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Effect of Different Vegetation Restoration on Recovery of Compaction-Induced Soil Degradation in Hyrcanian Mixed Forests: Influence on Soil C and N Pools and Enzyme Activities

Alireza Ramineh [1], Meghdad Jourgholami [1,*], Vahid Etemad [1], Mohammad Jafari [2] and Rodolfo Picchio [3]

[1] Department of Forestry and Forest Economics, Faculty of Natural Resources, University of Tehran, Karaj 999067, Iran
[2] Department of Reclamation of Arid & Mountainous Regions, Faculty of Natural Resources, University of Tehran, Karaj 999067, Iran
[3] Department of Agricultural and Forest Sciences, University of Tuscia, Via San Camillo de Lellis, 01100 Viterbo, Italy
* Correspondence: mjgholami@ut.ac.ir; Tel.: +98-02632249312

Abstract: Reforestation with native and non-native tree species is one of the most effective strategies to cope with climate change, and is also the most effective management method for solving soil erosion problems in degraded forests around the world. The current research investigates three skid trails, which were planted with three species in the clearcutting areas, in comparison with a natural forest of hornbeam (CB; *Carpinus betulus* L.) and velvet maple (AV; *Acer velutinum* Boiss.) and degraded land without trees (DL), as well as evaluates the recovery of soil characteristics in the skid trails in response to the planting of native species, including black alder (*Alnus glutinosa* (L.) Gaertn.), and non-native species, including eastern cottonwood (*Populus deltoides* L.) and Italian cypress (*Cupressus sempervirens* L. var. *horizontalis* (Mill.) Gord.) in a mid-term period of 25 years, in the Hyrcanian forests in northern Iran. Significantly higher litter nitrogen (N), phosphorus (P), and potassium (K) were detected in the plantation of black alder (AG), whereas the lowest values were measured under the DL treatment. Soil physio-chemical properties significantly differed among treatments, except silt content. Among the soil chemical properties, N storage and available nutrients of P and K under the black alder plantation were fully restored as compared to the value observed at the hornbeam and velvet maple (CB-AV) stand over a 25-year period after soil disturbance and planting. Over a 25-year period after logging operations, soil biological and microbial properties of carbon and nitrogen, and enzyme activity in the black alder plantation were partially recovered, but these values have not returned to pre-harvest level at the CB-AV treatment as control. Overall, these results suggested that black alder had greater positive effects on the recovery of soil properties than other trees due to the faster litter decomposition as a N-fixing species, and its labile substrate with low organic C and high N concentration. Therefore, black alder reforestation should be increase in future ecosystem restoration in the area influenced by logging operations.

Keywords: reforestation; mixed forests; skid trail; hornbeam-velvet maple; black alder; eastern cottonwood; Italian cypress; degraded land

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1. Introduction

In recent years, the mechanization of forest harvesting operations has increased productivity and improved ergonomic conditions, but damage to forest soil has also drastically increased [1–4]. The movement of heavy machinery in forested areas has caused the disturbance and compaction of soil layers, which has led to an increase in soil bulk density, reduced soil porosity, increased soil penetration resistance and soil strength, and impedes the gaseous exchange between the soil and atmosphere [4,5]. A very important effect of forestry machine traffic is the removal of the litter layer from the soil surface. As a consequence, raindrops directly hit on the surface of mineral soil, which leads to a decrease in water infiltration, increases soil particle detachment and overland flow, which results in an increase in sediment yield [6–8].

Forest soils play an important role in maintaining fertility, health and ecosystem services [1,4,9], and provide nutrients, organic matter and water for lower layers [10–12]. In fact, soil compaction applied by heavy machinery during logging operations significantly reduces the balance and regulation of forest stand productivity by destroying soil structure and disrupting the soil's physical properties [13]. As a result, these phenomena lead to a decrease in soil porosity [14,15], reduce the connection between pore spaces [16] and cause to an increase in soil density and strength [7] and reduce water infiltration and gas exchange [17,18], which have a negative effect on soil macro- and micro-organisms (e.g., earthworms) [15]. This prohibits the longitudinal growth of root systems [2,9], which ultimately reduces tree and seedling growth [11].

Studies have proved that tree species have an important role that affects soil physical and chemical properties [19,20]. Previous studies have shown that tree leaves affect many ecosystem functions [21,22] through the processes of nutrient decomposition [19,21,22]. Furthermore, the quality of the leaves in tree species significantly governs the decomposition of litter and subsequent release of nutrients into the soil [23,24]. Accordingly, Lucas-Borja et al. [20] indicated that there is a close relationship between tree leaves, the litter layer, and soil. Reforestation with native and non-native tree species is one of the most effective strategies to cope with climate change, which is also the most effective management method for solving soil erosion problems in degraded forests around the world. It is also an effective strategy to prevent soil erosion and soil degradation and restore degraded ecosystems [19–21]. Vegetation restoration with tree species have species-specific effects on the recovery of soil physical and chemical properties and soil micro- and macro-organisms [24], which also regulates climate and the nutrient cycle in surface and underground soil layers [19,21,22]. In addition, planting tree species can potentially lead to cycling and feedback of mineral nutrients in the degraded forest ecosystems imposed by intensive logging [22]. Therefore, the study of restoration processes after reforestation and its effects on nutrient cycling and soil properties provides an important guide for forest management to improve the ecological restoration of areas due to soil compaction. Restoration of compacted-induced soil degradation can lead to an increase in stand productivity and organic matter decomposition in forest stands [21,24].

The impacts of machinery traffic on soil remain for a long time. Natural cycles of freeze-thaw and wetting-drying lead to shrinkage and swelling processes, in addition to root-soil interaction and the activities of micro- and macro-organisms, which ultimately regulate the natural recovery of compaction-induced soil degradation [11]. Studies have shown that the process of natural recovery of compacted soils can take from a few years to several decades [13,15,17]. In recent years, several studies have been conducted to elucidate the acceleration of the natural processes in the recovery of soil properties after soil compaction [11,18]. The most important rehabilitative measures to recover from soil compaction are plantation of seedlings and the application of organic mulch, as well as the installation of water diversion structures to suppress surface flow and soil loss in skid trails [11,18,25]. For example, Meyer et al. [11] found that macroporosity and air permeability were augmented by planting black alder trees. Similarly, Flores Fernández et al. [5] concluded that soil aeration and root growth were enhanced compared to untreated areas, and CO_2 concentrations decreased as well. Furthermore, Jourgholami et al. [25] found that the planting of N-fixing Caucasian alder (*Alnus subcordata*) resulted in an amelioration of the soil physio-chemical and biological properties.

High-quality litter leads to the acceleration of biological activities (i.e., earthworms) and the increase in soil pH [21,25], which in turn improves the soil structure with different species of earthworms, and as a result, it increases soil aeration, pore space, and improves soil bulk density [10,26,27]. Several studies have shown that the storage of soil C and N and nutrients in plantations was higher than in primary forest ecosystems [22,28,29]. For example, Diao et al. [22] reported that native tree species significantly improved the soil chemical and microbial properties. Similarly, in a short-term laboratory study, Yang and Zhu [30] found that litter of *Fraxinus mandshurica* decomposed faster than litter of other species, which ultimately leads to an increase in the microbial population and strengthens the content of nutrients. Tree leaves with recalcitrant compounds (i.e., lignin, tannin and polyphenols) greatly inhibit the decomposition rate and speed, which determines the time required for nutrients cycling in the soil [30,31]. Accordingly, Langenbruch et al. [21] showed that the decomposing rate of ash leaves (*Fraxinus excelsior* L.) is faster than that of European beech (*Fagus sylvatica* L.) and lime (*Tilia cordata* Mill.).

