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Soil Recovery Assessment after Timber Harvesting Based on the Sustainable Forest Operation (SFO) Perspective in Iranian Temperate Forests

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Abstract: Minimizing the impact of timber harvesting on forest stands and soils is one of the main goals of sustainable forest operation (SFO). Thus, it is necessary to make an accurate assessment of forest operations on soil that is based on the SFO perspective. The present study was conducted according to SFO principles to investigate the time required for the natural recovery of soil after disturbance by skidding operations in some Iranian forests. The physical, chemical, and biological properties of soil found in abandoned skid trails from different time periods were compared with undisturbed forest soils. The soil bulk density, the penetration resistance, and the microporosity of a 25-year-old skid trail were 8.4–27.4% and 50.4% greater, and the total porosity, macroporosity, and soil moisture were 1.9–17.1% and 4.6% lower than the undisturbed area. In a 25-year-old skid trail, the values of pH, Electrical conductivity (EC), C, N, available P, K, Ca, and Mg, earthworm density, and biomass were lower than in the undisturbed area, and the C/N ratio value was higher than in the undisturbed area. High traffic intensity and slope classes of 20–30% in a three-year-old skid trail had the greatest impact on soil properties. In order to have sustainable timber production, SFO should be developed and soil recovery time should be reduced through post-harvest management operation.

Keywords: skidding operation; soil properties; sustainable forest operation; traffic intensity; soil recovery

1. Introduction

One of the main goals of sustainable forest operation (SFO) is to comply with the forest operations ecology [1–3]. Environmental issues and concerns have been increasing as quickly as the development of the mechanization of forest operations across most of the world over the last 50 years [4]. From an SFO perspective, forest operational planning must consider all possible factors affecting environmental impacts, as well as their interactions. Soil plays a vital role in forest ecosystems by providing nutrients, water, and energy flow, which leads to forest productivity and biodiversity conservation [5–7]. Due to their specific characteristics, forest soils are highly susceptible to disturbances caused by skidding operations, the effects of which may persist for years after skidding [8–10]. Log skidding in forest stands impacts the soil that, at the same time, is used as a growth substrate. However, due to soil disturbance, skidding operations lead to soil compaction, soil layer displacement, and the deformation of soil structure and texture [11–13]. Skidding operations generally require a wide and dense network of skid trails for proper access at the forest stand level. Also, finding the optimum space between the forest road to minimize the total cost of timber extraction and road construction plays a key role in planning sustainable forest operations [14]. In this case, a large area of forest soil is affected by the machinery traffic, with possible related changes or disturbances. In general, it may be possible to note an increasing trend in soil bulk density (BD) values [10,15–18], as well as shear and penetration resistance (PR) values [7,8,11,19,20]. At the same time, it may be possible to note a decreasing trend for the presence of macropores [21], hydraulic conductivity of water, air permeability, air–water and gas exchange [22], organic matter [5,20,23], the presence and quality of soil microorganisms [24,25], and carbon sequestration capacity [26]. The lack of recovery of soil properties, especially bulk density and penetration resistance, can also impact the regeneration and decrease of growth seedlings, as reported by Picchio et al. [9] and Sohrabi et al. [27].

Machinery traffic could also lead to variations in some soil features, but without a clear trend, including soil pH [20,28]; microbial biomass, due to inadequate respiration [29–31]; and nutrient availability, due to changes in mineralization process [20,29]. Variations in these soil features, depending on their degree and intensity, can influence plant growth [23,32–34].

The influence of important factors on soil property changes after skidding operation are traffic intensity (the number of passes), slope gradients, and skidding direction. Numerous studies have shown that high traffic intensity (more than 15 passes) and high slope gradient (more than 20%) in mountainous areas cause soil disturbance to a greater extent and with greater intensity [35–37].

The recovery of physical, chemical, and biological soil properties is a topic that has been extensively discussed but has not always been clearly stated due to the difficulties in assessing multiple complex variables. The processes of soil swelling and shrinkage, freezing and thawing, wetness and drought [38,39], root–soil interaction [40,41], fauna activities [39,41,42], precipitation, and the height of the stands are the main factors that can accelerate the recovery process of disturbed soils [43,44]. In addition, soil properties (structure, texture, thickness, and depth), soil moisture and litter layer, terrain slope, soil initial compaction, harvesting systems, and the type of machinery used in skidding operations also affect the soil recovery rate [8,45–48].

The recovery of the physical, chemical, and biological properties of compacted soils can take years and even decades without the use of improvement treatments [12,17,49–51]. Ezzati et al. [50] and Jaafari et al. [36] have shown that soil properties did not recover during a long-term period (20 years) after skidding operation. Von Wilpert and Schäffer [52] reached a similar conclusion; whereas Mohieddinne et al. [48] found that sandy neutral soils recovered in less than 20 years due to soil biological activities. According to some studies, the time required to recover the biological properties of soil is less than that of the physical and chemical properties [5,11]. For example, Mariani et al. [53] showed that soil biomass recovered on the forest floor between three and seven years after harvesting in Canada. Furthermore, Macedo et al. [54] reported that soil C and N were significantly recovered 13 years after harvesting. Picchio et al. [8] and Venanzi et al. [20] have shown that soil recovery after reduced impact logging activities can occur within 6–10 years, and this can be considered fairly fast. Accordingly, Hope [55] has shown that many of the changes that were visible in the first year after the harvesting operation disappeared in the 10 years following the operation, and the effects of machinery traffic on the chemical properties of the soil were significantly recovered, while the shortest time to recover physical properties such as bulk density was reported to be five years.

Three especially prominent approaches in the sustainability of forest operations are: environmentally sound forest harvesting, reduced-impact logging, and forest operations ecology [3]. Forest operations ecology applies the principles of industrial ecology to forest operations systems. It aims to develop and deploy environmentally sound forest operations technologies, to use resources efficiently, to minimize the overall production of waste and emissions, and to minimize the impacts on the structures and functions of environmental spheres (atmosphere, biosphere, hydrosphere, and lithosphere) [1]. Characterizing the effects of skidding operations on the physical, chemical, and biological properties of soil is one important step in protecting the forest ecosystem and forest soil fertility [56]. The aeration status and soil porosity, the quality and quantity of organic matter, the microbial biomass, and the soil nutrients are considered criteria for the evaluation of soil health and biological and chemical activity. Therefore, there is a need to investigate the changes in the physical, chemical, and biological properties of soil. Awareness of the time required for the recovery of disturbed soils is essential to sustainable forest management. We hypothesize that soil properties could not be recovered after skidding operations over a long-term period (20 years) under natural conditions. The main aim of this study is (1) to evaluate the time required for the recovery of the physical, chemical, and biological properties of soil; and (2) to assess the long-term effect of the slope of the skid trail, machine traffic, and soil depth on the recovery process of the soil environment after ground-based skidding operations in the Hyrcanian forests of Iran.

