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Impact Assessment of Skidding Extraction: Effects on Physical and Chemical Properties of Forest Soils and on Maple Seedling Growing along the Skid Trail

Ahmad Solgi [1,*], Ramin Naghdi [1], Enrico Marchi [2], Andrea Laschi [2], Farshad Keivan Behjou [3], Vahid Hemmati [4] and Ali Masumian [5]

1 Department of Forestry, Faculty of Natural Resources, University of Guilan, Guilan 1144, Iran; rnaghdi@guilan.ac.ir
2 Department of Agricultural, Food, Environmental and Forestry Science and Technology, University of Florence, 50145 Florence, Italy; enrico.marchi@unifi.it (E.M.); andrea.laschi@unifi.it (A.L.)
3 Department of Natural Resources, University of Mohaghegh Ardabili, Ardabil 5618913397, Iran; farshad.keivan@gmail.com
4 Islamic Azad University, Lahijan Branch 4135884818, Iran; vahidhemmatiliau@gmail.com
5 Faculty Member at University of Applied Science and Technology, Tehran 1193653471, Iran; masumian.class@gmail.com
* Correspondence: aforestsolgi@gmail.com; Tel.: +98-9189524316

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Abstract: Several studies investigated soil disturbances caused on skid trails by forest logging. However, there is still a lack of knowledge about the severity and the distance of disturbances along both sides from the trails. The aims of this study were: i) to investigate the changes in physical and chemical properties of soil along the sides of skidding trails; ii) to measure the effects of soil compaction on of maple seedlings growth. Two levels of trail gradient (<20% and >20%), four levels of traffic frequency (3, 8, 15, and 30 passes) and four distance buffer strip zones (0.5 m intervals from 0 to 2 m in distance) on both sides of skid trail edges were analyzed. Each treatment included three replicate plots. In order to investigate the effect of compaction on seedlings emergence and growth, maple seeds were sown after logging. The results highlighted significant changes in physical and chemical properties of soil for each traffic frequency in the closest buffer strip (from 0 to 0.5 m from the skid trail edges). The largest changes in soil properties were identified at 0.5 m distance zones for a slope gradient >20% after 3, 8, 15, and 30 skidding cycles. The highest changes were recorded on slope category >20%. The higher the soil compaction the lower the germination rate, root length, and stem height of seedlings.

Keywords: bulk density; skid trail edge; soil disturbance; traffic frequency; trail gradient

1. Introduction

Soil compaction, defined as a reduction in total soil porosity and increase in soil bulk density, can occur naturally or be induced by human activities. In the north mountainous forest of Iran, soil compaction caused by logging operation is a major environmental problem, especially when ground-based skidding is applied [1]. Rubber-tired skidders and crawler tractors have a negative impact on forest soils and represent one of the most important factors responsible for soil physical degradation [2–5].

Severe soil damage may seriously affect soil ecosystem functioning. Soil physical degradation leads to total soil porosity decline, mainly as a decrease in soil macroporosity (i.e., pores N 30 μm), pore connectivity reduction, and increased soil density and shear strength [6,7]. Soil compaction may result in reduced exchange of gasses with the atmosphere and movement of water, solutes, and gas through the soil, thus decreasing water, nutrient, and oxygen availability for the roots [8–10]. Reductions in air permeability and soil porosity reduce elongation and penetration of roots, and thus reduce root access to, and uptake of, water and nutrients [8,9,11]. The reduced development of root systems caused by soil compaction results in limited access to nutrients and water accompanied by lower photosynthetic rate [12]. A lower seedling establishment and survival and ultimately seedling growth and production was observed by Gebauer and Martinková [13], Naghdi et al. [1], and Cambi et al. [14] in compacted soils. However, the severity of these effects depends on soil type and tree species [15,16].

The main factors affecting extent and severity of soil compaction include the machine characteristics (e.g., axle load, type of traction device) [5], operating condition (e.g., traffic frequency, uphill or downhill extraction) [8,17,18] as well as climate, site, and soil characteristics and conditions [19,20].