During the last three to four decades, forests degraded due to extensive livestock grazing and fuelwood harvesting in the margins of rural areas were replaced with the reforestation of native and non-native tree species in the Hyrcanian forests in small areas, which formed pure, even-aged stands [32]. In different parts of the Hyrcanian forests (Northern Iran), reforestation and restoration programs of degraded forests with native broadleaf species, including maple, alder, ash, oak, wild cherry, elm and non-native species of eastern cottonwood and Italian cypress, have been carried out in an area of 115,000 hectares [32]. Understanding the relationships between tree species and above-ground and below-ground characteristics has a fundamental role in improving management outcomes that should be completed by mimicking the natural and environmental trends and dynamics [29,33]. However, the holistic effects of different types of trees on the recovery of soil physical and chemical characteristics are not clear. In addition, these areas planted with pure species have a fundamental role to maintain ecological and economic functions and services as well as biodiversity values in the forests of northern Iran, compared to the primary forest ecosystems. The current research investigates three skid trails planted in the clearcutting areas in comparison with the natural forest of hornbeam (*Carpinus betulus* L.)-velvet maple (*Acer velutinum* Boiss.) and the degraded land without trees, as well as evaluates the recovery of soil characteristics in the skid trails in response to the planting of native species, including black alder (*Alnus glutinosa* (L.) Gaertn.) and non-native species, including eastern cottonwood (*Populus deltoides* L.) and Italian cypress (*Cupressus sempervirens* L. var. *horizontalis* (Mill.) Gord.) in a mid-term period of 25 years. The hypothesis of the current study was: plantation with native and non-native tree species can restore the soil properties in the skid trails compared to an undisturbed natural forest stand. The aim of this study was to elucidate how to improve compacted soil properties in skid trail roads in response to planting different species over a 25-year period, and to determine the role of different tree species in restoring soil properties, compared to the undisturbed forest stand.

2. Materials and Methods

2.1. Site Description

The study site was located in the Tangar district in the Tyrumrud watershed, 12 km east of Tonekabon city, in the Hyrcanian forests in northern Iran (36°49′15′′ and 36°49′04′′ N, 50°44′30′′ and 50°44′45′′ E; Figure 1a), with an altitude of 340 m.a.s.l. According to World Reference Base for soil resources [34], the soil at the study site was a Calcic Cambisol (Alfisol according to the USDA Soil Taxonomy with loamy texture), derived from limestone. The mean annual temperature is 14.1 °C, and the mean annual precipitation is about 1180 mm. Before the clearcutting, the plant community was a *Carpinetum* forest (hornbeam, *Carpinus betulus* L.) with velvet maple (*Acer velutinum* Boiss.), accompanied by ironwood (*Parrotia persica* C.A.M.), chestnut-leaved oak (*Quercus castaneifolia* C.A.M.), and black alder (*Alnus glutinosa* (L.) Gaertn.). This area was extensively degraded due to the wood utilization of rural residences and overgrazing in the past decades. The degraded areas were clear-cut by Forest, Range, and the Watershed Management Organization (FRWO) in 1996, and planted with native trees, including black alder, and non-native species including eastern cottonwood (*Populus deltoides* L.) and Italian cypress (*Cupressus sempervirens* L. var. *horizontalis* (Mill.) Gord.) with spacing of 2 × 2 m. Hence, this study considered five treatments, including three 25-year stands of AG (Black alder), PD (eastern cottonwood), and CS (Italian cypress), degraded land without trees (DL), and natural, undisturbed stand of CB-AV (hornbeam-velvet maple) as a control, which were located near each other to avoid site effects (Figure 1a). The characteristics of each treatment are given in Table 1.

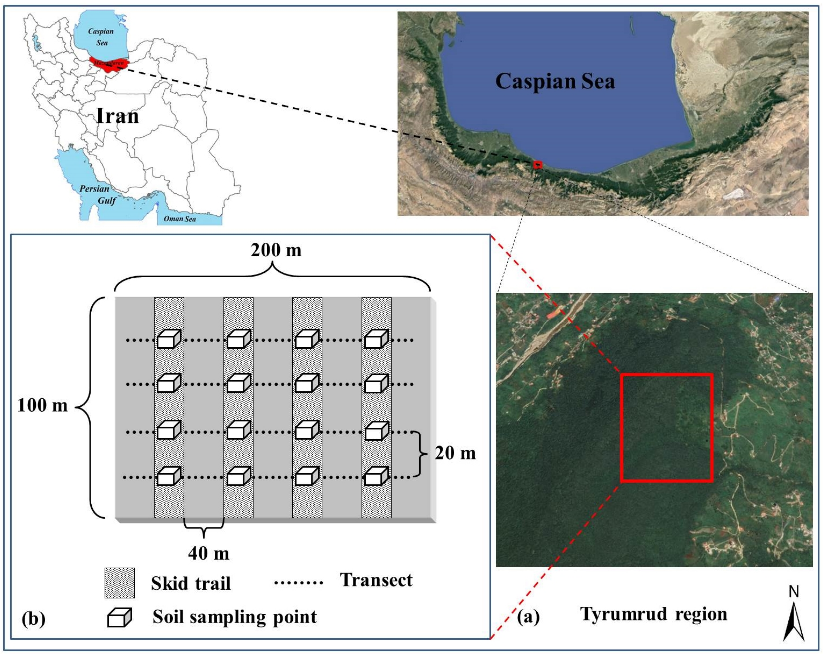

Figure 1. Location of the study area in the Hyrcanian forest, Northern Iran (**a**). A schematic diagram of the experimental design on the skid trails in each treatment of tree species (**b**).

Table 1. The treatment characteristics (mean ± std) in the study area.

Treatment	Main Species	Slope (%)	Aspect	Tree Density (N ha^{-1})	Growing Stock (m^3 ha^{-1})	Diameter at Breast Height (cm)
CB-AV	Hornbeam (*Carpinus betulus* L.)-Velvet maple (*Acer velutinum* Boiss.)	15 ± 5	Northeast	364.1 ± 41.7	286.3 ± 45.2	52.6 ± 9.4
AG	Black alder (*Alnus glutinosa* (L.) Gaertn.)	17 ± 3	Northeast	614.8 ± 45.3	394.1 ± 33.6	25.3 ± 6.2
PD	Eastern cottonwood (*Populus deltoides* L.)	17 ± 2	Northeast	587.6 ± 43.8	362.5 ± 39.5	24.2 ± 5.3
AC	Italian cypress (*Cupressus sempervirens* L. var. *horizontalis* (Mill.) Gord.)	16 ± 3	Northeast	531.8 ± 52.6	269.4 ± 51.7	20.6 ± 7.4
DL	Degraded land without trees	18 ± 4	Northeast	-	-	-

A TAF E655 rubber-tired skidder was used to extract the processed logs with a length of 6–8 m to the roadside, which was characterized as follows: empty weight 6.8 t, engine power 48 kW, tire size of 18.4–26 inflated to 659 kPa, and average payload 2.7 cubic meters. The length of the designated skid trails was 70 m with an average width of 3.7 m and slope gradient ranging 14%–23%.

2.2. Experimental Design

Afforestation with native species, including black alder, and non-native species, including eastern cottonwood and Italian cypress, was carried out in an area of about 5 hectares with a length of 250 m and a width of 200 m. In order to investigate and compare the recovery level of compacted soil characteristics after a period of 25 years (2021), three pure forestry stands were selected, including black alder, eastern cottonwood and Italian cypress, together with the mixed stand of hornbeam-velvet maple and the area of the skid trails without trees (DL) for soil sampling.

To avoid the interference effects of margin stands, the stands were selected with a distance of at least 200 m from each other. In each of the treatments and the control area (hornbeam-velvet maple), four skid trails were selected in an area of 2 hectares with dimensions of 100 m × 200 m. Four transects perpendicular to the longitudinal axis of the skid trail at a distance of 20 m were carried out as a systematic sampling to locate the soil samples. At the place of each sample, sampling of two parts of litter and soil were applied (Figure 1b). A total of 80 soil samples were collected and analyzed (i.e., 4 skid trails in each treatment × 4 transects at each plot × 5 treatments). Soil sampling and data collection was carried out during September 2021.

2.3. Data Collection and Laboratory Analysis

2.3.1. Litter Properties

In each sample location, litter was collected from an area of 20 × 20 cm square, stored in plastic bags, transported to the laboratory, and then oven-dried at 70 °C for 48 h to reach a constant mass, finely ground, and then analyzed by analysis methods shown in Table 2.

Table 2. Methods of analyzing litter and soil physio-chemical properties and calculations.