2. Materials and Methods

2.1. Site Description

This study was conducted in seven different forest compartments located in the Namkhaneh and Gorazbon districts of the Kheyrud forest, part of the Hyrcanian forest in northern Iran. The research area lies between 51°36′50″ E and 51°38′21″ E longitude and 36°34′21″ N and 36°33′34 5″ N latitude, at altitude of 1000–1232 m above sea level. The study area has no dry season and has a humid climate with an average annual rainfall of 1146 mm and an average annual temperature of 8.55 °C. The soil texture of the study site ranges from silt loam to loamy (Table 1). The soils are mainly brown forest (Alfisols) with good drainage and, in terms of geology, belong to the Jurassic period. This area is predominantly covered by deciduous trees such as oriental beech (*Fagus orientalis* Lipsky), hornbeam (*Carpinus betulus* L.), velvet maple (*Acer velutinum* Boiss.), Cappadocian maple (*Acer cappadocicum* Gled), large-leaved lime tree (*Tilia platyphyllos* Scop.), chestnut-leaved oak (*Quercus castaneifolia* C.A.M.), mountain elm (*Ulmus glabra* Huds.), and Caucasian alder (*Alnus subcordata* C.A. Mey). The silvicultural treatment applied in the study area was a combination of single-tree selection and group selection, resulting in uneven-aged stands. More general information of the experiments is given in Table 1. Motor-manual felling and processing (i.e., using chainsaws) were carried out at the felling site. The skidding machinery (Timberjack 450 C) was equipped with winch cables and was used to extract logs with a length of 5–15 m from the forest area to the landings. The Timberjack skidder is an articulated four-wheel drive vehicle with a weight of 10.3 tons (total weight with equipment) and an engine power of 177 hp. The front and rear axles in this machine are 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.

Table 1. Location and specifications of the study area.

Age of Skid Trail (years)	Replication	District (No. of Compartments)	Skid Trail Length (m)	Skid Trail Density (m ha^{-1})	Elevation (m)	Soil Texture
3	1st	Gorazbon (C. 315)	850	78.6	1186	Clay
	2nd	Gorazbon (C. 316)	1000	71.3	1214	Clay
	3rd	Gorazbon (C. 316)	900	71.3	1191	Silty clay loam
10	1st	Gorazbon (C. 318)	930	65.8	1186	Clay loam
	2nd	Gorazbon (C. 317)	1050	84.8	1200	Silty clay loam
	3rd	Gorazbon (C. 317)	860	84.8	1090	Clay loam
20	1st	Namkhaneh (C. 221)	1000	53.8	1120	Silt loam
	2nd	Namkhaneh (C. 220)	985	51.3	1010	Clay loam
	3rd	Namkhaneh (C. 220)	800	51.3	1117	Clay

Table 1. *Cont.*

Age of Skid Trail (years)	Replication	District (No. of Compartments)	Skid Trail Length (m)	Skid Trail Density (m ha^{-1})	Elevation (m)	Soil Texture
25	1st	Namkhaneh (C. 218)	1040	74.5	1050	Clay
	2nd	Namkhaneh (C. 218)	980	74.5	1140	Silty clay loam
	3rd	Namkhaneh (C. 221)	950	53.8	1020	Clay

2.2. Experimental Design

In this study, the long-term natural recovery of soil physical parameters (dry bulk density, total porosity, macroporosity, microporosity, penetration resistance, and soil moisture), chemical parameters (soil pH and Electrical conductivity (EC), C (%), N (%), C/N ratio, available P, K, Ca, and Mg), and biological parameters (earthworm density and biomass) on the surface soil layer of the skid trail was quantified at different levels of slope, traffic intensity, and soil depth and compared to the undisturbed area. Four abandoned skid trails with a downslope skidding direction that encompassed a wide range of longitudinal slope gradients (regardless of the lateral slope, area height, and soil texture and structure) in three replications at the forest level were selected for the study. The trails ranged from three years, through 10 years and 20 years, to 25 years since forest harvesting (Figure 1). A three-year-old skid trail instead of one-year-old skid trail was chosen because the study was conducted after the introduction of a prohibition of forest harvesting in the Hyrcanian forest, and the last trail on which the skidding operation was conducted was three years old. The average load volume and number of logs for each skidding cycle by the Timberjack skidder were 3.8 m^3 and 2, respectively. The motivation behind this research was to gain a retrospective view of the research conducted by Ezzati et al. [50] and Sohrabi et al. [27] in the Hyrcanian forest, who claimed that the recovery of soil physical properties can be lengthy. However, this research did not investigate the recovery of the chemical and biological properties of the soil in responses to soil compaction over the time, which is one of the most interesting ideas developed in the current research. On all the studied skid trails, the skidder only traveled on the skid trails at the time of skidding, and these skid trails were not used for timber extraction in later years. The entrances of skid trails were blocked by embankments after the timber extraction was completed. Felled trees were thick and high (dbh > 60 cm; height > 20 m), and were scattered around the skid trails (selection cutting silviculture), the logs from the bole of each felled tree formed a complete machine load (the logs of each felled tree were individually extracted in one skidding cycle). Due to the above conditions, the farther away from the landings the traffic intensity decreases (Figure 2A). The average length of skid trails in the study area was about 150 m, with the first 50 m (0–50 m) from the forest road considered as high traffic intensity (HST), the second 50 m (50–100 m) as medium traffic intensity (MST), and the third of 50 m (100–150 m) or subsidiary of the skid trail as low traffic intensity (LST) [35,36,50]. In the skid trails, three slope classes (0–10%, 10–20%, and 20–30%) were considered with regard to variations and maximum slope. Therefore, the research plots included three traffic-intensity classes and three slope-gradient classes, thus forming nine combinations of traffic frequency and trail gradients; each treatment combination was replicated three times at the forest level, totaling 27 treatment plots (N = 27 in each recovery period). On the skid trails, in each treatment (e.g., a combination of slope and traffic), sampling plots with the dimensions of 40 m^2 were designed. In each sampling plot, five sampling lines were designed at a distance of 2 m from each other and perpendicular to the skid trail, of which three lines were randomly selected for sampling. Soil samples were taken from a depth interval of 0–10 and 10–20 cm at three locations in each plot: (LW) the left wheel track, (BW) between the tracks, and (RW) the right wheel track (Figure 2B). To compare the soil properties between the skid trail and the undisturbed area, soil samples were taken inside the forest at least 20–30 m (the size of the average height of the dominant trees in the area) away from the skid trail, where the effects of the skidding operations on the soil completely disappeared (n = 81 in each recovery period). Ruts were measured on the skid trails at the site of the compaction measurement line, and ruts with a depth of 5 cm and a length of at least 2 m were considered to be caused by soil disturbance [57]. In each rut, at 25 mm horizontal intervals, depth was measured, and the mean was considered to be caused by soil disturbance. Obviously, the distance between the compaction and the rut sampling lines was not less than 2 m [58].