In the last decade, several studies investigated the impact of different parameters on the extent and severity of soil compaction on skid trails [8,19,21–23], including strategies to reduce impacts [24], but a lack of knowledge about the effect of compaction on the side buffer strips of skid trails still exists. In detail, the available studies investigated only the effect of machine trafficking on soil physical properties at various distance from edge of skid trail [23,25], without investigating the effect on the tree growth. To our knowledge, there is a lack of investigation about the combined effects of traffic frequency and trail gradient on the growth and survival of tree seedlings at various distances from the edge of skid trail.

The aims of this study are: (i) to determine the effect of skidding operations on extent and severity of soil compaction in the given conditions (up to 10 cm depth of soil profile); (ii) to investigate how far from the skid trail edge there is a significant effect of skidding on soil physical and chemical (organic carbon, OC; nitrogen, N; phosphorus, P; potassium, K; and pH) parameters, taking into consideration a 2 m buffer strip at both sides of the skid trail; (iii) to investigate these changes under varying conditions of slope and traffic intensity; and (iv) to investigate the effect of compaction along skid trail sides on velvet maple (*Acer velutinum* Boiss) seedling emergence and growth.

2. Material and Methods

2.1. Site Description

The area of study was included in the Sorkhekolah forest, Mazandaran province, northern Iran (36°21′ N and 36°25′ N and 53°5′ E and 53°6′ E). The research was carried out in 2016, in the period between late March and early October, in a research area located at about 1500 m above sea level, characterized by a northerly aspect, an average annual rainfall of 1300 mm, and a mean annual temperature of 15 °C (lowest value in February). Skidding operations were carried out in March, when weather conditions were wet and the average gravimetric soil moisture content was 28%. The research area was included in a mixed stand composed by two main species, oriental beech (*Fagus orientalis* Lipsky) and hornbeam (*Carpinus betulus* L.). Before harvesting, canopy cover was 88%, average diameter at breast height was 34 cm, stand density was 185 trees/ha, and the average height was 22.3 m. Regarding soil, texture was determined as clay texture with a particle size distribution of 53 % clay (<0.002 mm size), 26% silt (0.002–0.05 mm), and 21% sand (0.05–2 mm) along the machine operating trail. These values were measured—before the passage of machines—using the Bouyoucos hydrometer method to a depth of 10 cm.

2.2. Forest Operations and Machine Specifications

The silvicultural treatment applied in the study area was a combination of single-tree selection and group selection. Motor-manual felling and processing (i.e., using chainsaws and axes that is still the most common technique applied in Iran) were carried out at the felling site. The obtained assortments were 3- to 4-m-long logs. The logs were then extracted to the roadside by a rubber-tired cable skidder—model 'Timberjack 450C'—without chains on tires (Figure 1; Table 1). Logs were extracted along skid trails previously identified on a maximum slope of 30 percent and never used before this forest operation. During the study, the maximum load was applied to the skidder.

Table 1. Main technical characteristics of the Timberjack 450 C skidder.

Specifications	Timberjack 450C
Weight (kg)	10,257
Number of wheels	4
Tire size (mm)	775 × 813
Ground pressure (kPa)	221
Engine power (hp)	177
Year of manufacture	1998
Manufacturing location	Canada

Figure 1. The Timberjack 450C used for skidding operations.

2.3. Experimental Design and Data Collection

The physical parameters used for determining the compaction level of the soil upper layer (0–10 cm depth) were dry bulk density, total porosity (TP), and macroporosity (MP). The changes in the chemical soil properties were quantified using OC, N, P, and K concentrations, and soil pH. All the values obtained along the tracks were compared with data collected in control areas chosen next to the tracks, to have the same forest conditions. After the analysis of soil, the effects on maple seedlings due to skidding—in terms of germination rate and//growth—was assessed.

