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Effects of Forest Harvesting Operations on the Recovery of Earthworms and Nematodes in the Hyrcanain Old-Growth Forest: Assessment, Mitigation, and Best Management Practice

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Abstract: The quality and performance of forest soil is closely related to the characteristics of the faunal community in the soil. Focusing on soil organisms can provide good indicators to choose the best soil restoration methods to improve the properties of degraded forest soils. Therefore, the present study aimed to evaluate the effects of the tree litter of different species on the recovery of soil organisms (earthworms and nematodes) from skid trails over a 20-year period after harvest operations. For this purpose, three skid trails with different ages after harvest operations (6, 10, and 20 years), considering three tree litter treatments (beech, beech–hornbeam, and mixed beech) and three traffic intensity classes (low, medium, and high), were identified. The combination of treatments was carried out in the forest with three replications, and a total of 18 sample plots of 0.5 m^2 were harvested to measure earthworms and nematodes. The results showed that 20 years after harvest operations, the highest values of earthworm density (5.72 n m^{-2}), earthworm biomass (97.18 mg m^{-2}), and total nematodes (313.65 in 100 g of soil) were obtained in the mixed beech litter treatment compared to other litter treatments. With decreasing traffic intensity from high to low, the activity of soil organisms increased, and the highest values of earthworm density (5.46 n m^{-2}), earthworm biomass (87.21 mg m^{-2}), and soil nematodes (216.33 in 100 g soil) were associated with low traffic intensity. Additionally, in all three litter treatments and traffic intensities, the epigeic ecological species were more abundant than the anecic and endogeic species. Key soil variables including water content, porosity, available nutrients, pH, total organic C, and total N were significantly correlated with earthworm density and biomass and soil nematode population. Litter management and addition to compacted soil can support the functional dynamics and processes of the soil and maintenance of the abundances and activities of the soil fauna.

Keywords: earthworm; nematode; soil recovery; forest harvesting; traffic intensity

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1. Introduction

Forestry and agriculture practices for nonfood and food production have changed both physicochemical and biological soil features around the world. Particularly in the forestry sector, the constant need for wood products due to the increasing population has put a considerable amount pressure on forest ecosystems [1–3]. Mechanized ground-based skidding operations increase soil compaction and disturbance, which ultimately reduces soil quality and fertility [4–7] and affects root systems [8]. Understanding the impact of skidding operations and the factors influencing soil quality change is essential to achieving the most appropriate strategy to limit the negative effects on soil and to restore it to preharvest conditions [3,9–11]. Unlike the methods applied in agricultural fields, due to the special conditions in forest areas such as topography and presence of stumps and large roots, the use of tillage operations does not improve forest soil structures [4]. Therefore, compacted soils in forest ecosystems can be improved through long-term natural and ecological activities [7,12–14].

One of the most commonly applied ecological methods for soil recovery is planting trees to produce litter or adding litter to the soil surface, which has a positive effect on soil quality [1,15]. In order to recover forest soil, Vázquez et al. [16] showed that coniferous species led to an increase in soil organic matter. Wang et al. [17] reported that broadleaf species contribute to a further increase of organic matter, nutritional elements, and biological and enzyme activity. Thus, soil biological activities can be affected by an appropriate combination of tree litter [18].

Soil fauna are recognized as ecosystem engineers, as they alter the nutrient cycles by decomposing litter and modifying the soil habitat, which plays a crucial role in maintaining fertility and plant growth [19,20]. In many studies, evaluation of the condition of soil fauna (micro, meso, and macro) provides important information for the assessment of soil quality and the health of forest ecosystems, given that it is highly sensitive and thus has a rapid response to vegetation changes [21–25]. There are a wide range of organisms in the soil ecosystem that have diverse ecological needs. The abundance, variety, and relative composition of soil organisms are a function of soil properties (moisture, pH, and nutrients), climatic conditions, and vegetation [26,27]. In other words, biological properties are one part of the dynamic properties of soil, as the activity of soil organisms depends on the soil conditions [15,28].

Among soil organisms, earthworms are one of the most important factors in the decomposition of organic matter, soil fertility, and health [22,29]. Earthworms, which have the highest biomass among invertebrates, do not play a role in the initial decomposition of organic matter, but they are important in mixing organic matter and mineral particles in the soil. This activity of earthworms enhances the nutrient cycle, which increases the diversity of other invertebrates and also significantly increases soil microorganisms [22]. When ingested material is finally digested, absorbable nutrients are then released, becoming available to microorganisms and plants. A study by Le Bayon and Milleret [30] showed that the dynamics of phosphorus in soil increased during earthworm activity. Furthermore, earthworms affect the nitrogen (N) cycle and N-cycling microorganisms [20].

The presence of earthworms and their ability to recover compacted soils depend on the worms' tolerance threshold and the physical and chemical properties of the soil [4,24]. Therefore, different species of earthworms (epigeic, anecic, and endogeic) are present in different soil horizons due to their ecological nature, burrowing ability in soil, and feeding behavior [1,29,31–33]. According to Singh et al. [29], epigeic earthworms live on the upper surface of the soil, rarely burrow into mineral soil, and prefer food with a high organic matter content. These species are very small, dark in color, and are often the first to appear at the beginning of an invasion event. Anecic earthworms are geophagous and make deep, vertical burrows. They take organic matter from the forest floor and pull it deep into their burrows, burying organic matter in the subsoil. They are pigmented, quite large, and may plug their burrows with partially digested leaf material, making small piles on the soil surface. Endogeic earthworms are geophagous and largely responsible for soil aggregation, due to their consumption of organics associated with mineral soils. These species are geophagous and, because they live underground in mineral soil horizons, are nonpigmented, appearing light pink or gray. Babel et al. [34] showed that earthworms prefer to live in the litter layer and to consume high-quality organic matter with a low C/N ratio. In addition, Neirynck et al. [35] observed that the highest amounts of earthworm biomass were obtained in stands of linden (*Tilia begonifolia* Stev.) and velvet maple (*Acer velutinum* Boiss), due to the lower litter C/N ratio and improved soil conditions.