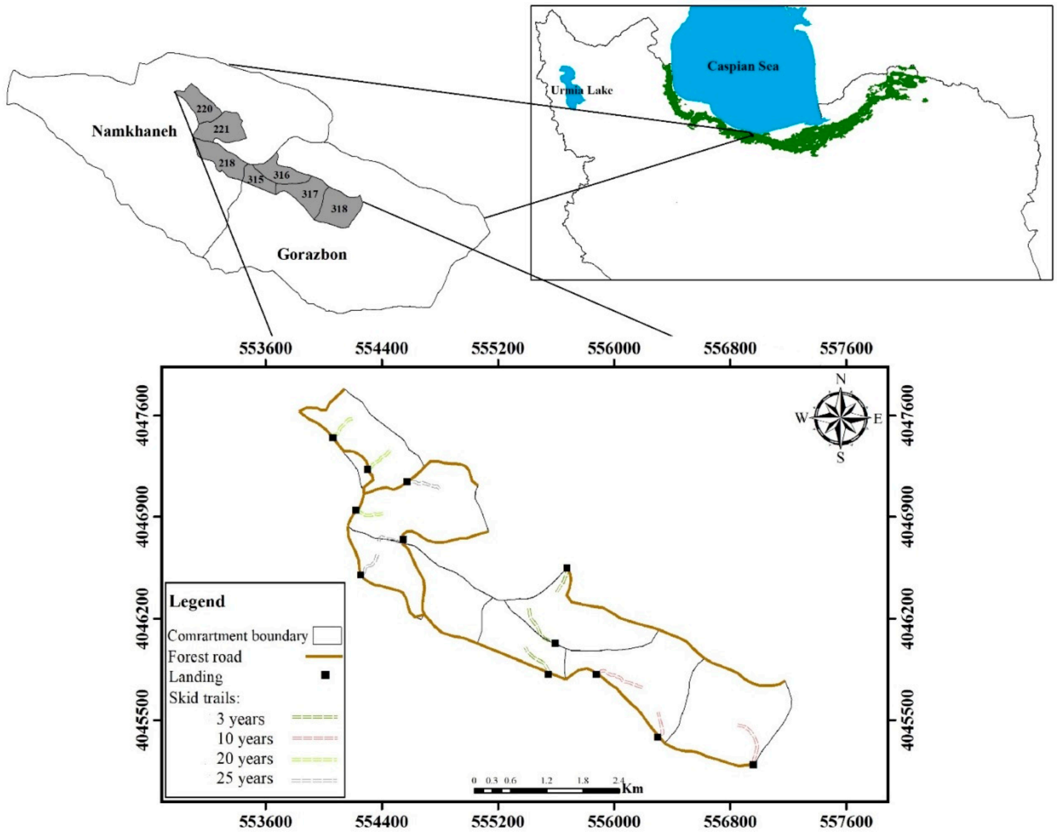

Figure 1. The study area in the Namkhaneh and Gorazbon districts in the Hyrcanian forests and the skid trails in different years after skidding operation (3, 10, 20, and 25 years).

2.3. Measurements and Laboratory Analysis

A steel ring (5 cm in diameter and 10 cm in height; 196.25 cm^3) was used to collect soil samples from depths of 0–10 and 10–20 cm. The soil samples were stored and coded in plastic bags. On the same sampling day, the wet weight of all samples was measured before transfer to the laboratory. In the laboratory, the soil samples were dried at 105 °C for 24 h to calculate the soil moisture content, dry bulk density, and porosity.

The bulk density and total porosity were calculated using Equations (1) and (2).

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

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).

$$\mathrm{TP} = 1 - \left(\frac{BD}{2.65}\right) \times 100 \quad (2)$$

where TP is the apparent total porosity (%), BD is the bulk density (g cm^{-3}), and 2.65 g cm^{-3} is the soil particle density [59].

Macroporosity and microporosity were calculated using Equations (3) and (4).

$$\mathrm{MIP} = \theta_m \times BD \quad (3)$$

where MIP is the microporosity (%), BD is the dry bulk density (g cm^{-3}), and θ_m is the water content on a mass basis (%).

$$MP = TP - MIP \quad (4)$$

where MP is the macroporosity (%), TP is the total porosity (%), and MIP is the microporosity (%).

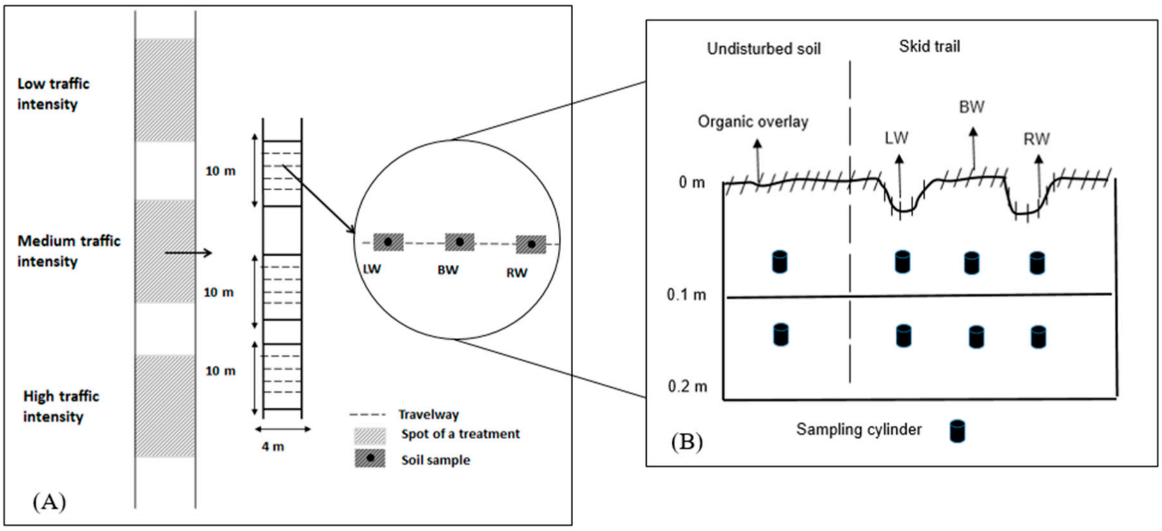

Figure 2. A sketch of the sampling design in the skid trails and the undisturbed area. (**A**): Each skid trail was divided into three traffic intensities (high, medium, and low traffic intensity), and in each traffic class three slope classes were considered (0–10%, 10–20%, and 20–30%). The sampling plots were designed with dimensions of 40 m^2 in each of the skid trail treatments, along with the sampling plots in the undisturbed area and the soil sampling point at depth intervals of 0–10 and 10–20 cm at the three locations in each plot (**B**): the left wheel track (LW), between the tracks (BW), and the right wheel track (RW).

The hydrometric method was used to determine the soil texture, whereas the determination of soil penetration resistance was made with a hand-held soil penetrometer (Eijkelkamp 06.01.SA penetrometer with a 60° cone and a 1 m maximum measuring depth) that was inserted vertically into the soil with equal pressure at the location of each sample. Since soil moisture influences the measurement of penetration resistance, all measurements were performed under similar conditions.

In order to measure the soil chemical properties, samples were taken from the mineral soil layer. Therefore, soil samples were air-dried and soil particles <2 mm were used for the experiments. The Orion Ionalyzer (Model 901, Cambridge, MA, USA) pH meter was used to measure soil pH in a soil/water ratio of 1:2.5. Electrical conductivity (EC) was determined using an Orion Ionalyzer EC meter in a 1:2.5 soil/water solution. The Walkley–Black procedure [60] was used to determine the organic carbon (OC) content in percentage, and the Kjeldahl method was used to measure total N [61]. The Olsen method was used by utilizing a spectrophotometer to determine the available phosphorus (P) of the soil, and an atomic absorption spectrophotometer (by ammonium acetate extraction at pH 9) was used to determine available potassium (K), calcium (Ca), and magnesium (Mg) of the soil [62]. To determine the earthworm density and biomass, sample plots of 25 × 25 cm were designed on the sampling lines and the number of earthworms were counted at soil depths of 0–10 and 10–20 cm. After collection, the earthworms were washed and weighed, and then to determine the dry weight, earthworms were dried for 24 h at 60 °C [62].

2.4. Statistical Analyses

Statistical analyses were performed using SPSS version 17 (Chicago, IL, USA) software. As a first step, data distribution was plotted and checked for normality (Kolmogorov–Smirnov) and homogeneity of variance (Levene test). One-way and two-way ANOVAs were used to assess the significance of the observed mean differences in the physical, chemical, and biological properties of the soil under different skidder traffic levels, trail gradients, wheel track locations, soil depths, and their interactions. The comparison between the physical, chemical, and biological properties of the soil was made by using one-way ANOVA (p-level $\alpha \leq 0.05$) and Duncan's multiple range tests. The relationships between soil properties were determined using Pearson correlation. Significant relationships between variables and principal components were determined by using principal component analysis (PCA) via the PC-ORD (Version 4, WILD BLUEBERRY MEDIA LLC, Corvallis, OR, USA) software.