Layer	Group	Properties	Unit	Method	Reference for Method
Litter	Physical and chemical properties	Litter depth or thickness	cm	Tape measure	Sohrabi et al. [8]
		C and N	%	The CN elemental analyzer	Hattenschwiler and Jørgensen [35]
		P	%	Olsen method	Homer and Pratt [36]
		K	%	Atomic absorption spectrophotometer	Bower et al. [37]
Soil	Physical properties	Soil bulk density	g cm^{-3}	Clod method	Kemper and Rosenau [38]
		Soil moisture	%	By drying soil samples at 105 °C for 24 h	Thien and Graveel [39]
		Soil particle size distribution	%	Hydrometer method	Gee and Bauder [40]
		Soil particle density	g cm^{-3}	ASTM D854-00 2000 standard	Thien and Graveel [39]
		Macroporosity	%	Water desorption method	Danielson and Sutherland [41]
		Penetration resistance	MPa	Analog hand-held soil penetrometer	Sohrabi et al. [8]
		Total porosity	%	was calculated using formula $TP = 1 - \frac{\frac{Ms}{VC}}{2.65} \times 100$	Sohrabi et al. [8]
		Aggregate stability	%	Yoder method	Kemper and Rosenau [38]
	Chemical properties	pH	1:2.5 H_2O	Using an Orion Ionalyzer Model 901 pH meter	Sohrabi et al. [8]
		C	%	Walkley-Black technique	Walkley and Black [42]
		N	%	The Kjeldahl method	Kooch et al. [43]
		C and N storage	Mg ha^{-1}	calculated using the bulk density data, C and N concentrations	Kooch et al. [43]
		Available P	mg kg^{-1}	Olsen method	Homer and Pratt [36]
		Available K, Ca, Mg	mg kg^{-1}	Determined with an atomic absorption spectrophotometer	Bower et al. [37]
		Fulvic and Humic acid	mg/100 g	The method of the International Humic Substances Society	Sparks and Bartels [43]

2.3.2. Soil Physical Properties

One part of soil samples was collected from a 20 × 20 × 10 cm section and air-dried to analyzing soil physical properties. The detailed methods of measuring and calculating are presented in Table 2.

2.3.3. Soil Chemical Properties

Second part of soil samples was collected from a 20 × 20 × 10 cm section, air-dried, and passed through a 2 mm sieve to analyze soil chemical properties by analysis methods shown in Table 2.

2.3.4. Soil Biochemical, Biological and Microbial Properties, and Enzyme Activity

The third part of soil samples was stored in polyethylene bags at 4 °C until processed to carry out the biological analysis, C and N Microbial properties, and enzyme activities by analysis methods shown in Table 3.

Table 3. Methods of analyzing soil biochemical, biological and microbial properties, enzyme activity, and calculations.

Layer	Group	Properties	Unit	Method	Reference for Method
Soil	Biological properties	Earthworm density	n m^{-2}	By hand sorting	Kooch et al. [43]
		Earthworm dry mass	mg m^{-2}	oven dried at 60 °C for 24 h	Kooch et al. [43]
		Fine root biomass	g m^{-2}	Oven dried at 70 °C to a constant mass	Neatrour et al. [44]
		Soil microbial respiration	mg CO_2-C g $soil^{-1}$ day^{-1}	Determined by measuring the CO_2 evolved in a 3-day incubation experiment at 25 °C	Alef [45]
	C and N Microbial properties	Microbial biomass carbon (MBC) and nitrogen (MBN)	mg kg^{-1}	Measured by fumigation-extraction method	Brookes et al. [46]
		Ammonium and Nitrate	mg kg^{-1}	Colorimetric techniques were used to extract soil NH_4^+ and NO_3- via 2 M KCl solution (soil: solution, 1:5)	Yang et al. [47]
		Nitrogen mineralization	mg N kg $soil^{-1}$	Aerobic incubation of the soils was applied	Robertson [48]
	Enzyme activity	Urease	µg NH_4^+–Ng^{-1} 2 h^{-1}	Analyzed using 200 µmol urea as substrate, incubated for 2 h at 37 °C	Yang et al. [47]
		Acid phosphatase (APH)	µg PNP g^{-1} h^{-1}	Determined in a MUB buffer (pH 6.5), incubated for 1 h at 37 °C	Yang et al. [47]
		Arylsulfatase	µg PNP g−1 h^{-1}	A p-Nitrophenyl sulphate was used for incubation for 1 h at 37 °C	Schinner and von Mersi [49]
		Invertase	µg Glucose g^{-1} 3 h^{-1}	1.2% sucrose solution was used for incubation at 3 h at 50 °C	Schinner and von Mersi [49]
		ß-N-acetylglucosaminidase (NAG)	µg g^{-1} h^{-1}	Analyzed in 100 µmol acetate buffer at pH 5.5	Yang et al. [47]

2.4. Statistical Analyses

The normality of the variables was examined with The Kolmogorov-Smirnov test and the equality of variance was applied using Levene's test. Due to no departure of the data from a normal distribution, generalized linear model (GLM, one-way analysis of variance) was used to test the differences in soil properties among different tree species and the undisturbed (control) area. The Duncan multiple range test was applied to test the significant differences between the soil properties among five treatments including three 25-year stands of AG (black alder), PD (eastern cottonwood), and CS (Italian cypress), degraded land without trees (DL), and natural, undisturbed stand of CB-AV (hornbeam-velvet maple) at $p \leq 0.05$. The Pearson correlation was employed to test the relationship between soil biochemical and biological properties with litter, sand, and soil physio-chemical properties in five treatments. The SPSS (release 17.0; SPSS, Chicago, IL, USA) statistical package was applied to examine all statistical analyses. The principal component analysis (PCA) method was employed for multivariate correlation analysis of litter and soil properties among different treatment using PC-Ord (v. 5.0).

3. Results

3.1. Litter Properties

Results demonstrated that the properties of the litter layer, including litter depth, litter C, N, and C/N ratio, litter P and K, differed significantly among different tree plantations, degraded land without trees (DL), and natural, undisturbed stand of CB-AV (hornbeam-velvet maple) as a control (Figure 2).