Nematodes, another large group of soil organisms, exist in the soil in free or parasite form (animals, plants, fungi, etc.) due to their adaptation to different climatic and environmental conditions. Nematodes are often used as indicators of soil health [36]. There are useful nematode species which play important roles in the health of soil ecosystems through helping to produce mineral matter, organic matter decomposition, and activity in the nutrient cycle. Parasitic species of nematodes, in addition to affecting the production and health of animals and plants, directly or indirectly affect human life [37].

The biodiversity of forest soil organisms, such as earthworms and nematodes, is drastically influenced by the compaction caused by forest harvesting operations, due to the increase in soil bulk density and impaired gas exchange leading to curbing of oxygen diffusion [4,38–40]. Soil disturbance due to harvesting operations, especially over the past few decades, has affected soil quality, plant and animal biomass production, and soil ecosystem health in the Hyrcanian mixed forests, which are registered as world natural heritage sites. The use of ecological remediation treatments (planting trees, adding litter and sawdust) on skid trails may improve soil properties in the long term. Previous studies on changes and activity of soil fauna in degraded soils and their relationships with soil properties have shown the increasing importance of soil fauna research [4,13,14,24]. Although many studies have addressed the postharvest recovery of soil physical and chemical properties, little is known about the recovery trajectories of soil fauna over a long-term period after heavy machinery traffic on forest soils.

It is evident that well-functioning forest soils can maintain a very rich and vital forest ecosystem. As a result, biodiversity in forest soils plays a key role in this issue, but it is not clear how this biodiversity can be maintained or restored during and after forest harvesting. For this reason, studying and recognizing the practical and complex aspects of forest floor ecology will have an important effect on the sustainable management of forest harvesting. Previous research has investigated the biological properties of forest soils under the influence of different conditions (canopy cover composition, plantation forests, elevation changes, and different management practices) over short-term periods of time, but study of forest soil biological properties under the influence of tree litter type over a long-term period has not been done in these forests to date. Therefore, the aim of this study was to investigate the recovery process of soil biological properties, specifically earthworms and nematodes, on skid trails under the influence of added tree litter falling from a tree under natural conditions as a long-term ecological strategy. The hypotheses were as follows: (1) there is a significant difference between the characteristics of earthworms (abundance, diversity, and biomass) and the number of soil nematodes associated with the litters of different trees; (2) soil biological properties can be recovered by adding the litters of different trees to the soil over a 20-year period following skidding operations.

2. Materials and Methods

2.1. Site Description

This research was conducted in the Namkhaneh and Gorazbon districts of the Kheyrud Forest Research Station of the University of Tehran, in the Hyrcanian forests in northern Iran during the period of August to September 2021 (between 51°36′50″ E and 51°38′21″ E longitude and 36°34′21″ N and 36°33′34″ N latitude) (Figure 1). The study areas had a total area of 2082 ha and were located at an elevation between approximately 1000 and 1360 m above sea level. The climate in the study area is very humid, with the heaviest precipitation occurring in summer and fall and an average annual rainfall of 1146 mm. The average daily temperature varies from a few degrees below 0 °C in winter to +25 °C in summer, and the average annual temperature is 8.6 ° C. The parent rock is composed of hard calcareous layers with a large number of cracks. This feature, in terms of geology, belongs to the Jurassic period. The soils are mainly brown forest (Alfisols) according to USDA soil taxonomy, and the soil texture of the study site ranges from clay to clay loamy. According to previous studies, the most abundant form of humus in pure and mixed beech stands in the Hyrcanian forests is the mull and amphi humus system [41,42]. Hyrcanian forests are composed of mixed deciduous trees that play an effective role in the formation of soil horizons, humus, and soil fertility through the return of leaves to the soil surface in the autumn. This area is predominantly covered by the forest types of beech (*Fagus orientalis* Lipsky), beech–hornbeam (*Fageto Carpinetum*), oak–hornbeam (*Querceto Carpinetum*), and mixed beech with velvet maple (*Acer velutinum* Boiss.), alder (*Alnus subcordata* C.A. Mey.), linden (*Tilia begonifolia* Stev.), and oak (*Quercus castaneifolia* C.A.Mey.) species. The study area is covered by dominant herbaceous species, including *Asperula odorata* L., *Euphorbia amygdaloides* L., *Hypericum androsaemum* L., *Oplismenus undulatifolius* (Ard.) Roem. & Schult., and *Polystichum* sp.

