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Regeneration of Belowground Properties and Nutrient Pools in Soil after Compaction: Response to the Reforestation with Native Tree Species in the Hyrcanian Forest †

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Abstract: The current study characterizes the regeneration in the floor layer and topsoil at a depth of 0-10 cm in the skid trails, dealing with the reforestation of four tree species (FE; *Fraxinus excelsior*, PA; *Prunus avium*, AC; *Acer cappadocicum*, and QC; *Quercus castaneifolia*) after clear-cutting in degraded forests, comparing to the undisturbed natural forest (CB-PP; *Carpinus betulus - Parrotia persica*). Results showed significant differences in litter layer properties among tree species, with the highest litter thickness, C, and C/N ratio under QC and AC, and the greatest litter N in CB-PP and FE. FE plantation resulted to enhance soil bulk density (1.14 g cm^{-3}), total porosity (55.85%), macroporosity (37.72%), penetration resistance (1.43 MPa), soil moisture (33.4%), and aggregate stability (51.7%), compared to other tree plantations, whereas these values under the FE plantation were still lower than those of the CB-PP stand over a 30-year period after logging operation. Litterfall on soil surface under planted tree species (FE and PA in particular) can be considered as a primary food resource (i.e., soil C and soil organic matter) driving biological and microbial activities. Results of the current study can improve our knowledge to select suitable tree species to maintain soil quality and nutrients pool to deal with ecosystem restoration programs and reforestation in degraded forest areas.

Keywords: Ecosystem restoration; degraded forest; hornbeam–Ironwood; common ash; wild cherry; Cappadocian maple; chestnut-leaved oak

1. Introduction

Forest soil has a crucial role to sustain ecosystem productivity, health, services [1,2], and supplies nutrients, organic matter, and water [3,4]. Furthermore, soil compaction imposed by heavy machines during logging operations may dramatically affect the balancing and regulation of forest productivity process by demolishing soil structure and impairing soil physical properties [5]. Consequently, this phenomena lead to reduce the porosity in soil volume [6,7], decrease the connectivity of pore spaces [8,9], increase soil bulk density and strength [10,11], and reduce water infiltration and gas exchange [12,13], with consequent negative influences on soil macro- and micro-organisms (e.g., earthworms

and microarthropods) [7,9], and elongation of root systems [14] and, ultimately, reducing tree and seedlings growth [15,16].

After compaction, for recovery processes of soil features may be needed from a few years to multiple decades to return to the pre-harvest levels, as documented in the previous studies [5,7,9,11,12]. One important issue to accelerate the recovery processes of soil properties and rehabilitate soil quality on areas affected by different degree of compaction is seedling planting [4,9,13]. For example, Meyer et al. [4] reported that planting black alder trees (*Alnus glutinosa*) along skid trails resulted in an increase in soil regeneration, especially concerning soil porosity and air permeability. Further, Flores Fernández et al. [13] indicated that compacted soil aeration was enhanced via soil-root system interactions, resulting in a return of soil properties to pre-harvest level four years after grey alder (*Alnus incana*) plantation. Likewise, Jourgholami et al. [9] concluded that tree species plantation including Caucasian alder, Velvet maple, and Italian cypress (*Cupressus sempervirens* var. *horizontalis*) had significant influence on the recovery level of soil after compaction over a 25-year period, compared to the natural hornbeam-oak stand.

Reforestation with native broad-leaved tree species changes the aboveground functions, allowing to regulate the quality of litter inputs and soil-root systems, thus affecting soil properties and nutrients pool [17,18]. Litter layer in forest ecosystems not only protects soil surface by raindrop impacts [19,20] but also regulates and supplies nutrients flow and cycling [19,21,22]. Forest litter layer and soil properties are influenced by tree species via litter input and root activities [17, 21,23,24]. Different qualities of trees litter have an effect on soil N, soil carbon and lignin, C/N and lignin/N ratios, which affect the decomposition rate of litter and organic matter as well as microbial and biological activities [21,25,26]. Moreover, Jourgholami et al. [22] reported that the application of high quality litters of hornbeam (*Carpinus betulus* L.) and velvet maple (*Acer velutinum* Boiss.) led to accelerate the recovery processes for soil organic C and nutrients availability to a greater extent than litter of beech (*Fagus orientalis* Lipsky).

Litter of high quality leads to accelerate the biological activities (i.e., earthworms) and enhances soil pH, heading therefore the soil to be burrowed by different earthworms species, resulting in an increase in soil aeration, pores spaces, and improving soil bulk density [3,9,27,28]. Numerous studies have revealed that soil C and N storage and available nutrients were greater in plantation forests than primary forest ecosystems [17,29,30]. For example, Diao et al. [17] found that native tree species including *Acer mono*, *Quercus mongolica*, *Juglans mandschurica*, *Fraxinus rhynchophylla*, and *Fraxinus mandschurica* significantly enhanced soil chemical and microbial properties, compared to larch plantation soils over a 60–70-year period. Similarly, in a short-term laboratory study, Yang and Zhu [31] determined that litter of *Fraxinus mandshurica* was decomposed quicker than litter of other species (i.e., *Quercus mongolica*, *Juglans mandshurica*, *Fraxinus rhynchophylla*, and *Acer mono*), which ultimately led to enhance microbial biomass and augment the nutrient pool. In addition, Jourgholami et al. [9] reported that litter of Italian cypress plantation tends to decompose slower than other planted trees species (e.g., Caucasian alder and Velvet maple) due to a lower microbial biomass, available N and P, which cause to impair the recycling of nutrients. The leaves litter of plants with recalcitrant compounds (i.e., lignin, tannins, and polyphenols) greatly suppresses the decomposition rate, and affects the time needed for material turnover in soil [31,32]. Accordingly, Langenbruch et al. [23] found that the turnover rate of ash (*Fraxinus excelsior* L.) leaves litter was faster than those of European beech (*Fagus sylvatica* L.) and lime (*Tilia cordata* Mill.), since the organic C and total N in litter layer was greater in beech than ash, but organic C and total N of 0-10 cm depth was lower in beech and lime than that of ash. Additionally, Kooch et al. [33] found that alder (*Alnus subcordata* C.A.M.) plantation, as N-fixing species, had a high quality of litterfall, which released macro-element nutrients due to the faster decomposition rate, which ultimately increased the biological activities, including earthworm density and dry mass, acari, collembola, nematode, and protozoa.