A skid trail (4 m wide and 800 m long with upslope skidding direction) that encompassed a wide range of longitudinal slope gradients without lateral slope was selected for the study. On the identified skid trails a 4 × 2 factorial experimental design was applied, including three replicates of each treatment combination: skidder passes (4 classes) × slope (2 classes) × 3 replicates (= 24 experimental units). Based on the longitudinal profile of the skid trail, trail segments that ranged between 6–14% were classified as gentle slopes (≤20%), and those between 24–28% as steep slopes (>20%). Traffic frequencies of the loaded skidder were 3, 8, 15, and 30 round trips (i.e., one empty and one loaded passes). Taking into consideration the main aims of the study, we preferred to assess the effect of a high number of passes (i.e., 30) than the effect of one pass.

A total of 24 plots (10 m long by 4 m wide), were identified. The minimum distance between two following plots was at least 2 m, in order to avoid disturbances. In each plot, five sampling perpendicular lines were chosen. Three of the five lines were randomly selected and used for the measurement of the soil physical properties.

Soil samples from the 0–10 cm depth were collected at different locations: left wheel track (LT), right wheel track (RT), and at four distances on both sides of the skid trail (i.e., four buffer strips. The buffer strips (SB) were delimited as follow: 1. From 0.0 to 0.5 m from the wheel track (SB1); 2. From 0.5 to 1.0 m from the wheel track (SB2); 3. From 1.0 to 1.5 m from the wheel track (SB3); 4. From 1.5 to 2.0 m from the wheel track (SB4). In each buffer strip, the extent of compaction was studied using four points at equal distance locations (0.5, 1, 1.5, and 2 m intervals from the edge of skid trail). The paired value of LT and RT were used to determine average values for the skid trail (ST). The samples were collected after 3, 8, 15, and 30 skidding cycles.

The soil samples were collected with a soil hammer and rings (diameter 5 cm, length 10 cm) after litter removal. The samples were placed in polyethylene bags, labeled, and transported to the laboratory. On average 317 g were collected from the soil upper layer (depth of 0–10 cm).

A 0.5 m wide by 2 m long microplot was designed around each sampling point. In each microplot, 14 sowing points were identified through a grid pattern characterized by a distance of 0.3 m between each point. For each sowing point, one seed of velvet maple was planted at a depth of 2 cm. These seeds were harvested inside the research area, from an uneven-aged stand, in 2014, during the growing season (Figure 2).

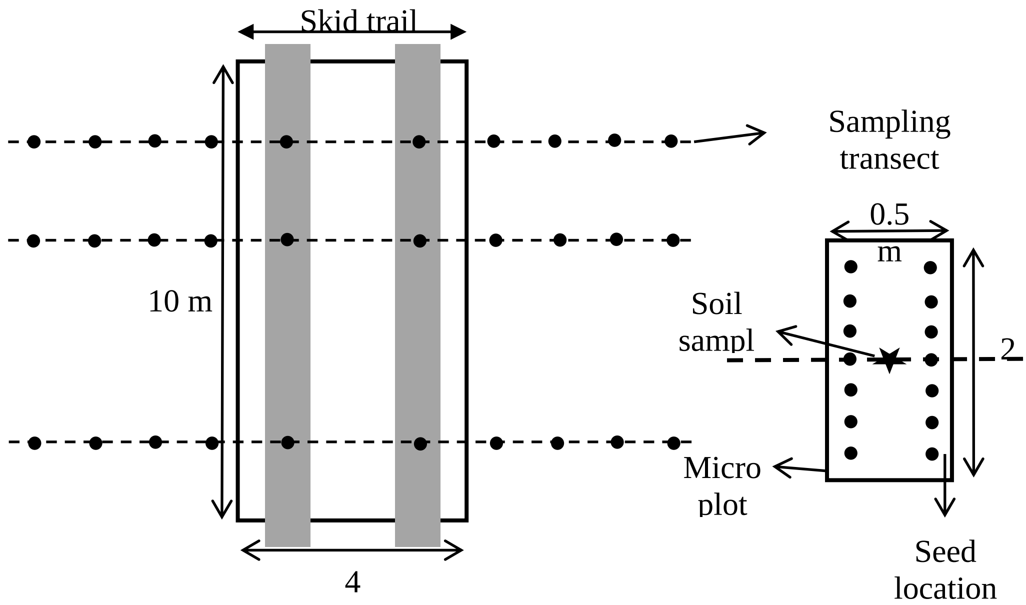

Figure 2. Schematic representation of both transect location along the trails and microplots.