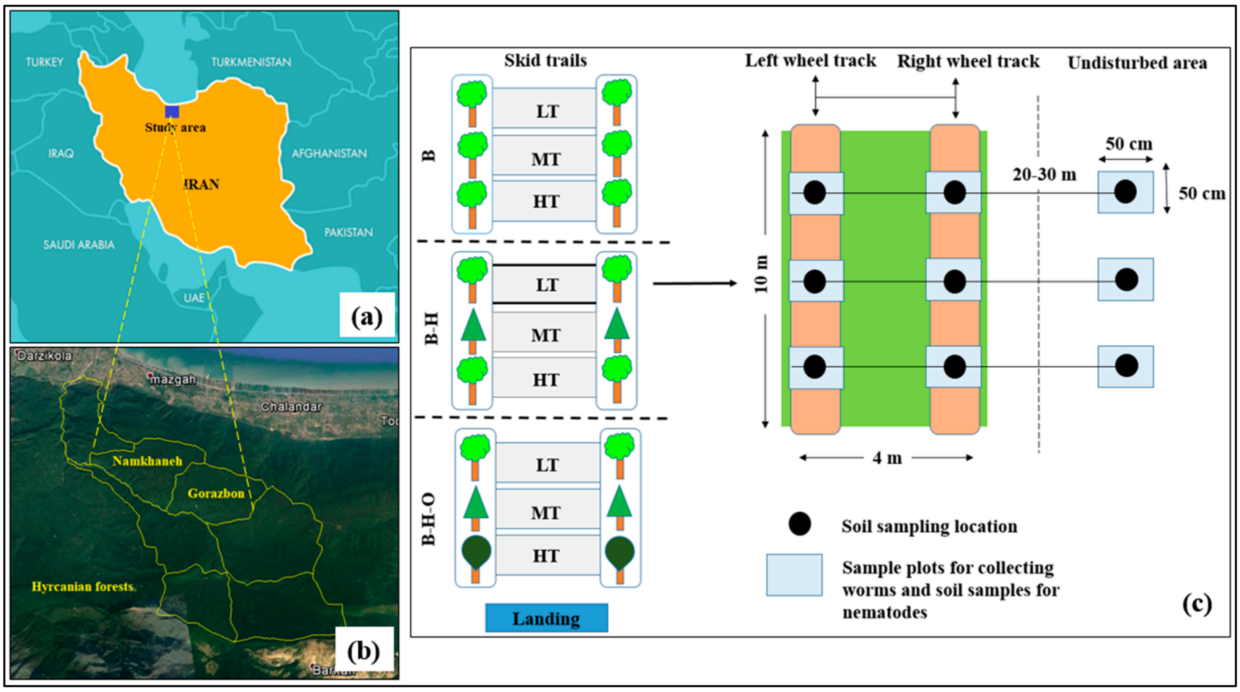

Figure 1. Location of the study area in northern Iran (**a**); Kheyrud forests (Namkhaneh and Gorazbon districts) within the Hyrcanian forests (**b**); schematic representation of the experimental design on the skid trail and undisturbed area (**c**). Different tree litter treatments: B: beech, B-H: beech–hornbeam, B-H-O: mixed beech or beech–hornbeam–other species. Different traffic intensities: HT: high traffic intensity, MT: medium traffic intensity, and LT: low traffic intensity.

The most common silvicultural system in the past was a combination of single-tree and group selection, resulting in uneven-aged stands. In the forests studied, trees were felled during the winter and the timber was extracted when the soil condition was dry during May and June. Six years before the study, the last harvest operations were carried out in these forest stands. The felled trees were transported to the roadside landings using Timberjack 450 C wheeled cable skidders on skid trails. This machine was equipped with 775 × 813 mm tires with an average ground pressure of 220 kPa and a ground clearance of approximately 0.6 m, with an overall width of 3.1 m. After the skidding operation, the skid trails were left without any treatment to improve the condition of the disturbed soil. A detailed description of each site is presented in Table 1.

2.2. Experimental Design

This research was carried out with a split-plot design in a randomized complete block with two main factors (three forest stands with different litters) and subfactors (three traffic intensity classes) at the level of three skid trails with different harvesting periods (6, 10, and 20 years since harvest) (Figure 1). Since the present study was retrospective, the determination of the time since harvest and information on the harvesting operations were based on the documents of the forestry plan and the reports of the forest managers. To achieve the objectives of the study, each skid trail in the forest was identified with three replications in three forest types (beech, beech + hornbeam, mixed beech). Three traffic intensities (low, medium, and high) were identified according to the length of the skid trail, the distance from log landing, and the number of sub-branches of the skid trail.

Table 1. Description of the skid trail/forest stand in the study area, northern Iran. B: beech, B-H: beech–hornbeam, B-H-O: mixed beech, and UND: undisturbed area.

Age of Skid Trail (Years)	Forest Stand (Main Species)	District (No. of Compartments)	Elevation (m a.s.l.)	Tree Canopy Cover (%)	Soil Texture
6	B (*Fagus orientalis* Lipsky)	Gorazbon (C. 315)	1209	80	Clay
	B-H (*Fagus orientalis* Lipsky, *Carpinus betulus* L.)	Gorazbon (C. 316)	1174	72	Clay
	B-H-O (*Fagus orientalis* Lipsky, *Carpinus betulus* L, *Alnus subcordata* C.A. Mey.)	Gorazbon (C. 318)	1177	85	Silt clay loam
10	B (*Fagus orientalis* Lipsky)	Gorazbon (C. 319)	1246	75	Clay
	B-H (*Fagus orientalis* Lipsky, *Carpinus betulus* L.)	Gorazbon (C. 320)	1345	80	Clay
	B-H-O (*Fagus orientalis* Lipsky, *Carpinus betulus* L, *Alnus subcordata* C.A. Mey. and *Acer velutinum* Boiss.)	Gorazbon (C. 318)	1133	80	Silt clay loam
20	B (*Fagus orientalis* Lipsky)	Namkhaneh (C. 215)	1040	85	Clay
	B-H (*Fagus orientalis* Lipsky, *Carpinus betulus* L)	Namkhaneh (C. 220)	1115	75	Silt loam
	B-H-O (*Fagus orientalis* Lipsky, *Carpinus betulus* L, *Alnus subcordata* C.A. Mey. and *Tilia begonifolia* Stev.)	Namkhaneh (C. 214)	1010	80	Clay loam

In each combination of treatments on skid trails, a sample plot with dimensions of 4×10 m^2 was selected for sampling (Figure 1). In each sample plot, three measurement lines were identified [43] and soil sampling was performed on the right and left wheel tracks at a depth of 0–10 cm. To compare natural recovery between the skid trails and the undisturbed areas, samples were also taken inside the forest stand in areas without any effect of skidding operations, at least 20–30 m from the skid trail and matched based on the average height of dominant trees. In this study, a total of 216 soil samples were measured for a combination of three skid trails, three litter treatments, four intensities of traffic (low, medium, high, and undisturbed area), and six soil samples (Figure 1).