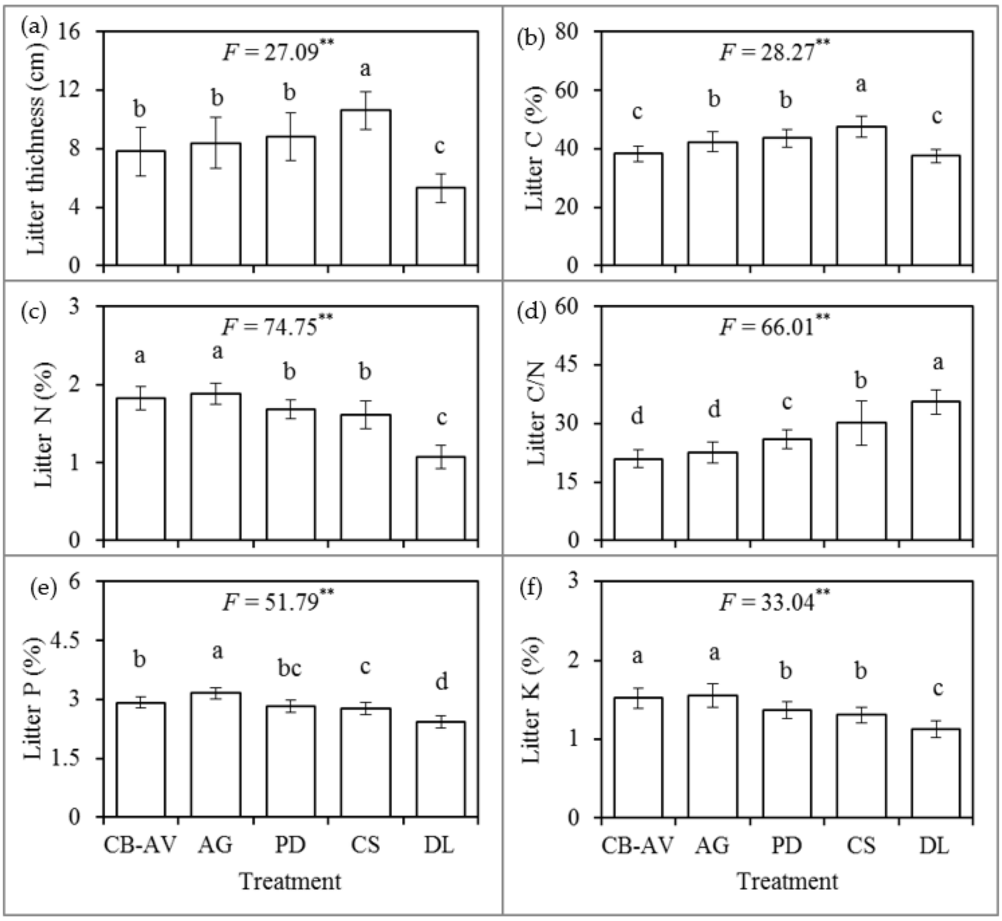

Figure 2. Mean values and standard deviation (SD) of litter properties: litter thickness (**a**), litter C (**b**), N (**c**), C/N (**d**), P (**e**), and K (**f**) in the different tree species treatments. Results of the ANOVAs (*F* test and *p* value) are given. Different letters after means within each treatment indicate significant differences by Duncan's test ($p < 0.05$). Note: ** $p < 0.01$. CB-AV = natural forest stand of *Carpinus betulus* L.-*Acer velutinum* Boiss.; AG = plantation of *Alnus glutinosa* (L.) Gaertn.; PD = plantation of *Populus deltoides* L.; CS = plantation of *Cupressus sempervirens* L. var. *horizontalis* (Mill.) Gord.; DL = degraded land without trees.

The highest litter thickness of 10.6 cm was observed under the Italian cypress plantation, followed by PD ≈ AG ≈ CB-AV, whereas the least value was found under the DL treatment. The amount of litter C in plantation treatment with Italian cypress was 24.1% higher than the value under the control CB-AV treatment. The litter C/N ratio was highest under the DL treatment, followed by CS > PD > AG ≈ CB-AV treatments. Significantly higher litter N, P, and K were detected in the plantation of black alder (AG), whereas the least values were measured under the DL treatment.

3.2. Soil Physio-Chemical Properties

Soil physio-chemical properties differed significantly among treatments, except silt content (Figures 3 and 4). The lowest amount of soil bulk density among the planation treatments is related to the black alder (AG) treatment, which is not significantly different from the CB-AV control treatment (Figure 3). Likewise, penetration resistance had the lowest value in the AG treatment, although it was 8.6% more than the value of the CB-AV treatment. The highest amount of total porosity was related to the CB-AV and AG treatments and there were no significant differences between them. However, the value of macroporosity was the highest under the control treatment, followed by the AG treatment. The soil moisture in the three treatments, including control, AG, and PD treatment, had the highest value, which showed no significant difference. The lowest value of aggregate stability was under the control treatment, followed by the AG treatment, while the lowest value was found under the DL treatment. The highest sand content was observed in the DL treatment and the lowest in the control treatment, while the highest amount of clay was measured in the control stand and the lowest in the DL area. Also, there was no significant difference between the amount of silt among different treatments.

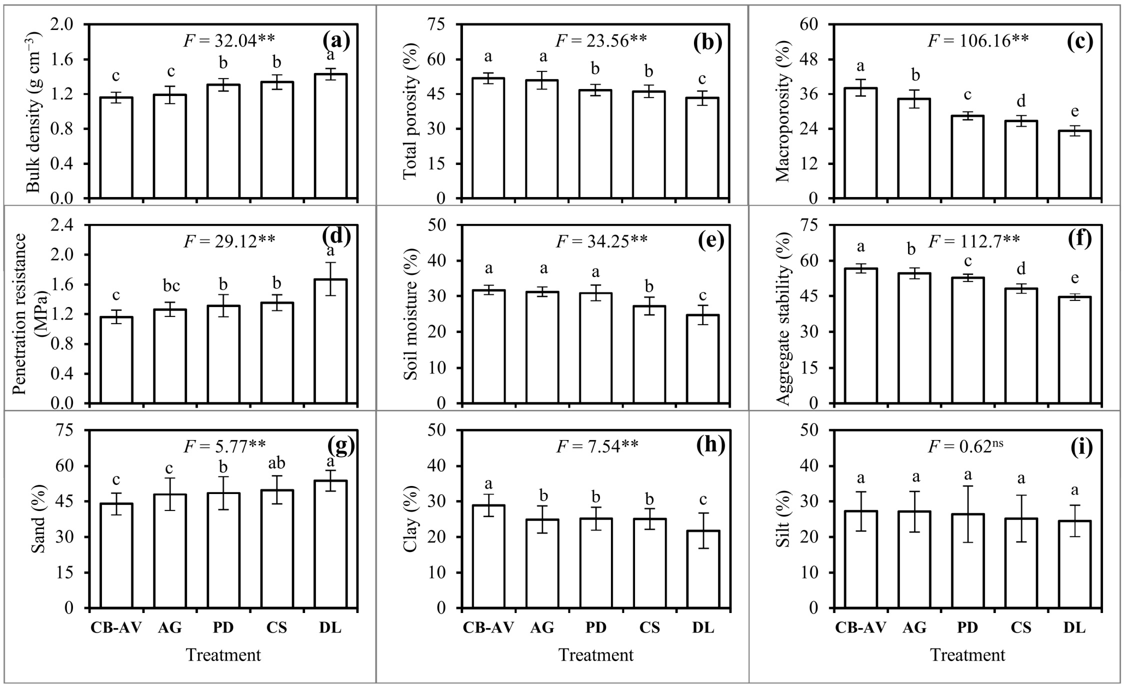

Figure 3. Mean values and standard deviation (SD) of soil physical properties: bulk density (**a**), total porosity (**b**), macroporosity (**c**), penetration resistance (**d**), soil moisture (**e**), aggregate stability (**f**), sand (**g**), clay (**h**), silt (**i**) in the different tree species treatments. Results of the ANOVAs (*F* test and *p* value) are given. Different letters after means within each treatment indicate significant differences by Duncan's test ($p < 0.05$). Note: ** $p < 0.01$; ^{ns}: Not significant. CB-AV = natural forest stand of *Carpinus betulus* L.-*Acer velutinum* Boiss.; AG = plantation of *Alnus glutinosa* (L.) Gaertn.; PD = plantation of *Populus deltoides* L.; CS = plantation of *Cupressus sempervirens* L. var. *horizontalis* (Mill.) Gord.; DL = degraded land without trees.