3. Results

3.1. Physical Properties of the Soil

The age of a skid trail and the sampling depth treatments had a significant effect on all the physical properties of the soil. Different traffic intensities had a significant effect on BD, PR, and total porosity (TP), while having no significant effect on the other properties. Different slopes had no significant effect on the physical properties (except PR and TP), nor did wheel track location (except PR) or the interaction of treatments (Table 2).

Table 2. Analysis of variance (p-values) of the effect of abandoned skid trails, traffic intensity, slope, wheel track location, soil sampling depth, and their interactions on the physical properties of the soil.

Source of Variance	Age of Skid Trail		Traffic Intensity		Slope		Wheel Track		Depth		Interaction	
	d.f.	p-Value	d.f.	p-Value	d.f.	p-Value	d.f.	p-Value	d.f.	p-Value	d.f.	p-Value
BD (g cm^{-3})	3	0.000 **	2	0.000 **	2	0.418 ^{ns}	2	0.254 ^{ns}	1	0.000 **	24	0.63 ^{ns}
PR (MPa)	3	0.000 **	2	0.000 **	2	0.000 **	2	0.000 **	1	0.000 **	24	0.998 ^{ns}
TP (%)	3	0.000 **	2	0.000 **	2	0.041 *	2	0.224 ^{ns}	1	0.005 **	24	0.993 ^{ns}
MP (%)	3	0.000 **	2	0.546 ^{ns}	2	0.305 ^{ns}	2	0.350 ^{ns}	1	0.000 **	24	0.998 ^{ns}
MIP (%)	3	0.000 **	2	0.549 ^{ns}	2	0.481 ^{ns}	2	0.783 ^{ns}	1	0.000 **	24	0.999 ^{ns}
SM (%)	3	0.000 **	2	0.549 ^{ns}	2	0.481 ^{ns}	2	0.783 ^{ns}	1	0.000 **	24	0.999 ^{ns}

Note: * $p < 0.05$; ** $p < 0.01$; ^{ns} not significant; BD, bulk density, PR, penetration resistance; TP, total porosity; MP, macroporosity; MIP, microporosity; SM, soil moisture; df, degrees of freedom.

Changes in the physical properties of the soil showed that soil properties recover within different years of skidding activities (Table 3). From the three-year-old skid trail to the 25-year-old skid trail, the BD, PR, and MIP decreased. In contrast, the TP, MP, and SM increased and differed significantly from the undisturbed area. Three years after the skidding operation, the BD, PR, and MIP were 12.6%, 107%, and 69.51% higher than the undisturbed area, respectively. Meanwhile, 25 years after the skidding operations, they were 8.4%, 27.4%, and 50.44% higher than the undisturbed area, respectively. Furthermore, three years after the skidding operation, the TP, MP, and SM were 2.47%, 23.3%, and 10.23% lower than the undisturbed area, respectively. Meanwhile, 25 years after the logging operations, they were 1.96%, 17.1%, and 4.58% lower than the undisturbed area, respectively (Table 3).

The investigation of the rut depth under different traffic intensities showed an increasing trend with the increase of traffic intensity in the skid trails (Figure 3). The rut depth in all the skid trails (except the 25-year-old skid trail) was significantly different for all three traffic intensities. The rut depth improved over the years following the skidding operation, so that by 25 years after the skidding operation, low and medium traffic intensity was fully recovered. The highest rut depth was observed in the three-year-old skid trail under high traffic intensity, with the amount of 20.1 cm, while the lowest was observed in the 25-year-old skid trail under high traffic intensity, with the amount of 5.3 cm (Figure 3). The results of this study show that the rut depth recovered in less time than other physical properties of the soil.

Table 3. Changes in the physical properties of the soil (mean ± standard error) in different years after the skidding operation.

	Different Years After the Skidding Operation (Years)				
Soil Physical Properties	**3**	**10**	**20**	**25**	**Un**
BD (g cm^{-3})	1.07 ± 0.01 ^{a}	1.12 ± 0.01 ^{b}	1.05 ± 0.01 ^{a}	1.03 ± 0.01 ^{a}	0.95 ± 0.03 ^{c}
PR (MPa)	3.25 ± 0.06 ^{a}	3.04 ± 0.04 ^{b}	2.90 ± 0.04 ^{b}	2.0 ± 0.04 ^{c}	1.57 ± 0.12 ^{d}
TP (%)	84.03 ± 0.23 ^{b}	83.0 ± 0.15 ^{c}	84.04 ± 0.15 ^{b}	84.47 ± 0.15 ^{ab}	86.16 ± 0.48 ^{a}
MP (%)	51.23 ± 0.57 ^{c}	52.66 ± 0.38 ^{c}	53.14 ± 0.38 ^{b}	55.36 ± 0.38 ^{b}	66.78 ± 0.19 ^{a}
MIP (%)	32.8 ± 0.63 ^{a}	30.34 ± 0.42 ^{a}	30.9 ± 0.42 ^{b}	29.11 ± 0.42 ^{b}	19.38 ± 1.3 ^{c}
SM (%)	40.2 ± 1.24 ^{c}	41.2 ± 0.82 ^{b}	41.76 ± 0.82 ^{b}	42.73 ± 0.82 ^{b}	44.78 ± 2.58 ^{a}

Note: Different letters in a row indicate significant differences among the intensities of the physical properties of the soil ($p < 0.05$), based on the Duncan's multiple range tests. The values 3, 10, 20, and 25 denote the age of the skid trails; Un, undisturbed area; BD, bulk density; PR, penetration resistance; TP, total porosity; MP, macroporosity; MIP, microporosity; SM, soil moisture.

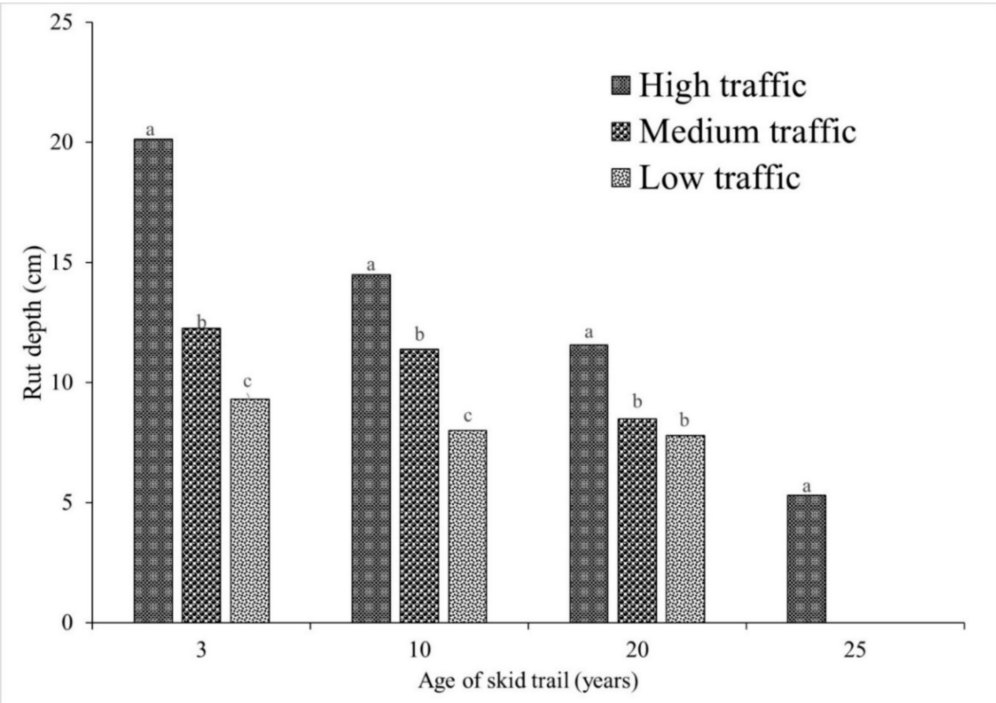

Figure 3. Average rut depth under different traffic intensities in different skid trail age classes, and results of the Duncan's multiple range tests.