As control area, where six plots and six microplots were made, an undisturbed zone 50 m far from the trails was chosen. The reason of this choice is to guarantee the undisturbance of the controls, placed at least at a distance of twice the tree height.

The study area was fenced to avoid deer and boar browsing. After sowing, manual weed control was applied within the plots to avoid any unwanted effect caused by vegetation competition pressure [26].

2.4. Laboratory Analysis

2.4.1. Soil Physical Properties

In the laboratory, soil bulk density (g cm^{-3}), soil porosity and soil moisture content were determined after oven-drying at 105 °C for 24 h.

The following Equation (1) was used to calculate total soil porosity (TP)

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

where

- TP is the total porosity in percentage;
- P_d is the dry bulk density (g cm^{-3});
- 2.65 g cm^{-3} is the particle density measured by a pycnometer on the same soil samples used to determine the bulk density [5].

The water description method was applied for determining macroporosity [27]. In this method, soil samples were saturated in plastic tubes and then weighed. The water level was slowly raised (over a period of five days) to prevent air entrapment. The samples were then drained for 3 h and weighed again [28,29]. Macroporosity was calculated as (2)

$$MP = \frac{W_s - W_{dr}}{V} \times 100 \quad (2)$$

where

- MP is macroporosity (%);
- W_s is saturated weight (g);
- W_{dr} is drained weight (g);
- V is the sample volume (cm^3).

2.4.2. Soil Chemical Properties

Chemical properties of soil were determined on ground and particles finer than 2 mm only, which were air-dried.

Particle size distribution was determined following the Bouyoucos hydrometer method [30], and soil acidity was measured using a pH meter with glass electrodes in 1/2.5 distilled water [31]. Walkley–Black procedure [32] was used to determine the organic carbon (OC) content in percentage, while nitrogen (N) was measured following the semi-micro-Kjeldahl method [31], phosphorus (P) following [33] no. 1 method with a spectrophotometer, and potassium (K) following the ammonium acetate method [31] using a flame photometer.

2.4.3. Seedling Emergence and Growth

Seedlings emergence and root and stem growth were assessed in early October 2016 (180 days after seeding in late March 2016). Several variables were monitored: (1) germination rate; (2) stem height, and (3) root length (the length of main root) at the end of the study.

2.5. Statistical Analysis

SPSS 11.5 statistical package [34] was used for statistical analyses, after the application of Kolmogorov–Smirnov test to check normality and Levene test to check homogeneity of variance.

Differences in chemical and physical properties of soil, as well as seedling parameters, were assessed through one-way and two-way ANOVAs, considering different skidder traffic levels, trail gradients, and related interactions. The comparison between soil properties and seedling parameters was made by one-way ANOVA (p-level $\alpha \leq 0.05$) and Tukey's HSD test.

3. Results

3.1. Soil Physical Properties

The average value of dry BD in undisturbed soil was 0.78 g cm^{-3} (ranging from 0.74 and 0.82) and did not differ significantly among slope gradients. After skidding, dry BD significantly increased due to traffic intensity, slope gradient, and distance from skid trail, showing a significant interaction between slope gradient × distance from skid trail and traffic intensity × distance from skid trail. The maximum value of BD was reached on the skid trail with a gradient higher than 20% after 30 passes. On the skid trail buffer strips the higher the distance from the wheel ruts, the lower the BD. In the four SBs, the greatest value of BD was found SB1 after 30 skidding passes on slope class >20 % (Table 2). At each number of skidding cycles, the lowest compaction occurred on the slope gradient treatments <20% in all SBs. The higher the number of passes the higher the BD increase (Table 3). On slope <20%, significant statistical differences were recorded only between control and ST after 3 and 8 passes, between control and both ST and SB1 after 15 passes and between control and ST, SB1, and SB2 after 30 passes. On slope >20%, significant statistical differences were recorded only between control and ST after 3 passes; between control and both ST and SB1 after 8 passes; control and ST, SB1, and SB2 after 15 passes; and between control and ST, SB1, SB2, and SB3 after 30 passes.