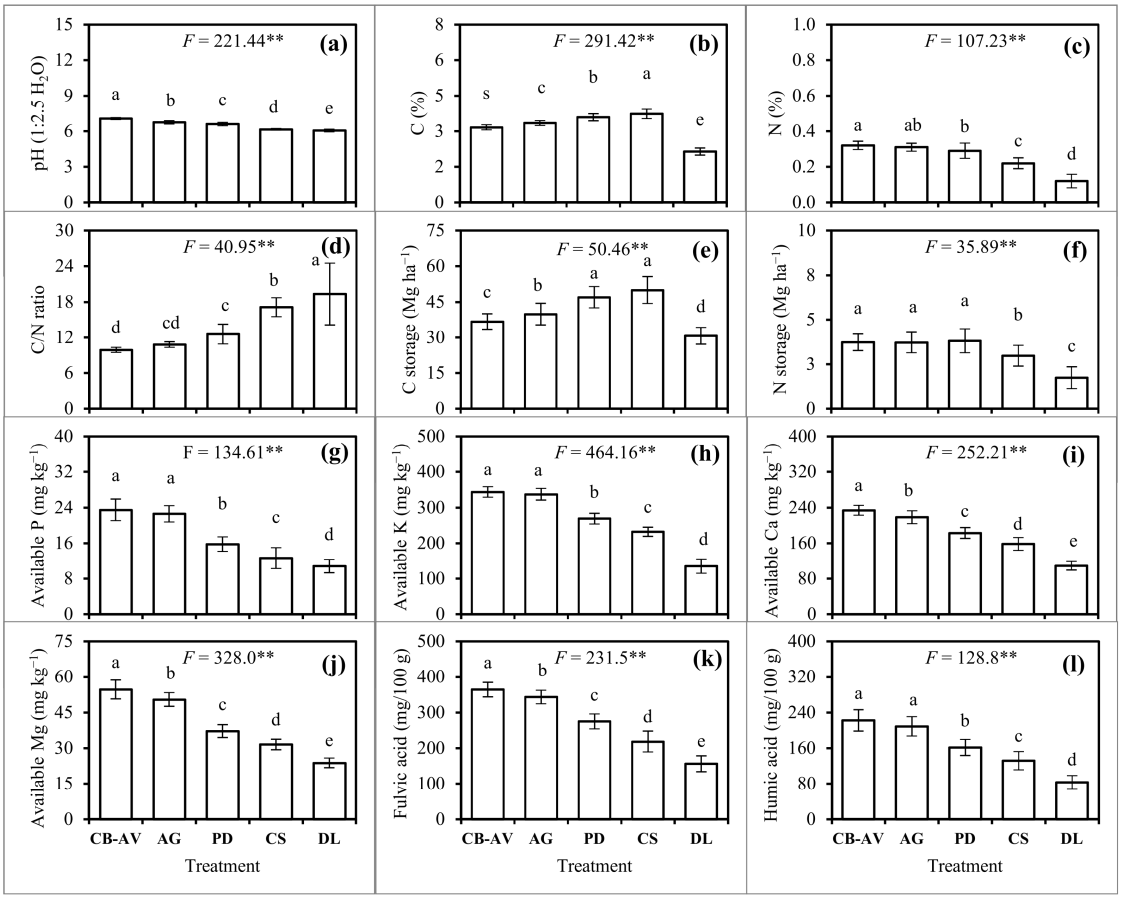

Figure 4. Mean values and standard deviation (SD) of soil chemical properties: pH (1:2.5 H_2O) (**a**), C (**b**), N (**c**), C/N ratio (**d**), C storage (**e**), N storage (**f**), available P (**g**), K (**h**), Ca (**i**), Mg (**j**), fulvic acid (**k**), and humic acid (**l**) in the different tree species treatments. Results of the ANOVAs (*F* test and *p* value) are given. Different letters after means within each treatment indicate significant differences by Duncan's test ($p < 0.05$). Note: ** $p < 0.01$. CB-AV = natural forest stand of *Carpinus betulus* L.-*Acer velutinum* Boiss.; AG = plantation of *Alnus glutinosa* (L.) Gaertn.; PD = plantation of *Populus deltoides* L.; CS = plantation of *Cupressus sempervirens* L. var. *horizontalis* (Mill.) Gord.; DL = degraded land without trees.

Soil pH was at the highest level under the CB-AV, followed by AG treatment, whereas the soil pH was lowest level at the DL and CS plantations (Figure 4). The value of soil C and C storage was at the highest level in the CS plantation. The soil C/N ratio was at highest level under the DL treatment, followed by the CS plantation, whereas the lowest soil C/N ratio was found in the CB-AV > AG plantation. The values of soil N, N storage, available P, K, Ca, and Mg, fulvic acid and humic acid were at the highest level under the CB-AV, followed by the AG plantation, whereas these values were at the lowest level under the DL and CS plantation. Among the soil chemical properties, N storage and available P and K under the black alder plantation (AG) were fully restored as compared to the value observed at the CB-AV stand over a 25-year period after tree planting (Figure 4).

3.3. Soil Biochemical, Biological and Microbial Properties

Results showed that there were significant differences in soil biological and microbial properties of C and N among different tree plantations, degraded land without trees (DL), and the natural, undisturbed stand of CB-AV (hornbeam-velvet maple) (Figure 5; $p < 0.001$). The values of soil biological properties, including earthworm density and dry mass, and fine root biomass, were at the highest level at the CB-AV treatment, followed by the black alder plantation (AG), whereas the lowest values of earthworm density and dry mass, and fine root biomass were found at the DL and CS treatments. The values of soil microbial respiration (SMR), microbial biomass carbon (MBC), ammonium (NH_4^+), nitrate (NO_3^-), nitrogen mineralization, and microbial biomass nitrogen (MBN) were at the highest level in the CB-AV treatment compared to the AG plantation. Over a 25-year period after logging operations, soil biological and microbial properties of C and N in the black alder plantation (AG) were partially recovered, but these values have not returned to pre-harvest level observed in the CB-AV treatment as control.

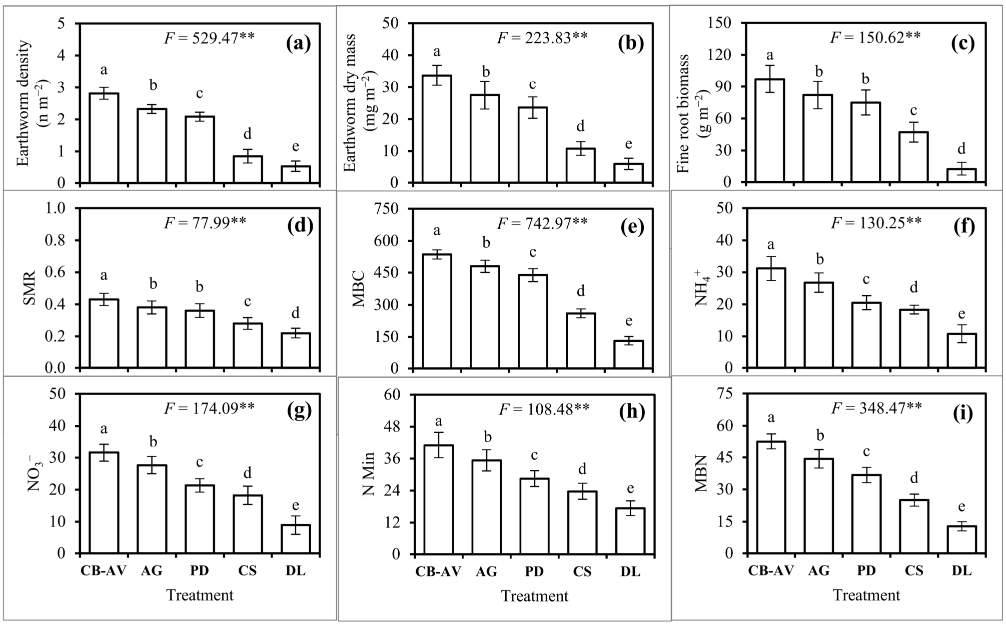

Figure 5. Mean values and standard deviation (SD) of soil biological and biochemical properties in the different treatments of tree species. Results of the ANOVAs (*F* test and *p* value) are given. Different letters after means within each treatment indicate significant differences by Duncan's test ($p < 0.05$). Note: ** $p < 0.01$. SMR = soil microbial respiration (mg CO_2-C g soil^{-1} day^{-1}); MBC = microbial biomass carbon (mg kg^{-1}); NH_4^+ = ammonium (mg kg^{-1}); NO_3^- = nitrate (mg kg^{-1}); N Min = nitrogen mineralization (mg N kg soil^{-1}); MBN = microbial biomass nitrogen (mg kg^{-1}). CB-AV = natural forest stand of *Carpinus betulus* L.-*Acer velutinum* Boiss.; AG = plantation of *Alnus glutinosa* (L.) Gaertn.; PD = plantation of *Populus deltoides* L.; CS = plantation of *Cupressus sempervirens* L. var. *horizontalis* (Mill.) Gord.; DL = degraded land without trees.

3.4. Enzyme Activitiy

Soil enzyme activities, including urease, acid phosphatase, arylsulfatase, invertase, ß-N-acetylglucosaminidase, significantly differed among treatments (Figure 6; $p < 0.001$). The values of urease, acid phosphatase, arylsulfatase, invertase, and ß-N-acetylglucosaminidase were at the highest level in the CB-AV treatment, followed by the black alder (AG) plantation. Results showed that soil enzyme activities were partially recovered over a 25-year period, but these values did not return to pre-logging operations compared to the CB-AV treatment.

