333*, 149–162. [CrossRef]
15. Zhang, Q.; Jia, X.; Wei, X.; Shao, M.; Li, T.; Yu, Q. Total Soil Organic Carbon Increases but Becomes More Labile after Afforestation in China's Loess Plateau. *For. Ecol. Manag.* **2020**, *461*, 117911. [CrossRef]
16. Paul, K.I.; Polglase, P.J.; Nyakuengama, J.G.; Khanna, P.K. Change in Soil Carbon Following Afforestation. *For. Ecol. Manag.* **2002**, *168*, 241–257. [CrossRef]
17. Vopravil, J.; Formánek, P.; Janků, J.; Holubík, O.; Khel, T. Early Changes in Soil Organic Carbon Following Afforestation of Former Agricultural Land. *Soil Water Res.* **2021**, *16*, 228–236. [CrossRef]
18. Vangi, E.; Dalmonech, D.; Morichetti, M.; Grieco, E.; Giannetti, F.; D'Amico, G.; Nakhavali, M.; Chirici, G.; Collalti, A. Stand Age and Climate Change Effects on Carbon Increments and Stock Dynamics. *Forests* **2024**, *15*, 1120. [CrossRef]
19. Kuśmierz, S.; Skowrońska, M. Carbon Farming and Nutrient Management. Influential Factors of Polish Farmers' Perception of pro-Climate Measures. *Agron. Sci.* **2024**, *79*, 5–20. [CrossRef]

20. Jonard, M.; Nicolas, M.; Coomes, D.A.; Caignet, I.; Saenger, A.; Ponette, Q. Forest Soils in France Are Sequestering Substantial Amounts of Carbon. *Sci. Total Environ.* **2017**, *574*, 616–628. [CrossRef]
21. Acosta-Hernández, A.C.; Padilla-Martínez, J.R.; Hernández-Díaz, J.C.; Prieto-Ruiz, J.A.; Goche-Telles, J.R.; Nájera-Luna, J.A.; Pompa-García, M. Influence of Climate on Carbon Sequestration in Conifers Growing under Contrasting Hydro-Climatic Conditions. *Forests* **2020**, *11*, 1134. [CrossRef]
22. Friggens, N.L.; Hester, A.J.; Mitchell, R.J.; Parker, T.C.; Subke, J.; Wookey, P.A. Tree Planting in Organic Soils Does Not Result in Net Carbon Sequestration on Decadal Timescales. *Glob. Chang. Biol.* **2020**, *26*, 5178–5188. [CrossRef]
23. Rajeev, J.; Hukum, S. Carbon Sequestration Potential of Disturbed and Non-Disturbed Forest Ecosystem: A Tool for Mitigating Climate Change. *Afr. J. Environ. Sci. Tech.* **2020**, *14*, 385–393. [CrossRef]
24. Machar, I.; Vlckova, V.; Bucek, A.; Vozenilek, V.; Salek, L.; Jerabkova, L. Modelling of Climate Conditions in Forest Vegetation Zones as a Support Tool for Forest Management Strategy in European Beech Dominated Forests. *Forests* **2017**, *8*, 82. [CrossRef]
25. Van Hoof, S. Climate Change Mitigation in Agriculture: Barriers to the Adoption of Carbon Farming Policies in the EU. *Sustainability* **2023**, *15*, 10452. [CrossRef]
26. Ren, X.; He, J.; Huang, Z. Innovation, Natural Resources Abundance, Climate Change and Green Growth in Agriculture. *Resour. Policy* **2023**, *85*, 103970. [CrossRef]
27. Hui, D.; Ray, A.; Kasrija, L.; Christian, J. Impacts of Climate Change and Agricultural Practices on Nitrogen Processes, Genes, and Soil Nitrous Oxide Emissions: A Quantitative Review of Meta-Analyses. *Agriculture* **2024**, *14*, 240. [CrossRef]
28. PCC Summary for Policymakers. In *Climate Change 2013—The Physical Science Basis*; Intergovernmental Panel on Climate Change, Ed.; Cambridge University Press: Cambridge, UK, 2014; ISBN 9781107057999.
