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Unveiling the Transformative Effects of Forest Restoration on the Soil Chemistry and Biology of Sandy Soils in Southern Nyírség, Hungary

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Abstract: Protecting humankind's natural resources and soils, including forestry, represents a top priority in agriculture. Addressing climate change should prioritize preserving and enhancing organic carbon, specifically humus, in soils. In this paper, we examine the impact of soil preparation on soil humus and microbial life during the reforestation of Southern Nyírség, Hungary. We determined soil plasticity, pH in distilled water solution, the quantity and quality of humus content, the total number of bacteria and microbial fungi, as well as CO_2 production. In addition to stump removal and plowing, the wealthiest layer of organic matter was detached from the surface. A significant decrease in humus content (HU%) was observed at the five experimental sites (loss of 19.20–40.14 HU% at 0–30 cm depth). Soil organic matter is concentrated in the stump depositions. According to the results, the quantity of humus content is strongly correlated with the measured parameters of soil life, specifically with the number of microbial fungi (r = 0.806 **) and the total number of bacteria (r = 0.648 **). Another correlation (r = 0.607 **) was assessed between the humus content and CO_2 production. This study helps to understand the importance of the no-tillage methods used in reforestation.

Keywords: soil fertility; soil properties; reforestation; humus content; microbial fungi; soil bacteria

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1. Introduction

There are about 900 million hectares of sandy soil on Earth, mostly in arid and semi-arid regions. Sandy soils can be found on all continents and, according to WRB, are referred to as arenosols [1]. About 51% of the world's arenosols are located in Africa, 21% in Australia, 10% in Asia, 14% in South and Central America, and a total of 4% in North America and Europe [2]. Nyírség is the second-largest sand ridge in Hungary, occupying a territory of 510,600 hectares, over 20.8% of which is covered by forests [3].

The afforestation of lowland sandy soils in Hungary was conducted in the first half of the 19th and 20th centuries to reduce wind erosion [4]. Deforestation amplified from the 1980s to the 2000s and started to decline after 2007. Subsequently, Hungary experienced the most significant net increase in forest area in Eastern Europe, at 27%, partly because of land conversion [5].

Economical forestlands are increasing worldwide, also due to the growing human population and the resulting increase in demand for wood products, resulting in the continuous transformation of primary forests into secondary forests [6].

In the Mediterranean, many native forests have been converted into agroforestry systems, while abandoned agricultural lands have also been reforested. These land use changes have reduced soil degradation, such as soil erosion. Reforestation on these soils can increase the soil organic carbon (SOC) storage capacity [7].

While carbon sequestration occurs more slowly in soils than in biomass, C stored in soils is more resistant than C stored in biomass [8]. It should be remembered that, globally, soil C storage is decreasing [9]. Soil organic matter concentrations and stocks can be increased through increased organic matter inputs and reduced soil disturbance [7], which we investigated in this paper. The amount of C stored in forest soils is a significant fraction of the world's total C stock. One estimates that SOC stored in forest soil is more than 70% of the global SOC [10]. Other research estimates this value to be just over 40% [11]. Forest conversion and changing human impacts on forests are likely to affect forest biomass and soil C stocks [12]. In forest soils, trees modify microclimatic conditions (especially soil moisture and temperature), increase organic matter (OM) uptake, and improve soil quality [13]. In addition, the absence of tillage in these systems improves soil microbial and faunal communities and the formation of stable aggregates [14], protecting against OM degradation [15]; C/N ratios of afforested soils are more similar to those of arable [16] and horticultural [17] crops than to native forest soils [18]. Forest soils have been recognized as important reservoirs of stable carbon (C) in the biosphere and thus play a key role in the global carbon cycle [19].

Forests are essential for biodiversity conservation and climate change mitigation [20]. According to forestry research, models show a high similarity with the drying and warming weather in the sand ridge area between the Danube and the Tisza rivers (Hungary) [21]. Quicksand and humus sandy soils were formed here [22]. In these soils, proper management practices are required for effective plant production [23]. Kong and co-workers examined the environmental consequences of soil management, comparing the results obtained for Hungarian and Japanese soils. According to their research, land use significantly impacts the cumulative production of N_2O and CO_2 in soil [24]. Ecological management positively affects the quality and fertility of the sandy soils in the Nyírség region by improving the chemical soil parameters and increasing the community size and activity of microbes [25].

The dominant and characteristic element of the forest ecosystem is the woody vegetation [26]. The open surface is less resistant to weather events; in sandy areas, in particular, sand erosion, deflation, and surface warming may be a problem for the survival of young trees. Seedlings try to establish an extended cover as soon as possible; this explains why black locusts (*Robinia pseudoacacia*, L.) show intensive height growth at 1–5 years of age [27]. To initiate forest regeneration growth, it may be advisable to intervene actively in soil improvement, mainly where the topsoil is very shallow, i.e., only a few cm thick, and its humus content is less than 1.0–1.5%, as we found in many cases after tillage in our study.

Deforestation is the most critical factor in soil degradation, as it changes the soil environment, the availability of nutrients, and the carbon cycle [28,29]. With changes in land use, the natural ecosystem deteriorates, and soil erosion may occur [30].

Forest management practices can positively and negatively affect forest soil, greenhouse gases, and carbon balance [12,31]. Clear-cutting is the most common and impactful deforestation practice worldwide. It usually negatively affects soil organic C content, resulting in a 10% reduction in soil OM in the overall soil profile [32]. Coniferous forest floor C stocks decreased 30 years after clear-cutting: when at its lowest stock level, Picea and Pinus forest floor C stocks were reduced relative to the initial stock levels by 23% and 14%, respectively [33].

Post-cutting reforestation promotes the rapid establishment of new stands. Nevertheless, reforestation causes additional soil disturbance (rotation), affecting soil temperature and moisture, potentially impacting soil biological activity and respiration [34].

Following tree harvesting in the study area, forest exploitation primarily involves the removal of stumps using rotary excavators. The stumps are then sorted into depositions. This operation also removes the wealthiest layer of organic matter, specifically the top 0–5 cm. The relocation of organic matter is assumed to be highly detrimental to soil life and, therefore, to the subsequent development of forest regeneration. One should protect the soil from erosion and deflation damage. Soil organic carbon and total nitrogen content were reduced. In contrast, soil pH, electrical conductivity, and soil nutrients (available P, K, and Ca) were increased for at least 2 years after field burning in fallow years [35]. Dissolved organic carbon (DOC) and soil organic carbon (SOC) react differently on sloping lands with water erosion, where plant age and density may cause variances in nutrient loss [36]. Their physical properties and topsoil thickness mainly determine the water-holding capacity of soils [37].

Humus is a complex variable material consisting of several high-molecular-weight compounds with roughly the same basic structure [38]. Seasonal fluctuations in biological activity are more pronounced in soils with low humus content than in soils with higher humus content [39,40]. Based on this finding, it is essential to investigate the impact of soil cultivation on humus content and preserve the soil's organic matter stock.

The sample plots were selected in the Nyírerdő Ltd. (Nyíregyháza, Hungary) areas with forest end-use. Our research focused on investigating the properties of different soil types at the sites of the planned forest renewal (afforestation). After the end-use tree harvesting, various operations were conducted, including stump extraction, landscaping, and deep plowing. As the sampling posed severe difficulties and was time-consuming, the authors had to limit their investigation to collecting and processing 60 samples, which were needed for statistical evaluation. The results presented here were obtained by exploring five different soil profiles. On each sample, we performed 8 types of tests, so that 480 data points were processed in the study. We examined the changes in properties across different soil layers using physical, chemical, and microbiological methods. We aim to identify correlations between the measured chemical and microbial parameters of soils with varying physical and chemical properties, demonstrating the adverse effects of complete tillage on reforestation efforts.

2. Materials and Methods

2.1. Overview of the Sampling Sites

Soil profiles were excavated after the end-use harvesting of trees at several villages in the Hosszúpályi and Debrecen areas. Five soil profiles were explored in the examined regions after tree harvesting at four locations. Soil samples were collected in unplowed areas before stump removal (Figure 1).

The maximum humus content was found in the top 0–30 cm layer. At depths below 30 cm, we determined a humus content of less than 0.1% in each soil profile before plowing. After plowing (Figure 2), samples were extracted from depths of 0–30 cm and 30–70 cm, as well as from the rows where the stumps were deposited.

