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Earthworms as an Ecological Indicator of Soil Recovery after Mechanized Logging Operations in Mixed Beech Forests

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Abstract: Soil damage caused by logging operations conducted to obtain and maximize economic benefits has been established as having long-term effects on forest soil quality and productivity. However, a comprehensive study of the impact of logging operations on earthworms as a criterion for soil recovery has never been conducted in the Hyrcanian forests of Iran. The aim of this study was to determine the changes in soil biological properties (earthworm density and biomass) and its recovery process under the influence of traffic intensity, slope and soil depth in various intervals according to age after logging operations. Soil properties were compared among abandoned skid trails with different ages (i.e., 3, 10, 20, and 25 years) and an undisturbed area. The results showed that earthworm density and biomass in the high traffic intensity and slope class of 20–30% at the 10–20 cm depth of the soil had the lowest value compared to the other treatments. Twenty-five years after the logging operations, the earthworm density at soil depth of 0–10 and 10–20 cm was 28.4% (0.48 ind. m^{-2}) and 38.6% (0.35 ind. m^{-2}), which were less than those of the undisturbed area, respectively. Meanwhile, the earthworm biomass at a soil depth of 0–10 and 10–20 cm was 30.5% (2.05 mg m^{-2}) and 40.5% (1.54 mg m^{-2}) less than the values of the undisturbed area, respectively. The earthworm density and biomass were positively correlated with total porosity, organic carbon and nitrogen content, while negatively correlated with soil bulk density and C/N ratio. According to the results, 25 years after logging operations, the earthworm density and biomass on the skid trails were recovered, but they were significantly different with the undisturbed area. Therefore, full recovery of soil biological properties (i.e., earthworm density and biomass) takes more than 25 years. The conclusions of our study reveal that the effects of logging operations on soil properties are of great significance, and our understanding of the mechanism of soil change and recovery demand that harvesting operations be extensively and properly implemented.

Keywords: earthworms; skid trails; traffic intensity; forest soil recovery; soil biological properties

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1. Introduction

Monitoring the restoration of soil biological properties is an important strategy to prevent soil degradation, which is key for promoting the success of restoration [1,2]. Soil quality and biodiversity in response to landscape use is still an open frontier, and therefore, more detailed and comprehensive knowledge is needed to provide guidance for an appropriate sustainable forest management [3,4]. There is a strong link between human economic activities and natural resources, especially in the forest areas [5]. A sustainable forest management will have to consider conservative as well as productive aspects, with the aim to plan and monitor forest operations. According to the specifications described in the techno-scientific approach referred to as Sustainable Forest Operations (SFOs), forest operational planning must consider all possible factors affecting environmental impacts as well as their interactions [6–8] so as to ensure the necessary coordination between economic benefits and the protection of the forest ecosystem. The concepts of sustainability, with related principles and sustainability indicators (SI) in the forestry sector were developed 300 years ago and operationally implemented as a main guideline [7], in particular within the last four decades. The idea of "Sustainable Development" (SD) has appeared as a major topic on international policy agendas [7]. Evaluation of changes in soil organisms as one of the indicators to assess the sustainability of forest soil after logging operations is essential according to the Sustainable Forest Operation (SFO) principles (compliance with environmental conditions or forest operations ecology) [5,6]. These aspects are referred to as environmental and engineering data, and for these reasons, as detailed by Mitsch and Jørgensen [9] studies on these topics, they are considerably well within the scope of ecological engineering.

Due to the development, increase in size and weight of operating machines and their associated accessories in combination with the intensity of logging operations, especially in high humidity conditions, machine traffic in forest stands [7,10–12] produces soil disturbance with drastically negative consequences. Soil disturbances caused by ground-based mechanized forest operations are usually considered as soil compaction (increase in soil bulk density) and soil displacement (lateral and longitudinal displacement of soil caused by the machine running gear), commonly referred to as rutting [7,13–17]. Soil disturbances can have an adverse effect in several ways on forest soil ecosystems. By destroying the soil structure and aggregation [18], increasing runoff levels, and inhibiting root growth and disrupting the activity of soil organisms [19], which result in reducing the activity of soil organisms by decreasing pores and air exchange [20], soil disturbances lead to a reduced water infiltration rate and a decrease in seedlings' survival and growth [7,19].

Soil habitat quality is one of the prominent factors in the sustainability of various ecosystems [21–23]. To study the quality of forest soil, researchers have presented various indicators, including soil physical [24], chemical and biological properties [25–31]. Soil organisms play an important role both in sustainable management and in maintaining soil quality because soil organisms and soil nature interact with each other [29]. Any disturbance in physical and chemical properties due to soil compaction caused by forestry-machine traffic may affect the distribution, activity and environment of macro-organisms such as earthworms [20]. Soil compaction is a physical disturbance that leads to a decrease in the population of earthworms as a result of increased bulk density and a reduced amount of soil pores [21].

The intensity and extent of soil compaction varies according to the intensity of impact (i.e., type of machinery, traffic intensity and terrain slope), soil properties (i.e., texture, structure, and moisture) and the level of biological activity (i.e., roots and macro- and micro- organisms). Natural soil recovery to return to initial conditions will normally take from a few years to several decades [5,13,14,16,32–35]. Where there are no improvement treatments in the compacted forest soils, the natural processes such as climate cycles (alternation of dry-wet cycles and freeze-thaw processes) and biological activity (mainly root growth and macro- and micro-organisms) take on the critical role of improving soil structure [36–39]. Earthworms are one of the most important groups of soil fauna worldwide and are a good example of ecosystem engineers due to their ability to physically modify their habitat by focusing on large pores, structural features, and water infiltration and conduction [29].The main role of earthworms in the recovery of the structure and aggregation processes begins by making burrows, swallowing soil, crushing organic matter and excreting it as excreta in the upper layers of the soil [40–42]. Most earthworms have a crucial role in making burrows [43] and the production of casts [18,44] within the soil and bringing the soil from the bottom to the surface and mixing it, which results in an appropriate condition to form the stable aggregates, restore soil aeration, increase the vital activity and abundance of other soil organisms, and improve water holding capacity [45].

It is appeared that earthworms have an key role in soil ecological ecosystems and have a great ability to change soil and plant communities, but their activity is strongly dependent on the quality of vegetation and soil physical conditions (especially low soil bulk density and high large pores) [30,46–49]. The effect of vegetation cover on the physical and chemical properties of soil can be mediated by soil fauna, which may substantially affect topsoil properties as a consequence of bioturbation [30]. Several studies have focused on the changes in the abundance, presence or absence, and biomass of earthworms under the influence of harvesting operations in forest soils in different zones [10,18,20,21,43,50–52]. For example, Bhadauria et al. [53] showed that conservation practices including the restoration of destroyed forests improved earthworm communities and organic matter for the duration of 20 years. Moreover, Bottinelli et al. [21] showed that earthworms recover after 3–4 years of logging operations and play an important role in improving soil structure during the first few years following forest soil compaction.

Previous studies have indicated that the earthworm population decreased by increasing soil compaction, since reduction in pore sizes resulted in a decrease in movement of larger soil fauna (e.g., earthworms) [5,21,43]. In addition, burrowing the compacted soil with Lumbricidae species resulted in an increase macroporosity, which lead to enhanced saturated hydraulic conductivity, and augmented soil aeration [20]. However, few studies have examined the effect of forest soil compaction on earthworm communities in the Hyrcanian forests [5,10,23,38]. For example, Jurgholami et al. [10] showed, in a study of compacted soil recovery following reforestation (different treatments), that the earthworm density and biomass had fully recovered 25 years after different types of treatment for reforestation had been applied (*Cupressus sempervirens* L. var. *horizontalis* (Mill.) Gord and *Acer velutinum* Boiss).