29. Liang, S.; Peng, S.; Chen, Y. Carbon Cycles of Forest Ecosystems in a Typical Climate Transition Zone under Future Climate Change: A Case Study of Shaanxi Province, China. *Forests* **2019**, *10*, 1150. [CrossRef]
30. Li, N.; Skaggs, T.H.; Ellegaard, P.; Bernal, A.; Scudiero, E. Relationships among Soil Moisture at Various Depths under Diverse Climate, Land Cover and Soil Texture. *Sci. Total Environ.* **2024**, *947*, 174583. [CrossRef]
31. Zhang, M.; Gao, Y. Time of Emergence in Climate Extremes Corresponding to Köppen-Geiger Classification. *Weather Clim. Extrem.* **2023**, *41*, 100593. [CrossRef]
32. Beck, H.E.; Zimmermann, N.E.; McVicar, T.R.; Vergopolan, N.; Berg, A.; Wood, E.F. Present and Future Köppen-Geiger Climate Classification Maps at 1-Km Resolution. *Sci. Data* **2018**, *5*, 180214. [CrossRef]
33. Doelman, J.C.; Stehfest, E.; van Vuuren, D.P.; Tabeau, A.; Hof, A.F.; Braakhekke, M.C.; Gernaat, D.E.H.J.; van den Berg, M.; van Zeist, W.; Daioglou, V.; et al. Afforestation for Climate Change Mitigation: Potentials, Risks and Trade-offs. *Glob. Chang. Biol.* **2020**, *26*, 1576–1591. [CrossRef]
34. Bellassen, V.; Angers, D.; Kowalczewski, T.; Olesen, A. Soil Carbon Is the Blind Spot of European National GHG Inventories. *Nat. Clim. Chang.* **2022**, *12*, 324–331. [CrossRef]
35. De Vos, B.; Cools, N.; Ilvesniemi, H.; Vesterdal, L.; Vanguelova, E.; Carnicelli, S. Benchmark Values for Forest Soil Carbon Stocks in Europe: Results from a Large Scale Forest Soil Survey. *Geoderma* **2015**, *251–252*, 33–46. [CrossRef]
36. Vanguelova, E.I.; Bonifacio, E.; De Vos, B.; Hoosbeek, M.R.; Berger, T.W.; Vesterdal, L.; Armolaitis, K.; Celi, L.; Dinca, L.; Kjønaas, O.J.; et al. Sources of Errors and Uncertainties in the Assessment of Forest Soil Carbon Stocks at Different Scales—Review and Recommendations. *Environ. Monit. Assess.* **2016**, *188*, 630. [CrossRef] [PubMed]
37. Van Damme, F.; Mertens, H.; Heinecke, T.; Lefevre, L.; De Meulder, T.; Portillo-Estrada, M.; Roland, M.; Gielen, B.; Janssens, I.A.; Verheyen, K.; et al. The Impact of Thinning and Clear Cut on the Ecosystem Carbon Storage of Scots Pine Stands under Maritime Influence in Flanders, Belgium. *Forests* **2022**, *13*, 1679. [CrossRef]
38. Available online: https://igig.amu.edu.pl/strona-glowna/igig/badania-naukowe/badania-dla-praktyki/mapa-geomorfologiczna-niziny-wielkopolsko-kujawskiej (accessed on 16 May 2024).
39. Mantel, S.; Dondeyne, S.; Deckers, S. World Reference Base for Soil Resources (WRB). In *Encyclopedia of Soils in the Environment (Second Edition)*; Goss, M.J., Oliver, M., Eds.; Elsevier: Amsterdam, Netherlands, 2023; pp. 206–217.
40. Mátra, Z.S.; Heil, B.; Kovács, G.; Lang, F.; Schack-Kirchner, H. Increased Accuracy and Precision of Hydrometric Soil Texture Measurements (Pario Classic Method) with Semi-empiric Correction Functions. *J. Plant Nutr. Soil Sci.* **2022**, *185*, 417–426. [CrossRef]
41. Smith, J.L.; Doran, J.W. Measurement and Use of PH and Electrical Conductivity for Soil Quality Analysis. In *Methods for Assessing Soil Quality*; Soil Science Society of America: Madison, WI, USA, 2015; pp. 169–185.
42. Page, A.L. (Ed.) *Methods of Soil Analysis*; Wiley: Hoboken, NJ, USA, 1982; Volume 9, ISBN 9780891180722.
43. *ISO 11272:2014*; Soil Quality—Determination of Dry Bulk Density. International Organization for Standardization: Geneva, Switzerland, 2014.
44. Hoover, C.M. (Ed.) *Field Measurements for Forest Carbon Monitoring*; Springer: Dordrecht, The Netherlands, 2008; ISBN 978-1-4020-8505-5.