Figure 1. Stump depositing is in progress (HP 7 H)—original photograph taken by the author István Attila Kocsis.

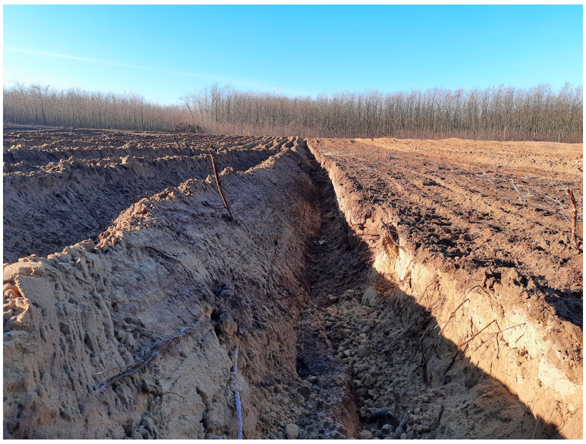

Figure 2. Deep plowing is in progress (HP 4 L)—original photograph taken by the author István Attila Kocsis.

During planting, roots are placed in the 0–30 cm layer, crucial for saplings to access water and nutrients. Table 1 lists the extracted tree species and species for afforestation.

Table 1. The location of the examined forest areas, the deforested areas, and planned tree species for afforestation.

Location of the Forest	Extracted Tree Species	Tree Species for Afforestation
Hosszúpályi 7 H	Scotch pine (*Pinus sylvestris*, L.)	Black locust (*Robinia pseudoacacia*, L.)
Hosszúpályi 8 M	Cotton wood (*Populus x*)	Black locust (*Robinia pseudoacacia*, L.)
Hosszúpályi 8 M	Cotton wood (*Populus x*)	Cottonwood (*Populus x*)
Hosszúpályi 4 L	Black locust (*Robinia pseudoacacia*, L.)	Scotch pine (*Pinus sylvestris*, L.)
Debrecen 369 A	Scotch pine (*Pinus sylvestris*, L.)	Black locust (*Robinia pseudoacacia*, L.)

Table 2 is a summary table indicating the sampling locations, their GPS coordinates, cultivation methods, sampling depths, and the number of collected samples. The forests in the study were unmixed plantations unaffected by extraordinary events, such as storm damage. They were at the age recommended for end-use cutting according to Hungarian regulations.

Sampling locations are shown on the map (Figure 3). These forest restorations coincided.

Table 2. The sites of soil sampling and the applied cultivation methods.

Sampling Sites with GPS Coordinates (GPSWGS84)	Cultivation Methods	Depth (cm)	Sample No.
Forest I. Hosszúpályi 7 H 47.431, 21.730	* HP 7 H: unplowed	0–30	1
	HP 7 H: deep plowed upper layer	0–30	2
	HP 7 H: deep plowed lower layer	30–70	3
	HP 7 H: row of tree stumps with soil content	0–15	4
Forest II. (high-altitude area) Hosszúpályi 8 M 47.424, 21.734	HP 8 M: unplowed	0–30	5
	HP 8 M: deep plowed upper layer	0–30	6
	HP 8 M: deep plowed lower layer	30–70	7
	HP 8 M: row of tree stumps with soil content	0–15	8
Forest II. (deep-altitude area) Hosszúpályi 8 M 47.427, 21.733	HP 8 M: unplowed	0–30	9
	HP 8 M: deep plowed upper layer	0–30	10
	HP 8 M: deep plowed lower layer	30–70	11
	HP 8 M: row of tree stumps with soil content	0–15	12
Forest III. Hosszúpályi 4 L 47.407, 21.702	HP 4 L: unplowed	0–30	13
	HP 4 L: deep plowed upper layer	0–30	14
	HP 4 L: deep plowed lower layer	30–70	15
	HP 4 L: row of trees stumps with soil content	0–15	16
Forest IV. Debrecen 369 A 47.503, 21.811	DB 369 A: unplowed	0–30	17
	** DB 369 A: deep plowed upper layer	0–30	18
	DB 369 A: deep plowed lower layer	30–70	19
	DB 369 A: row of tree stumps with soil content	0–15	20

* Hosszúpályi (HP). ** Debrecen (DB).

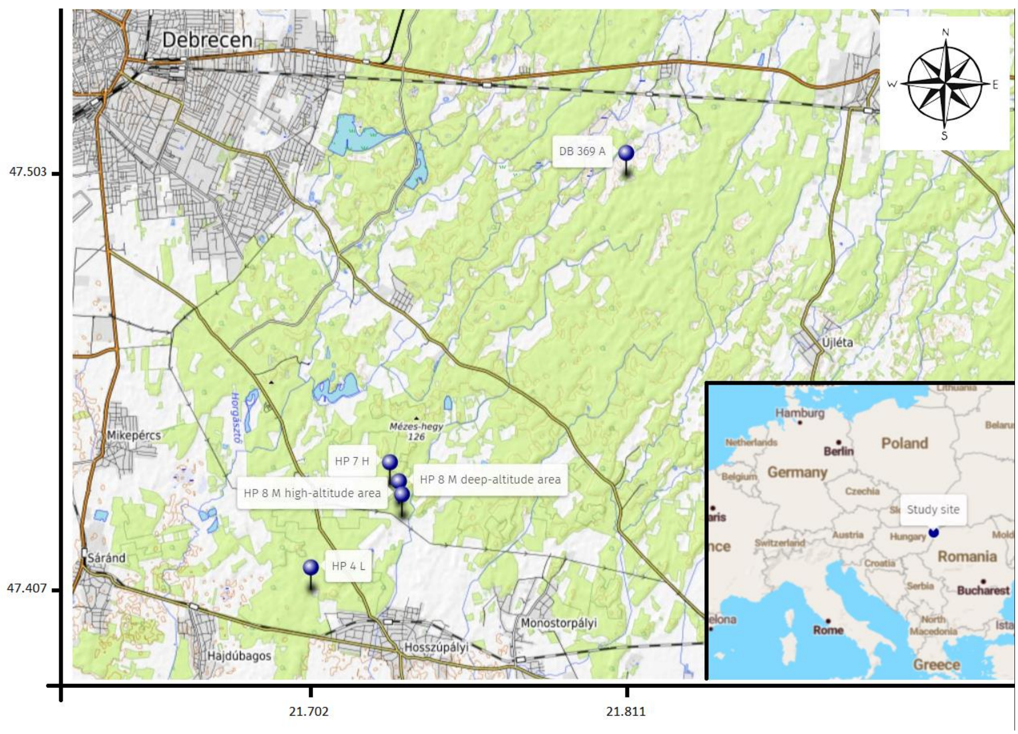

Figure 3. Sampling locations in the Southern Nyírség (Hungary).

2.2. Soil Sampling and Analyses

In the five selected forest sections, soil profile excavations were performed according to simple random sampling [41]. Samples were taken from 3 locations within each examined layer to characterize the profiles. We performed physical, chemical, and microbiological analyses for the collected soil samples to evaluate soil fertility quality. We determined the following soil properties: soil plasticity, pH in distilled water solution, and humus content quantity and quality. We measured the total number of bacteria, microbial fungi, and CO_2 production among the microbiological properties. A key objective of the study was to establish correlations among humus content, microscopic fungi, soil bacteria, CO_2 production, soil pH, and humus stability parameters.

Soil samples were measured at the soil chemistry and biology laboratories of the Institute of Agricultural Chemistry and Soil Science at the DE MÉK in Debrecen, Hungary, during the 2022 growing season. Among the physical properties measured, the Arany-type plasticity index (KA) was determined [42].

The humus content of the soil (HU%) was measured using the Székely colorimetric method, according to the Hungarian standard procedure [43,44]. This method is based on the ability of soil organic matter to be oxidized with $K_2Cr_2O_7$, where the reaction proceeds with a change in solution color from orange to green. To determine the organic carbon content of the samples, the measurement was performed at a 580 nm wavelength using a Philips Unicam PU 8600 UV spectrophotometer. The CO_2 production was evaluated via NaOH trapping after 10 days of incubation [45].