In previous research, the identification of organisms that indicate the ecological characteristics of the soil and reflect the natural process of soil recovery after logging disturbances has not often been done in mixed beech forests. However, there is no comprehensive study to elucidate, in detail, the natural recovery of earthworms after soil compaction as a recovery in biological indicator based on an age sequence study. Indeed, the results of such a study can offer managers and researchers the information needed to examine the potential of earthworms as a biological indicator for the evaluation of predominating conditions in forest ecosystems. Since the effect of logging operations on physical and chemical properties has been investigated in most studies, the idea behind this study is to investigate changes in earthworms in relation to changes in soil properties under the influence of logging operations. In this study, we hypothesized that the earthworm number and biomass can regenerate with various types of treatment applied according to skid trail age, traffic intensity, trail slope and soil depth over a 25-year period after logging operations. Therefore, the main objectives of this study were to (1) evaluate the overall effects of soil compaction on changes in earthworm number and biomass under different traffic conditions, slope and depth of soil in skid trails; (2) characterize the recovery process of earthworm number and biomass in a different numbers of years after logging operations; and (3) determine the correlation between earthworms and the physical and chemical properties of soil.

2. Materials and Methods

2.1. Site Description

This study was conducted during the period from August to October 2018 in seven different compartments of the Namkhaneh and Gorazbon districts of the Kheyrud Research Forest Station of the University of Tehran (between 36°34′21″ N and 36°33′34″ N latitude and 51°36′50″ E and 51°38′21″ E longitude) in the central part of the Hyrcanian forest in northern Iran (Figure 1). The size of the Namkhaneh and Gorazbon districts were 1080.66 and 1001.58 ha, respectively, and the elevation of the study sites ranged between approximately 1000–1232 m a.s.l. The climate in the study area is very humid with cold winters, an annual rainfall of 1146 mm, and a mean annual temperature of 16 °C. The terrain is moderately steep with the majority of the slopes between 5% and 45%. The parent rock is composed of hard calcareous layers with a large number of cracks, and the soil is generally brown forest (Alfisols) according to USDA soil taxonomy. The soil texture of the study site ranges from clay to clay loamy. This area is predominantly covered by deciduous trees with *Fageto-Carpinetum* forest type, with 54% of beech (*Fagus orientalis* Lipsky), 35% of hornbeam (*Carpinus betulus* L.), and 11% other species, including Cappadocian maple (*Acer cappadocicum* Gled), Caucasian alder (*Alnus subcordata* C.A.M.), Date-plum (*Diospyrus lotus* L.), common ash (*Fraxinus excelsior* L.), ironwood (*Parrotia persica* C.A.M.), large-leaved lime tree (*Tilia platyphyllos* Scop.), and mountain elm (*Ulmus glabra* Hudson). For the studied forest stands, the average height of the trees is 28 m, the average number of trees is 251 trees per hectare, and their average volume is 290.4 m^3 per hectare. The study area is covered by dominant herbaceous species including *Asperula odorata* L., *Euphorbia amygdaloides* L., *Hypericum androsaemum* L. and *Polystichum* sp.

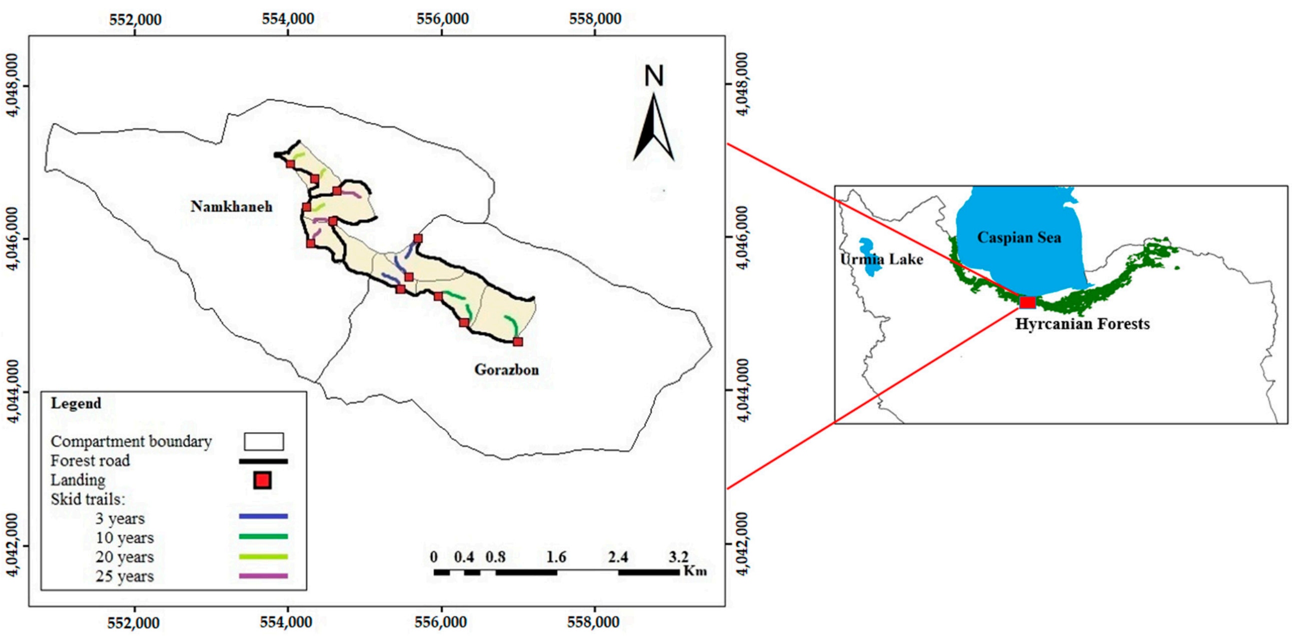

Figure 1. The study area in Kheyrud forests (Namkhaneh and Gorazbon districts) in the Hyrcanian forests, the location of skid trails with different ages (3, 10, 20 and 25 years) in the selected compartments after logging operations.

The common silvicultural methods were group and single tree selection cutting systems. Motor-manual felling and processing was carried out using chainsaws, and logs were extracted from the stump area to the roadside landings using Timberjack 450 C. The Timberjack skidder is an articulated four-wheel drive vehicle with 10.3 tons without a load (axle weight proportion was 55% on the front and 45% on the rear). Other important characteristics of the Timberjack 450 C are as follows: tire inflation pressure of 220 kPa, equipped with a 6BTA5.9 engine (engine power 130 kW), and skid trail width set at 3.5 m. During the extraction, the average load volume was 2.9 m^3. The machine passages were strictly bound to the skid trails, and the logging from the stand area to the skid trail was performed by a steel rope. The last logging operation in the forests of the study area dates back to three years ago in May 2019. In the studied forests, trees are felling during the winter and the timber is extracted when the soil condition is dry in May and June. After the end of the timber extraction operation, the beginning of the skid trails at the junction of the forest road with the embankment are blocked.