In the Hyrcanian forests, over the past three to four decades, degraded forests due to extensive cattle grazing and harvests for fuelwoods in rural areas have been replaced with mono-silviculture plantations by native and non-native tree species [9,34]. In the Hyrcanian (Caspian) forest region, reforestation and restoration programmes in degraded forests have been carried out with native

broad-leaved species including velvet maple, Caucasian alder, ash, chestnut-leaved oak, Cappadocian maple, wild cherry, elm, and other species, covering an area of 115000 ha [34]. Understanding the relations between tree species and above- and below-ground features has a key role to improve the management implications and learning from the natural and ecological processes and dynamics [18,30]. These mono-silviculture plantations play a key role to sustain the ecological and economical functions and services as well as the biodiversity value in Caspian region, compared to the primary forest ecosystems [9].

The current study characterizes four plantation stands of tree species adopted after clear-cutting of degraded forests through the comparison with the undisturbed natural forest (*Carpinus betulus* L. - *Parrotia persica* C.A.M.) and assesses the regenerating of soil properties along skid trails in response to the reforestation by different tree species (*Fraxinus excelsior* L., *Prunus avium* L., *Acer cappadocicum* Gled, and *Quercus castaneifolia* C.A.M.). The objectives of the study were to (1) assess the recovery of compacted-induced soil properties in the skid trails in response to the reforestation with different tree species over a 30-year period, (2) characterize the extent of regenerating in soil properties of different tree species, in comparison to the undisturbed natural forest, and (3) assay soil biological C and N microbial properties after planting the clear-cutted area with different tree species in the Hyrcanian temperate forest.

2. Materials and Methods

2.1. Site Description

This study was conducted in the compartment no.631 of the Tyrumrud forested watershed, which is located in Tonekabon city in western Mazandaran Province, northern Iran (36° 48′ 06″ and 36° 47′ 18″ N, 50° 43′ 21″ and 50° 43′ 14″ E; Fig. 1a). The study area has a humid climate with an annual rainfall of 1090 mm, characterized by cold winters. The altitude of the study area ranges between 440–480 m a.s.l. which is comparable to northeastern aspect. The mean annual temperature is 13.8 °C and highest and lowest monthly temperatures were measured in July (22.4 °C) and February (−2.0 °C), respectively. The soil could be classified as deep brown (Alfisols) according to the United States Department of Agriculture (USDA) soil taxonomy derived from limestone and dolomite limestone, belonging to the upper Jurassic and lower Cretaceous periods. The soil texture is clay loam. Prior to reforestation of 1990, this area was extensively degraded by cattle grazing and exploited by rural residences. The study area was formerly dominated by native deciduous broad leaves stands of hornbeam (*Carpinus betulus* L.) - Ironwood (*Parrotia persica* C.A.M.), complemented by chestnut-leaved oak (*Quercus castaneifolia* C.A.M.), Caucasian alder (*Alnus subcordata* C.A.M.), and Velvet maple (*Acer velutinum* Boiss.).

This area was clear-cutted and logs were processed and extracted in 1990 by Forest, Range, and Watershed Management Organization (FRWO), then it was reforested with spacing of 2×2 m, with native tree species including common ash (FE; *Fraxinus excelsior* L.), Wild cherry (PA; *Prunus avium* L.), Cappadocian maple (AC; *Acer cappadocicum* Gled), chestnut-leaved oak (QC; *Quercus castaneifolia* C.A.M.). The current study is focused on 30 years old stands of FE, PA, AC, and QC, and undisturbed stands of hornbeam – Ironwood (CB-PP), located near the planted stands, were selected as the control (Fig. 1). The characteristics of each treatment are given in Table 1. Trees were felled and processed with chainsaw, and the timbers with length of 4-12 m were extracted by TAF E655 wheeled cable skidder in June 1992. TAF E655 skidder main characteristics are: articulated, four-wheel-drive vehicle weighing 6.8 metric tons (55% of the mass on the front axle and 45% on the rear axle), engine power of 65 hp (48 kW), tires size of 18.4–26 inflated to 659 kPa on both front and rear axles, ground clearance of 0.45 m, overall width of 2.85 m, average machine load of 2.5 cubic meters, and slope gradient ranging 11-18%.

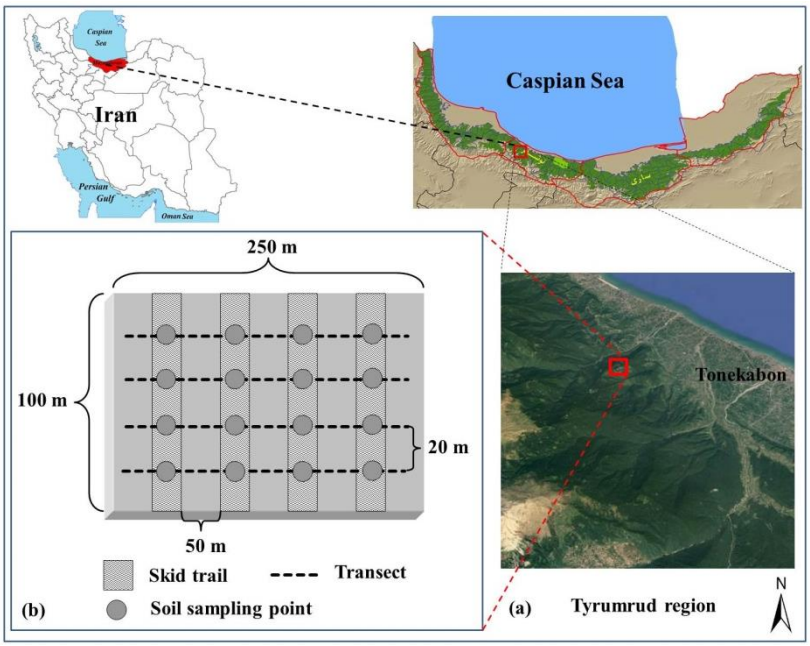

Figure 1. Location of the study area in the Hyrcanian forest, Northern Iran (a). A schematic diagram of the experimental design on the skid trails in each treatments of tree species (b).