The "Hargitai two-solvent" method was utilized to determine the humus quality [46,47]. The samples were treated with aqueous NaOH (0.5 wt.%) and NaF (1.0 wt.%) solutions, respectively, and the stability of the humic substances was estimated from the light absorption (extinction, E NaOH, E NaF) of the two extracts. Measurements were performed by colorimetry with a Philips UPU 8600 UV spectrophotometer at the wavelengths of 480 nm (Q4), 540 nm (Q5), and 670 nm (Q6), respectively. The stability value Q of the humus was calculated according to Equation (1).

$$Q = \text{E NaF}/\text{E NaOH}. \quad (1)$$

While its mean value is given by Equation (2).

$$Q_{average} = (Q4 + Q5 + Q6)/3. \quad (2)$$

The stability coefficient (K) per unit humus content was calculated according to Equation (3).

$$K = \text{E Na}/(\text{E NaOH} \times \text{HU\%}). \quad (3)$$

The higher the value of the coefficient K, the more stable the quality of the humus is. Soil pH was measured by adding 1.0 part soil to 2.5 parts distilled water, pH (H_2O) solution (according to the Hungarian standard [48]). The pH was measured with a Jenway 570 pH Meter digital instrument [49].

Two microbiological parameters, the total number of bacteria, $\times 10^6$ (g soil)$^{-1}$ (colony-forming units, CFUs), and the number of microscopic fungi, $\times 10^3$ (g soil)$^{-1}$, were determined by plate dilution on a bouillon plate and peptone–glucose agar, respectively [50]. To evaluate the total bacteria, incubation was conducted at 30 $\pm$ 1 °C for 48 h. For the microscopic fungi, incubation was 72 h at 25 $\pm$ 1 °C. After incubation, colony counting was performed on a Leica-type colony counter. The CO_2 production was evaluated by NaOH trapping from fresh soil samples after 10 days of incubation at 25 °C [45,51,52].

2.3. Statistical Methods

The effect of soil preparation technologies on the soil's physical, chemical, and biological properties was assessed by one-way ANOVA ($p < 0.05$) analysis. The cultivation methods at each sampling site were compared with the Tukey post hoc test. All measurements were conducted in triplicate, and data analysis was performed using Microsoft

Excel 2016 and IBM SPSS (version 29.0.0.0) to process and evaluate the results. Pearson's correlation was applied to explore the relationships between the examined parameters.

3. Results

The soil profile of the Hosszúpályi (HP) 7 H forest is displayed in Table 3; the measurements acquired in the study are listed in Table 4.

Table 3. The soil profile of the Hosszúpályi 7 H sampling area of the forest (humous sand; WRB Arenosols). Original photograph taken by the author István Attila Kocsis.

Horizon Designation	Horizon Depth (cm)	Description of the Soil Layer
Ah	0–5	Reddish gray (2.5YR 5/1) color, single-grain sand, slightly humic level
AC	5–50	Light reddish gray (2.5YR 7/1) color, single-grain sand, slightly humus-like, roots interspersed
Bw	50–110	Light red (2.5YR 7/6) color, single-grain sand, sparsely rooted
Cl/Bt	110–140	Reddish brown (2.5YR 5/4) color, single-grain sand
Cl/Bt	140–170	Pinkish gray (7.5YR 6/2) color, single-grain sand
Clr	170–	Gray (7.5YR 6/1) color, single-grain sand with reductive features

Table 4. The examined physical, chemical, and biological properties of the Hosszúpályi forest (HP) 7 H sample site.

Sample	KA	HU%	Stability Coefficient (K)	pH (H_2O)	Microscopic Fungi × 10^3 g^{-1}	Soil Bacteria × 10^6 g^{-1}	mg CO_2 × 100 g^{-1} Soil	mg CO_2 × 100 g^{-1} × 10 Day^{-1}
1	19.80 ± 0.79 ab	0.36 ± 0.28 a	1.26 ± 0.14 a	4.59 ± 0.20 a	31.50 ± 5.27 ab	0.95 ± 0.27 a	12.97 ± 1.85 a	13.67 ± 2.46 a
2	18.20 ± 1.42 a	0.22 ± 0.13 a	7.06 ± 1.40 b	5.41 ± 0.23 b	51.50 ± 4.36 b	0.41 ± 0.09 a	12.47 ± 1.38 a	13.27 ± 1.17 a
3	18.40 ± 1.64 a	0.10 ± 0.04 a	0.53 ± 0.13 a	5.22 ± 0.22 b	10.50 ± 1.50 a	0.68 ± 0.24 a	13.45 ± 0.47 a	16.78 ± 1.22 ab
4	21.70 ± 0.70 b	4.20 ± 0.53 b	0.07 ± 0.03 a	4.69 ± 0.12 a	121.50 ± 21.78 c	7.68 ± 0.64 b	17.88 ± 1.14 b	17.86 ± 1.11 c

Data marked with the same letter in the columns is not significantly different at $p \leq 0.05$.

Our measurements found an extremely low humus content (HU% = 0.36) in the upper soil underlying the harvested pine (*Pinus sylvestris*, L.) forest. In contrast, the soil's pH was strongly acidic, with a pH (H_2O) of 4.59. Fungal activity of 31.5 × 10^3 (g soil)$^{-1}$ was considerable. After deep plowing, the organic matter content of the upper soil layer decreased to 0.22 HU%; however, according to our measurements, more stable humus materials from the deeper layers moved toward the surface (K = 7.06). After plowing, 0.10 HU% was measured at a depth of 30–70 cm, while a considerable quantity of organic matter (4.20 wt.%) accumulated in the stump row. The stability coefficient (K) was very low (K = 0.07), indicating poor humus quality. As a result of the stump removal, the upper soil layer containing the humus was concentrated in the stump row, having weakly decomposed plant remains. As a result of the large amount of accumulated organic matter, the number of microbial fungi in the stump row increased significantly to 121.5 × 10^3 (g soil)$^{-1}$.

Table 5 displays the soil profile of the Hosszúpályi (HP) 8 M forest area, while Table 6 includes the measurements performed.

Table 5. The soil profile of the Hosszúpályi 8 M higher-lying area is brown forest soil with alternating thin layers of clay substance (WRB Arenosols). Original photograph taken by the author István Attila Kocsis.

Horizon Designation	Horizon Depth (cm)	Description of the Soil Layer
Ah	0–10	Dark gray (2.5Y 4/1) color, sandy loam, strong humus level, interwoven with roots
E1	10–15	Grayish white (2.5Y 8/1) color, single-grain sand, slightly humus level, interwoven with roots
A/E	15–45	Gray (2.5Y 6/2) color, single-grain sand, interspersed with roots, traces of soil mixing
E2	45–50	Light gray (2.5Y 7/1) color, single-grain sand, root interspersed
Bw	50–55	Gray (7.5YR 6/1) color, single-grain sand, interspersed with roots, organic matter accumulation
C	55–85	Pinkish gray (7.5YR 7/2) color, more compacted, single-grain sandy loam
C/Bt	85–140	Dark reddish brown (2.5YR 3/3) color, compacted loam layer
Clr	140–150	Grayish brown (2.5Y 5/2) color, rootless sand
Clr	150–	Gray (2.5Y 5/1) color single-grain sand with reductive features

Table 6. The examined physical, chemical, and biological properties of the Hosszúpályi forest (HP) 8 M higher sample site.

Sample	KA	HU %	Stability Coefficient (K)	pH (H_2O)	Microscopic Fungi $\times 10^3$ g^{-1}	Soil Bacteria $\times 10^6$ g^{-1}	mg CO_2 $\times$ 100 g^{-1} Soil	mg CO_2 $\times$ 100 g^{-1} $\times$ 10 Day^{-1}
5	36.20 ± 1.49 c	2.84 ± 0.24 b	0.46 ± 0.14 a	6.68 ± 0.27 b	151.75 ± 36.52 b	0.70 ± 0.21 a	14.70 ± 2.39 a	15.13 ± 2.05 ab
6	22.00 ± 2.12 a	1.70 ± 0.32 a	0.99 ± 0.31 b	5.66 ± 0.32 a	28.00 ± 7.37 a	1.55 ± 0.34 b	12.56 ± 1.23 a	13.36 ± 0.94 a
7	28.60 ± 1.39 b	1.27 ± 0.26 a	0.38 ± 0.05 a	6.31 ± 0.24 ab	12.50 ± 4.92 a	1.06 ± 0.26 ab	12.05 ± 1.54 a	17.51 ± 1.07 b
8	31.50 ± 0.92 b	1.41 ± 0.16 a	1.39 ± 0.17 b	7.23 ± 0.56 b	15.00 ± 2.18 a	5.55 ± 0.34 c	13.08 ± 1.14 a	16.47 ± 1.42 ab

Data marked with the same letter in the columns is not significantly different at $p \leq 0.05$.