2.2. Experimental Design and Data Collection

In order to compare the recovery of earthworms as a biological indicator to assess the recovery rate of compacted-induced soil after logging operations, four abandoned skid trails with a wide range of longitudinal slope gradients and downslope logging direction (regardless of the lateral slope, area height, and soil texture and structure) were evaluated in three replications. Many studies have been conducted on the effects of skidding operations on the soil of skid trail under controlled conditions, but since the present study is retrospective, the statistics and information of harvesting operations are based on the forestry plan documents and the reports of the plan managers. According to the documentation of forestry plans in the Kheyrud forests, after the initial harvest, no re-entry of machinery or a history of soil disturbance in skid trails has been reported. The trails ranged from 3, 10, 20, and 25 years since their last forest harvesting and irregular skid trails from different exploitation campaigns were examined. The skid trails density ranged 51.3–84.8 m ha^{-1} [54]. Since 2016, forest harvesting has been implemented in the Hyrcanian forests, and three years have passed since the last logging operations on skid trails.

In each of the skid trails, three classes of traffic intensity (high, medium and low) and three slope classes (0–10, 10–20 and 20–30%) were determined and soil samples were taken at the depths of 0–10 and 10–20 cm of soil (Figure 2). The beginning of the skid trails (landing) was considered to have the highest traffic intensity. In the study area, the average length of skid trails was about 150 m, so the first 50 m of the length of the skid trail (distance 0–50 m to the forest road) was considered as high traffic intensity (HT50), the second 50 m from the length of the skid trail (distance 50–100 m to the forest road) as medium traffic intensity (MT100), and the third 50 m (the distance of 100–150 m to the forest road) or subsidiary of the skid trail as low traffic intensity (LT150), giving the basis of the traffic intensity classification to be considered [54]. Moreover, three slope classes (0–10%, 10–20%, and 20–30%) were determined in the skid trails. Each treatment plots included the combination of the three levels of traffic intensity and the three levels of trail slope, thus forming 9 combinations of traffic frequency and slope classes, and each treatment was replicated three times at the forest area thus totaling 27 sample plots (3 traffic frequency $\times$ 3 levels of trail slope $\times$ 3 replicate = 27). At each skid trail (treatments combination of slope and traffic), a total of 27 plots (dimensions of 40 m^2) were identified. In each sampling plot, three lines were randomly selected from five sampling lines that were designed perpendicularly to the skid trail, and a distance of 2 m from each other was arranged to prevent interactions (Figure 2). Soil samples were taken at the right (RW) and left wheel (LW) track as well as between the tracks (BW) to measure the physical, chemical, and biological properties of the soil. To compare between the skid trails and the undisturbed area, 81 soil samples in each recovery period (n = 9 plots $\times$ 3 lines $\times$ 3 sample = 81) were taken from an undisturbed area at least 20–30 m (the size of the average height of the dominant trees in the area) away from the skid trail in locations where there were no direct logging impacts (Figure 2).

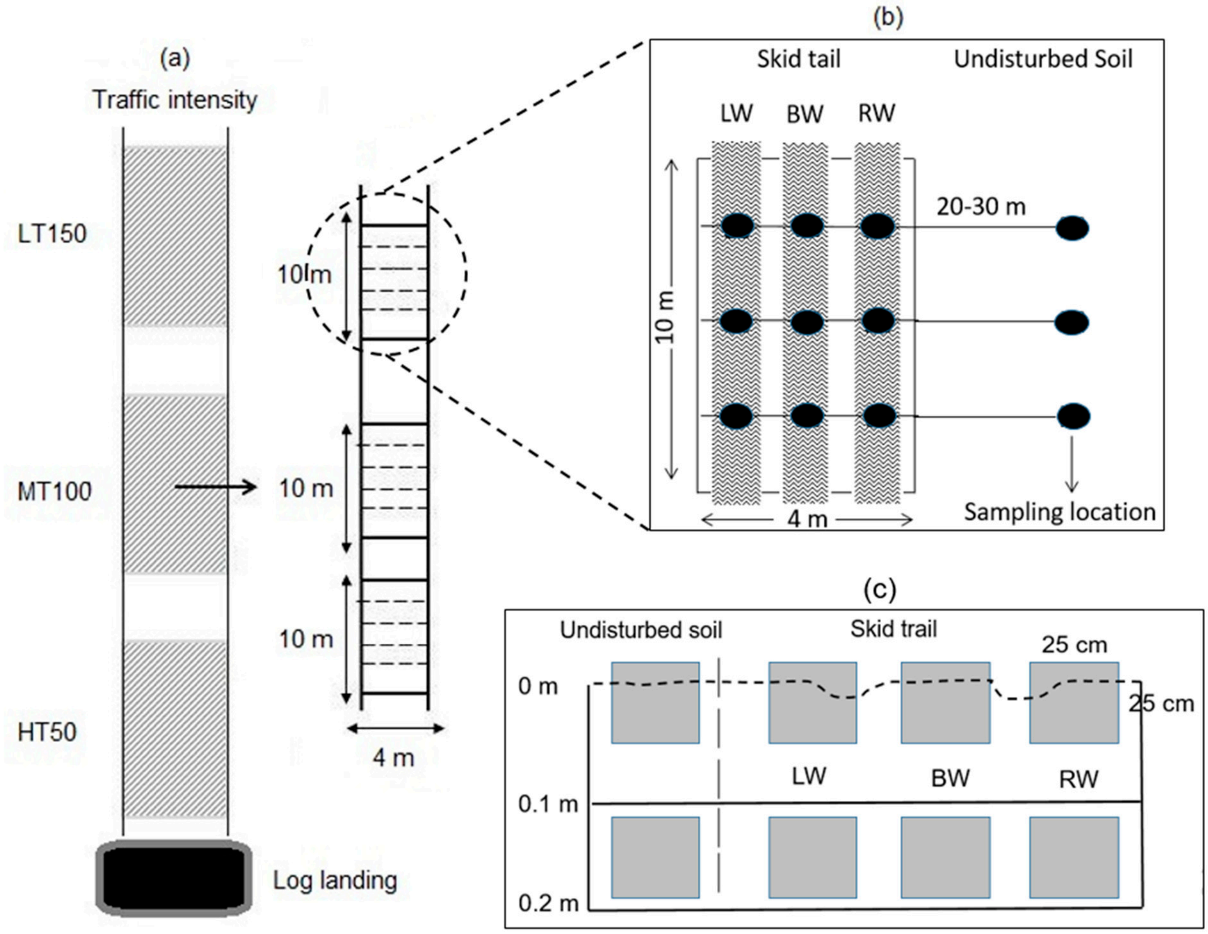

Figure 2. Schematic representation of the experimental design on the machine operating trail and undisturbed area. Different traffic intensities (HT50: high traffic intensity, MT100: medium traffic intensity, and LT150: low traffic intensity) on each skid trail, and in each traffic class, three slope classes (0–10%, 10–20%, and 20–30%) were considered (**a**). The sampling plots (10 m long by 4 m wide) with sampling lines were designed in each treatment combination of slope and traffic on the skid trails (**b**). Design of sample plots with dimensions of 25 × 25 cm (surface 625 cm^2) in two depths of 0–10 and 10–20 cm of soil in skid trails (LW: left wheel track, BW: between wheel track and RW: right wheel track) and undisturbed area for earthworm collection (**c**).