Table 2. Effect of traffic and slope on mean values of bulk density (g cm^{-3}) at various distances from skid trail edge. ST: skid trail. Different letters show significant differences ($p < 0.05$): capital letters highlight statistically significant differences among distance zones (skid trail and four buffer strip distances) (column). Lower case letters refer to the comparison made among four classes of traffic intensity on each slope class and buffer strip distance zone (row).

	Passes	Slope (%)							
		<20				>20			
		3	8	15	30	3	8	15	30
Distance Zone (m)	Undisturbed	0.74 ^{Ba}	0.74 ^{Ba}	0.74 ^{Ca}	0.74 ^{Da}	0.82 ^{Ba}	0.82 ^{Ca}	0.82 ^{Da}	0.82 ^{Ea}
	ST	0.97 ^{Ac}	1.25 ^{Ab}	1.40 ^{Aa}	1.45 ^{Aa}	1.15 ^{Ac}	1.36 ^{Ab}	1.51 ^{Aa}	1.55 ^{Aa}
	SB1 (0.0–0.5 m)	0.81 ^{Bc}	0.85 ^{Bc}	0.94 ^{Bb}	1.11 ^{Ba}	0.84 ^{Bd}	0.91 ^{Bc}	1.08 ^{Bb}	1.25 ^{Ba}
	SB2 (0.5–1.0 m)	0.80 ^{Bb}	0.82 ^{Bb}	0.83 ^{Cb}	0.92 ^{Ca}	0.82 ^{Bc}	0.84 ^{Cc}	0.93 ^{Cb}	1.09 ^{Ca}
	SB3 (1.0–1.5 m)	0.81 ^{Ba}	0.80 ^{Ba}	0.82 ^{Ca}	0.82 ^{Da}	0.80 ^{Bb}	0.82 ^{Cb}	0.83 ^{Db}	0.94 ^{Da}
	SB4 (1.5–2.0 m)	0.78 ^{Ba}	0.79 ^{Ba}	0.78 ^{Ca}	0.78 ^{Da}	0.79 ^{Ba}	0.80 ^{Ca}	0.80 ^{Da}	0.84 ^{Ea}

Table 3. Average changes in soil physical properties (%) compared to undisturbed area after 3, 8, 15, and 30 skidding passes at various distance from the skid trail edge for the two slopes categories. DB = dry bulk density; TP = total porosity; MP = macroporosity.

Slope (%)	Distance Zone (m)	Passes											
		3			8			15			30		
		DB	TP	MP	DB	TP	MP	DB	TP	MP	DB	TP	MP
<20	ST	24.4	−10.2	−32.5	60.3	−25.1	−55.0	79.5	−33.2	−69.5	85.9	−35.8	−75.2
	SB1 (0.0–0.5 m)	3.8	−1.6	−8.1	9.0	−3.7	−15.4	19.2	−8.0	−29.6	42.3	−17.6	−37.9
	SB2 (0.5–1.0 m)	2.6	−1.1	−2.4	5.1	−2.1	−5.5	6.4	−2.7	−6.1	17.9	−7.5	−27.4
	SB3 (1.0–1.5 m)	3.8	−1.6	−2.6	2.6	−1.1	−3.1	5.1	−2.1	−3.3	5.1	−2.1	−6.4
	SB4 (1.5–2.0 m)	0.0	0.0	−0.9	1.3	−0.5	0.0	0.0	0.0	−3.3	0.0	0.0	−2.9
>20	ST	47.4	−19.8	−40.6	74.4	−31.0	−64.5	93.6	−39.0	−77.9	98.7	−41.2	−79.8
	SB1 (0.0–0.5 m)	7.7	−3.2	−13.6	15.4	−6.4	−26.5	38.5	−16.0	−39.0	60.3	−25.1	−53.1
	SB2 (0.5–1.0 m)	5.1	−2.1	−7.9	10.3	−4.3	−14.9	19.2	−8.0	−30.0	39.7	−16.6	−40.4
	SB3 (1.0–1.5 m)	2.6	−1.1	−4.8	5.1	−2.1	−6.4	6.4	−2.7	−7.5	20.5	−8.6	−31.6
	SB4 (1.5–2.0 m)	1.3	−0.5	−0.9	2.6	−1.1	−3.3	2.6	−1.1	−3.7	7.7	−3.2	−15.4