The Hosszúpályi 8 M forest profile was diverse in terms of micro-topography. Soil plasticity was loam in the upper soil layer and sand in the deeper layer. The soil profile of the area located at a higher elevation is displayed in Table 5, while the results are shown in Table 6. Historically, the area was home to poplar trees (*Populus* spp.). The soil layer near the surface contained 2.84 wt.% humus with a stability coefficient of K = 0.46. After deep plowing, these values changed to HU% = 1.70 and K = 0.99, respectively; thus, the organic matter content decreased due to plowing. Nonetheless, the deeper soil layer's humus materials of better quality were repeatedly brought closer to the soil surface. The soil was mildly acidic with high fungal activity, peaking at 151.75 $\times$ 10^3 g^{-1} soil before plowing. The stump row's humus content and quality were like the plowed soil layers.

Table 7 displays the second explored soil profile of the Hosszúpályi 8 M forest section.

Table 7 reveals an intense glaciation in depth. During deep plowing, the ironstone located at 40 to 60 cm depths was loosened. These test results are listed in Table 8. The humus accumulated extensively (4.01 HU%) in the upper layer, where a dark-colored layer is visible to the naked eye. The pH was slightly alkaline (pH 7.79), and the bacterial activity of the soil was substantial, equal to 10.73 $\times$ 10^6 (g soil)$^{-1}$, which was found to be the highest value among the samples in our study. After soil cultivation, we determined the HU% to be 3.24 in the upper soil layer, almost identical to the accumulated humus in the stump row (HU% = 3.11). Meanwhile, the humus content at a 30–70 cm depth was 1.03% HU. We found high-quality humus materials within this depth range with a K value of 2.33.

Table 7. The soil profile of the Hosszúpályi 8 M deep-lying area (meadow soil; WRB Chernic Gleysoil). Original photograph taken by the author István Attila Kocsis.

Horizon Designation	Horizon Depth (cm)	Description of the Soil Layer
Ah1	0–10	Very dark gray (10YR 3/1) color, subangular blocky structure, clay loam, heavily humic level, heavily rooted.
Ah2	10–35	Dark grayish brown (10YR 4/21) color, subangular blocky structure, loamy loam, highly humic level, heavily rooted, slightly calcareous
Blo	35–55	Red (2.5YR 4/6) color, single-grain structure loam, sparsely rooted
Ab	55–80	Dark reddish gray (2.5YR 4/1) color, grain structure loam, less rooted
C	80–120	Grayish white (2.5Y 8/1) color, single-grain sand
Clo	120–160	Olive gray (2.5Y 5/2) color, single-grain sand
Clr	160–	Bluish-gray color (GLEY2 5/5B) loam

Table 8. The examined physical, chemical, and biological properties of the Hosszúpályi forest (HP) 8 M deeper sample site.

Sample	KA	HU %	Stability Coefficient (K)	pH (H_2O)	Microscopic Fungi $\times 10^3$ g^{-1}	Soil bacteria $\times 10^6$ g^{-1}	mg CO_2 $\times$ 100 g^{-1} Soil	mg CO_2 $\times$ 100 g^{-1} $\times$ 10 Day^{-1}
9	42.60 ± 1.59 c	4.01 ± 0.16 b	2.11 ± 0.22 a	7.79 ± 0.36 a	37.00 ± 5.41 bc	10.73 ± 1.22 c	14.54 ± 0.72 a	15.81 ± 1.41 a
10	30.60 ± 1.99 a	3.24 ± 0.36 b	2.26 ± 0.18 a	7.52 ± 0.33 a	24.00 ± 6.61 ab	6.45 ± 0.28 b	13.69 ± 1.28 a	14.34 ± 1.33 a
11	34.10 ± 1.04 ab	1.03 ± 0.48 a	2.33 ± 0.21 a	7.92 ± 0.27 a	11.50 ± 2.65 a	0.73 ± 0.10 a	15.69 ± 1.45 a	17.88 ± 1.98 a
12	38.40 ± 2.38 bc	3.11 ± 1.03 b	2.07 ± 0.13 a	7.84 ± 0.28 a	43.50 ± 8.35 c	7.12 ± 0.35 b	14.26 ± 1.01 a	15.39 ± 0.92 a

Data marked with the same letter in the columns is not significantly different at $p \leq 0.05$.

In the past, the area was home to black locust (*Robinia pseudoacacia*, L.) trees. The upper layer consists of sandy loam, and sand is in the deeper layers (see Table 9). Before tillage, the soil's humus content was only 0.26 wt.%, which decreased after deep plowing to 0.17 wt.% in the upper 0–30 cm layer. Nevertheless, close to the surface, the small organic matter content exhibited high stability (K = 1.55), which increased in part with depth in the 30–70 cm range after deep plowing (K = 1.87). Such an increase may be favorable to the later development of the tree seedlings. The pH of the soil was strongly acidic (pH 4.15), resulting in a low total bacterial count. By contrast, the number of fungi increased considerably.

Table 10 lists the results of examining the physical, chemical, and biological properties of the Hosszúpályi forest (HP) 4 L sample site. Standard deviations are also provided.

The Debrecen 369 A forest area (Table 11) is characterized by an old pine (*Pinus sylvestris*, L.) forest, which results in a highly acidic soil pH.

The soil plasticity was sand in all layers of the profile. A high organic matter accumulation was found close to the surface (HU% = 4.33, Table 12). Nevertheless, it mainly consisted of raw humus with clearly recognizable remains of plant parts. Therefore, the stability coefficient was very low (K = 0.07). As a result of the extremely high content of organic matter, we found a vast number of fungi, 430.5 $\times$ 10^3 (g soil)$^{-1}$, which indicated a high rate of decomposition by microscopic fungi. The pH of the soil was strongly acidic (pH 4.08), and the pH did not increase significantly after cultivation (pH 4.63). The humus content decreased, however, in the 0–30 cm depth range (HU% = 2.82). A significant amount of organic matter (HU% = 3.11) appeared on the established stump row. High CO_2 production was measured in all soil samples because of the large quantity of organic matter.

Table 9. The soil profile of the Hosszúpályi 4 L forest section (Blownsand; WRB: Arenosols). Original photograph taken by the author István Attila Kocsis.

Horizon Designation	Horizon Depth (cm)	Description of the Soil Layer
Ah	0–20	Brown (7.5YR 5/2) color, single-grain sand, slightly humus-like, rooted
A/C	20–40	Brown (7.5YR 4/4) color, single-grain sand, buried in a lightly humic layer, interspersed with roots. The shape of layer boundaries is irregular
C	40–90	Light Brown (7.5YR 6/4) color, single-grain sand, sparsely rooted
C/Bt	90–180	Brown (7.5YR 4/4) color, single-grain sand
Cl	180–	Gray (7.5YR 6/1) color, single-grain sand

Table 10. The examined physical, chemical, and biological properties of the Hosszúpályi forest (HP) 4 L sample site.

Sample	KA	HU%	Stability Coefficient (K)	pH (H_2O)	Microscopic Fungi × 10^3 g^{-1}	Soil Bacteria × 10^6 g^{-1}	mg CO_2 × 100 g^{-1} Soil	mg CO_2 × 100 g^{-1} × 10 Day^{-1}
13	26.70 ± 1.39 c	0.26 ± 0.09 a	1.55 ± 0.38 b	4.15 ± 0.12 a	39.50 ± 8.35 b	0.73 ± 0.18 a	10.76 ± 0.44 a	16.30 ± 1.21 b
14	18.10 ± 1.25 a	0.17 ± 0.07 a	0.48 ± 0.10 a	4.25 ± 0.22 a	16.50 ± 2.50 a	1.24 ± 0.26 a	11.17 ± 2.50 a	12.73 ± 1.39 a
15	21.80 ± 1.14 b	0.41 ± 0.10 a	1.87 ± 0.18 b	5.63 ± 0.34 b	4.50 ± 1.00 a	0.87 ± 0.19 a	12.68 ± 1.57 a	15.22 ± 0.75 ab
16	28.90 ± 1.14 c	0.96 ± 0.32 b	0.32 ± 0.15 a	5.02 ± 0.54 ab	73.50 ± 13.43 c	3.46 ± 0.17 b	13.82 ± 0.49 a	14.02 ± 0.27 ab

Data marked with the same letter in the columns is not significantly different at $p \leq 0.05$.