2.3. Measurements and Laboratory Analysis

Soil samples were collected with a steel ring (inside diameter 5 cm, length 10 cm) and immediately put in plastic bags and labeled. 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 reaching a constant mass to determine the soil moisture content, dry bulk density, and porosity. Soil texture was determined using a hydrometric method [55].

Dry soil bulk density (BD, g cm^{-3}) was calculated using Equation (1).

$$BD = WD/VC \quad (1)$$

where WD = weight of the dry soil (g) and VC = is the volume of the cylinder (196.25 cm^3).

Total soil porosity (TP; %) was calculated using Equation (2).

$$TP = 1 - (BD/2.65) \times 100 \quad (2)$$

where 2.65 (g cm^{-3}) is the soil particle density.

Soil samples were also collected from each sampling point, transported to the laboratory, and stored in plastic bags to analyze the chemical properties. In the laboratory, soil samples were air-dried at room temperature and then passed through a 2-mm sieve. The Walkley-Black technique was used to determine soil organic C [56]. The Kjeldahl method was used to measure total N [57].

By designing a 25 × 25 cm (surface 625 cm^2) sample plot at the sampling lines of each plot in the skid trails and the undisturbed area, the number of earthworms at two soil depths of 0–10 and 10–20 cm was manually counted as earthworm density [10]. The climate was warmer than usual when the earthworms were sampled. To determine the dry weight (biomass) of the earthworm, the collected earthworms were weighed. Earthworms were then euthanized by placement into hot water and dried in an oven at 60 °C for 24 h and reweighed [10,38].

2.4. Statistical Analysis

A factorial experiment with a completely randomized block design was designed to determine the effects of the age of the skid trail, traffic intensity, slope changes and sampling depth on earthworm density and biomass. SPSS software version 17 (Chicago, IL, USA) was used for statistical calculations. The Kolmogorov–Smirnov test ($\alpha = 0.05$) verified the normality distribution of data. Homogeneity of variance among treatments was verified by Levene's test ($\alpha = 0.01$). One-way and four-way ANOVAs were used to assess the significance of the observed mean differences in the physical (dry bulk density, total porosity), chemical (organic carbon and total N content), and biological properties (earthworm density and biomass), considering the different ages of the skid trails, different traffic intensities, skid trail gradients, sampling depth, and related interactions. An independent sample t-test was used to compare the mean of earthworm density and biomass at two soil depths. Duncan's multiple range tests ($\alpha \leq 0.05$) were used to compare the soil's physical and chemical properties among treatments. The Pearson correlation was applied to assess the relationship among the soil's physical, chemical and biological properties. Multivariate correlations were applied to evaluate significant relationships among principal components and variables by using the PC-ORD (Version 4, WILD BLUEBERRY MEDIA LLC, Corvallis, OR, USA) software. In particular, Principal Component Analysis (PCA) was applied to investigate any possible linear correlations between treatments (trail age, traffic, and slope) and soil properties. The main criteria used were eigenvalue (>1), scree plot (retain all components within the sharp descent), loading score for each factor (±0.10), and meaningfulness of each dimension. To minimize the scaling effect caused by different measurement units, the data corresponding to each independent variable were standardized using the Box–Cox lambda.

3. Results

The ANOVA results showed that the effect of trail age (A), traffic intensity (T), trail slope classes (S), soil depth (D) as well as their interaction on BD and TP was significant (Table 1). For organic C, N, and C/N ratio, the effect of trail age, traffic intensity, trail slope classes, and depth were significant, while their interaction was not significant. The interaction of trail age and traffic intensity (A × T) on soil physio-chemical properties was significant, while their interaction on soil biological properties was not significant. One of the important results was that in addition, to the effect of trail age and soil depth independently on soil biological properties was significant, but their interaction (A × D) on soil biological properties was also significant. The effect of treatments (except for A, D and A × D) on the earthworm density and biomass was not significant. The interaction of all treatments (A × T × S × D) on the soil's physical, chemical (except C/N ratio), and biological (i.e., earthworm density and biomass) properties was not significant (Table 1).

Table 1. ANOVA (p-values) of the effect of abandoned skid trail age (A), traffic intensity (T), slope (S), depth (D), and their interaction on the bulk density (BD), total porosity (TP), organic carbon content (OC), nitrogen content (N), C/N; C/N ratio, earthworm density (Ew D), and earthworm biomass (Ew B).

Source of Variable	d.f.	p-Values						
		BD (g cm^{-3})	TP (%)	OC (%)	N (%)	C/N ratio	Ew D (ind. m^{-2})	Ew B (mg m^{-2})
A	3	**≤0.01**	**≤0.01**	**≤0.01**	**≤0.01**	**≤0.01**	**≤0.01**	**≤0.01**
T	3	**≤0.01**	**≤0.01**	**≤0.01**	**≤0.01**	**≤0.01**	0.422	0.429
S	2	**≤0.01**	**≤0.01**	**≤0.05**	**≤0.01**	**≤0.01**	0.090	0.115
D	1	**≤0.01**	**≤0.01**	**≤0.01**	**≤0.01**	**≤0.01**	**≤0.05**	**≤0.05**
A × T	9	**≤0.01**	**≤0.01**	**≤0.05**	**≤0.01**	**≤0.01**	0.824	0.817
A × S	6	**≤0.01**	**≤0.05**	0.770	0.148	**≤0.01**	0.903	0.940
A × D	3	**≤0.05**	**≤0.01**	0.889	0.735	**≤0.01**	**≤0.01**	**≤0.01**
T × S	6	**≤0.05**	**≤0.05**	0.522	**≤0.01**	**≤0.05**	0.798	0.828
T × D	3	**≤0.01**	**≤0.01**	0.420	0.530	0.059	0.843	0.897
S × D	2	**≤0.05**	**≤0.01**	0.544	0.870	0.216	0.757	0.728
A × T × S	18	**≤0.05**	**≤0.05**	0.847	**≤0.01**	**≤0.05**	0.982	0.980
A × T × D	9	**≤0.05**	**≤0.05**	0.452	0.918	0.188	0.933	0.917
A × S × D	6	**≤0.05**	0.418	0.155	0.656	0.562	0.915	0.908
T × S × D	6	**≤0.05**	0.082	0.524	0.768	0.117	0.867	0.848
A × T × S × D	18	0.117	0.316	0.914	0.920	**≤0.05**	0.832	0.855

p-values (<0.01 and <0.05) are given in bold.

Over the years following the skidding operations, physical and chemical soil properties improved from the 3-year-old skid trail to the 25-year-old skid trail (Table 2). From the 3-year-old skid trail to the 25-year-old skid trail, the BD and C/N ratio decreased, in contrast, the TP, OC%, and N% increased. However, none of them were fully recovered, and they were significantly different from values in the undisturbed area. Three years after the skidding operations, the BD and C/N ratio were 32.63% and 91.54% higher than the undisturbed area, respectively. Meanwhile, 25 years after the skidding operations, they were 13.68% and 26.20% higher than the undisturbed area, respectively. Furthermore, three years after the skidding operations, the TP, OC%, and N% were 18.24%, 42.82%, and 70.15% lower than the undisturbed area, respectively. Meanwhile, 25 years after the logging operations, they were 7.64%, 22.77%, and 38.81% lower than the undisturbed area, respectively (Table 2).

Table 2. Changes in soil properties (mean ±SE) in different years after the logging operations. BD: bulk density, TP: total porosity, OC: organic carbon, N: nitrogen content, C/N: C/N ratio.