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

Treatment	Main species	Slope (%)	Aspect	Tree density (N ha^{-1})	Growing stock (m^3 ha^{-1})	d.b.h. (cm)
CB-PP	Hornbeam (*Carpinus betulus L.*) – Ironwood (*Parrotia persica C.A.M.*)	19±3	NE	342.3±29.6	291.5±31.7	58.6±5.3
FE	Common ash (*Fraxinus excelsior L.*)	16±4	NE	635.7±45.7	414.2±25.7	22.3±1.3
PA	Wild cherry (*Prunus avium* L.)	15±5	NE	618.2±39.2	342.4±29.4	21.4±2.5
AC	Cappadocian maple (*Acer cappadocicum* Gled)	17±2	NE	584.6±40.8	208.6±34.1	18.6±2.9
QC	Chestnut-leaved oak (*Quercus castaneifolia* C.A.M.)	14±3	NE	561.8±36.5	190.9±21.6	17.7±3.7

2.2. Experimental design

Four planted stands including common ash (FE), Wild cherry (PA), Cappadocian maple (AC), chestnut-leaved oak (QC) and one stand as undisturbed or control (hornbeam – Ironwood ;CB-PP), located 200-300 m away from each others, were selected and soils were sampled in July 2019. In each monoculture stands and in the undisturbed (control) area, four skid trails within an area of 2.5 ha with dimension of 100×250 m were selected. Four transects were established perpendicular to the longitudinal axis of the skid trail, at 25 m interval as a systematic sampling to positioning the soil samples (Fig. 1b). This sampling procedure was also carried out for the hornbeam – Ironwood stands as control area. A total of 80 soil samples (i.e., 4 skid trails for each treatment × 4 transects in each plot × 5 treatments) were collected and analyzed.

2.3. Data collection and laboratory analysis

In each sample point, litter was gathered from a 20×20 cm square, stored in bags, transported to the laboratory, and dried at 70 °C for 48 h to reach a constant mass, finely ground, and then analyzed. To carry out the biological analysis, soil samples were stored in polyethylene bags at 4 °C until being

processed. Litter depth or thickness was determined using a tape measure. To measure the C and N of litter, the CN elemental analyzer (Flash EA1112 Series; Thermo Finnigan, Milan, Italy; [35]) was used. To take soil sample cores from the top mineral soil (depth of 10 cm), a thin-walled steel cylinder with length of 100 mm and diameter of 56 mm was used; subsequently, soil cores were weighed, stored in the bags, labelled, transported to the lab, oven-dried to get a constant mass at 105 °C for 24 h and determine soil bulk density and water content. Also, soil samples were collected from a 20×20×10 cm, air-dried, and passed through a 2-mm sieve. The hydrometer method [36] was used to determine the soil particle size distribution. To determine the macroporosity, the water desorption method [37] was used. To measure soil penetration resistance (PR), the analog hand-held soil penetrometer (Eijkelkamp 06.01.SA penetrometer with a 60° cone and a 1 m maximum measuring depth) was used. To determine the aggregate stability, the wet sieving procedure was used [38]. To determine the soil particle density, the ASTM D854-00 2000 standard was used and then Eq. 1 was implemented to calculate total porosity as follows:

$$\mathrm{TP} = 1 - \frac{\frac{M_S}{VC}}{2.65} \times 100 \quad (1)$$

where TP is the apparent total porosity (%), M_s is the mass of soil (g), VC is the volume of the intact soil cores (246.30 cm^3), and 2.65 (g cm^{-3}) is the particle density.

After soil sieving, chemical properties were analyzed as follows: Soil pH was determined by the Orion Ionalyzer (Model 901) pH meter in a soil:water ratio of 1:2.5. An Orion Ionalyzer EC meter in a 1:2.5 soil:water solution was used to measure EC. The Walkley-Black technique was applied to measure soil organic C [39]. The Kjeldahl method was applied to determine total N [40]. Soil C and N storage at depth of 0-10 cm was determined as Eq. 2:

$$SO\ (C\ or\ N)\ s = C\ or\ N\ \times BD\ \times e\ \times 0.1 \quad (2)$$

where SO (C or N) s indicates the organic C or N storage at soil (Mg ha^{-1}); C or N is the organic C or N content (g kg^{-1}); BD is the bulk density (g cm^{-3}); e is the thickness of the layers (cm), and 0.1 is a depth conversion factor.

Available phosphorous (P) was measured by the Olsen method with a spectrophotometer, and available potassium (K), calcium (Ca), and magnesium (Mg) (by ammonium acetate extraction at pH 9) were determined by applying an atomic absorption spectrophotometer [41]. The method of the International Humic Substances Society (IHSS) was applied to isolate and purify the soil humic acid and fulvic acid [40]. To determine the number and density of earthworms, sampling was manually carried out at the soil surface of 25×25 cm with depth of 0-10 cm [41]. The earthworms were counted in the sampling area, transported to the laboratory, washed, oven-dried at 60 °C for 24 h to reach a constant mass, and then reweighted to determine the earthworm dry mass [33]. Fine roots (< 2 mm diameter) were separated from each sample and dried at 70 °C to a constant mass, to determine fine root biomass [42]. Soil microbial respiration was determined by measuring the CO_2 evolved in a 3-days incubation experiment at 25 °C [40]. The microbial biomass carbon (MBC) and nitrogen (MBN) in the soils were determined via the chloroform fumigation–extraction method [43]. The colorimetric techniques were used to extract soil NH_4^+ and NO_3^- via 2 M KCl solution (soil: solution, 1:5) [44]. The aerobic incubation of the soils was applied to determine N mineralization [45].