To determine the density and biomass of earthworms, sample plots of 0.5 m^2 were designated on the sampling lines, crossing the wheel tracks on the skid trails, and in the undisturbed area. The worms were harvested at a depth of 0–10 cm (Figure 1). To determine soil nematodes, as in the sampling method for earthworms, 1 kg of soil was collected at the sampling site. Therefore, 18 samples were taken on each skid trail to study soil fauna. Since soil moisture and different seasons influence the activity and presence of soil organisms, all measurements were performed under similar conditions.

2.3. Data Collection and Laboratory Analysis

In order to measure soil properties, litter from the organic layer was removed and samples were taken from the mineral soil layer at a depth of 10 cm from the soil layer. Soil samples were collected with a thin-walled steel cylinder (5 cm in diameter and 10 cm in height; 196.25 cm^3). The wet weight of all samples was measured before transfer to the laboratory on the same sampling day. In the laboratory, soil samples were dried in an oven at 105 °C for 24 h until a constant mass was reached to determine the moisture content, the dry bulk density, and the porosity. The soil texture was determined using the Bouyoucos hydrometric method [44]. Bulk density was calculated according to Equation (1):

$$BD = \frac{\mathrm{WD}}{\mathrm{VC}} \quad (1)$$

where BD is the dry bulk density (g cm^{-3}), WD is the weight of the dry soil (g), and VC is the volume of the cylinder (cm^3).

Soil porosity was calculated using Equation (2) [43]

$$\text{Porosity} = [1 - (\frac{\text{BD}}{2.65})] \quad (2)$$

where BD is the dry bulk density (g cm^{-3}) and 2.65 (g cm^{-3}) is the density of soil particles.

In order to analyze some chemical properties of the soil, two kilograms of each soil sample was transferred to the laboratory. Soil pH was determined using an Orion Ionalyzer Model 901 pH meter in a 1:2.5 soil: water solution. Organic C was measured using the Walkey-Black method [45] and total N using a semi micro-Kjeldahl method [46]. Available P was determined with a spectrophotometer using the Olsen method [47], and available K, Ca, and Mg (via ammonium acetate extraction at pH 9) were determined with an atomic absorption spectrophotometer [48].

The earthworms were collected simultaneously with the soil sampling by hand sorting, and were placed separately in plastic bags along with a little parent soil [49]. Each was washed clean of adhering soil particles, placed on blotting paper, and identified by external characteristics using the Edwards and Bohlen key [50] based on ecological categories including epigeic, anecic, and endogeic. To determine the dry weight biomass of the earthworms, the collected earthworms were weighed. The earthworms were then sacrificed by placing into hot water, dried in an oven at 60 °C for 24 h, and reweighed [1,22,51]. The nematodes were extracted from 100 g fresh weight of soil sample using a modified cotton-wool filter method [52].

2.4. Statistical Analyses

Before statistical analysis, data for normality and homogeneity of variances were tested using Kolmogorov–Smirnov (data were normally distributed; p-value > 0.05) and Levene's (variances were homogeneous; p-value > 0.05) tests. Differences in soil physical, chemical, and biological properties in relation to litter type (beech, beech–hornbeam, and mixed beech), traffic intensity (low, medium, and high) and time since harvest (6, 10, and 20 years) were analyzed using three-way analysis of variance. Duncan multiple comparison tests were used to separate the means of the dependent variables that were significantly affected by treatment. Relationships between the measured parameters were also investigated using Pearson's correlation. All statistical analyses were performed using the statistical software package SPSS ver. 20 (IBM, Armonk, NT, USA). Factor analysis is a statistical tool used to explore complex relationships among variables. Multivariate correlations and principal components were used to identify significant relationships among variables using PC-Ord ver. 5.0 [53].

3. Results

Treatment with mixed beech litter showed the highest values of density (5.72 n m^{-2}) and biomass (97.18 mg m^{-2}) of earthworms 20 years after harvest compared to other treatments (Figure 2). In all three litter treatments, the epigeic ecological group had a greater proportion than anecic and endogeic earthworms. With increasing litter quality (B > B-H > B-H-O) and time interval since harvest operations, the proportion of the ecological groups of anecic and endogeic earthworms increased. Twenty years after harvest, the density and biomass of earthworms in all litter treatments were less than in the undisturbed area (Figure 2).