Soil Properties	Recovery Time (Skid Trails)				
	3 Years	10 Years	20 Years	25 Years	Undisturbed Area
BD (g cm^{-3})	1.26 ± 0.01 ^{a}	1.21 ± 0.01 ^{b}	1.18 ± 0.03 ^{b}	1.08 ± 0.01 ^{c}	0.95 ± 0.03 ^{d}
TP (%)	52.45 ± 0.24 ^{c}	54.34 ± 0.24 ^{c}	55.47 ± 0.24 ^{c}	59.25 ± 0.24 ^{b}	64.15 ± 0.15 ^{a}
OC (%)	2.31 ± 0.13 ^{d}	2.78 ± 0.13 ^{c}	2.9 ± 0.13 ^{c}	3.12 ± 0.13 ^{b}	4.04 ± 0.09 ^{a}
N (%)	0.2 ± 0.05 ^{d}	0.27 ± 0.05 ^{c}	0.36 ± 0.05 ^{b}	0.41 ± 0.05 ^{b}	0.67 ± 0.01 ^{a}
C/N ratio	11.55 ± 0.07 ^{a}	10.29 ± 0.07 ^{a}	8.05 ± 0.07 ^{b}	7.61 ± 0.07 ^{b}	6.03 ± 0.13 ^{c}

Note: Different letters indicate significant differences among the intensities of the soil properties ($p < 0.05$), based on Duncan's multiple range tests.

3.1. Earthworm Density and Biomass

The earthworm density showed a decreasing trend with increasing traffic intensity (Table 3) and slope (Table 4). The highest mean of earthworm density by 0.58 ind. m^{-2} was found in low traffic and a soil depth of 0–10 cm of the 25-year-old skid trail, while the lowest value of 0.11 ind. m^{-2} was observed in high traffic at a depth of 10–20 cm of soil in the 3-year-old skid trail (Table 3). The 25-year-old skid trail had the highest earthworm density of 0.58 ind. m^{-2} at a slope of 0–10% and a soil depth of 0–10 cm, while the lowest value of 0.11 ind. m^{-2} was found at a slope of 20–30% at a depth of 10–20 cm in a 3-year-old skid trail (Table 4). In all skid trails, the earthworm density in different traffic intensities and three slope classes in both soil depths was less than in the undisturbed area. Moreover, the earthworm density in a soil depth of 10–20 cm was less than in soil depth of 0–10 cm and there was a significant difference between them ($F = 20.16$, $p < 0.01$) (Tables 3 and 4).

Table 3. Mean values (±SE) of earthworm density (ind. m^{-2}) at different traffic intensities and two soil depths in skid trail age classes.

		Traffic Intensity			
Recovery Time (Skid Trails)	**Depth (cm)**	**Undisturbed Area**	**Low**	**Medium**	**High**
3 years	0–10	0.78 ± 0.24^{a}	0.33 ± 0.22^{b}	0.30 ± 0.20^{b}	0.22 ± 0.20^{c}
	10–20	0.33 ± 0.24^{a}	0.15 ± 0.22^{b}	0.11 ± 0.19^{c}	0.11 ± 0.19^{c}
10 years	0–10	0.89 ± 0.24^{a}	0.44 ± 0.20^{b}	0.44 ± 0.20^{b}	0.33 ± 0.20^{c}
	10–20	0.33 ± 0.24^{a}	0.22 ± 0.19^{b}	0.22 ± 0.19^{b}	0.11 ± 0.19^{c}
20 years	0–10	0.78 ± 0.24^{a}	0.56 ± 0.20^{b}	0.33 ± 0.20^{c}	0.33 ± 0.20^{c}
	10–20	0.67 ± 0.24^{a}	0.44 ± 0.19^{b}	0.33 ± 0.19^{bc}	0.22 ± 0.19^{c}
25 years	0–10	0.89 ± 0.24^{a}	0.58 ± 0.20^{b}	0.56 ± 0.20^{b}	0.33 ± 0.20^{c}
	10–20	0.68 ± 0.24^{a}	0.33 ± 0.19^{b}	0.33 ± 0.19^{b}	0.30 ± 0.19^{b}

Note: Different letters after means within each treatment indicate significant differences by Duncan's test ($p < 0.05$).

Table 4. Mean values (±SE) of earthworm density (ind. m^{-2}) at slope classes and two soil depths in skid trail age classes.

		Slope Classes			
Recovery Time (Skid Trails)	**Depth (cm)**	**Undisturbed Area**	**0–10%**	**10–20%**	**20–30%**
3 years	0–10	0.78 ± 0.24^{a}	0.33 ± 0.31^{b}	0.30 ± 31^{b}	0.22 ± 0.31^{c}
	10–20	0.33 ± 0.24^{a}	0.11 ± 0.26^{b}	0.15 ± 0.26^{b}	0.11 ± 0.26^{b}
10 years	0–10	0.89 ± 0.24^{a}	0.44 ± 0.31^{b}	0.44 ± 0.31^{b}	0.33 ± 0.31^{c}
	10–20	0.33 ± 0.24^{a}	0.11 ± 0.26^{b}	0.11 ± 0.26^{b}	0.11 ± 0.26^{b}
20 years	0–10	0.78 ± 0.24^{a}	0.56 ± 0.31^{b}	0.56 ± 0.31^{b}	0.11 ± 0.31^{c}
	10–20	0.67 ± 0.24^{a}	0.44 ± 0.26^{b}	0.44 ± 0.26^{b}	0.11 ± 0.26^{c}
25 years	0–10	0.89 ± 0.24^{a}	0.58 ± 0.31^{b}	0.56 ± 0.31^{b}	0.33 ± 0.31^{c}
	10–20	0.68 ± 0.24^{a}	0.56 ± 0.26^{b}	0.22 ± 0.26^{b}	0.22 ± 0.26^{b}

Note: Different letters after means within each treatment indicate significant differences by Duncan's test ($p < 0.05$).

Results show that the earthworm biomass decreased by increasing traffic intensity (Figure 3) and slope (Figure 4). The highest earthworm biomass (3.36 mg m^{-2}) was found in a low traffic intensity at a 0–10 cm depth of the soil in the 25-year-old skid trail, while the lowest value of 0.46 mg m^{-2} was measured in high traffic at a 10–20 cm depth of the soil in the 10-year-old skid trail (Figure 3). The 25-year-old skid trail has the highest earthworm biomass (3.31 mg m^{-2}) at a slope of 0–10% and a soil depth of 0–10 cm, while the lowest value (0.47 mg m^{-2}) was detected at a slope of 20–30% (Figure 4). The earthworm biomass in all skid trails with different traffic intensity and slopes at both soil depths was significantly less than the undisturbed area. Moreover, the earthworm biomass in 10–20 cm soil depth was significantly less than the value of 0–10 cm depth, and there was a significant difference between them ($F = 15.41$, $p < 0.01$) (Figures 3 and 4).