Table 11. The soil profile of the Debrecen 369 A forest section (humous sand; WRB: Arenosols)—Original photograph taken by the author István Attila Kocsis.

Horizon Designation	Horizon Depth (cm)	Description of the Soil Layer
Ah	0–3	Gray (7.5YR 5/1) color, single-grain sand, slightly humus-like level, rooted
E	3–20	Light gray (7.5YR 7/1) color, single-grain sand, slightly humus-like level, rooted
Bw	20–55	Dark brown (7.5YR 3/3) color, single-grain sand, heavily rooted
C	55–90	Reddish yellow (7.5YR 6/6) color, single-grain sand, lightly rooted
Clr	90–160	Dark gray (7.5YR 4/1) color, single-grain sand

The loss of humus content in each area is illustrated (Figure 4). The humus content of each sample area was marked with a dark color, while the data relating to the new soil condition measured after the soil preparation at the same depth (0–30 cm) was marked with a light color.

Table 12. The physical, chemical, and biological properties of the Debrecen Forest (DB) 369 A sample site were examined.

Sample	KA	HU %	Stability Coefficient (K)	pH (H_2O)	Microscopic Fungi × 10^3 g^{-1}	Soil Bacteria × 10^6 g^{-1}	mg CO_2 × 100 g^{-1} Soil	mg CO_2 × 100 g^{-1} × 10 Day^{-1}
17	19.70 ± 0.62 ab	4.33 ± 0.28 c	0.07 ± 0.03 a	4.08 ± 0.19 a	430.50 ± 30.43 d	7.77 ± 1.60 c	16.68 ± 3.98 a	17.19 ± 2.25 a
18	17.60 ± 1.73 a	2.82 ± 0.22 b	0.16 ± 0.07 a	4.63 ± 0.29 b	124.50 ± 17.68 b	2.70 ± 0.63 ab	12.54 ± 2.05 a	15.72 ± 1.35 a
19	17.90 ± 0.69 ab	1.03 ± 0.33 a	0.32 ± 0.25 a	5.42 ± 0.22 c	22.50 ± 4.58 a	0.78 ± 0.28 a	15.85 ± 5.19 a	17.63 ± 1.73 a
20	20.40 ± 082 b	3.11 ± 0.48 b	0.09 ± 0.03 a	4.61 ± 0.10 ab	184.50 ± 23.11 c	4.11 ± 0.16 b	17.62 ± 1.18 a	17.81 ± 1.36 a

Data marked with the same letter in the columns is not significantly different at $p \leq 0.05$.

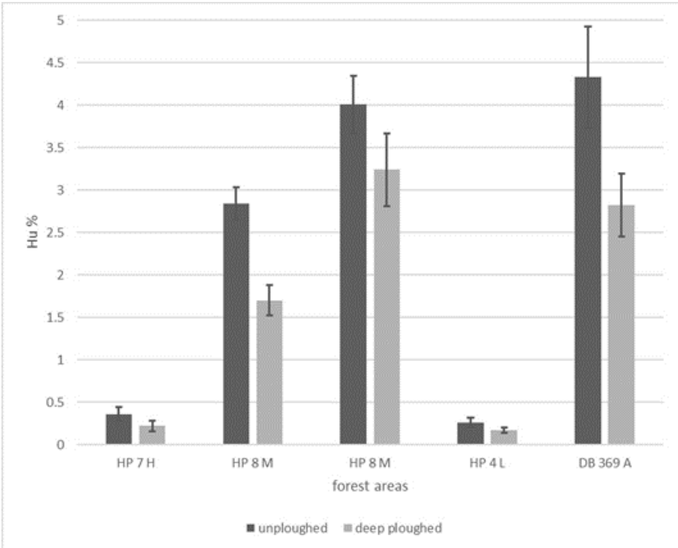

Figure 4. Change in the humus content in the upper 0–30 cm layer of the total sample areas (summary diagram) (n = 3).

The diagram reveals that the amount of organic matter decreased at all planting depths, with no exception. The organic matter accumulated in the row of tree stumps.

In the Hosszúpályi 7 H forest unit, a loss of 38.89 HU% was ascertained in the 0–30 cm planting soil depth. In the high-altitude part of the Hosszúpályi 8 M forest unit, one assessed 40.14 HU% loss, while in the low-altitude part of the area, only 19.20 HU% loss was found. The loss determined in the Hosszúpályi 4 L forest unit was 34.62 HU%, while in the Debrecen 369 A forest unit, the loss was equal to 34.87 HU%. The average amount of organic matter loss caused by the tillage practices in the study areas was 33.54% (see Table 13).

Table 14 lists the results of a correlation analysis among the parameters studied. This analysis enabled us to understand the relationships between the variables. The correlation values highlighted medium and close correlations. The correlation table includes all the sections and their tested parameters.

The humus content strongly correlates with the number of microscopic fungi (r = 0.806). The decomposition of organic matter can explain this. Nonetheless, the humus content also correlates positively with the number of bacteria (r = 0.648) and at a medium level with the CO_2 production (r = 0.607). Hence, as expected, the organic matter content is related to the number of soil microbes.

The decrease in organic matter content assessed in the upper layer of the deep-plowed soil layer is particularly hazardous in sandy soils because it results in lower colloid content of the soil, along with decreased amounts of nutrients and water. When the afforestation of these areas is completed, professionals must pay special attention to the new young plants and provide thorough care for soil preparation.

Table 13. Losses of humus content of the sample areas in the upper 0–30 cm layer.

Forest	Sample	HU (%)	HU (%) Loss
HP 7 H: unplowed HP 7 H: deep plowed	1 2	0.36 0.22	38.89
HP 8 M: upper lying unplowed HP 8 M: upper lying deep plowed	5 6	2.84 1.70	40.14
HP 8 M: deep-lying area unplowed HP 8 M: deep-lying area deep plowed	9 10	4.01 3.24	19.20
HP 4 L: unplowed HP 4 L: deep plowed	13 14	0.26 0.17	34.62
DB 369 A: unplowed DB 369 A: deep plowed	17 18	4.33 2.82	34.87
			Average: 33.54%

Table 14. Pearson-type correlation table (n = 24).

Pearson Correlations						
	HU%	**K-Coefficient**	**pH (H_2O)**	**Microscopic Fungi**	**Total No. of Bacteria**	**CO_2 Production**
HU%	1					
K coefficient	−0.330	1				
pH (H_2O)	0.017	0.055	1			
Microscopic fungi	0.806 **	−0.254	−0.360	1		
Total no. of bacteria	0.648 **	−0.248	−0.155	0.469 *	1	
CO_2 production	0.607 **	−0.364	0.122	0.238	0.223	1

** Correlation is significant at the 0.01 level (one-tailed). * The correlation is significant at the 0.05 level (one-tailed).

4. Discussion

Extreme weather events resulting from global climate change necessitate developing measures to mitigate these changes. The growth of forest cover can help reduce atmospheric CO_2 concentrations [53]. Land use change from arable land [54] or orchards [55] to forest can lead to differences in soil nutrient and organic matter content. The reforestation efforts motivated us to research the soil profiles in this territory and investigate the organic matter stocks and the distribution of humus materials within the soil profile. With this goal, we measured several physical, chemical, and microbiological properties of soil samples where reforestation is planned. Deep plowing was carried out before planting the new nursery stock to loosen the compacted topsoil and reduce weed competition. This mixing of soil layers caused a relocation of the organic matter content. The tillage of reforestation soil layers significantly affected soil organic carbon and microbial community, as found in other studies [56,57]. Results show a significant reduction in humus content in every planting area (in 0–30 cm layers), with an average decrease of 33.54%. At a 30–70 cm depth, low humus content (<0.10 HU%) did not increase with soil preparation; we can still find a low humus content after deep plowing. HP 4 L has the highest humus content (0.41 HU%) in the deeper layer, where fallow land deep plowing probably happened earlier before afforestation, as we can guess from its soil profile. The chances of survival of future seedlings were reduced. Stump depositions presented one of the highest values in microscopic fungi and soil bacteria, except for the HP 8 M higher sample site, where, after tillage, the upper 0–30 cm layer had the highest number of microscopic fungi (28.00×10^3 (g soil)$^{-1}$), with most of the humus content concentrated in this layer. This sample site probably offered the best conditions (HU%, pH, KA) for microbial activity in the study area.