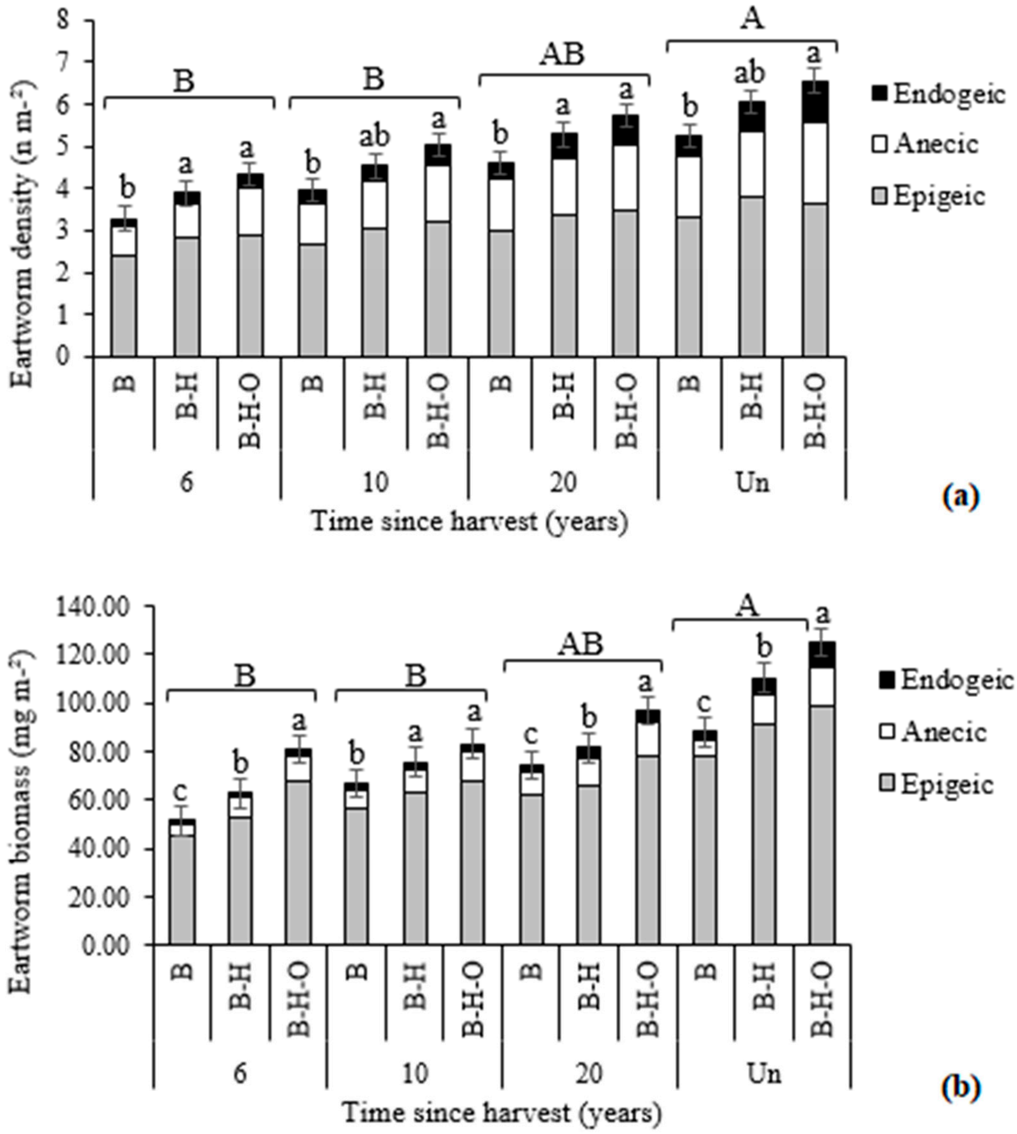

Figure 2. Mean values of earthworm density (epigeic, anecic, and endogeic) (**a**) and biomass (**b**) in different years since harvest and in undisturbed area, under three litter treatments. The litter treatments studied were beech (B), beech–hornbeam (B-H), and mixed beech (B-H-O). Harvesting period: 6, 10, and 20 years since harvest. For earthworm density, time since harvest (F = 69.441; $p < 0.001$), litter treatment (F = 52.393; $p < 0.001$), and their interaction (F = 3.216; $p = 0.035$). For earthworm biomass, time since harvest (F = 20.742; $p < 0.001$), litter treatment (F = 47.574; $p < 0.001$), and their interaction (F = 10.560; $p < 0.001$). Different capital and lowercase letters indicate significant differences ($p < 0.05$ by Duncan test) between the harvesting period (year since harvest) and the litter treatments, respectively.

The highest values of soil earthworm density and biomass were found 20 years after harvest in the low traffic intensity samples (Figure 3). Earthworm density and biomass showed a decreasing trend with increasing traffic intensity. In all traffic intensity classes, the proportion of the epigeic ecological group was the highest. However, in different time periods after the harvest operation, the ratio of anecic and endogeic ecological groups increased with decreasing traffic intensity. Twenty years after harvest operations, the highest values of earthworm density and biomass were obtained at low traffic intensity, and these were 7.46% and 19.21% less than in the undisturbed area (Figure 3).

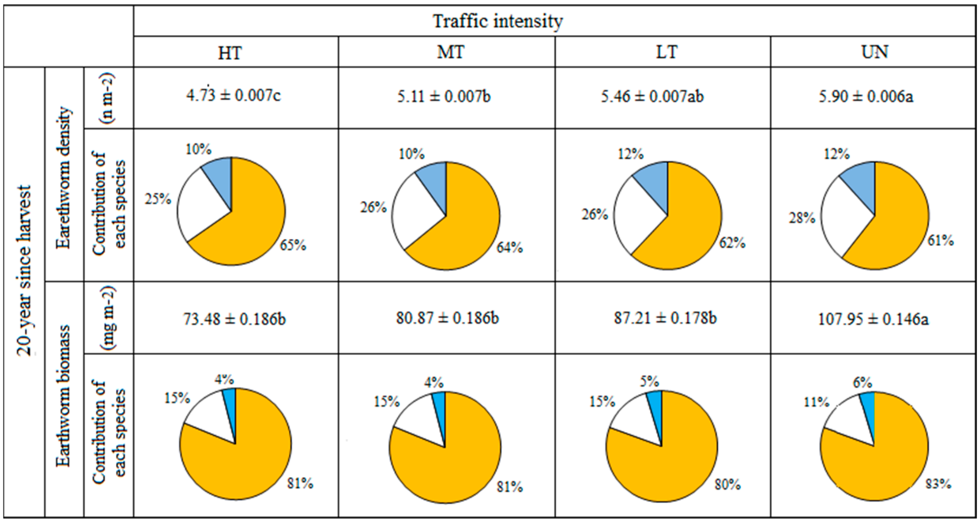

Figure 3. Mean values (±SD) of the earthworm density and biomass 20 years after harvesting under different traffic intensities (HT: skid trail with high traffic intensity, MT: skid trail with medium traffic intensity, LT: skid trail with low traffic intensity, and UN: undisturbed area). Contribution of epigeic (orange color), anecic (white color), and endogeic (blue color) earthworm density and biomass under different traffic intensities. Different letters in a row indicate significant differences among the total nematodes of the soil ($p < 0.05$), based on Duncan's multiple range tests.