2.4. Statistical analyses

The Kolmogorov-Smirnov test was applied to check the normality of the variables. Levene's test was employed to check the equality of variance. Since no departure of data from a normal distribution was observed, generalized linear model (GLM, one-way analysis of variance) was used to examine 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 different tree species and the undisturbed (control) area at $P < 0.05$. The relationship between soil biochemical and biological properties with litter sand oil physio-chemical properties in different treatments was tested with Pearson correlation. All statistical analyses were done using SPSS (release 17.0; SPSS, Chicago, IL, USA) statistical package.

3. Results

3.1. Litter properties

Results showed significant differences in litter layer properties among planted tree species and natural forest stand (CB-PP) (Fig. 2). The thickness of litter layer differed significantly among the different tree species treatments ($p < 0.05$, Fig. 2). A significantly higher litter C was found under the QC than AC > CB-PP > PA ≈ FE. Litter N was found in ranked order of FE ≈ PA ≈ CB-PP > AC > QC. The highest litter C/N ratio was detected in the QC planted stand, followed by AC plantation, whereas this value did not differ significantly between tree species of CB-PP ≈ FE ≈ PA (Fig. 2).

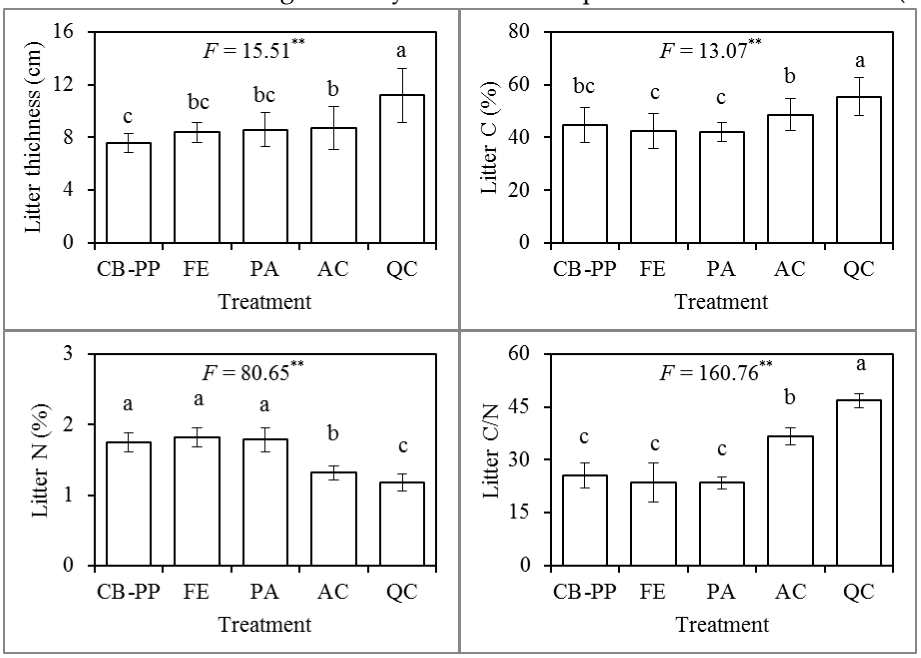

Figure 1. Mean values and standard deviation (SD) of litter properties in the different tree species treatments. Results of the ANOVAs (*F* test and *P* value) are given. Different letters after means within each treatment indicate significant differences by Duncan's test ($P < 0.05$). CB-PP = Undisturbed natural stand of *Carpinus betulus* L. - *Parrotia persica* C.A.M.; FE = Plantation of *Fraxinus excelsior* L.; PA = Plantation of *Prunus avium* L.; AC = Plantation of *Acer cappadocicum* Gled; QC = Plantation of *Quercus castaneifolia* C.A.M.

3.2. Soil physio-chemical properties

Results showed that there were significant differences in soil physio-chemical properties among different treatments (Tables 2 & 3). Plantation with FE resulted to enhance soil bulk density, penetration resistance, sand and, by a comparison with other tree species plantations, these values under the FE plantation were still lower than those of the undisturbed (CB-PP) stand over a 30-year period after logging operation. Total porosity, macroporosity, soil moisture, aggregate stability, clay, and silt were significantly greatest in the natural forest stand of CB-PP followed FE plantation, whereas the lowest amount of these values was detected under the QC plantation (Table 2).

The highest soil pH was found under the FE ≈ PA plantations followed by natural stand of CB-QC, whereas the lowest pH was observed at the AC ≈ QC plantation. The lowest amounts of soil C, soil C/N ratio, and C storage were measured under the FE plantation in comparison to the other tree species plantations. Significantly greatest amounts of soil N, N storage, available nutrients (P, K, Ca, and Mg), fulvic acid as well as humic acid were found under the FE plantation compared to the others , whereas these values were still least than those of the natural forest stands of CB-PP over a 30-year period after soil compaction (Table 2).

Table 2. Mean values and standard deviation (SD) of soil physio-chemical properties in the different treatments of tree species. CB-PP = Undisturbed natural stand of *Carpinus betulus* L. - *Parrotia persica* C.A.M.; FE = Plantation of *Fraxinus excelsior* L.; PA = Plantation of *Prunus avium* L.; AC = Plantation of *Acer cappadocicum* Gled; QC = Plantation of *Quercus castaneifolia* C.A.M.