3.2. The Chemical and Biological Properties of the Soil

The effect of the age of the skid trail and traffic intensity on all chemical properties was significant, while it was not significant on biological properties (Table 4). The slope of the skid trail had a significant effect on chemical properties (except C), while it had no significant effect on biological properties. The wheel track location had a significant effect on the pH and EC of the chemical properties. It also had a significant effect on biological properties at the 0.01% level. Furthermore, the soil depth has a significant effect on the chemical (except C) and biological properties. However, the interaction effects of treatments on the chemical (except EC and C/N ratio) and biological properties were not significant (Table 4).

Over the years following the skidding operation, the chemical and biological soil properties improved from the three-year-old skid trail to the 25-year-old skid trail (Table 5). Twenty-five years after the skidding operation, the values of pH, EC, C%, N%, available P, K, Ca, and Mg, earthworm density, and biomass soil were 6.4%, 20%, 22.77%, 38.8%, 11.2%, 14.2%, 10.3%, 15.1%, 28.3%, and 30.5% lower than the control area, respectively, and value of the C/N ratio was 26.2% higher than the control area (Table 5). The chemical and biological properties of the soil were significantly different from the control area 25 years after the skidding operation (Table 5).

Table 4. Analysis of variance (*p*-values) of the effect of abandoned skid trail, traffic intensity, slope, wheel track location, soil sampling depth, and their interaction on the chemical and biological properties of the soil.

Source of Variance	Age of Skid Trail		Traffic Intensity		Slope		Wheel Track		Depth		Interaction	
	d.f.	*p*-Value	d.f.	*p*-Value	d.f.	*p*-Value	d.f.	*p*-Value	d.f.	*p*-Value	d.f.	*p*-Value
pH (1:2.5 H_2O)	3	0.000 **	2	0.000 **	2	0.000 **	2	0.000 **	1	0.000 **	24	0.690 ^{ns}
EC (ds/m)	3	0.000 **	2	0.000 **	2	0.000 **	2	0.000 **	1	0.000 **	24	0.000 **
C (%)	3	0.000 **	2	0.000 **	2	0.107 ^{ns}	2	0.999 ^{ns}	1	0.722 ^{ns}	24	1.000 ^{ns}
N (%)	3	0.000 **	2	0.000 **	2	0.000 **	2	0.361 ^{ns}	1	0.000 **	24	1.000 ^{ns}
C/N ratio	3	0.000 **	2	0.000 **	2	0.000 **	2	0.302 ^{ns}	1	0.000 **	24	0.035 *
Available P (mg kg^{-1})	3	0.000 **	2	0.000 **	2	0.000 **	2	0.513 ^{ns}	1	0.006 **	24	1.000 ^{ns}
Available K (mg kg^{-1})	3	0.000 **	2	0.000 **	2	0.000 **	2	0.694 ^{ns}	1	0.020 *	24	1.000 ^{ns}
Available Ca (mg kg^{-1})	3	0.000 **	2	0.000 **	2	0.000 **	2	0.256 ^{ns}	1	0.000 **	24	1.000 ^{ns}
Available Mg (mg kg^{-1})	3	0.000 **	2	0.000 **	2	0.001 **	2	0.813 ^{ns}	1	0.050 *	24	1.000 ^{ns}
Earthworm density (n m^{-2})	3	0.199 ^{ns}	2	0.422 ^{ns}	2	0.090 ^{ns}	2	0.001 **	1	0.019 *	24	0.652 ^{ns}
Earthworm biomass (mg m^{-2})	3	0.215 ^{ns}	2	0.429 ^{ns}	2	0.115 ^{ns}	2	0.002 **	1	0.030 *	24	0.687 ^{ns}

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

Table 5. Changes in the chemical and biological properties of the soil (mean ± standard error) in different years after the skidding operation.

Soil Chemical and Biological Properties	Different Years after the Skidding Operation (Years): 3	10	20	25	Un
pH (1:2.5 H_2O)	5.96 ± 0.04 ^{c}	6.07 ± 0.04 ^{c}	6.32 ± 0.04 ^{b}	6.59 ± 0.04 ^{b}	7.04 ± 0.07 ^{a}
EC (ds/m)	0.26 ± 0.19 ^{c}	0.26 ± 0.19 ^{c}	0.29 ± 0.19 ^{b}	0.32 ± 0.19 ^{b}	0.4 ± 0.35 ^{a}
C (%)	2.31 ± 0.05 ^{d}	2.78 ± 0.05 ^{c}	2.9 ± 0.05 ^{c}	3.12 ± 0.05 ^{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 ^{b}	8.05 ± 0.07 ^{c}	7.61 ± 0.07 ^{d}	6.03 ± 0.13 ^{d}
Available P (mg kg^{-1})	9.59 ± 0.05 ^{d}	12.01 ± 0.05 ^{c}	14.49 ± 0.05 ^{bc}	17.11 ± 0.05 ^{b}	19.28 ± 0.09 ^{a}
Available K (mg kg^{-1})	138.1 ± 1.08 ^{d}	187.8 ± 1.08 ^{cd}	238.4 ± 1.08 ^{c}	275.7 ± 1.08 ^{b}	321.49 ± 2.03 ^{a}
Available Ca (mg kg^{-1})	105.7 ± 0.39 ^{d}	137.1 ± 0.39 ^{c}	176.6 ± 0.39 ^{c}	214.3 ± 0.39 ^{b}	239.05 ± 0.75 ^{a}
Available Mg (mg kg^{-1})	28.85 ± 0.23 ^{d}	37.23 ± 0.23 ^{c}	44.27 ± 0.23 ^{bc}	51.94 ± 0.23 ^{b}	61.18 ± 0.43 ^{a}
Earthworm density (n m^{-2})	0.22 ± 0.07 ^{d}	0.33 ± 0.07 ^{c}	0.41 ± 0.07 ^{b}	0.48 ± 0.07 ^{b}	0.67 ± 0.14 ^{a}
Earthworm biomass (mg m^{-2})	0.94 ± 0.31 ^{d}	1.41 ± 0.31 ^{c}	1.71 ± 0.31 ^{bc}	2.05 ± 0.31 ^{b}	2.95 ± 0.59 ^{a}

Note: Different letters in a row indicate significant differences among the intensities of the physical properties of the soil ($p < 0.05$), based on Duncan's multiple range tests. The values 3, 10, 20, and 25, denote the age of the skid trails; Un, undisturbed area.

Changes in the earthworm number and biomass under different traffic intensities and soil depths were lower at depths of 10–20 cm than depths of 0–10 cm, and lower under high rather than medium and low traffic intensities (Figure 4). The lowest earthworm number and biomass were obtained under high traffic intensity at soil depths of 10–20 cm. The earthworm number and biomass under different traffic intensities in both depths of soil were lower than the undisturbed area and were significantly different (Figure 4).