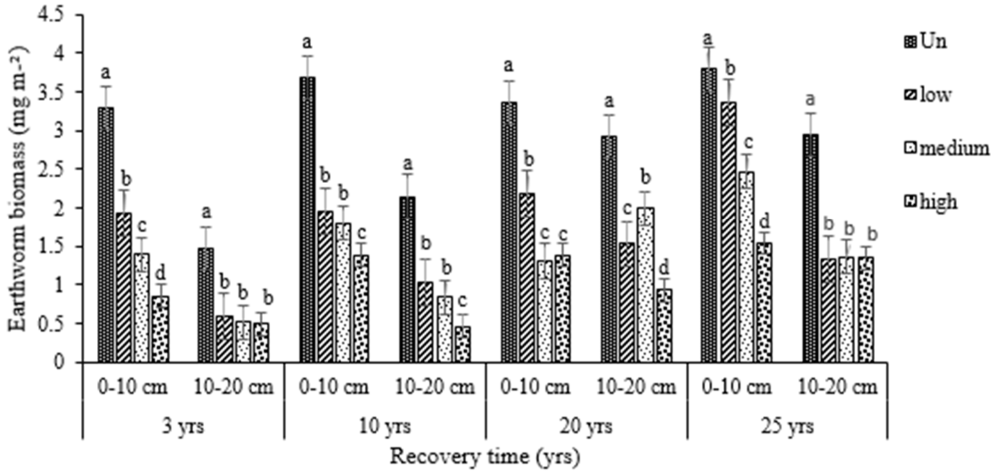

Figure 3. Changes in earthworm biomass (mg m^{-2}) at different traffic intensities (low, medium, and high) and two soil depths (0–10 and 10–20 cm) in skid trail age classes. Different letters indicate statistically significant differences among treatments by Duncan's test ($p < 0.05$).

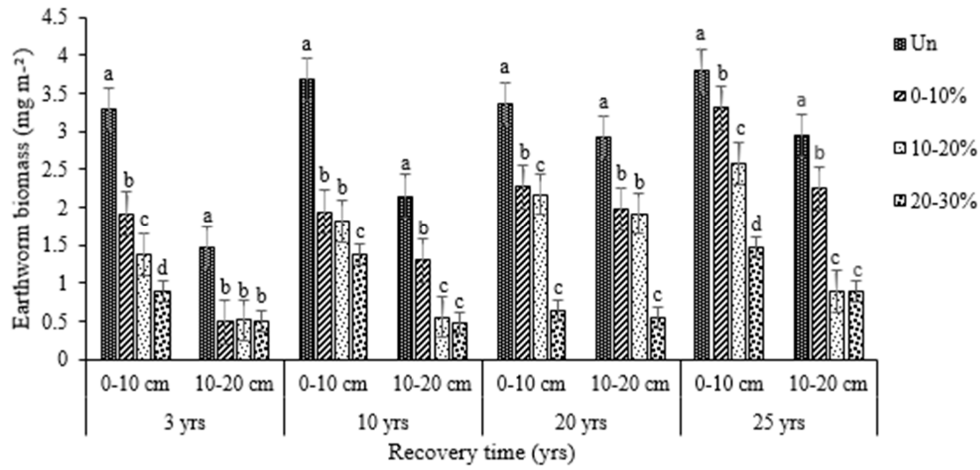

Figure 4. Changes in earthworm biomass (mg m^{-2}) at slope classes (0–10%, 10–20%, and 20–30%) and two soil depths (0–10 and 10–20 cm) in skid trail age classes. Different letters indicate statistically significant differences among treatments by Duncan's test ($p < 0.05$).

Even if a clear positive recovery trend is showed (Figure 5), from the results it is clear that earthworm density was not fully recovered over a period of 25 years after logging operations (Table 3). From a 3-year to a 25-year-old trail, the earthworm density increased at two soil depths; although those were significantly different from the values of the undisturbed area, it important to note that over the 20 years the rate of increase of the earthworm density slowed down, even if referred to a short period (5 years). Three years after the logging operations, earthworm density at depths of 0–10 and 10–20 cm were 67.16% (0.22 ind. m^{-2}) and 80.70% (0.11 ind. m^{-2}) less than those of the undisturbed area, respectively, while 25 years after the logging operations, earthworm density values were 28.36% (0.48 ind. m^{-2}) and 38.59% (0.35 ind. m^{-2}) less than the values of the undisturbed area. What is more, the earthworm density in all the skid trails and the undisturbed area at a depth of 10–20 cm was less than the values in soil depth of 0–10 cm (Figure 5).

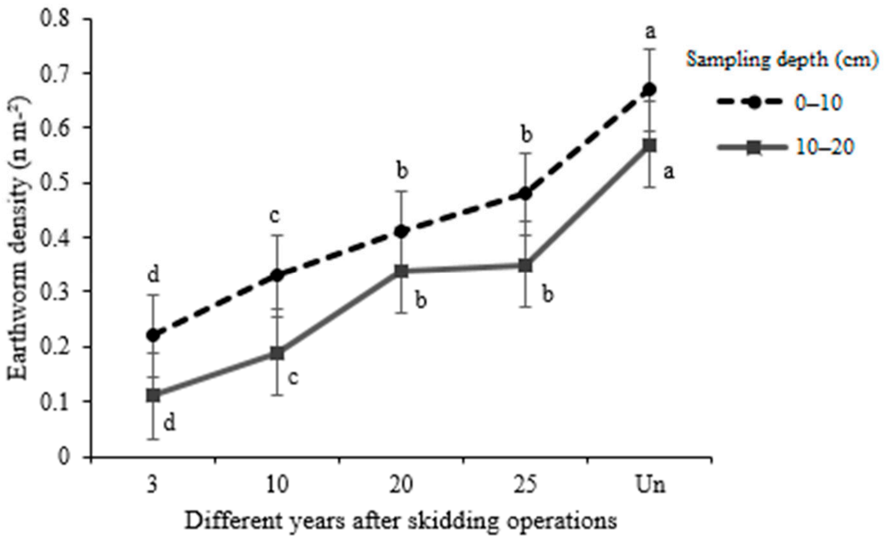

Figure 5. Changes in earthworm density in a different number of years after the logging operations (i.e., 3, 10, 20, 25 years, and Un: Undisturbed area). Different letters indicate statistically significant differences among skid trails and undisturbed area by Duncan's test ($p < 0.05$).

The earthworm biomass was partially recovered after a different number of years of logging operations from the 3-year-old to the 20-year-old and 25-year-old trail at both soil depths, compared to the undisturbed area (Figure 6). Three years after the logging operations, the earthworm biomass at soil depths of both 0–10 and 10–20 cm was 67.45% (0.96 mg m^{-2}) and 79.92% (0.52 mg m^{-2}) less than the values of the undisturbed area, respectively, while 25 years after the logging operations, these values were 30.51% (2.05 mg m^{-2}) and 40.54% (1.54 mg m^{-2}) less than those of the undisturbed area. Moreover, the earthworm biomass in all the skid trails and the undisturbed area at a depth of 10–20 cm was significantly less than the value at a depth of 0–10 cm (Figure 6).