Our study has demonstrated, however, that a more significant accumulation of humus content does not always imply a high quality of the organic matter [58,59]. A low stability coefficient (e.g., stump row in HP 7H, K = 0.07) can still have a high microbial number (microscopic fungi and bacteria), suggesting that this factor alone does not fully explain the biological activity. For example, Debrecen 369 A had the highest HU% (4.33) with the lowest stability coefficient (K = 0.07) and pH (H_2O) = 4.59, whereas the Hosszúpályi 8 M deeper sample site had 4.01 HU% with K = 2.11 and pH (H_2O) = 7.79. The main difference between the compared forest sites is the soil pH. This outcome indicates that the content of organic matter is closely related to the abundance of soil microbes. A similar result was reported by Hicks et al. [60], who found that soil organic matter content improves nutrient cycling, soil microorganism dynamics, abundance, and activity [46,61–63]. Samples with high HU% (e.g., DB 369 A unplowed 0–30 cm layer with 4.33 HU% or stump row in HP 7H with 4.20 HU%) indicate higher microbial presence and CO_2 emissions. Higher organic matter content may result from more active soil life [64]. With low humus content, we found low microbial counts (e.g., Sample 19—0.10 HU%, 22.50 thousand microscopic fungi g^{-1}, 0.78 million soil bacteria g^{-1}) at a depth of 30–70 cm in the sample sites. Our statistical evaluation demonstrated that the humus content is strongly correlated with the number of microscopic fungi and positively correlated with the number of bacteria. At the same time, there is a significant correlation level with CO_2 production. The highest emissions (e.g., Sample 20—17.81 mg) align with high microbial abundance, elevated HU% and KA, and moderate pH. Depending on the soil pH, the number of microbial fungi (in acidic medium, e.g., Sample 17—430.50 thousand microscopic fungi g^{-1}) or soil bacteria (in neutral to alkaline medium, e.g., Sample 12—7.12 million soil bacteria g^{-1}) increased, similar to the results reported by Anderson [65] and Buckeridge and colleagues [66].

Reforestation can also play other frequently overlooked but essential roles in helping society and ecosystems adapt to climate variability and change [67]. Over time, the rapid and drastic changes in climatic conditions suggest that regular soil monitoring, particularly in less favorable areas, is becoming increasingly meaningful in the examined region.

5. Conclusions

Deep plowing, which inverts, covers, or mixes the soil's organic layer (forest floor) and surface mineral A horizon into the mineral subsoil, burying the upper soil horizon in deeper layers and disrupting pedogenic processes, is a debatable topic in forest plantation management [68]. Traditional technologies of forest soil preparation by dump plowing are outdated and do not allow for a radical increase in labor productivity [69]. The outcome of our study is evidence that the targeted interventions to maintain and improve soil fertility are highly justified in the examined area of sandy soils. The organic and inorganic colloid content of sandy soils is very low, so nutrient and water management are essential [23], as well as the availability of humus content for the plants' early growth. As our results indicate, in the study site, after deep plowing, only a lower amount of humus was turned into the 0–30 cm layers and much less into the deeper (30–70 cm) layers. We found an adverse effect of soil preparation before reforestation because a large amount of humus was concentrated in the stump depositions. Well-thought-out soil preparation will become increasingly important for all professionals to reduce abiotic stress and facilitate successful reforestation. The study documents the significant organic matter-reducing effect of complete soil preparation on forest regeneration in the seedlings' root depth. Consequently, we expect the role of partial soil preparation (no stump removal) to increase, primarily to mitigate the unfavorable effects of climate change and ensure proper seedling development.

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Abbreviations

The following abbreviations are used in this manuscript:

HP	Hosszúpályi
DB	Debrecen
K	stability coefficient
KA	Arany-type plasticity index
HU%	humus content of the soil
SOC	soil organic carbon
OM	organic matter
DOC	dissolved organic carbon

References

1. IUSS Working Group WRB. *World Reference Base for Soil Resources 2022: International Soil Classification System for Naming Soils and Creating Legends for Soil Maps*, 4th ed.; International Union of Soil Sciences: Vienna, Austria, 2022; ISBN 979-8-9862451-1-9.
2. Hartemink, A.E.; Huting, J. Land Cover, Extent, and Properties of Arenosols in Southern Africa. *Arid Land Res. Manag.* **2008**, *22*, 134–147. [CrossRef]
3. Szemerédy Miklós Erdőtörténelem, I. *A Felső-Tisza-Vidék Erdeinek Másfél Évszázada (Hajdú-Szabolcs vm.) 1848-Től 2000-Ig*; Nyomdaipari SZKKT: Debrecen, Hungary, 2009.
4. Erdozain, M.; Alberdi, I.; Aszalós, R.; Bollmann, K.; Detsis, V.; Diaci, J.; Đodan, M.; Efthimiou, G.; Gálhidy, L.; Haase, M.; et al. The Evolution of Forest Restoration in Europe: A Synthesis for a Step Forward Based on National Expert Knowledge. *Curr. For. Rep.* **2024**, *11*, 4. [CrossRef]
5. Griffiths, P.; Müller, D.; Kuemmerle, T.; Hostert, P. Agricultural Land Change in the Carpathian Ecoregion after the Breakdown of Socialism and Expansion of the European Union. *Environ. Res. Lett.* **2013**, *8*, 45024. [CrossRef]
6. Hansen, M.C.; Potapov, P.V.; Moore, R.; Hancher, M.; Turubanova, S.A.; Tyukavina, A.; Thau, D.; Stehman, S.V.; Goetz, S.J.; Loveland, T.R.; et al. High-Resolution Global Maps of 21st-Century Forest Cover Change. *Science* **2013**, *342*, 850–853. [CrossRef]
7. Guo, L.B.; Gifford, R.M. Soil Carbon Stocks and Land Use Change: A Meta Analysis. *Glob. Change Biol.* **2002**, *8*, 345–360. [CrossRef]
8. Vesterdal, L.; Ritter, E.; Gundersen, P. Change in Soil Organic Carbon Following Afforestation of Former Arable Land. *For. Ecol. Manag.* **2002**, *169*, 137–147. [CrossRef]
9. Jandl, R.; Lindner, M.; Vesterdal, L.; Bauwens, B.; Baritz, R.; Hagedorn, F.; Johnson, D.W.; Minkkinen, K.; Byrne, K.A. How Strongly Can Forest Management Influence Soil Carbon Sequestration? *Geoderma* **2007**, *137*, 253–268. [CrossRef]
10. Six, J.; Callewaert, P.; Lenders, S.; De Gryze, S.; Morris, S.J.; Gregorich, E.G.; Paul, E.A.; Paustian, K. Measuring and Understanding Carbon Storage in Afforested Soils by Physical Fractionation. *Soil Sci. Soc. Am. J.* **2002**, *66*, 1981–1987. [CrossRef]