3.3. Principal Component Analysis (PCA)

The different traffic intensities (high, medium, and low) and different slopes (0–10%, 10–20%, and 20–30%) in the skid trails and the physical, chemical, and biological properties of the PCA analysis are presented in Figures 5 and 6. The PCA results show the relation between traffic intensity in the skid trails and the soil properties and reveal that the first and second axes explain 76.98% and 14.63% of the total variance, respectively (Figure 5). The PCA analysis results for the relationship between the different slopes in the skid trails and the soil properties show that the first and second axes explain 74.34% and 13.91% of the total variance, respectively (Figure 6). The analysis of the traffic intensity and the slope of the skid trails three and 25 years after the skidding operation show that as these two treatments increase, the effect on the soil increases. The results also show that high traffic intensity (H3) and slope classes of 20–30% (C3) in three-year-old skid trails had the greatest impact on soil properties (according to maximum distance from the coordinate center and proximity to axis 1) (Figures 5 and 6). The PCA analysis shows that 25-year-old skid trails under different traffic intensities and slopes had the least impact on soil properties (according to proximity to the coordinate center and away from the axis 1). The TP, MP, MIP, SM, and pH were close to the center axis, indicating that the effect of traffic and slope treatments was lower on these properties. However, the effects of these treatments on other physical, chemical, and biological properties were greater due to the distance from the coordinate center. The location of treatments affecting soil variables indicates that the undisturbed area is on the left side of the graph (Figures 5 and 6). The undisturbed area is slightly different, with older trails in low traffic and slope classes, whereas younger trails have high traffic and slope classes.

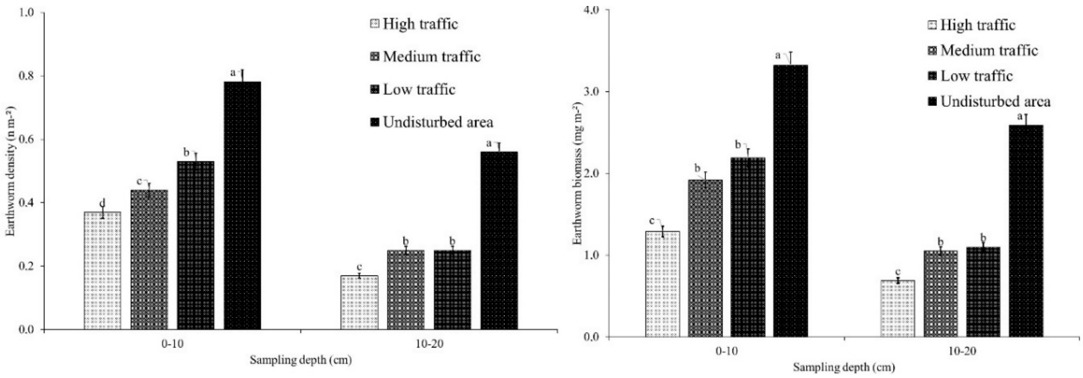

Figure 4. Changes in earthworm density (left) and biomass (right) under different traffic intensities in the two soil depths.

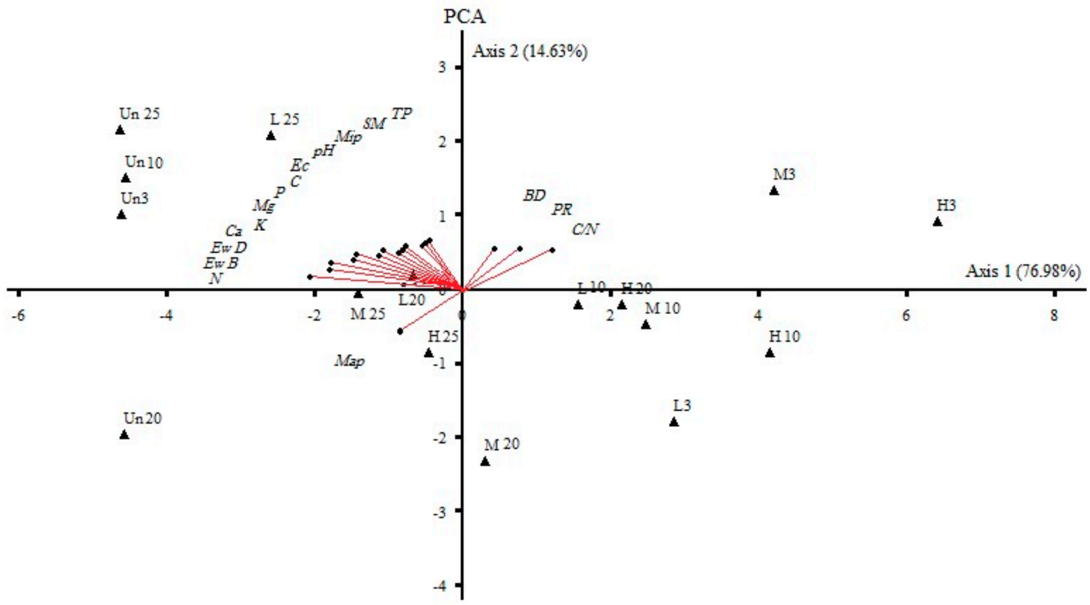

Figure 5. Principal component analysis (PCA) ordination of the traffic intensity in skid trails (3, 10, 20, and 25, age of the skid trails; H, M, L, and Un, high, medium, and low traffic intensity and undisturbed area, respectively), and soil physical (BD, bulk density; TP, total porosity; MP, macroporosity; MIP, microporosity; PR, penetration resistance; SM, soil moisture), chemical (pH; EC, electrical conductivity; C, organic C; N, nitrogen content; C/N, C/N ratio; P, available phosphorous; K, available potassium; Ca, available calcium; Mg, available magnesium), and biological (Ew D, earthworm density; Ew B, earthworm biomass) properties.