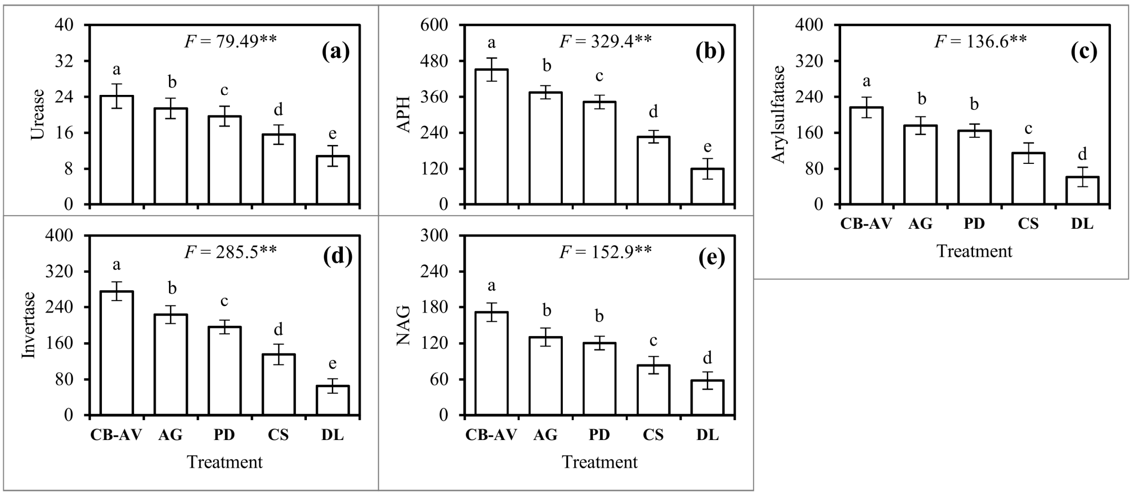

Figure 6. Mean values and standard deviation (SD) of soil enzyme activity in the different treatments of tree species. Results of the ANOVAs (F test and p value) are given. Different letters after means within each treatment indicate significant differences by Duncan's test ($p < 0.05$). Note: ** $p < 0.01$. Urease (μg NH_4^+-Ng^{-1} 2 h^{-1}); APH: acid phosphatase (μg PNP g^{-1} h^{-1}); arylsulfatase (μg PNP g^{-1} h^{-1}); invertase (μg glucose g^{-1} 3 h^{-1}); NAG: ß-N-acetylglucosaminidase (μg g^{-1} h^{-1}). CB-AV = natural forest stand of *Carpinus betulus* L.-*Acer velutinum* Boiss.; AG = plantation of *Alnus glutinosa* (L.) Gaertn.; PD = plantation of *Populus deltoides* L.; CS = plantation of *Cupressus sempervirens* L. var. *horizontalis* (Mill.) Gord.; DL = degraded land without trees.

Results showed that there were significant positive relationships between earthworm density and dry mass, fine root biomass, soil microbial respiration (SMR), microbial biomass carbon (MBC), ammonium (NH_4^+), nitrate (NO_3^-), nitrogen mineralization, microbial biomass nitrogen (MBN), urease, acid phosphatase, arylsulfatase, invertase, ß-N-acetylglucosaminidase, N, P, and K of litter, total porosity, macroporosity, soil moisture, aggregate stability, clay, pH, soil N, N storage, available nutrients (P, K, Ca, and Mg), fulvic acid and humic acid, and significant negative relationships between C/N of litter layer, bulk density, sand, soil C/N ratio (Table S1).

PCA analysis among the different treatment and litter and soil properties are presented (Figure 7), which reveal the total of variance explained via the first and second axes by 85.47% and 14.53%, respectively. The plantation stands of CS and degraded land without trees (DL) were correlated with litter and soil C/N, soil bulk density, penetration resistance, and sand, which are located at the right side of the principal component. On the left side of principal component, the CB-AV natural forest stand and black alder plantation (AG) were related to high soil quality properties, including litter and soil N, soil biochemical and biological, C and N Microbial properties, and enzyme activity.

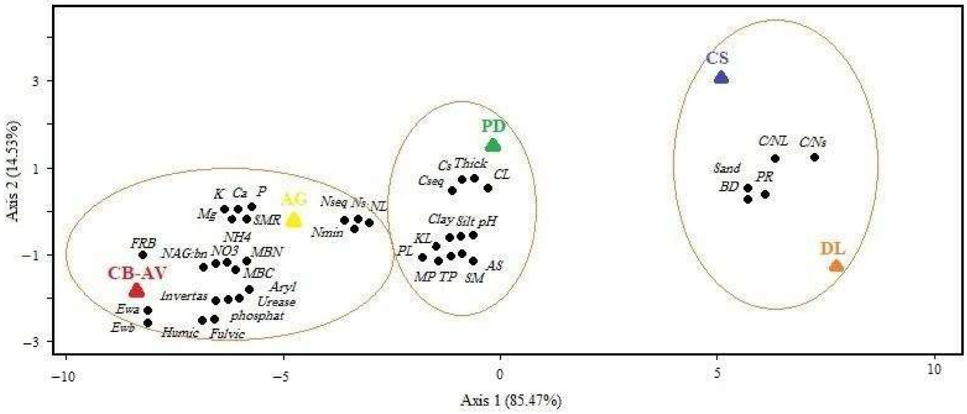

Figure 7. PCA ordination among different treatments (CB-AV = natural forest stand of *Carpinus betulus* L.-*Acer velutinum* Boiss.; AG = plantation of *Alnus glutinosa* (L.) Gaertn.; PD = plantation of *Populus deltoides* L.; CS = plantation of *Cupressus sempervirens* L. var. *horizontalis* (Mill.) Gord.; DL = degraded land without trees), and litter properties (Litter T = litter thickness; CL = litter C; NL = litter N (%); C/NL = litter C/N ratio; PL = litter P; KL = litter K), soil physical (BD = bulk density, TP = total porosity, MP = macroporosity, PR = penetration resistance, MC = moisture content, AS = aggregate stability, sand, silt, clay), chemical (pH, EC, C = organic C, N = nitrogen content, C/N = C/N ratio, Cseq = C storage, Nseq = N storage, P = available phosphorous, K = available potassium, Ca = available calcium, Mg = available magnesium), biochemical and biological (EW = earthworm density, Ewb = earthworm biomass, SMR = soil microbial respiration, FRB = fine root biomass, Fulvic = fulvic acid, Humic = humic acid), C and N microbial properties (SMR = soil microbial respiration, MBC = microbial biomass carbon, NH_4^+ = ammonium, NO_3- = nitrate, N Min = nitrogen mineralization, MBN = microbial biomass nitrogen) and enzyme activity (Urease, APH = acid phosphatase, aryl = arylsulfatase, invertase, NAG: ß-N = NAG: ß-N-acetylglucosaminidase).

4. Discussion

4.1. Litter Properties

Ground-based logging operations have introduced significant changes in the soil environment via soil disturbance, mixing of topsoil, and soil compaction [12], thereby reducing the infiltration of water into underground layers of mineral soil [4,6,9,50]. According to the present study, several studies have shown that machinery traffic has harmful effects on soil quality [25,51,52]. In addition, soil microbial biomass is sensitive to fluctuations of ecological and environmental properties due to the increase in soil bulk density and decrease in topsoil organic matter [53,54]. Litter shedding on the soil surface by planted tree species is used as a food source, which plays a remarkable role in microbial activities [10,55]. According to the results of present study, previous studies revealed an alteration in the characteristics of the substrate and topsoil after planting of different tree species, which was positively correlated to substrate quality [56,57]. Soil aggregate stability, which plays a crucial role in retaining soil productivity, was significantly affected after the machinery traffic on forest soil, leading to increased surface runoff rather than soil infiltration [21,22,24]. The C and N components of litter substrate are decomposed and bound with mineral particles, leading to increase in the formation of soil C and N [54,58].