Average TP of undisturbed soil was 70.6% (ranging from 68.5% to 73.1%). TP decreased significantly due to traffic intensity, slope gradient, distance from skid trail, as well as the interaction of traffic intensity × slope gradient, traffic intensity × distance from skid trail, and traffic intensity ×

slope gradient × distance from skid trail. The analyses of data with increasing buffer distance from the skid trail showed that TP values increased considerably with increasing distance from skid trail within all the numbers of skidding cycles (Table 4). On slope <20%, significant reduction in TP values were recorded up to 0.5 and 1 m interval zone for 15 and 30 passes, respectively; any significant difference was recorded on the side buffer strip for three and eight passes. On slope >20%, significant reduction in TP were found up to 1.5 m interval zone. In detail, significant differences were recorded: up to 0.5 m after eight passes; up to 1.0 m after 15 passes; and up to 1.5 m after 30 passes. Any significant difference was recorded on the side buffer strips for three passes. The TP percentage reduction values are shown in Table 3.

Table 4. Effect of traffic and slope on mean values of total porosity (%) at various distances from skid trail edge. ST: skid trail. Different letters show significant differences ($p < 0.05$): capital letters highlight statistically significant differences among distance zones (skid trail and four buffer strip distances) (column). Lower case letters refer to the comparison made among four classes of traffic intensity on each slope class and buffer strip distance zone (row).

		Slope (%)							
		<20				**>20**			
	Passes	**3**	**8**	**15**	**30**	**3**	**8**	**15**	**30**
Distance Zone (m)	Undisturbed	73.1 ^{Aa}				68.5 ^{Aa}			
	ST	63.4 ^{Ba}	52.8 ^{Bb}	47.2 ^{Cc}	45.3 ^{Dd}	56.6 ^{Ba}	48.7 ^{Cb}	43.0 ^{Dc}	41.5 ^{Ec}
	SB1 (0.0–0.5 m)	69.4 ^{Aa}	67.9 ^{ABab}	64.9 ^{Bb}	58.1 ^{Cc}	68.3 ^{Aa}	66.0 ^{Bb}	59.2 ^{Cc}	52.8 ^{Dd}
	SB2 (0.5–1.0 m)	69.8 ^{Aa}	69.1 ^{Aa}	68.7 ^{Aa}	65.3 ^{Bb}	69.1 ^{Aa}	67.5 ^{Aa}	64.9 ^{Bb}	58.9 ^{Cc}
	SB3 (1.0–1.5 m)	69.4 ^{Aa}	69.8 ^{Aa}	69.1 ^{Aa}	69.1 ^{Aa}	69.8 ^{Aa}	69.1 ^{Aa}	68.7 ^{Aa}	64.5 ^{Bb}
	SB4 (1.5–2.0 m)	70.6 ^{Aa}	70.2 ^{Aa}	70.6 ^{Aa}	70.6 ^{Aa}	70.2 ^{Aa}	69.8 ^{Aa}	69.8 ^{Aa}	68.3 ^{Aa}

The mean value of macroporosity was 45.6% in the undisturbed area. After skidding, MP decreased (reduction ranged from 44.5 to 46.7%) and was significantly affected by traffic intensity, slope gradient, distance from skid trail, as well as the interaction of traffic intensity × slope gradient, and traffic intensity × distance from skid trail. Significant changes of MP mean values were registered increasing traffic intensity and slope gradient on skid trails margins (Table 5). The highest reduction in mean MP value occurred after 30 skidding cycles in the first 0.5 m interval for a slope gradient >20% (Table 3). On slope gradient <20%, any effect on MP was recorded on the buffer strips after 3 passes, after 8 and 15 passes a significant reduction was recorded in SB1, and after 30 passes a significant MP reduction was recorded up to SB2. On slope gradient >20%, a significant reduction in MP was recorded in SB1 after three passes, up to SB2 after eight and 15 passes and up to SB3 after 30 passes. Table 5 summarizes the percentage differences in MP values among the distance treatments compared to the undisturbed state.