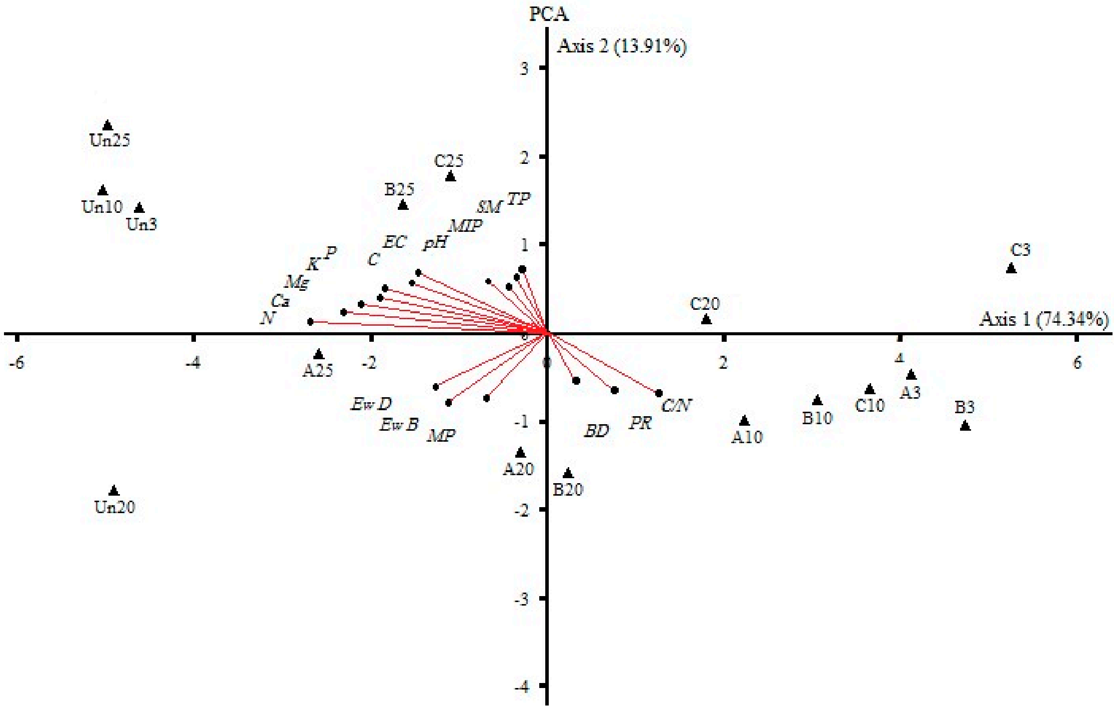

Figure 6. PCA ordination of the slope classes in the skid trails (3, 10, 20, and 25, age of the skid trails; A, B, C, and Un, 0–10%, 10–20%, and 20–30% slope classes and undisturbed area, respectively), and soil physical (BD, bulk density; TP, total porosity; MP, macroporosity; MIP, microporosity; PR, penetration resistance; SM, soil moisture), chemical (pH; EC, electrical conductivity; C, organic C; N, nitrogen content; C/N, C/N ratio; P, available phosphorous; K, available potassium; Ca, available calcium; Mg, available magnesium), and biological (Ew D, earthworm density; Ew B, earthworm biomass) properties.

The traffic intensity of three-year-old skid trails (H3) was positively correlated with BD (r = 0.92), PR (r = 0.95), and C/N ratio (r = 0.84), while it was negatively correlated with the other soil properties (Table 6). Also, the slope classes of three-year-old skid trails was positively correlated with BD (r = 0.83), PR (r = 0.93), and C/N ratio (r = 0.67), while it was negatively correlated with the other soil properties (Table 6).

Table 6. Pearson correlation coefficients between the soil properties and the effective treatments on soil (traffic intensity and slope classes of three-year-old skid trails).

Variable		Traffic Intensity		Slope Classes	
		Pearson Correlation (R)	*p*-Value	Pearson Correlation (R)	*p*-Value
Soil physical properties	BD	0.92 **	0.000	0.83 **	0.000
	PR	0.95 **	0.000	0.93 **	0.000
	TP	–0.76 **	0.000	–0.91 **	0.000
	MP	–0.52 *	0.021	–0.99 **	0.000
	MIP	–0.51 *	0.015	–0.58 *	0.020
	SM	–0.52 *	0.015	–0.58 *	0.020
Soil chemical properties	pH	–0.98 **	0.000	–0.98 **	0.000
	EC	–0.94 **	0.000	–0.95 **	0.000
	C	–0.97 **	0.000	–0.98 **	0.000
	N	–0.98 **	0.000	–0.98 **	0.000
	C/N	0.84 **	0.000	0.67 **	0.000

Table 6. *Cont.*

Variable		Traffic Intensity		Slope Classes	
		Pearson Correlation (R)	*p*-Value	Pearson Correlation (R)	*p*-Value
Soil chemical properties	Available P	−0.98 **	0.000	−0.98 **	0.000
	Available K	−0.98 **	0.000	−0.98 **	0.000
	Available Ca	−0.98 **	0.000	−0.97 **	0.000
	Available Mg	−0.99 **	0.000	−0.98 **	0.000
Soil biological properties	Ew D	−0.96 **	0.000	−0.88 **	0.000
	Ew B	−0.96 **	0.000	−0.90 **	0.000

** A significant difference at the 0.01% level. * A significant difference at the 0.05% level. BD, bulk density; TP, total porosity; MP, macroporosity; MIP, microporosity; PR, penetration resistance; SM, soil moisture; EC, electrical conductivity; C, organic C; N, nitrogen content; C/N, C/N ratio; P, available phosphorous; K, available potassium; Ca, available calcium; Mg, available magnesium; Ew D, earthworm density; Ew B, earthworm biomass.

4. Discussion

A comprehensive review of the natural recovery of the physical, chemical, and biological properties of the soil after skidding operations can complement the previous research chain and can be a guide to reducing the detrimental effects of skidding operations on forest soil and acquiring new knowledge on the sustainability of forest operations. In the past, there have been many studies conducted on the effects of skidding operations on soil of skid trails in controlled conditions. It is important to specify that the present research is retrospective, and the statistics and information obtained from the skidding operation were descriptive. Further experiments and sampling were performed on the desired trails and compared with the control area to evaluate the soil recovery process after skidding operations and to validate the descriptive data. Our study confirms that the effects of the age of the skid trail, traffic intensity, and sampling depth are more than those of other treatments. In this study, the slope of the skid trail changed the physical properties of the soil but had no significant effect due to the slope being divided into classes with less variation range (0–10%, 10–20%, and 20–30%). There appears to be a threshold to the slope gradient that has to be surpassed, however, before slope effects become visible [36]. Similarly, Najafi et al. [35] observed that the disturbance in soil physical properties was not significant in the slope classes of 0–10% and 10–20%, whereas for slopes of more than 20%, soil disturbance was significantly increased.

The change in the physical properties of the soil under the influence of skidding has been confirmed by other researchers, including Tavankar et al. [63], Ezzati et al. [50], Jourgholami at al. [32], Picchio et al. [9], and Sohrabi et al. [27]. The highest soil changes were obtained for high traffic intensity and slope, three years after the skidding operation. Further soil changes under high traffic intensity may be due to the high soil moisture during the skidding operation, the output timber volume of the area, and the number of passes. Skidding operations on steep terrain cause severe wheel slips of the machine, resulting in more puddling and dragging of the soil [44,64]. In addition, the slower speed of a machine on steeper terrain, especially upward skidding, causes more vibration of the surface soil and is disturbed more severely than compared to flat terrain [65]. With an increasing number of passes on steep terrain, the proportion of microporosity to macroporosity increases, and previous studies have confirmed this result [44,66]. During the skidding operation, the pores in the soil surface layer are compressed, which increases the soil strength, thereby reducing and changing the soil pores. The Soil moisture content decreases with the increasing traffic intensity and slope of the skid trail, so that the lowest moisture content is obtained under high traffic intensity and for a slope of 20–30%. The decrease in soil moisture is mainly due to a decrease in total porosity and macroporosity and an increase in the bulk density at the surface and in the soil profile [10,35,50].

Over the years after the skidding operation, the soil physical properties improve from the three-year-old trail to the 25-year-old trail, although there are significant differences with the control area. The results show that 25 years after the skidding operations, the BD, PR, and MIP were 8.4%, 27.4%, and 50.44% greater, respectively, and the TP, MP, and SM, which were 1.96%, 17.1%, and 4.58% lower than the undisturbed area, respectively. The results of this study are consistent with the results of the study by Ezzati et al. [50], which reported that, 20 years after skidding operations, under high traffic intensity and gentle slope class (<20%), the bulk density was 35–42% higher and the total porosity and macroporosity were 18–24% and 19–28% lower than the undisturbed area, respectively. After 25 years of skidding, the BD was lower than the threshold value of 1.40–1.55 g/cm^{-3} [38], indicating a recovery process for this feature. According to the findings of Ampoorter et al. [67], increasing the PR to more than 2 MPa limits the infiltration and growth of root trees in soil types. In this study, 25 years after skidding, the PR was less than 2 MPa, which indicates its recovery over time. One important effect of soil compaction is a decrease in total porosity by a decrease in macroporosity and an increase in microporosity [50]. The increase in the proportion of TP and MP over 25 years after the skidding operation is not unexpected. The MP in this study exceeded the threshold value of 10% [22], which is a prerequisite for airflow, microbial activity, and rooting. The soil moisture content increased in different years after skidding operation from the three-year-old trail to 25-year-old trail, which may be due to the reduced soil compaction and increased litter layer of the soil surface for water infiltration, as well as the reduced surface runoff through more pores in the soil [67].