11. Wei, X.; Shao, M.; Gale, W.; Li, L. Global Pattern of Soil Carbon Losses Due to the Conversion of Forests to Agricultural Land. *Sci. Rep.* **2014**, *4*, 4062. [CrossRef]
12. Mayer, M.; Prescott, C.E.; Abaker, W.E.A.; Augusto, L.; Cécillon, L.; Ferreira, G.W.D.; James, J.; Jandl, R.; Katzensteiner, K.; Laclau, J.-P.; et al. Tamm Review: Influence of Forest Management Activities on Soil Organic Carbon Stocks: A Knowledge Synthesis. *For. Ecol. Manag.* **2020**, *466*, 118127. [CrossRef]
13. Bouwman, A.F.; Leemans, R. The Role of Forest Soils in the Global Carbon Cycle. In *Carbon Forms and Functions in Forest Soils*; McFee, W.W., Kelly, J.M., Eds.; Soil Science Society of America: Madison, WI, USA, 2006; pp. 503–525. ISBN 978-0-89118-869-8.
14. Jégou, D.; Cluzeau, D.; Hallaire, V.; Balesdent, J.; Tréhen, P. Burrowing Activity of the Earthworms *Lumbricus Terrestris* and *Aporrectodea Giardi* and Consequences on C Transfers in Soil. *Eur. J. Soil Biol.* **2000**, *36*, 27–34. [CrossRef]
15. Del Galdo, I.; Six, J.; Peressotti, A.; Francesca Cotrufo, M. Assessing the Impact of Land-use Change on Soil C Sequestration in Agricultural Soils by Means of Organic Matter Fractionation and Stable C Isotopes. *Glob. Change Biol.* **2003**, *9*, 1204–1213. [CrossRef]
16. Kincses, I.; Filep, T.; Nagy, P.; Kovács, A. Water Soluble Nitrogen Forms on Two Different Soils as Affected by Biofertilization. *Cereal Res. Commun.* **2007**, *35*, 597–600. [CrossRef]
17. Nagy, P.; Racskó, J.; Vágó, I.; Holb, I. Effect of Different Groundcover Matter on Nitrogen and Sulphur Content of Soil and Leaf in Apple Orchard in Eastern Hungary. *Cereal Res. Commun.* **2006**, *34*, 585–588. [CrossRef]
18. 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]
19. Leuschner, C.; Feldmann, E.; Pichler, V.; Glatthorn, J.; Hertel, D. Forest Management Impact on Soil Organic Carbon: A Paired-Plot Study in Primeval and Managed European Beech Forests. *For. Ecol. Manag.* **2022**, *512*, 120163. [CrossRef]
20. Maes, J.; Bruzón, A.G.; Barredo, J.I.; Vallecillo, S.; Vogt, P.; Rivero, I.M.; Santos-Martín, F. Accounting for Forest Condition in Europe Based on an International Statistical Standard. *Nat. Commun.* **2023**, *14*, 3723. [CrossRef]
21. Führer, E.; Gálos, B.; Rasztovics, E.; Jagodics, A.; Mátyás, C. Erdészeti Klímaosztályok Területének Változása. *Erdészeti Lapok* **2017**, *152*, 174–177.
22. Kádár, I.; Szemes, I. *A Nyírlugosi Tartamkísérlet 30 Éve*; MTA Talajtani és Agrárkémiai Kut. Int.: Budapest, Hungary, 1994.
23. Mayer, J.; Gunst, L.; Mäder, P.; Samson, M.-F.; Carcea, M.; Narducci, V.; Thomsen, I.K.; Dubois, D. Productivity, Quality and Sustainability of Winter Wheat under Long-Term Conventional and Organic Management in Switzerland. *Eur. J. Agron.* **2015**, *65*, 27–39. [CrossRef]
24. Kong, Y.; Nagano, H.; Kátai, J.; Vágó, I.; Oláh, Á.Z.; Yashima, M.; Inubushi, K. CO_2, N_2O and CH_4 Production/Consumption Potentials of Soils under Different Land-Use Types in Central Japan and Eastern Hungary. *Soil Sci. Plant Nutr.* **2013**, *59*, 455–462. [CrossRef]
25. Demeter, I.; Makádi, M.; Tomócsik, A.; Aranyos, T.J.; Michéli, E.; Posta, K. Chemical and Microbiological Properties of Hungarian Sandy Soils under Different Management Practices. *Appl. Ecol. Environ. Res.* **2018**, *16*, 3473–3488. [CrossRef]
26. Kristó, L. *Erdészeti Szaporítóanyag-Termelés*; Hermann Ottó Intézet Nonprofit Kft.: Budapest, Hungary, 2017.
27. Rédei, K. *Az Akác Termesztés-Fejlesztésének Biológiai Alapjai És Gyakorlata*; Erdészeti Tudományos Intézet: Budapest, Hungary, 2006.
28. Rezapour, S.; Alipour, O. Degradation of Mollisols Quality after Deforestation and Cultivation on a Transect with Mediterranean Condition. *Environ. Earth Sci.* **2017**, *76*, 755. [CrossRef]
29. Christopoulou Olga, G. Deforestation/Reforestation in Mediterranean Europe: The Case of Greece. In *Soil Erosion Studies*; Godone, D., Ed.; InTech: Vienna, Austria, 2011; pp. 41–50. ISBN 978-953-307-710-9.
30. Bruun, T.B.; Elberling, B.; De Neergaard, A.; Magid, J. Organic Carbon Dynamics in Different Soil Types After Conversion of Forest to Agriculture. *Land Degrad. Dev.* **2015**, *26*, 272–283. [CrossRef]
31. 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]
32. Achat, D.L.; Fortin, M.; Landmann, G.; Ringeval, B.; Augusto, L. Forest Soil Carbon Is Threatened by Intensive Biomass Harvesting. *Sci. Rep.* **2015**, *5*, 15991. [CrossRef]
33. Johannesson, C.-F.; Ilvesniemi, H.; Kjønaas, O.J.; Larsen, K.S.; Lehtonen, A.; Nordén, J.; Paré, D.; Silvennoinen, H.; Stendahl, J.; Stupak, I.; et al. Decadal Decline in Forest Floor Soil Organic Carbon after Clear-Cutting in Nordic and Canadian Forests. *For. Ecol. Manag.* **2025**, *586*, 122668. [CrossRef]
34. Wang, Y.; Zhu, X.; Bai, S.; Zhu, T.; Qiu, W.; You, Y.; Wu, M.; Berninger, F.; Sun, Z.; Zhang, H.; et al. Effects of Forest Regeneration Practices on the Flux of Soil CO2 after Clear-Cutting in Subtropical China. *J. Environ. Manag.* **2018**, *212*, 332–339. [CrossRef]
35. Arunrat, N.; Sereenonchai, S.; Kongsurakan, P.; Iwai, C.B.; Yuttitham, M.; Hatano, R. Post-Fire Recovery of Soil Organic Carbon, Soil Total Nitrogen, Soil Nutrients, and Soil Erodibility in Rotational Shifting Cultivation in Northern Thailand. *Front. Environ. Sci.* **2023**, *11*, 1117427. [CrossRef]