Soil properties		**Undisturbed natural stand and plantation treatment**					***F* test**	***P* value**
		CB-PP	**FE**	**PA**	**AC**	**QC**		
Physical properties	Bulk density (g cm^{-3})	1.04±0.08d	1.14±0.09c	1.16±0.08c	1.23±0.07b	1.34±0.09a	30.02	0.00
	Total porosity (%)	57.2±3.23a	53.85±3.74b	54.15±3.03b	51.92±2.62b	48.06±3.34c	17.54	0.00
	Macroporosity (%)	43.17±2.08a	37.72±1.99b	35.14±1.56c	32.03±1.39d	28.29±1.97e	154.5	0.00
	Penetration resistance (MPa)	1.23±0.12c	1.43±0.16b	1.46±0.17b	1.64±0.16a	1.73±0.14a	27.11	0.00
	Soil moisture (%)	35.7±7.04a	33.4±3.74ab	32.3±7.21ab	28.6±9.35bc	26.5±9.92c	3.66	0.01
	Aggregate stability (%)	61.1±6.37a	51.7±8.67b	50.5±7.5b	46.8±7.86bc	42.3±9.24c	12.21	0.00
	Sand (%)	44.67±1.84d	46.03±0.88d	49.93±1.9c	54.59±3.44b	59.44±1.94a	128.33	0.00
	Clay (%)	30.67±1.54a	30.7±0.87a	29.48±0.79a	30.01±2.9a	27.39±1.17b	10.95	0.00
	Silt (%)	24.66±1.24a	23.26±1.12b	20.59±1.72c	15.41±1.58d	13.17±1.13e	207.41	0.00
Chemical properties	pH (1:2.5 H_2O)	6.29±0.11b	6.61±0.08a	6.59±0.12a	6.11±0.08c	6.05±0.08c	120.49	0.00
	C (%)	3.13±0.07d	3.34±0.07c	3.37±0.1c	3.55±0.11b	3.73±0.14a	82.5	0.00
	N (%)	0.28±0.03a	0.23±0.02b	0.22±0.02bc	0.21±0.03c	0.19±0.02d	26.28	0.00
	C/N ratio	11.31±1.16d	14.58±0.83c	15.48±1.63c	17.32±3.08b	19.95±2.97a	35.96	0.00
	C storage (Mg ha^{-1})	32.6±3.23d	38.13±3.78c	39.15±3.58c	43.73±3.67b	49.88±1.75a	62.16	0.00
	N storage (Mg ha^{-1})	2.93±0.54a	2.64±0.40ab	2.57±0.42b	2.57±0.25b	2.56±0.45b	2.29	0.04
	Available P (mg kg^{-1})	17.67±2.23a	15.53±1.4b	14.75±1.45bc	13.88±1.56cd	13.14±1.53d	17.63	0.00
	Available K (mg kg^{-1})	266.48±20.8a	235.55±10.5b	228.64±9.3b	214.83±7.8c	192.54±10.9d	73.38	0.00
	Available Ca (mg kg^{-1})	186.45±10.2a	171.92±8.4b	165.15±7.6b	152.32±10.2c	134.73±11.8d	65.08	0.00
	Available Mg (mg kg^{-1})	41.48±3.75a	36.57±2.9b	34.23±2.21c	28.61±1.94d	27.42±2.81d	68.82	0.00
	Fulvic acid (mg/100 g)	313.6±20.1a	282.7±15.2b	274.3±16.5b	260.8±10.6c	232.7±12.1d	60.41	0.00
	Humic acid (mg/100 g)	160.7±16.2a	134.5±9.2b	123.8±9.2c	122.4±9.5c	105.6±11.1d	51.16	0.00

Note: 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 ($P < 0.05$).

Table 3. Mean values and standard deviation (SD) of soil biological and biochemical properties in the different treatments of tree species. CB-PP = Undisturbed natural stand of *Carpinus betulus* L. - *Parrotia persica* C.A.M.; FE = Plantation of *Fraxinus excelsior* L.; PA = Plantation of *Prunus avium* L.; AC = Plantation of *Acer cappadocicum* Gled; QC = Plantation of *Quercus castaneifolia* C.A.M.; 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}).

Soil properties		**Undisturbed natural stand and plantation treatment**					***F* test**	***P* value**
		CB-PP	**FE**	**PA**	**AC**	**QC**		
Biological properties	Earthworm density (n m^{-2})	2.12±0.26a	1.82±0.15b	1.62±0.15c	1.54±0.12c	1.37±0.09d	48.94	0.00
	Earthworm dry mass (mg m^{-2})	26.61±2.63a	22.57±2.16b	20.48±2.13c	19.36±2.41c	16.14±1.7d	48.79	0.00
	Fine root biomass (g m^{-2})	88.45±7.28a	76.31±7.4b	71.46±5.68c	69.27±4.87c	61.93±3.5d	43.99	0.00
C and N Microbial properties	SMR	0.38±0.03a	0.33±0.02b	0.32±0.02b	0.27±0.02c	0.26±0.02c	96.08	0.00
	MBC	492.2±34.5a	438.7±25.2b	380.6±17.5c	365.9±14.2c	325.3±20.4d	124.68	0.00
	NH_4^+	19.73±2.89a	16.54±1.46b	15.67±1.3b	14.12±1.62c	11.86±1.44d	40.46	0.00
	NO_3^-	18.61±2.12a	15.92±0.89b	14.65±0.69c	13.25±1.17d	11.67±1.09e	67.29	0.00
	N Min	32.37±2.04a	27.04±1.41b	25.81±1.35c	21.68±1.4d	20.75±1.5d	142.27	0.00
	MBN	34.71±2.61a	28.35±2.36b	26.46±1.52c	20.58±1.96d	19.83±1.42d	144.7	0.00

Note: 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 ($P < 0.05$).

3.2. Soil biochemical and biological properties

Soil biological C and N microbial properties significantly differed among different tree plantations and the natural CB-PP forest stand (Table 3; $P < 0.001$). The greatest values of earthworm density and dry mass, as well as fine root biomass, were found under the natural CB-PP forest stand followed by FE plantation, whereas the significantly least amount of these values were measured under the QC plantation. Following the establishment of different tree plantations, significantly higher values of soil microbial respiration, MBC, NH_4^+, NO_3^-, N mineralization, and MBN were found under the FE plantation, whereas the values did not return to the pre-harvest level, as observed under the CB-PP natural forest stand over a 30-year period (Table 3).