The creation of soil ruts contributed to the increase in traffic intensity in this study, which was also reported by Botta [68], Eliasson [69], and Ezzati et al. [50]. When the soil moisture is saturated and soil cavities are filled with water, the skidding operation removes the surface layers of the soil and thus creates deep ruts in the soil. Soil ruts are more specified in the immediate years after skidding and high traffic intensity, leading to the disruption of natural drainage structures and reduced stability and soil aggregation. The tire size and average pressure on the soil are other effective factors in creating a rut in the soil during the skidding operation [50]. The rut depth improves in different years after the skidding operation, so that 25 years after the skidding operation, under low and medium traffic intensity, the soil is fully recovered. Consistent with the current study, Hatchel et al. [70] stated that rut recovery created after skidding operations requires a period of 18–19 years. The results of this study show that rut depth recovery requires less time than other physical properties of the soil.

Our study indicates that the effects of the treatments on the chemical properties were more intense than on the physical properties, which may be due to the mixing of the surface soil with the lower layers, the removal of soil, and soil sampling from the deep layers when compared to the undisturbed area [36]. On the other hand, the puddling and dragging of the soil of the skid trail after the skidding operation causes erosion and the loss of soil nutrients, which ultimately results in prolonged recovery for soil chemical properties. Changes in soil chemical properties under the influence of skidding operations have also been confirmed in previous studies [17,36,71].

In this study, the changes (decrease) in organic matter content and in different slopes and under different traffic intensities of the skidding trails compared to the control area are due to low levels of litter layer at the soil surface. Cutting down trees along the skidding trails for easier logging operation results in reduced tree density and, consequently, in reduced the litter layer of the forest floor [10,28,35,70]. C and N in soil have a close relationship with each other, in which, in this study, the trend changes were similar. A decrease in C and N levels after the skidding operations can be due to the displacement and mixing of organic and mineral soils, as well as the appearance of deep soil layers following the skidding operations [36]. The skidding operations reduce soil acidity on different slopes and under different traffic intensities of the skid trails compared to the undisturbed area. Consistent with the results of the current study, Hosseini et al. [71] reported that soil acidity on skid trails was lower than in undisturbed areas in the Hyrcanian forest. Soil compaction, disturbance, surface runoff, and soil erosion caused by skidder traffic are the main reasons for these changes [51]. Therefore, based on this hypothesis, the soil C, N, P, K, and pH concentrations in skid trails are significantly lower than in control areas [17,36]. The decrease in soil organic matter content and available P, K, Ca, and Mg, in soil after the skidding operations was reported in this study and in other studies [17,36,72,73].

The results show that soil chemical properties are not fully recovered after 25 years following skidding operations; thus, the difference compared to the undisturbed area is significant. The chemical soil properties improved over the years following the skidding operations. Accordingly, Hosseini et al. [69] reported that seven years after skidding operations in the Hyrcanian forest, the chemical properties of the soil were recovered and had no significant difference compared to the undisturbed area. The improvement of soil chemical properties can be due to climatic conditions, a decrease in bulk density over time, the litter layer thickness, the type and quality of the litter layer, and the activity of soil organisms. Since there is a direct relationship between the chemical properties of the soil and the vegetation type and density and the amount of litter, changes in the forest floor cover and the soil organic layer have direct effects on the chemical properties. In line with the current results, Jourgholami et al. [74] reported that, by adding a litter layer to the soil surface, the chemical properties can be partially recovered.

The results show that the earthworm number and biomass under different traffic intensities of the skid trails was lower than in the undisturbed area; thus, these changes were higher under a high traffic intensity. The soil habitat had a lower quality in terms of coarse porosity, temperature and moisture, organic matter content, and vegetation under different traffic intensities compared to the undisturbed area. In addition, the earthworm number and biomass at a soil depth of 10–20 cm was lower than at a depth of 0–10 cm. Earthworm immobilization plays an important role in the reduction of earthworm number and biomass due to the increase in penetration resistance and the reduction of coarse pores at a depth of 10–20 cm. The soil habitat quality and earthworm mobility are two effective factors in the recovery of earthworm communities after skidding operations [24]. Twenty-five years after a skidding operation, soil biological properties in skid trails will be improved, and will be significantly different from the undisturbed area. The earthworm density (0.48 n m^{-2}) and biomass (2.05 mg m^{-2}) were higher in the 25-year-old skid trail than the 20- > 10- > 3-year-old skid trails. Furthermore, Jourgholami et al. [74] reported that by adding a litter layer of different trees (beech + hornbeam + velvet maple) to the skid trail soil, 5 years after skidding operations, an increase in earthworm density (1.02 n m^{-2}) and biomass (13.26 mg m^{-2}) can be observed, but this differs significantly from the undisturbed area. The lack of full recovery of earthworm number and biomass after 25 years may be due to unfavorable soil properties and a low litter layer. The litter layer increases the organic matter content and the decomposition rate of organic matter at the soil surface, which increases soil respiration by positively impacting the microbial communities of the soil [51,74–76]. Previous studies have shown that increasing organic matter decomposition rate, decreasing C/N ratio in organic layers, and fine soil texture all have a significant relationship with earthworm biomass [17,77,78].

5. Conclusions

From a sustainable forest operation perspective, forest operational planning must consider all possible factors affecting environmental impacts, as well as their interactions. The evaluation of the time required for soil recovery is essential for managing forests on the basis of SFO, particularly in ground-based logging systems. This study was designed to determine the effects of different levels of traffic intensity, slope gradient, soil depth, and wheel track on the physical, chemical, and biological properties of the soil on the soil recovery assessment after timber harvesting. We found increased BD, PR and MIP and decreased TP, MP, SM, in the chemical and biological properties of the soil following ground-based skidding compared to the undisturbed areas, particularly on steep slopes with high traffic intensity and a sampling depth greater than 0.1 m. Twenty-five years after the skidding operations, the physical, chemical, and biological properties of the soil were somewhat recovered in the skid trails, but remained significantly different to the undisturbed area. The outcomes of this study indicate that the recovery time of the chemical properties of the soil is longer than that of the biological and physical properties, and that the complete recovery of these properties takes more than 25 years. Accordingly, forest managers need to consider the potential impacts of skidding operations on soil disturbance. Therefore, due to the long recovery process of compacted soils, reducing the area covered by skidding trails, avoiding or limiting skidding trails on steep slopes, using appropriate machinery, designing exact and specified skidding trails, and cutting down trees in the correct direction are all essential to avoiding unnecessary traffic. On the other hand, the use of improvement treatments (different foliage mulch and tree planting(, and comparing their performance in terms of the recovery of the soil properties of skid trails, are essential in order to accelerate biological activities and natural regeneration, prevent soil water erosion, and regulate the water cycle. A careful use of machines and tools, a mindful choice of operating season and meteorological conditions, well thought out logging planning and practices, and the training and skill development of forest operators can mitigate the negative environmental impacts of forest operations. The "reevaluation of logging practices" and "logging development programs" should be developed as the main aims of SFO to reduce soil compaction during timber skidding and extraction.

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