Soil organic matter influences the different physicochemical properties, including pH and soil bulk density, which play a key role in the substrate [54], leading to the augmentation of the intensity of macro- and microorganisms, which ultimately results in an increase in the displacement and mixture of the litter substrate and further decomposition [58]. Soil organic C contributes remarkably to the development of soil structures and the supply of nutrient substrates, leading to increased biological activity that influences the healthy conditions in the soil environment [21,22,24]. High quality litter in the black alder (AG) plantation resulted in a greater increase in the release of nitrogen content than other treatments, including the PD and CS plantations with low quality litter. In addition, the C/N ratio of substrate and soil regulated the rate of decomposition. The recalcitrant materials in the PD and CS substrates were the main drivers of higher C/N ratios than those in the AG and CB-AV stands, which caused to enhance in an accumulation of organic materials in the surface area.

The litter substrates of the PD and CS plantations contain a large amount of lignin and decomposed more slowly than the litter of the black alder (AG) plantation and hornbeam-velvet maple stand, whose litter substrates contain a large amount of starch, as reported by Berg and Laskowski [59]. Hence, the litter of the PD and CS plantations with high lignin content need more time to be fed on by special microorganisms. Therefore, the recovery of soil properties significantly correlated with the treatment with high quality litter.

4.2. Soil Physio-Chemical Properties

Under natural conditions, the recovery of soil properties after mechanized traffic is a slow process, which may take from just a few years to several decades [9,10,55,57]. However, the leaf litter on the skid trails augments the surface roughness, enhances soil aggregate stability, reduces the velocity of raindrops, increases the water interception capacity, and improves the infiltration rate, which ultimately reduces the splash detachment of soil particles, overland runoff, and soil loss [25,50–52,56]. The results of the present study showed that the recovery values of soil physical properties, including soil bulk density, total porosity and macroporosity, penetration resistance, and aggregate stability, were at the highest level in the AG plantation in comparison to the PD and CS plantations due to the lower amounts of organic C and high N concentration. Due to the establishment of seedlings in the skid trails, the root system elongated and developed, which ultimately enhanced the swelling forces on soil aggregates [19,21,25]. The results of the current study showed that soil penetration resistance was partially improved in the black alder (AG) plantation compared to the values measured in the control stand (CB-AV) during the 25 years after soil compaction, which can be explained by elongation of roots in the planted trees, which led to the restoration of soil structure and enhanced the soil physical properties, as reported by previous studies [54,60]. Furthermore, soil physical properties, which indirectly regulate soil temperature and moisture content, influence the decomposition of litter in the soil [54]. Krishna and Mohan [60] found that soil texture affected the dynamics of water and nutrients, soil porosity, gas exchange and permeability. Soil texture is very important for the dynamics of organic matter. Also, the water-holding capacity is higher in finer textured soils than coarser soils. As a result, the amount of water generally has a relatively small effect on litter decomposition in sandy soils, but it has a significant effect on fine-grained soils [54].

Based on the results, the recovery trajectory of soil physical properties showed that the AG plantation resulted in the full recovery of soil bulk density, porosity and soil moisture over a 25-years-period, compared to the CB-AV treatment. However, other soil physical properties, including macroporosity, penetration resistance, sand, and clay in the black alder (AG) treatment, had a significant difference compared with the control treatment and the 25-year time period was not enough for their complete recovery.

The planting of native broadleaf tree species alters land surface functions that can regulate the quality of litter input and the root-soil system, which ultimately affects soil properties and nutrient content [22,33]. The litter layer in forest ecosystems not only protects the soil surface and absorbs the effects of raindrops [61], but also regulates and provides the flow and cycle of nutrients [53]. Litter layers and forest soil properties are affected by tree species through tree leaves and root activities [21,22,24]. The different qualities of tree leaves mainly regulate litter and nitrogen, soil carbon and lignin, C/N and lignin/nitrogen ratios, which affect the rate of decomposition of litter and organic matter, microbial and biological activities [53,62,63]. In addition, Jourgholami et al. [64] reported that the use of high-quality litter such as hornbeam and maple leads to the acceleration of the recovery processes for soil organic carbon and the availability of more nutrients than beech litter.

Litter layer decomposition is a remarkable process in the functioning of forest ecosystems because it is responsible for replenishing the soil nutrients pool available to plants, and creating long-term carbon storage as organic matter [65]. Two important factors that play a very important role in controlling the process and speed of litter decomposition include the nitrogen and lignin content of the litter [62,63]. At the level of plantation stands, litter decomposition is essential and significant for different reasons. The pool of nutrient cycling, especially C and N, is clearly controlled by the litter decomposition process. The availability of nutrients in the soil of the studied treatments, especially the planted stands, is largely due to the dynamics of the decay of organic matter in that soil. In addition, the accumulation of organic matter in the soil due to the faster decomposition of litter, especially in the black alder treatment (AG), can increase the cation exchange capacity to a great extent and have positive effects on the nutrient retention capacity in the soil of the AG treatment as compared to the CS and PD plantations. Subsequently, studies have shown that the decomposition process can influence soil pH [30,60].

The faster decomposition of black alder (AG) leaves, a N-fixing tree species, in comparison with Italian cypress (CS) and eastern cottonwood (PD) leaves, leads to the formation of humus and organic acids, which play a significant role in soil weathering, which provides a supply of nutrients for the growth of seedlings. The decomposition of litter and formation of humus resulted in an increase in the storage and controlled release of nutrients available for plants and microbial communities, as well as the storage of carbon compounds. The slower recovery of soil properties and less storage of nutrients in the plantations of CS, PD, and also in the DL treatment may also be due to the leaching process leading to nutrient loss and the transfer of organic compounds that have not been completely decomposed.

Previous studies elucidated that the most important factors which influence litter decomposition are litter quality and soil organisms [19,21,25,66]. Earthworms can affect litter decomposition via feeding and fragmentation of litter, leading to enhanced microbial activities by stimulating the microbial communities [66]. Most recent research results conclude that litter decomposition attributes to litter quality, which is driven by N and lignin concentrations and lignin: N ratio [21,22,24].

The highest level of litter N in the black alder plantation (AG) compared to other treatments can be attributed to the faster rate of decomposition. Moreover, previous studies recognized that the N concentration regulates the decomposition rate of litter, hence, the litter of the black alder as a N-fixing species and labile substrate and component improves the decomposition rate compared to the recalcitrant component of litter under the plantation of Italian cypress and eastern cottonwood [60,66,67]. Instead, the litter with high lignin concentration and recalcitrant component suppress the decomposition rate [30,60]. Another important factor that governed the rate of decomposition is the C/N ratio of the litter. According to the current results, the C/N ratio of litter at the AG plantation was higher than the values of the CS and PD treatments, since the litter with a high C/N ratio, considered as recalcitrant compounds, is not easily fed on by soil fauna, which resulted in a decrease in the decomposition rate [68].

The physical aspect and chemical component of leaves varies greatly between plant species, which has a remarkable impact on the characteristics and performance of forest ecosystems. The biochemical and physical qualities of the litter substantially influence the appropriate function of the forest ecosystem [69]. The leaf quality variation can be attributed to the differences in leaf lifespan. The amount of lignin and tannin and variabilities among plant litter contribute highly to the quality of litter [54].

The litter of the black alder (AG) plantation and hornbeam-velvet maple stand decomposed faster than the litter of the PD and CS plantations, particularly the black alder as N-fixing tree species and its labile substrate with low organic C and high N concentration. This phenomenon can be explained by the high N content of the initial substrate in the CB-AV and AG stands. Instead, the low speed of decomposition, such as in the PD and CS plantations, can be attributed to the C/N and lignin/N ratio of these initial substrates as reported by Berg and Laskowski [59]. Litter C/N in the black alder (AG) plantation and hornbeam-velvet maple stand was at the lowest level, which led to faster decomposition than substrates with a higher C/N ratio, such as the PD and CS plantations, as concluded by Giweta [54]. Accordingly, Berg and Laskowski [59] indicated that substrates such as the black alder (AG) plantation and hornbeam-velvet maple stand with high N concentrations decompose faster than litter of the PD and CS plantations due to the higher growth rate of microbe communities. In agreement with this, Chapman and Koch [70] demonstrated that the processes of decomposition and the nutrient pool and cycling is regulated by the spatiotemporal variation in in litter quality. The C and N in litter released by decomposition processes were used by microbial communities, which adjusted the dynamics of carbon and nutrients.