Results showed that the recovery of soil properties after planting native tree species was mainly depended on the quality of litter under different treatments, compared to the CB-PP natural stands. Significantly positive relationships were observed between earthworm density and biomass, soil microbial respiration, MBC, NH_4^+, NO_3^-, N mineralization, and MBN with litter N, total porosity, macroporosity, soil moisture, aggregate stability, clay, silt, pH, soil N, N storage, available nutrients (P, K, Ca, and Mg), fulvic acid and humic acid, and negatively correlated with litter thickness, litter and soil C, litter and soil C/N ratio, bulk density, penetration resistance, sand, and C storage (Table 4).

4. Discussion

4.1. Litter Properties

Mechanized forest harvesting brought dramatic changes to soil habitat through soil disturbance, displacement of topsoil and compaction, resulting in a decrease in water infiltration [5,12,13]. In line with the current study, numerous studies have evidenced that forest machinery traffic had detrimental impacts on soil quality [6,10,15,16]. Further, soil microbial biomass is susceptible to the ecological and environmental fluctuations due to soil compaction and reduction of soil organic matter [23,46,17]. Litterfall on the soil surface by planted tree species may be considered as food resource (i.e., soil C and soil organic matter) which is a primary driver to microbial activities [47]. In accordance to the results of the current study, previous studies showed changes in litter and topsoil properties after establishing of plantation with native and non-native tree species and primarily linked with quality of litter [9,33,41]. Soil aggregation that plays a key role in maintaining soil productivity was dramatically impacted after logging vehicle traffic, resulting in an increased overland flow instead of infiltration into soil [20].

C and N compounds of leaves litter were decomposed and bind with mineral particles, and then formed soil C and N [9,23,48,49]. Soil organic C has a crucial role to develop soil structures and supply food substrates, resulting in an augment of the biological activity that contributes to soil functions, quality, and ecosystem services [17].

The greatest values of litter thickness were found under QC followed by AC > PA ≈ FE > natural stand of CB-PP. The superiority of production or decomposition process determines litter thickness after plantation, which supplies soil organic C and regulates nutrient cycling [23,46]. High quality litter under the FE and PA plantation allows a greater N content than other stands with low quality litter. Further, litter and soil C/N ratio is an important factor that influences the decomposition rate. The recalcitrant compounds of QC and AC litters are the main driver for a greater C/N ratio than those under the FE and PA plantations, leading to a higher accumulation of organic matter on the soil surface.

Previous studies evidenced that different tree species varied in composition of leaves litter, which in turn determined the recalcitrant compounds of litter, nitrogen, lignin, and the C/N and lignin/nitrogen ratios in litter [17,23,32,46]. Further, nitrogen and lignin content have a crucial role to regulate the decomposition rate of leaves litter [31,46].

Table 4. Pearson correlation between soil biological and biochemical properties 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; Litter $_T$ = Litter Thickness; C_L = Litter C; N_L = Litter N (%); C/N_L = Litter C/N ratio; BD = Bulk density; TP = Total porosity; MP = Macroporosity; PR = Penetration resistance; SM = Soil moisture; AS = Aggregate stability; C_S = Soil C; N_S = Soil N; C/N_S = Soil C/N; Fulvic = Fulvic acid; Humic = Humic acid.

Soil properties		**Litter properties**				**Soil physical properties**								
		Litter $_T$	**C_L**	**N_L**	**C/N_L**	**BD**	**TP**	**MP**	**PR**	**SM**	**AS**	**Sand**	**Clay**	**Silt**
Biological properties	ED	-0.29**	-0.50**	0.51**	-0.63**	-0.73**	0.66**	0.85**	-0.50**	0.03ns	0.32**	-0.69**	0.32**	0.74**
	EB	-0.27*	-0.54**	0.55**	-0.67**	-0.74**	0.67**	0.85**	-0.44**	-0.01ns	0.31**	-0.70**	0.38**	0.72**
	FRB	-0.29**	-0.46**	0.62**	-0.65**	-0.61**	0.52**	0.77**	-0.31**	0.23*	0.51**	-0.69**	0.48**	0.68**
C and N Microbial properties	SMR	-0.31**	-0.57**	0.65**	-0.74**	-0.74**	0.66**	0.87**	-0.57**	0.11ns	0.39**	-0.76**	0.33**	0.81**
	MBC	-0.40**	-0.49**	0.68**	-0.71**	-0.63**	0.52**	0.85**	-0.49**	0.31**	0.57**	-0.82**	0.51**	0.81**
	NH_4^+	-0.27*	-0.54**	0.54**	-0.67**	-0.76**	0.69**	0.84**	-0.49**	-0.04ns	0.28*	-0.67**	0.31**	0.72**
	NO_3^-	-0.33**	-0.53**	0.59**	-0.69**	-0.76**	0.68**	0.88**	-0.56**	0.05ns	0.36**	-0.73**	0.34**	0.78**
	N Min	-0.38**	-0.37**	0.65**	-0.66**	-0.57**	0.45**	0.81**	-0.60**	0.22*	0.45**	-0.78**	0.48**	0.78**
	MBN	-0.35**	-0.52**	0.68**	-0.73**	-0.77**	0.69**	0.91**	-0.61**	0.18ns	0.46**	-0.78**	0.35**	0.84**
Soil properties		**Soil chemical properties**												
		pH	**C_S**	**N_S**	**C/N_S**	**C_{stor}**	**N_{stor}**	**P**	**K**	**Ca**	**Mg**	**Fulvic**	**Humic**	
Biological properties	ED	0.27*	-0.83**	0.61**	-0.74**	-0.80**	0.17ns	0.94**	0.91**	0.93**	0.96**	0.76**	0.74**	
	EB	0.30**	-0.87**	0.67**	-0.81**	-0.83**	0.24*	0.95**	0.89**	0.96**	0.96**	0.83**	0.79**	
	FRB	0.35**	-0.76**	0.83**	-0.83**	-0.71**	0.48**	0.69**	0.68**	0.82**	0.78**	0.97**	0.98**	
C and N Microbial properties	SMR	0.44**	-0.89**	0.67**	-0.79**	-0.84**	0.23*	0.90**	0.90**	0.95**	0.98**	0.83**	0.77**	
	MBC	0.44**	-0.82**	0.83**	-0.85**	-0.75**	0.46**	0.68**	0.76**	0.84**	0.83**	0.95**	0.95**	
	NH_4^+	0.30**	-0.87**	0.59**	-0.76**	-0.84**	0.14ns	0.96**	0.92**	0.97**	0.96**	0.75**	0.72**	
	NO_3^-	0.33**	-0.90**	0.64**	-0.78**	-0.85**	0.18ns	0.92**	0.94**	0.96**	0.97**	0.78**	0.75**	
	N Min	0.51**	-0.82**	0.89**	-0.89**	-0.71**	0.57**	0.65**	0.84**	0.81**	0.82**	0.88**	0.88**	
	MBN	0.42**	-0.89**	0.69**	-0.80**	-0.86**	0.22*	0.88**	0.89**	0.94**	0.98**	0.84**	0.79**	