Soil nematode populations in the B-H-O litter treatment were significantly higher than in the B-H followed by B treatments, especially 20 years after harvest (Figure 4). The soil nematode population increased with increasing litter quality and time interval from harvest operations (Figure 4). However, with increasing traffic intensity from low to high, the population of soil nematodes decreased, so that their lowest population (166.78 in 100 g of soil) was observed in the high traffic intensity area 6 years after harvest operation (Table 2). Twenty years after harvest, the largest population of soil nematodes in the mixed beech litter treatment (313.65 in 100 g of soil) and low traffic intensity (216.33 in 100 g of soil) was less than in the undisturbed area (Figure 4; Table 2).

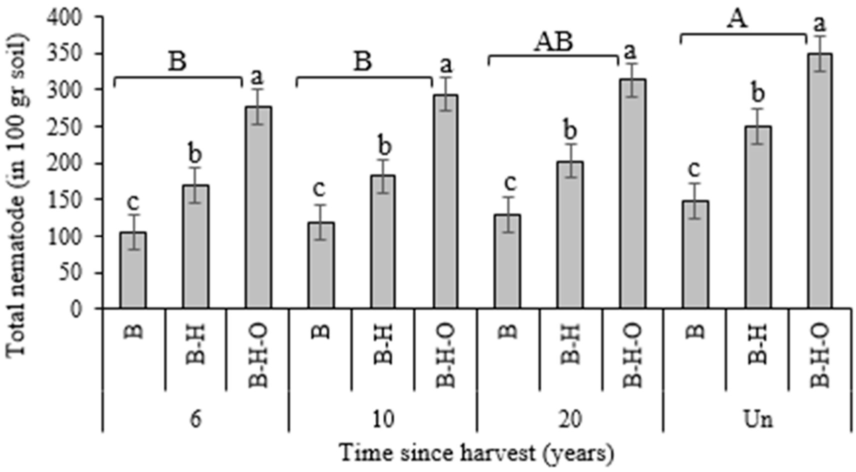

Figure 4. Mean values of total nematodes in different years since harvest under three litter treatments. The studied litter treatments were beech (B), beech–hornbeam (B-H), and mixed beech (B-H-O). Harvesting period: 6, 10, and 20 years after harvest. For total nematodes, time since harvest (F = 473.015; $p < 0.001$), traffic intensity (F = 220.172; $p < 0.001$), and their interaction (F = 29.145; $p = 0.021$). Different capital and lowercase letters indicate significant differences ($p < 0.05$ by Duncan test) between harvesting period (year after harvest) and litter treatments, respectively.

Table 2. Mean values (±SE) of total nematodes (in 100 g soil) in different years after harvest under different traffic intensities; HT: skid trail with high traffic intensity, MT: skid trail with medium traffic intensity, LT: skid trail with low traffic intensity, and UN: undisturbed area.

	Traffic Intensity			
Time Since Harvest	**HT**	**MT**	**LT**	**UN**
6 years	166.78 ± 20.24c	174.33 ± 18.22b	180.82 ± 18.22b	250.22 ± 15.74a
10 years	183.60 ± 20.24c	190.82 ± 18.22b	196.70 ± 18.22b	249.99 ± 15.74a
20 years	204.25 ± 23.18c	210.56 ± 18.15bc	216.33 ± 18.15b	249.71 ± 15.74a

Note: Different letters in a row indicate significant differences among the total nematodes in the soil ($p < 0.05$), based on Duncan's multiple range tests.

From PCA analysis, the first and second axes explained 79.68% and 13.89% of the variance in relation with litter type, years after harvest, traffic intensity, and soil properties (Figure 5). The left side of the graph showed alkaline soil, high porosity, accumulation of macro-element nutrients (available P, K, Ca, Mg), and more biological activities (earthworm and nematode population), and this can be attributed to the litter type B-H-O and the 20-year period after harvesting (ST20 treatment), while the right side of the graph showed the positions of high BD, acidic soil, lower levels of macro-element nutrients, and low biological activities imposed by B, B-H, HT, MT, LT, ST6 (6-year period), and ST10 treatments (10-year period) (Figure 5).

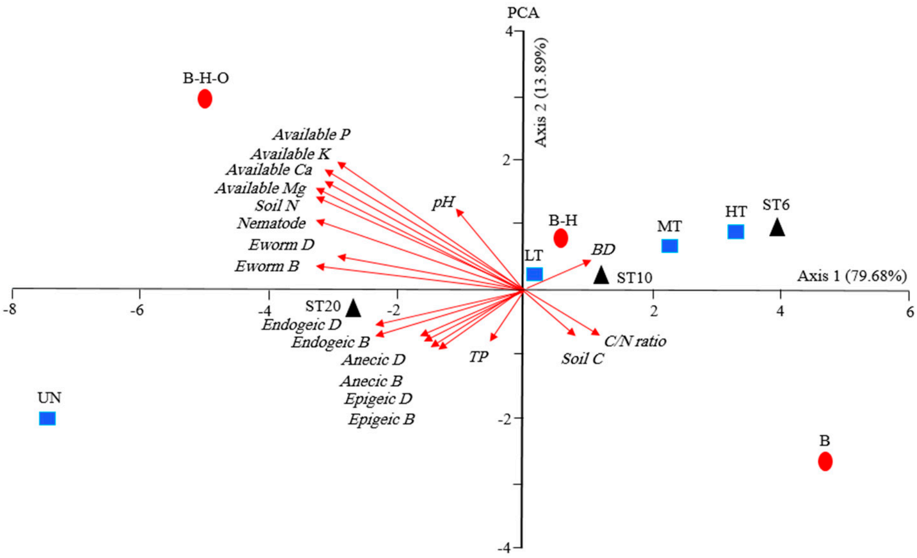

Figure 5. PCA analysis of the measured variables (soil physicochemical and biological properties) in various treatments; Litter type: B: beech, B-H: beech–hornbeam, B-H-O: mixed beech; time since harvest: ST6: 6 years, ST10: 10 years, ST20: 20 years; Traffic intensity: HT: high traffic, MT: medium traffic, LT: low traffic, and UND: undisturbed area). Soil physical properties; BD: bulk density; TP: total porosity; SM: soil moisture.