36. He, Z.; Xu, H.; He, S.; Liang, X.; Zheng, Z.; Luo, Z.; Wang, Y.; Zhang, Y.; Tan, B. Characteristics of Soil Organic Carbon (SOC) Loss with Water Erosion in Sloping Farmland of Southwestern China during Maize (*Zea mays* L.) Growth Stages. *Agronomy* **2023**, *13*, 738. [CrossRef]
37. Bidló, A.; Horváth, A. Talajok Szerepe a Klímaváltozásban. *Erdészettudományi Közlemények* **2018**, *8*, 57–71.
38. Stefanovits, P.; Filep, G.; Füleky, G. *Talajtan*; Mezőgazda Kiadó: Budapest, Hungary, 1999.
39. Csubák, M.; Posta, J.; Zsuposné, O.Á. *Összefüggések a Humuszsavak Kémiai Összetétele És a Talaj Biológiai Aktivitása Között*; Food and Agriculture Organization of the United Nations: Rome, Italy, 2007; pp. 1–10.
40. Kotroczó, Z.; Fekete, I. Significance of Soil Respiration from Biological Activity in the Degradation Processes of Different Types of Organic Matter. *DRC Sustain. Future* **2020**, *1*, 171–179. [CrossRef]
41. Boncz, I. *Kutatásmódszetani Alapismeretek*; Pécsi Tudományegyetem: Pécs, Hungary, 2015; ISBN 978-963-642-826-6.
42. Bodó, A.; Farkas, Á.; Nagy, D.U.; Rudolf, K.; Hoffmann, R.; Kocsis, M.; Morschhauser, T. Soil Humus, Iron, Sulphate and Magnesium Content Affect Nectar Traits of Wild Garlic (*Allium ursinum* L.). *Plants* **2021**, *10*, 597. [CrossRef] [PubMed]
43. *MSZ-08-0210:1977*; Testing Organic Carbon Content. Hungarian Standards Institution: Budapest, Hungary, 1977.
44. Bálint, S.; Füleky, G.; Győri, D.; Hargitai, L.; Kardos, J.; Lukács, A.; Molnár, E. *Talaj-És Agrokémiai Vizsgálati Módszerkönyv 2*; Mezőgazdasági Könyvkiadó Vállalat: Budapest, Hungary, 1988.
45. Schinner, F.; Öhlinger, R.; Kandeler, E.; Margesin, R. *Methods in Soil Biology*; Springer: Berlin, Heidelberg, 1996; ISBN 978-3-642-64633-1.
46. Kátai, J.; Zsuposné, Á.O.; Tállai, M.; Alshaal, T. Would Fertilization History Render the Soil Microbial Communities and Their Activities More Resistant to Rainfall Fluctuations? *Ecotoxicol. Environ. Saf.* **2020**, *201*, 110803. [CrossRef]
47. Ragályi, P.; Lončarić, Z.; Rebekić, A.; Rékási, M.; Borsányi, B.; Molnár, S.; Szabó, A.; Draskovits, E.; Uzinger, N. The Effect of Sewage Sludge and Sludge Compost on Soil Fertility, Organic Matter Content and Yield of Perennial Ryegrass (*Lolium perenne*). Sveučilište u Zagrebu, Agronomski fakultet. In Proceedings of the 55th Croatian & 15th International Symposium on Agriculture, Vodice, Croatia, 16–21 February 2020; pp. 76–80.
48. *MSZ-08-0206/2:1978*; Determination of the pH of Soil (in Hungarian) Hungarian Standard. Available online: http://szabvanykonyvtar.mszt.hu/ (accessed on 3 May 2025).
49. Takamoto, A.; Takahashi, T.; Togami, K. Estimation Models from Soil pH with a Solid-to-Liquid Ratio of 1:2.5 to pH Measured by Other Methods Using Soils in Japan. *Soil Sci. Plant Nutr.* **2023**, *69*, 190–198. [CrossRef]
50. Khan, R.; Jan, S.; Amin, R.; Haq, I.U.; Shoukat, A.; Khan, A.; Akbar, M.S.; Ali, T.; Younas, O.; Rasheed, S.M. Impact of Atrazine and Bromoxynil on the Colony Forming Units (Cfu) of Soil Bacteria. *Agric. Sci. J.* **2023**, *5*, 1–7. [CrossRef]
51. Irving, D.; Bakhshandeh, S.; Tran, T.K.A.; McBratney, A.B. A Cost-Effective Method for Quantifying Soil Respiration. *Soil Secur.* **2024**, *16*, 100162. [CrossRef]
52. Sándor, Z.; Kincses, I.; Tállai, M.; Lowy, D.A.; Melendez, J.R.; Guananga Diaz, N.I.; Guevara Iñiguez, L.E.; Cuenca Nevarez, G.; Talledo Solórzano, V.; Kátai, J. Effect of Herbicides on Soil Respiration: A Case Study Conducted at Debrecen-Látókép Plant Cultivation Experimental Station. *F1000Res* **2020**, *9*, 1348. [CrossRef]
53. Obasi, G.O.P.; Töpfer, K. (Eds.) *Land Use, Land-Use Change, and Forestry: A Special Report of the Intergovernmental Panel on Climate Change*; IPCC: Geneva, Switzerland, 2000; ISBN 978-92-9169-114-2.
54. Balláné Kovács, A.; Kremper, R.; Kincses, I.; Leviczky, Á. Influences of Different Organic Fertilizers on Nutrients of Humic Sandy Soil and on the Growth of Spinach (*Spinacia oleracea* L.). *Acta Agrar. Debr.* **2016**, *70*, 23–28. [CrossRef]
55. Nagy, P.T.; Gonda, I.; Dremák, P.; Holb, I.J. Study on the Micronutrient Content of Soil and Leaf of an Organic Apple Orchard in Eastern Hungary. *Int. J. Hortic. Sci.* **2006**, *12*, 7–11. [CrossRef]
56. Zhang, N.; Chen, X.; Ren, T.; Luo, J.; Liang, J.; Wang, E.T.; Shi, F. Differentiation of Soil Metabolic Function and Microbial Communities between Plantations and Natural Reforestation. *Front. Microbiol.* **2025**, *16*, 1544641. [CrossRef]
57. Libus, J.; Mauer, O.; Vavříček, D. Soil Preparation by Ploughing in the Floodplain Forest and Its Influence on Vegetation and Primary Soil Characteristics. *J. For. Sci.* **2010**, *56*, 183–196. [CrossRef]
58. Zanella, A.; Jabiol, B.; Ponge, J.F.; Sartori, G.; De Waal, R.; Van Delft, B.; Graefe, U.; Cools, N.; Katzensteiner, K.; Hager, H.; et al. A European Morpho-Functional Classification of Humus Forms. *Geoderma* **2011**, *164*, 138–145. [CrossRef]
59. Meurer, K.H.E.; Chenu, C.; Coucheney, E.; Herrmann, A.M.; Keller, T.; Kätterer, T.; Nimblad Svensson, D.; Jarvis, N. Modelling Dynamic Interactions between Soil Structure and the Storage and Turnover of Soil Organic Matter. *Biogeosciences* **2020**, *17*, 5025–5042. [CrossRef]
60. Hicks, L.C.; Meir, P.; Nottingham, A.T.; Reay, D.S.; Stott, A.W.; Salinas, N.; Whitaker, J. Carbon and Nitrogen Inputs Differentially Affect Priming of Soil Organic Matter in Tropical Lowland and Montane Soils. *Soil Biol. Biochem.* **2019**, *129*, 212–222. [CrossRef]
61. Kátai, J.; Oláh, Á.; Sándor, Z.; Tállai, M. Comparison of Soil Parameters of the Carbon and Nitrogen Cycles in a Long-Term Fertilization Field Experiment. *Agrokémia és Talajtan* **2014**, *63*, 129–138. [CrossRef]
62. Szili-Kovács, T.; Kátai, J.; Takács, T. Mikrobiológiai Indikátorok Alkalmazása a Talajminőség Értékelésében. 1. Módszerek. *Agrokémia és Talajtan* **2011**, *60*, 273–286. [CrossRef]

63. Zhao, B.; Chen, J.; Zhang, J.; Xin, X.; Hao, X. How Different Long-term Fertilization Strategies Influence Crop Yield and Soil Properties in a Maize Field in the North China Plain. *J. Plant Nutr. Soil Sci.* **2013**, *176*, 99–109. [CrossRef]
64. Tállai, M.; Kátai, J.; Zsuposné, O.Á.; Sándor, Z.; Balláné, K.A. *Különböző Hasznosítású Talajtípusok Összehasonlítása Néhány Mikrobiológiai Jellemző Alapján*; Talajvédelem Talajvédelmi Alapítvány, Magyar Talajtani Társaság, SZTE Mezőgazdasági Kar: Hódmezővásárhely, Hungary, 2023; pp. 204–217. ISBN 978-615-01-9177-5.
65. Anderson, T.-H. Microbial Eco-Physiological Indicators to Asses Soil Quality. *Agric. Ecosyst. Environ.* **2003**, *98*, 285–293. [CrossRef]
66. Buckeridge, K.M.; Mason, K.E.; McNamara, N.P.; Ostle, N.; Puissant, J.; Goodall, T.; Griffiths, R.I.; Stott, A.W.; Whitaker, J. Environmental and Microbial Controls on Microbial Necromass Recycling, an Important Precursor for Soil Carbon Stabilization. *Commun. Earth Environ.* **2020**, *1*, 36. [CrossRef]
67. John Raphael, L.; Mromba, C. Reforestation for Mitigation and Adaptation to Climate Change in North-Eastern Highlands of Tanzania: Beyond Carbon Sequestration. *Tanzan. J. Popul. Stud. Dev.* **2024**, *31*, 1–15. [CrossRef]
68. Varnagirytė-Kabašinskienė, I.; Survila, G.; Armolaitis, K. Deep Soil Ploughing for Afforestation: A Review of Potential Impacts on Soil and Vegetation. *Balt. For.* **2022**, *27*, 1–11. [CrossRef]
69. Dolmatov, S.; Makunina, Y.; Voinash, S.; Tikhonov, E.; Aksenov, A.; Alekseeva, S.; Parfenopulo, G. Search for Reserves to Improve the Efficiency of Forest Soil Preparation Technology and Land Clearing during Reforestation by Reducing the Energy Intensity of the Process. *E3S Web Conf.* **2023**, *390*, 7045. [CrossRef]