Note: * $P < 0.05$; ** $P < 0.01$; ns: not significant.

4.2. Soil Physio-Chemical Properties

The results of the current study showed that recovery level of soil bulk density, and total porosity and macroporosity observed in the FE and PA plantations were greater compared to QC and AC, which can be attributed to the lower amounts of organic C and higher soil N. As a consequence of the development and elongation of root systems, the roots thickness expands, exerting greater swelling forces to the soil [4]. Results of the current study showed that the soil penetration resistance partially recovered to pre-harvest level in the FE and PA plantations, compared to the natural stand of CB-PP over a 30-year period after soil compaction. Previous studies have demonstrated that the development of planted tree root systems can be linked to the rehabilitation of soil structure, consequently improving soil physical properties [4,9,13].

The formation of soil aggregates and the aggregate stability is highly dependent on the development of tree root systems and root-soil interactions water absorption and shrink of soil ambience after tree plantations [49]. According to the present study, litter of the FE and PA plantations, compared to the other species (i.e., QC and AC plantations), appears to modify soil bulk density and penetration resistance as a result of the greater decomposition rate of their litter, which augments organic matter content, enhances nutrients viability, improves water retention, increases soil moisture contents, which in turn resulted in an amelioration of soil bulk density and penetration resistance [50,51].

Results of the current study showed that sand articles were greater in the QC and AC than those of the FE and PA plantations, as reported by Jourgholami et al. [9]. The loss of litter layer after vehicle traffic leads to have a direct impact of raindrops on bare mineral soil, increases overland flow, which ultimately results in an increase in transport of clay and silt by water erosion [14]; this event has continued until the establishment and development of the plantation, especially in the AC and QC plantations [22]. The enhancing trend in soil pH under FE and PA plantations may be related to the high quality litter and the increase in litter decomposition rate, which increased soil alkalinity, improved cation exchange capacity of soil, thus augmenting soil biological activities and accumulation of the essential element nutrients [17,52].

The greatest soil organic C and soil C/N ratio was found under the QC and AC plantations, compared to the FE and PA plantations as well as natural stand of CB-PP. According to Langenbruch et al. [23] findings, the least level of soil organic C and soil C/N ratio can be attributed to the faster mineralization of soil organic matter and also to the enhancement of soil pH under the FE and PA plantations. Foliage properties and high quality litter of FE and PA plantations led to improve the litter decomposition rate and enhanced soil pH, which in turn augmented the soil N, in comparison with QC and AC plantations; however, these values were still lower than those under CB-PP natural stand, which haven't recovered to pre-harvest level over a 30-year period after soil compaction and subsequent plantation. In contrast, Meyer et al. [4], Flores Fernández et al. [13], and Jourgholami et al. [9] observed that planations of Caucasian alder (*Alnus subcordata*), known as N-fixing species, provided a high quality litter with greater N content and least C/N ratio, resulting in a faster recovery process to return pre-harvest level. The establishment of native species resulted in an increase in carbon storage, ranging 38.13-49.88 Mg ha^{-1}, compared to the natural stand of CB-PP, whereas the greatest values of N storage were found under the CB-PP natural stand and FE plantation. Reforestation of degraded forests with native species has a crucial role to sequester carbon, as reported by Garten et al. [53]. Furthermore, several studies concluded that the accumulation, turnover, and decomposition rate of leaves layer were associated with the litter quality, which is regulated by the different tree species [23,46].

Results of the present study evidenced that the highest level of available nutrients (P, K, Mg, and Ca) was found under the FE and PA plantations compared to the QC and AC, however, these values were still lower than those of the natural stand of CB-PP. According to the current results, the values of available nutrients partially recovered, but the full recovery aforementioned parameters haven't occurred over a 30-year period after soil compaction. In contrast, Jourgholami et al. [9] found that Caucasian alder plantation, known as N-fixing tree species, led to restore soil properties over a 25-

year period following compaction thanks to the higher soil N and lower C/N ratio, which caused to accelerate the decomposition rate and N mineralization, resulting in a greater nutrients pool. Results of the current study showed that the recovery of soil chemical properties was faster in FE plantation than in the other tree species, which can be attributed to the labile components of ash trees litter that decomposed faster than recalcitrant litter. The low content of lignin and high content of N, leading to a greater lignin/nitrogen ratio in FE (ash) leaves litter compared to other tree species (i.e., PA, AC, QC), causes to accelerate the litter decomposition rate, as reported by Langenbruch et al. [23] and Diao et al. [17]. Our results are in line with the conclusion of Langenbruch et al. [23] assuming that topsoil properties were mainly regulated by ash (FE) leaves litter, which contained the greatest amounts of Mg and Ca. The results of the current study showed that fulvic acid and humic acid were greatest under the FE and PA plantations, compared to the natural stand of CB-PP. In fact, the litters of FE and PA have been characterized by high N content and low C/N ratio, which allowed to release greater levels of nutrients thanks to the faster decomposition rate thus improving soil quality and augmenting the fulvic acid and humic acid [9,23,48].