Pearson correlation analysis showed that there were significant correlations between most physicochemical and biological properties (earthworm and nematode activity) (Figure 6). N content, available nutrients (available P, K, Ca, Mg), soil moisture content, and porosity as key variables had positive correlations with the activities of earthworms (epigeic, anecic, and endogeic) and nematodes. In contrast, pH, bulk density, C content, and C/N ratio had significant negative correlations with soil biological properties (Figure 6).

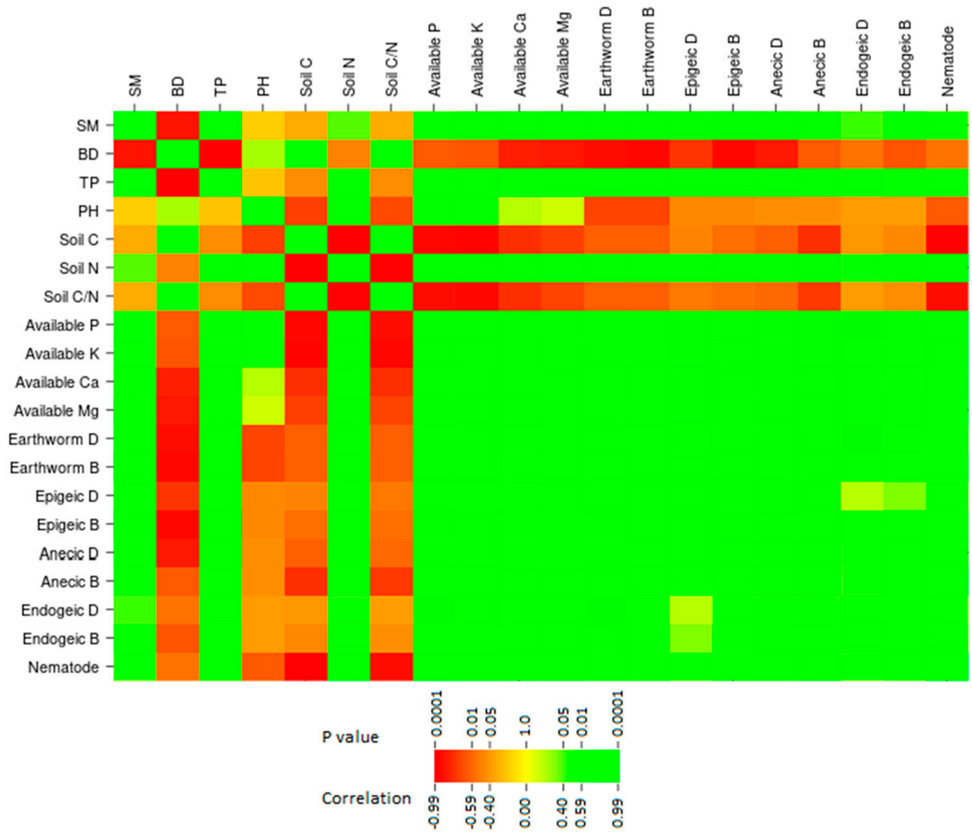

Figure 6. Pearson correlation coefficients (heat map) between soil physicochemical and biological properties. Soil physical properties (SM: soil moisture; BD: bulk density; TP: total porosity; D: density; B: biomass).

4. Discussion

4.1. The Effect of Tree Litter

Since forest tree species and their litter production affect the physicochemical properties of soil, we expected changes in the activity of soil organisms. On the other hand, forest harvesting operations lead to disturbance and change of the physical, chemical, and biological properties of soil. Therefore, the main objective of this study was to determine whether the litter produced by trees affects the diversity and activity of earthworms and nematodes under the conditions of skidding operations in the forest. In line with previous studies, our results showed that changes of earthworm populations in the horizontal structure of the soil were dependent on the litter of different trees (e.g., differences in litter quality), soil properties (such as pH, moisture, porosity), and the amount of available food potential (decomposable organic matter) and production potential [26,54,55]. By studying organic matter removal in a central USA hardwood region, Jordan et al. [38] found that the removal of organic matter diminished the biomass of two dominant earthworm species, *Diplocardia ornata* and *Diplocardia smithii*.

Earthworm density and biomass (all three ecological groups) had the highest value in the B-H-O litter treatment and the lowest value in the B (beech) litter treatment. According to the current study, Kooijman et al. [56] reported that the abundances and activities of earthworms were more pronounced in the high-quality litter of hornbeam (*Carpinus betulus* L.) than in the low-quality litter of European beech (*Fagus sylvatica* L.). Soil pH and the nutrient pool of litter, which are governed by litter quality, were the most critical factors associated with the abundance and biodiversity of fauna both in the soil and in the litter [57]. In addition, we also observed differences among ecological groups, with higher epigeic abundance compared to anecic and endogeic earthworms. In a study by Smith et al. [58], epigeic and anecic earthworms were more abundant than the endogeic ecological group in forest lands, which is consistent with the results of the present study. According to previous studies, this may be due to the deep burrowing ability of anecic and endogeic earthworms [59,60]. Furthermore, the activity of these species in the lower soil layers can partly explain their low dispersal rates in surface soil (0–20 cm) under different tree litters [1,23].