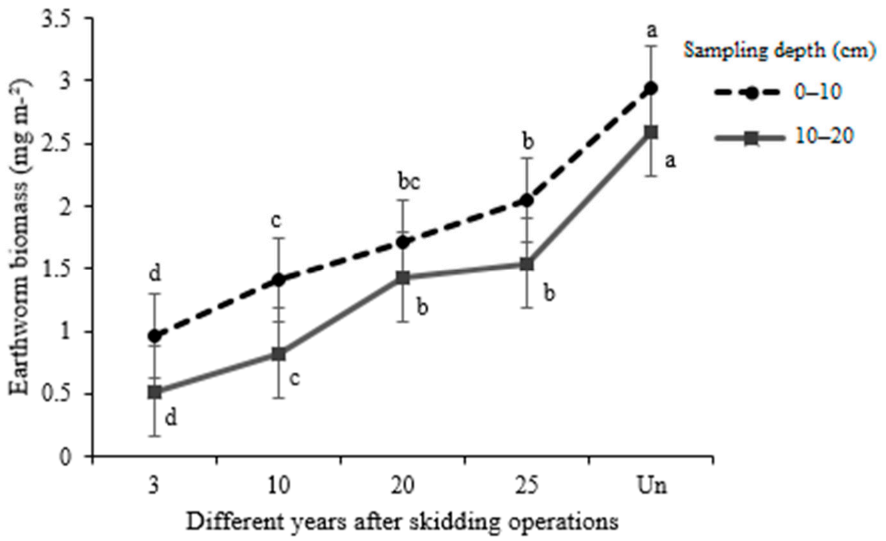

Figure 6. Changes in earthworm biomass (Mean ± SD) in different years after the logging operations (i.e., 3, 10, 20, 25 years, and Un: Undisturbed area) in two soil depths. Different letters indicate statistically significant differences among skid trails and undisturbed area by Duncan's test ($p < 0.05$).

3.2. Principal Component Analysis (PCA)

According to multivariate correlations for treatments (trail age, traffic, and slope) and soil properties, results of a principal component analysis (PCA) revealed that first and second axes explained 93.33% and 3.08% of the total variance, respectively (Figure 7). Three-year-old skid trails (ST3), high traffic intensity (HT50), and slope of 20–30% (SC30) have a negative correlation with soil properties and the greatest effect on them (based on the maximum distance from the coordinate center and proximity to axis 1). The impact of treatments on soil properties decreased with the increasing age of the skid trail and the reducing traffic intensity and slope classes. The Un, ST20, ST25, LT150, and SC10 treatments on the left side of the graph were positively correlated with soil properties (i.e., total porosity, organic carbon, nitrogen content) and soil organisms (earthworm density and biomass). In other words, the favorable conditions of the soil's physical, chemical, and biological properties with low changes were imposed by Un, ST20, ST25, LT150, and SC10 treatments. The ST3, ST10, HT50, MT100, SC30, and SC20 treatments on the right side of the graph resulted in an unfavorable effect on the soil's physical properties (higher soil bulk density and C/N ratio as well as lower soil porosity) (Figure 7).

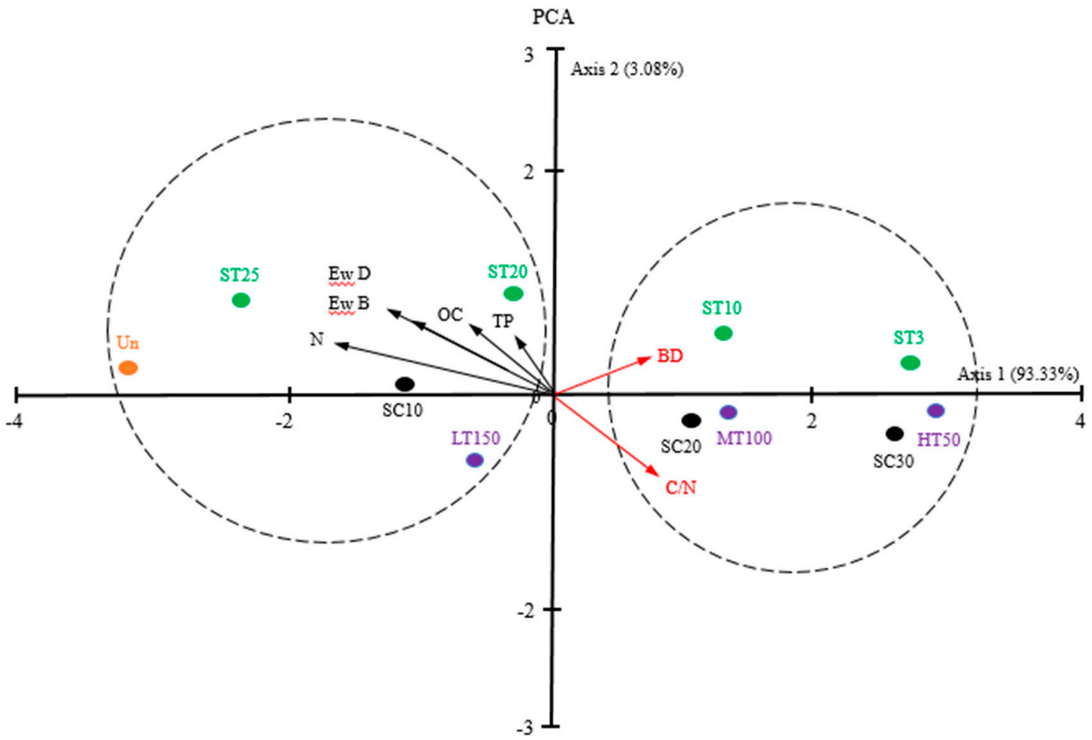

Figure 7. Principal Component Analysis (PCA) ordination of the skid trail age (ST3: 3 year-old, ST10: 10 year-old, ST20: 20 year-old, ST25: 25 year-old), traffic intensities (HT50: high traffic intensity, MT100: medium traffic intensity, and LT150: low traffic intensity), slope classes (SC10: 0–10%, SC20: 10–20%, and SC30: 20–30%), Un: undisturbed area and soil properties (BD: bulk density, TP: total porosity, OC: organic carbon, N: nitrogen content, C/N: C/N ratio, Ew D: earthworm density, Ew B: earthworm biomass).

The Pearson correlation results showed that there were strong correlations between the soil's physical, chemical, and biological properties (Table 5). The soil bulk density was negatively correlated with the other soil parameters (except C/N ratio). The earthworm density and biomass were positively correlated with total porosity and organic carbon and nitrogen content and negatively correlated with soil bulk density and C/N ratio. Earthworm density and biomass significantly increased as TP, OC, and N increased.

Table 5. Pearson correlation between soil physical (BD: bulk density, TP: total porosity), chemical (OC: organic carbon, N: nitrogen content, C/N: C/N ratio), and biological (Ew D: earthworm density, Ew B: earthworm biomass) properties.

Soil Properties	BD	TP	OC	N	C/N	Ew D	Ew B
BD	1	−0.96 **	−0.95 **	−0.92 **	0.40 ns	−0.55 *	−0.54 *
TP		1	0.92 **	0.90 **	−0.39 ns	0.67 **	0.66 **
OC			1	0.99 **	−0.67 **	0.98 **	0.98 **
N				1	−0.82 **	0.97 **	0.96 **
C/N					1	−0.90 **	−0.88 **
Ew D						1	0.99 **
Ew B							1

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

4. Discussion

Study of the soil biological characteristics following soil disturbances would provide a substantial guide for forest managers in order to accelerate the ecological restoration of forest soils [4]. The results of this study showed that the earthworm density and biomass related to traffic intensity and trail slope have significant changes, in as much that these changes are higher in high traffic intensity and for a slope of 20–30%. Consistent with the results of our study, several studies proved that earthworm frequency and activity can be changed by soil conditions under the impact of logging operations [18,20,21,49–51]. Accordingly, the reduction in the earthworm density and biomass under the impacts of forest harvesting operations and land use change has been mentioned in numerous studies [5,10,21,58]. This result could be due to an increase in the bulk density and a decrease in total porosity with increasing traffic intensity and slope [59,60]. This data is confirmed by the negative correlation between the soil's physical and biological properties in the present study, which showed it to be a harsh environment for soil organisms, especially the earthworm [5]. Regarding the strong correlation between the soil's physical, chemical, and biological properties, it can be said that the presence of the litter layer on the soil surface changes the amount of organic carbon, nitrogen content, bulk density, and soil pores, and will affect soil biological activities such as earthworms and some microorganisms [10]. Similarly, Ampoorter et al. [61] showed that achieving different soil ecological recovery methods mainly depends on soil properties and conditions such as pH, the presence of a litter layer, access to nutrients and moisture.