4.3. Soil Physio-Chemical Properties

Earthworms, categorized as macro-fauna and known as ecosystem engineers, play a key role to ingest organic matter, change soil nutrient dynamics, augment soil structures, taking part in nutrient cycling and soil fertility [33,54]. In the current study, the earthworm density and dry mass were increased in FE plantation than others species (i.e., PA, AC, QC), which can be associated to the chemical properties of litter layer such as the less C and C/N ratio and the greater N and available nutrients [7,33,22]. The soil floor layer is regulated by different tree species and it acts not only as an habitat but also as a food resource for soil fauna [7,33,47,48]. In contrast, Bottinelli et al. [7] found that earthworm density and biomass were detrimentally impacted by forwarder traffic and showed no signs of recovery over a 4-year period after compaction, which can be linked to the unfavorable topsoil habitant and slow recovery of litter layer. However, Althoff et al. [47] stressed that soil fauna (i.e., earthworm) can be considered as an effective bioindicator for microbial communities to characterize soil recovery, because of the greater levels in food web, and their easy assessment. Results of the current study showed a positive relationship between earthworm density and biomass, in relation to litter N, soil pH, soil N, N storage, available nutrients (P, K, Ca, and Mg) as reported by Aponte et al. [48], Salehi et al. [41], and Kooch et al. [33].

Results of the current study showed that the greatest fine root biomass was found under the FE and PA plantations, but these values were still lower than those of fine root biomass under the CB-PP stand. In line with the current study, Wang et al. [55] concluded that fine root biomass was significantly different between natural stand and plantations. Similarly, Jourgholami et al. [9] indicated that the significantly greater fine root biomass was found under the Caucasian alder in comparison with other tree species. Litter layer which is formed by yearly litterfall in plantation plays an important role to provide food resource; however, the quality of leaves litter is a key driver for nutrient cycling and fauna activities in soil, which have influence on soil fertility, and consequently affect fine root biomass under the plantations [4,13,23]. Likewise, Flores Fernández et al. [13] determined that soil aeration and root growth improved on the skid trail during 2 year following seedling planting.

Our findings showed that the greatest levels of soil microbial respiration were measured under the FE and PA plantations; however, these values were lower than those under the natural stand of CB-PP, which can be associated to the higher quality litter, lower carbon and lignin, faster leaf decay rate, and lower C/N ratio [17,23,48]. Our findings showed that the greatest levels of soil microbial biomass C and N were observed under the FE and PA plantations, compared to the natural stand of CB-PP. Consistent to the results of the current study, Diao et al. [17] found that the establishment of *Fraxinus mandschurica* resulted in a greater increase in soil N and available P, MBC, and MBN in comparison with *Acer mono*, *Quercus mongolica*, *Juglans mandschurica*. Consistent with our findings, several studies have reported that the differences of microbial C and N in soils are closely related to the differences in tree species [17,48,56]. Our results are in line with the conclusion of Aponte et al.

[48], stating that leaf-fall of *Quercus canariensis* brings lower carbon to nutrient ratios and higher nutrient content than *Quercus suber*, which in turn leads to enhance soil microbial biomass and nutrients. In line with the current study, Aponte et al. [48] stated that soil microbial biomass was positively correlated with soil moisture content, organic matter, and substrate availability. Tree species were significantly influenced by soil N and available P, MBC, and MBN as reported by Diao et al. [17].

Results of the current study showed that the greatest level of NH_4^+, NO_3^-, and N mineralization was found under FE and PA plantations, and values were lower than those under CB-PP natural stand. The higher soil moisture content, greater organic matter, and more litter input under FE and PA plantations allow the soil to rehabilitate and become a favorable ambience, increase microbial biomass and activity, which ultimately enhances NH_4^+, NO_3^-, and N mineralization [23,48]. High quality litter (i.e., lower C/N and lignin/N ratios) in one of several important drivers that mainly affect the litter decay rate, microbial communities and activities, suppress microbial immobilization of N, leading to augment N mineralization and plant available N [26,57,58].

Results of the present study demonstrate a positive relationship between NH_4^+, NO_3^-, and N mineralization and litter N, soil moisture, soil N, N storage, and available nutrients (P, K, Ca, and Mg). Consistent with our findings, several studies reported that soil N mineralization was mainly linked to the soil N content and greater soil nutrient content [59,60].

5. Conclusion

In the present study, soil compaction and the efficacy of four plantations with native tree species (common ash, wild cherry, Cappadocian maple, chestnut-leaved oak) to rehabilitate properties of compacted soil along the skid trails, over a 30-year period after clear-cutting, have been examined and compared with the undisturbed natural stand of hornbeam–Ironwood in the Hyrcanian temperate forest. The results revealed that different tree species can regulate soil physical, chemical and biological properties, especially concerning topsoil, through different litter quality as food resource (i.e., soil C and soil organic matter) which is considered an important driver for soil microbial C and N activities. Our findings evidenced that *F. excelsior* and *P. avium* plantations improved litter input quality (lower amount of C and carbon to nitrogen ratio as well as greater N) and soil physical (lower soil bulk density and penetration resistance with greater soil moisture and aggregate stability), chemical (higher soil pH, soil N, and nutrients availability), biological (greater amount of earthworm density and dry mass, fine root biomass and soil microbial respiration) properties and greater levels of MBC, MBN, NH_4^+, NO_3^-, and N mineralization in comparison with *A. cappadocicum* and *Q. castaneifolia* plantations. However, the aforementioned values did not return to the pre-harvest levels as observed under the undisturbed natural stand of *C. betulus – P. persica* over a 30-year period, and more than 30 years were necessary to restore soil quality to undisturbed level.

Results of the current study can promote our knowledge to select suitable tree species, which make possible to maintain soil quality and nutrients pool within ecosystem restoration programs and reforestation in degraded forest areas.

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