Accordingly, Langenbruch et al. [21] found a close relationship between the CEC and soil pH, which was attributed to leaf litter quality, depending on different tree species. By increasing soil pH, the CEC is improved, which leads to boosting the functional diversity of the soil and augments soil micro- and macro-organisms (i.e., fungi, bacteria, arthropods, and earthworms) [25]. However, Chalker-Scott [71] emphasized that the excessive application of organic mulch, such as leaf litter, on the soil surface can increase soil acidity. Accordingly, by providing adequate water and temperate conditions, organic mulch such as leaf litter substantially enhanced soil organic C and N, due to the decomposition process [51].

Furthermore, leaf litter covering the soil surface was infiltrated by throughfall flux, including chemical content such as nitrogen within tree canopies [72]. Leaf litter mulching has been shown to have a significant effect in mitigating surface runoff and increasing the infiltration rate, as reported by Jourgholami et al. [25]; hence, the water storage and runoff interacting with soil C and N can be dramatically influenced by litter mulching, which is well-known as the main driver regulating the rate of nutrient cycling [73]. Similar to our findings, Krishna and Mohan [60] demonstrated that tree species regulate the litter quality, influencing the decomposition rate by differences in the recalcitrant components of leaf, nitrogen, lignin, C/N ratio, and lignin/nitrogen ratio [60]. In line with the current study, Xu et al. [56] confirmed that the addition of litter enhanced total N and C/N ratio in the minerals. Furthermore, tree species with high quality litter can be more effective than low quality litter to boost soil microbial activity and to accelerate the decomposition rate of leaf litter mulch [21,64].

4.3. Soil Biochemical, Biological, and Microbial Properties and Enzyme Activity

Results of the current study showed that the recovery value of earthworm density and dry mass was higher in the black alder plantation than the other treatments, which can be contributed to the high quality of the black alder litter and low C/N ratio of its litter, which augment the mineralization of nutrients, which in turn, stimulate the micro- and macro-organisms, such as fungi, bacteria, arthropods, and earthworms in accordance with the results of Bottinelli et al. [15]. Litter layer plays a crucial role in supplying organic C and regulating the nutrient budget, not only for plants but also for soil macro- and micro-fauna [60,74]. The addition of leaf litter reduces the fluctuations in soil temperature and soil moisture, creating favorable ambient conditions for microbial communities and allowing the acceleration of microbial activity and decomposition of organic mulch [25,51]. Furthermore, microbial activity is dependent on the amount of organic matter. In contrast, Xu et al. [56], when reviewing 70 litter manipulation studies, concluded that litter addition resulted in an increase in soil respiration, microbial biomass carbon, and total carbon by 31%, 26%, and 10%, respectively. Previous studies have shown that leaf litter decomposition and organic matter cycling are markedly governed by the microbial biomass and community [25,51]. Consistent with our study, Jourgholami et al. [64] reported that organic mulch treatments (leaf litter mulch, in particular) enhanced the soil N, compared to the untreated area. Consequently, nitrifying bacteria can use the ammonia to render ammonium (NH_4^+) and nitrate (NO_3^-), which are then available to be used by soil organisms. Similarly, Zhang et al. [75] found that microbial biomass N is strongly associated with the amount of total N. Furthermore, previous studies have found that soil enzymes react to changes in soil conditions more instantly than other soil properties and, so, can be considered as a biological indicator for soil health [51].

The strong correlations between soil chemical properties, enzymatic activity, and soil physical properties contributed to improving the soil organic matter content by increasing the mulching ratios [76], which ultimately augmented the soil bulk density. Hence, the increase in soil chemical properties and enzymatic activity were related to the soil physical properties. The litter layer not only plays a crucial role in cycling nutrients and organic matter, but also acts as a protective layer which absorbs raindrop and throughfall impacts and prevents overland runoff flow [52,56,64,77]. When soil compaction occurs in forest soil following skidding operations, the air-filled pore spaces decrease, with an increase in soil bulk density [10,14]. Furthermore, applied organic mulch is gradually decomposed on the surface soil, significantly increasing the organic matter, maintaining soil structures, improving soil bulk density, and developing a suitable environment for soil fauna [1], which, ultimately, ameliorates the microbial population [52].

Litter quality, which is affected by different species, determines the accumulation, turnover, and decomposition rate of the floor layer [78–82]. According to previous studies, recalcitrant compounds of litter, nitrogen, lignin, and the C/N and lignin/nitrogen ratios in litter vary between different species [56,60,75]. However, the most important factors which regulate the litter decomposition rate are nitrogen and lignin content [60]. Soil resilience (or recovery capacity) refers to the intrinsic ability of a soil to recover from degradation and return to its former conditions. Additionally, several studies have highlighted the importance of planting N-fixing tree species, such as *Alnus* spp., in machine operating trails to recover soil structures [11,18]. Similarly, Fang et al. [74] found that the addition of fresh organic mulch (biomass) increased the N-mineralization in degraded agricultural soils.

The highest level of soil biological properties, C and N microbial properties, and enzyme activity in the black alder plantation can be explained by the high quality of litter under the black alder treatment, compared to the recalcitrant substrate of Italian cypress and eastern cottonwood, which increase the nutrient content, leading to an increase in the litter decomposition rate, which ultimately stimulates the microbial activity, increases nutrient content, leading to augmented soil respiration and enzyme activity [51,74].

When assessing soil recovery effects, it is best to take into account all measurements, rather than just some of them. In order to comprehensively compare the soil recovery effects of different restoration approaches, the analyzing data can be suggested using specific mathematical methods, such as the subordinate function value (SFV) method [83,84].

5. Conclusions

In the present study, the recovery level of soil properties was examined in the three plantation tree species (i.e., AG—black alder (*Alnus glutinosa* (L.) Gaertn.), PD—eastern cottonwood (*Populus deltoides* L.), CS—Italian cypress (*Cupressus sempervirens* L. var. *horizontalis* (Mill.) Gord.) compared to the natural forest stand of hornbeam-velvet maple (CB-AV; *Carpinus betulus* L.-*Acer velutinum* Boiss.) as well as degraded land without trees (DL), after a 25-year period following soil compaction and subsequent plantation. Results revealed that litter properties returned to pre-harvest level at the black alder (AG) plantation compared to the hornbeam-velvet maple natural stand. The full recovery of soil bulk density, porosity and soil moisture were found under the black alder plantation over a 25-year period, compared to the CB-AV treatment, but the 25-year time period was not enough for the full recovery of macroporosity, penetration resistance, sand, and clay in the black alder (AG) treatment. Among the soil chemical properties, only N storage and available nutrients of P and K under the black alder plantation (AG) were fully restored as compared to the CB-AV stand. Over a 25-year period after logging operations, soil biochemical, biological, microbial properties of C and N and enzyme activity in the black alder plantation (AG) were partially recovered, but these values have not returned to pre-harvest levels observed in the CB-AV treatment as control. Overall, these results suggested that black alder had greater positive effects on the recovery of soil properties than other trees due to the faster litter decomposition as a N-fixing species and its labile substrate with low organic C and high N concentrations. Therefore, black alder reforestation should be increased in future ecosystem restoration in areas influenced by logging operations.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/f14030603/s1, Table S1: Pearson correlation between soil biological and biochemical properties and enzymes activity with soil physio-chemical and litter properties in the different treatments of tree species. ED = Earthworm density; EB = Earthworm biomass; FRB = Fine root biomass; SMR = Soil microbial respiration; MBC = Microbial biomass carbon; NH_4^+ = ammonium; NO_3^- = nitrate; N Min = Nitrogen mineralization; MBN = Microbial biomass nitrogen; Enzymes activity; Urease; APH = Acid phosphatase; Arylsulfatase; Invertase; NAG = ß-N-acetylglucosaminidase; Litter T = Litter Thickness; CL = Litter C; NL = Litter N (%); C/NL = Litter C/N ratio; PL = Litter P; KL = Litter K; BD = Bulk density; TP = Total porosity; MP = Macroporosity; PR = Penetration resistance; SM = Soil moisture; AS = Aggregate stability; CS = Soil C; NS = Soil N; C/NS = Soil C/N; Fulvic = Fulvic acid; Humic = Humic acid.

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