Following logging operations, soil habitat has lower quality on the skid trails as compared to the undisturbed area due to the adverse changes of key parameters including porosity, temperature and humidity, litter layer, type and quality of litter layer, organic matter content, nutrients cycle and vegetation [10,21,62]. In line with the current study, Jordan et al. [19] indicated that earthworm density and types depend on soil organic matter, so that in organic matter with low C/N ratio, litter with a low amount of tannins and mixed broadleaf forests are higher than other soils. Heavy soil texture in the study area reduces the earthworm density and biomass more than lightly textured soils because some soil properties such as moisture and nutrient status depend on soil texture.

According to previous studies, if other soil conditions are the same, the population of earthworms in soils with heavy texture is less than light to medium soils [63,64]. A decrease in earthworm density and biomass can adversely affect the litter layer removed by tree felling, timber extraction, and the dominant beech trees with high C/N ratio, when compared to the undisturbed area [5,54]. According to research, the earthworm population is affected by the C/N ratio [65]. The C/N ratio and soil acidity in the study area (pure beech stand) is higher than in other forest types, which leads to longer litter layer decomposition. Therefore, high C/N ratio and high soil acidity in pure beech, the long decomposition of the litter layer, and earthworm susceptibility to soil acidity have led to a further reduction in the number of earthworms [66]. On the other hand, about 80–90% of the earthworm weight is water, and therefore their need for moisture is very high. Consequentially dryness can easily eliminate earthworms and other soil organisms [67]. According to previous studies, in spring and autumn, environmental conditions are more favorable for earthworm reproduction and growth, and their number increases, but in summer and winter, unfavorable conditions, especially high heat and cold, cause earthworms to migrate to greater depths and further reduce their number [68]. In the present study, high heat in summer (sampling time) and low soil moisture (according to the high bulk density of the soil) have a negative effect on the earthworm number and biomass in skid trails and undisturbed area.

Results of the current study showed that the earthworm density and biomass at a depth of 10–20 cm was less than the depth of 0–10 cm. Studies have shown that the highest activity and composition of earthworm populations is observed in the organic and mineral horizons up to 10 cm of soil. Proper ventilation, adequate space and abundant nutrients are the main factors that increase the earthworms number and biomass at a depth of 0–10 cm. Consistent with the current study, Bottinelli et al. [21] indicated that earthworm immobility plays an important role in reducing the earthworm density and biomass due to the increase of penetration resistance and to the reduction of the total porosity at a depth of 10–20 cm. Furthermore, soil habitat quality and earthworm motility are two factors which influence the regeneration of earthworms after logging operations [21].

The earthworm density and biomass of were significantly different between skid trails and undisturbed area, but there was no difference in ecological diversity. According to the observations obtained from earthworm sampling, their appearance and general characteristics, and previous studies in the Hyrcanian forests of Iran [69], the type or species of epigeic earthworms is more than two types of anecic and endogeic earthworms. In all of the skid trails as well as the undisturbed area, density and dry mass of epigeic earthworms were higher than the corresponding values for anecic and endogeic earthworms. Since different combinations of tree species have different effects on soil quality and development, so the type of forest management will affect soil quality through changes in vegetation characteristics and tree species. Accordingly, Frouz et al. [30] showed that the effect of tree species on soil development is substantially mediated by soil fauna activity and especially by earthworm bioturbation.

The decomposition and incorporation processes of organic matter in the forest soil are highly dependent onw the earthworm populations and activities [70–74]. Consistent to the current study, Pižl [70] found both earthworm density and biomass negatively affected after high traffic intensity in the soil of an apple orchard. The soil particles ingested by earthworms is important for the earthworms' capability to burrow and penetrate in compacted soil with soil penetration resistance of 3 mPa [73]. Furthermore, Ampoorter et al. [63] and Jordan et al. [19] reported that the density and quality of cast production is adversely affected by soil compaction.

From the ecosystem restoration viewpoint, the responses of compacted soil to disturbances consist of the complicated interactions of biological, chemical, and physical characteristics [2,75,76]. The response of the soil ecosystem, which aims to restore its properties to the original state, may require a long time and complex processes [77,78].

In line with the current study, soil structure was significantly affected by anecic and epigeic earthworms, since they can mix the detritus materials with mineral soil by burying large amounts of organic materials of soil surface, as reported by Andriuzzi et al. [79]. Some earthworm species make burrows in soil, resulting in an increase in the water flow pathways, enhanced hydraulic conductivity and increased infiltration rate [80]. For example, Andriuzzi et al. [79] concluded that some anecic earthworms such as *Lumbricus terrestris* can have diverse ranges of functions, such as mixing soil, digging burrows, and thinning forest floor, which promotes the drainage capacities in soil, leading to increased soil macroporosity, which results in increased soil physical features.

5. Conclusions

The study of the ecological recovery of soil properties under natural conditions can provide valuable information to reduce the negative effects of logging operations on forest soil. According to our results, the greatest decrease in earthworm density and biomass was observed in the high traffic intensity and the slope class of 20–30% at the 10–20 cm depth of the soil. Based on the relationship between soil properties, the earthworm density and biomass were positively correlated with total porosity, organic carbon, and nitrogen content, while negatively correlated with bulk density and C/N ratio. According to our hypothesis, after 25 years of logging operations, the earthworm density and biomass on the skid trails had recovered, but there is a significant difference with the undisturbed area. Therefore, the full regeneration of the soil's biological properties (earthworm density and biomass) needs more than 25 years to return to that of the undisturbed level. In order to maintain the forest soil ecosystem, it is necessary to pay attention to the interrelationships of soil organisms, vegetation and soil during the harvesting operations. Due to the fact that forest soils have been attenuated by disorderly and unprincipled exploitation, SFO can provide guidelines for selecting the most appropriate forest operations systems to reduce the negative effects on soil as follows:

- Selection of advanced technologies such as real-time mapping, sensors, and optimization of skid trails to reduce unnecessary traffic and prevent the passage of machinery on sensitive areas (wet soils, regenerated tree areas) and thus reduce potential soil damage and increase regeneration capacity of forest stands.
- Assessing soil disturbances during harvesting operations using live monitoring techniques such as machine-mounted LiDAR systems or other types of remote sensing technologies to scan the physical environment is a fundamental step to a better understanding of forest soil disturbances.
- Use of high-powered machinery (high engine power) with flexible tires to reduce the number of passes required to complete timber extraction.
- Using techniques such as wide tires or slash mats to reduce soil compaction.
- The use of improvement treatments such as different foliage mulch and tree planting (especially mixed broadleaf species with low C/N ratio) and comparing their performance in terms of the recovery of the soil properties of skid trails to accelerate biological activity (especially earthworms) and the natural regeneration of trees.

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