45. Lee, Y.J.; Lee, H.I.; Lee, C.B.; Lee, K.H.; Kim, R.H.; Ali, A. Abiotic and Stand Age-Induced Changes in Tree Diversity and Size Inequality Regulate Aboveground Biomass and Soil Organic Carbon Stock in Temperate Forests of South Korea. *Catena* **2024**, *237*, 107827. [CrossRef]
46. Lili, Z.; Vivek, Y.; Hengchen, Z.; Yaya, S.; Xiangxiang, H.; Xiaoxia, W.; Xiaoping, Z.; Babu, S.; Yongxiang, K. Climate Drivers of Litterfall Biomass Dynamics in Three Types of Forest Stands on the Loess Plateau. *Ecol. Indic.* **2024**, *163*, 112088. [CrossRef]

47. Vesterdal, L.; Ritter, E.; Gundersen, P. Change in Soil Organic Carbon Following Afforestation of Former Arable Land. *For. For. Ecol. Manag.* **2002**, *169*, 137–147. [CrossRef]
48. Shang, S.; Jiang, P.; Chang, S.; Song, Z.; Liu, J.; Sun, L. Soil Organic Carbon in Particle Size and Density Fractionations under Four Forest Vegetation-Land Use Types in Subtropical China. *Forests* **2014**, *5*, 1391–1408. [CrossRef]
49. Dignac, M.-F.; Derrien, D.; Barré, P.; Barot, S.; Cécillon, L.; Chenu, C.; Chevallier, T.; Freschet, G.T.; Garnier, P.; Guenet, B.; et al. Increasing Soil Carbon Storage: Mechanisms, Effects of Agricultural Practices and Proxies. A Review. *Agron. Sustain. Dev.* **2017**, *37*, 14. [CrossRef]
50. Lunstrum, A.; Chen, L. Soil Carbon Stocks and Accumulation in Young Mangrove Forests. *Soil Biol. Biochem.* **2014**, *75*, 223–232. [CrossRef]
51. Malunguja, G.K.; Devi, A. Dynamics of Leaf Litter Decomposition and Macronutrient Mineralisation of Dominant Tree Species in Urban Subtropical Reserve Forests. *Ecol. Front.* **2024**. [CrossRef]
52. Prescott, C.E.; Vesterdal, L. Decomposition and Transformations along the Continuum from Litter to Soil Organic Matter in Forest Soils. *For. Ecol. Manag.* **2021**, *498*, 119522. [CrossRef]
53. Wei, Y.; Chen, Y.; Wang, J.; Wang, B.; Yu, P.; Hong, Y.; Zhu, L. Unveiling the Explanatory Power of Environmental Variables in Soil Organic Carbon Mapping: A Global–Local Analysis Framework. *Geoderma* **2024**, *449*, 117011. [CrossRef]
54. Ugbemuna Ugbaje, S.; Karunaratne, S.; Bishop, T.; Gregory, L.; Searle, R.; Coelli, K.; Farrell, M. Space-Time Mapping of Soil Organic Carbon Stock and Its Local Drivers: Potential for Use in Carbon Accounting. *Geoderma* **2024**, *441*, 116771. [CrossRef]
55. Ward, E.B.; Ashton, M.S.; Wikle, J.L.; Duguid, M.; Bradford, M.A. Local Controls Modify the Effects of Timber Harvesting on Surface Soil Carbon and Nitrogen in a Temperate Hardwood Forest. *For. Ecol. Manag.* **2024**, *572*, 122268. [CrossRef]
56. Wang, G.; Xie, B.; Lv, Y.; Yin, J.; Zhou, Y.; Xu, L.; Shi, Y. Interaction Effect of Stand Age and Diversity on Aboveground Wood Carbon Accumulation in Subtropical Mixed Forests of the Zhejiang Province (China). *Forests* **2023**, *14*, 262. [CrossRef]
57. Zhang, L.; Zhang, P.; Yu, M.; Wu, T. Soil Organic Carbon Content and Stocks in an Age-Sequence of Metasequoia Glyptostroboides Plantations in Coastal Area, East China. In Proceedings of the 2015 4th International Conference on Sustainable Energy and Environmental Engineering, Shenzhen, China, 20–21 December 2015; Atlantis Press: Paris, France, 2016.
58. LAGANIÈRE, J.; ANGERS, D.A.; PARÉ, D. Carbon Accumulation in Agricultural Soils after Afforestation: A Meta-analysis. *Glob. Chang. Biol.* **2010**, *16*, 439–453. [CrossRef]
59. Shi, S.; Zhang, W.; Zhang, P.; Yu, Y.; Ding, F. A Synthesis of Change in Deep Soil Organic Carbon Stores with Afforestation of Agricultural Soils. *For. Ecol. Manag.* **2013**, *296*, 53–63. [CrossRef]
60. Hooker, T.D.; Compton, J.E. Forest ecosystem carbon and nitrogen accumulation during the first century after agricultural abandonment. *Ecol. Appl.* **2003**, *13*, 299–313. [CrossRef]
61. Kang, H.; Gao, H.; Yu, W.; Yi, Y.; Wang, Y.; Ning, M. Changes in Soil Microbial Community Structure and Function after Afforestation Depend on Species and Age: Case Study in a Subtropical Alluvial Island. *Sci. Total Environ.* **2018**, *625*, 1423–1432. [CrossRef] [PubMed]
62. Smal, H.; Ligęza, S.; Pranagal, J.; Urban, D.; Pietruczyk-Popławska, D. Changes in the Stocks of Soil Organic Carbon, Total Nitrogen and Phosphorus Following Afforestation of Post-Arable Soils: A Chronosequence Study. *For. Ecol. Manag.* **2019**, *451*, 117536. [CrossRef]
63. Leifeld, J.; Zimmermann, M.; Fuhrer, J. Simulating Decomposition of Labile Soil Organic Carbon: Effects of PH. *Soil Biol. Biochem.* **2008**, *40*, 2948–2951. [CrossRef]
64. European Commission. *A Clean Planet for All—A European Strategic Long-Term Vision for a Prosperous, Modern, Competitive and Climate Neutral Economy*; European Commission: Brussels, Belgium, 2018.