According to the results of the correlation between soil physicochemical properties and earthworm and nematode activity, soil biological activity was found to have a significant correlation with soil moisture, pH, and available nutrients (Figure 6), which has also been observed in other studies [1,15,22,23,55]. Consistent with our results, previous studies revealed that the richness, abundance, and biodiversity of earthworms and nematodes were remarkably determined by litter quality and soil physicochemical parameters, including available nutrients, bulk density, moisture, soil temperature, and soil pH [18,54,56,57,61,62].

With increasing time intervals of harvesting operations (20 years since harvest), the activity of earthworms and nematodes under B-H-O litter treatment increased as compared to other treatments. In line with the results of the current study, Xue et al. [20] revealed that the addition of litter and organic matter influenced the N cycle, and also the activities and feeding of earthworms. The coverage and depth of the litter layer are affected by the litter decomposition rate, which is governed by the litter quality. In this study, the litter of mixed beech was composed of high-nutrient compounds and materials with less acidity, leading to a faster decomposition rate and ultimately to suitable conditions for the activity of soil organisms, as reported by Meng et al. [62]. In other words, 20 years after harvesting, the activity of earthworms and nematodes showed the highest recovery in the B-H-O treatment. Bird and Chatarpaul [63] reported that the densities of soil fauna returned to the preharvest level over a 10–13-year period, but in our study, the situation 20 years later remained significantly different compared to the undisturbed area.

4.2. The Effect of Traffic Intensity

The direct effect of soil compaction is the reduction of soil pores and changes in soil structure, which significantly impedes the formation of earthworm habitat and activity [64]. For example, the volume and length of burrowing in forest soil can be dramatically decreased due to mechanical loads caused by heavy machinery traffic [65]. Biopores and burrows created by deep-burrowing earthworms play a key role in soil structure, contributing to the habitat arrangement in soil, and these are remarkably affected during soil compaction, leading to deterioration of soil functional equilibrium and nutrient cycling [66]. It was found that the indirect effect of soil compaction occurs during waterlogging processes as a result of reduction in hydraulic conductivity, which leads to an increase of oxygen deficits arising from anaerobic situations, which results in a drastic decrease in earthworm activities [40,67].

In this study, negative changes in key soil parameters (porosity, soil moisture, soil pH, organic matter content, and nutrient cycles) after harvesting operations (as depicted in Figure 5) led to the creation of unfavorable habitats for the activity of soil organisms on skid trails [4,68]. According to the results, with increasing traffic intensity, the earthworm density and biomass as well as nematode populations decreased, so that the lowest amount was found in the high traffic situation and the highest amount of earthworm and nematode activity in the low traffic area. In line with the current study, Nazari et al. [40] demonstrated that heavy machine traffic (>20 machine passes) dramatically eradicated cracks and fissures as well as biopores such as earthworm burrows, soil preferential flow paths, or root channels, resulting in a decline in earthworm and nematode populations. Additionally, Battigelli et al. [69] found that whole-tree harvesting and litter removal combined with excessive soil compaction drastically decreased the densities of soil mesofauna by 93% in comparison to an undisturbed (control) forest stand.

In terms of earthworm ecological groups, under the influence of all three classes of traffic intensity, the epigeic ecological group had the highest proportion and the endogeic worms the lowest proportion. However, with the reduction of traffic intensity from high to low, the proportion of anecic and endogeic ecological species increased. Bottinelli et al. [4] concluded that both density and biomass of three earthworm ecological categories (i.e., epigeic, anecic, and endogeic species) were negatively impacted by machinery traffic. Since endogeic species mostly live in the topsoil, litter layer, and the upper parts of mineral soils, with a relatively high reproduction rate and high growth rate, they respond instantly to environmental stimuli and changes in surface soil conditions [19,70]. In other words, the traffic of skidding machines on the soil surface, associated with removal of the litter layer, loss of organic matter, and changes in the soil moisture and temperature regimes, has more detrimental effects on endogeic species compared to the anecic and endogeic species [4,38].

The total values of soil nematodes increased significantly with decreasing traffic intensity from high to low, so the highest value was obtained at low traffic intensity and the lowest value was obtained at high traffic intensity. According to these results, the nematode population has a significant positive correlation with earthworm activity (Figure 6). The richness and activity of earthworms can enhance the abundance and richness of nematodes due to their activities such as burrowing, casting, and feeding, which promote N transformation and boost the availability of N, as reported by Liu et al. [71]. Twenty years after harvesting under low traffic intensity, the nematode population had improved, but was still less than the undisturbed area and significantly different.

5. Conclusions

Our study showed that skidding operations on skid trails reduce the density and activity of earthworms and nematodes, but the presence of good-quality tree litter improved the activity of soil organisms compared to the undisturbed area. According to the results, the mixed beech litter treatment (B-H-O) was more fertile than the other litter treatments in terms of the physical, chemical, and biological parameters of the soil. Additionally, the activity of earthworms and nematodes was higher at low traffic intensity compared to the other traffic classes and was less different from the undisturbed area. In confirmation of the main hypothesis of the study, 20 years after harvest operations, the activity of earthworms and soil nematodes under the influence of different litters was improved and was less than that of the undisturbed area. High traffic intensity, especially in the early years after skidding operations, and tree litter with poor quality with a negative impact on soil quality were limiting factors for rehabilitation and soil fauna activity in this study. It seems that the mixed beech litter composition (beech, hornbeam, and other species) was able to improve the soil properties under study more than the other litter compositions. Planting with suitable mixed broadleaved species can be considered to rehabilitate the compacted soils of skid trails by improving soil quality and helping to mitigate the negative effects on soil fauna activity. Therefore, we can confidently suggest that forest managers apply the results of this study to soil reclamation methods in degraded forest areas.

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