Table 5. Effect of traffic and slope on mean values of macroporosity (%) at various distances from skid trail edge. ST: skid trail. Different letters show significant differences ($p < 0.05$): capital letters highlight statistically significant differences among distance zones (skid trail and four buffer strip distances) (column). Lower case letters refer to the comparison made among four classes of traffic intensity on each slope class and buffer strip distance zone (row).

		Slope (%)							
		<20				**>20**			
	Passes	**3**	**8**	**15**	**30**	**3**	**8**	**15**	**30**
Distance Zone (m)	Undisturbed	46.7 ^{Aa}				44.5 ^{Aa}			
	ST	30.8 ^{Ba}	20.5 ^{Cb}	13.9 ^{Cc}	11.3 ^{Dc}	27.1 ^{Ca}	16.2 ^{Db}	10.1 ^{Dc}	9.2 ^{Ec}
	SB1 (0.0–0.5 m)	41.9 ^{Aa}	38.6 ^{Bb}	32.1 ^{Bc}	28.3 ^{Cd}	39.4 ^{Ba}	33.5 ^{Cb}	27.8 ^{Cb}	21.4 ^{Dc}
	SB2 (0.5–1.0 m)	44.5 ^{Aa}	43.1 ^{Aa}	42.8 ^{Aa}	33.1 ^{Bb}	42.0 ^{ABa}	38.8 ^{Ba}	31.9 ^{Bb}	27.2 ^{Cc}
	SB3 (1.0–1.5 m)	44.4 ^{Aa}	44.2 ^{Aa}	44.1 ^{Aa}	42.7 ^{Aa}	43.4 ^{Aa}	42.7 ^{Aa}	42.2 ^{Aa}	31.2 ^{Bb}
	SB4 (1.5–2.0 m)	45.2 ^{Aa}	45.6 ^{Aa}	44.1 ^{Aa}	44.3 ^{Aa}	45.2 ^{Aa}	44.1 ^{Aa}	43.9 ^{Aa}	38.6 ^{Ab}

3.2. Soil Chemical Properties

Soil chemical properties showed significant differences among undisturbed area, skid trails and buffer strips of the skid trails. Average OC content in undisturbed areas was 7.1% (ranging from 6.9 to 7.3%) and decreased significantly with traffic intensity and the slope gradient. The highest reduction was recorded on the skid trail. However, the higher the distance from the skid trail and the lower the traffic intensity, the lower the OC reduction (Table 6). In general, the control area had the highest amount of OC. Along the side of the skid trail, a significant effect of trafficking was recorded in the in SB1 after 30 passes on <20% gradient. On slope >20%, significant changes were recorded: in SB1 after eight passes; in SB1 and SB2 after 15 passes; and in SB1, SB2, and SB3 after 30 passes.

Table 6. Effect of traffic and slope on mean values of OC (%) at various distances from skid trail edge. ST: skid trail. Different letters show significant differences ($p < 0.05$): capital letters highlight statistically significant differences among distance zones (skid trail and four buffer strip distances) (column). Lower case letters refer to the comparison made among four classes of traffic intensity on each slope class and buffer strip distance zone (row).

	Passes	Slope (%)							
		<20				>20			
		3	8	15	30	3	8	15	30
Distance Zone (m)	Undisturbed	7.3 ^{Aa}				6.9 ^{Aa}			
	ST	5.42 ^{Ba}	4.36 ^{Bb}	3.52 ^{Bc}	3.39 ^{Cc}	4.95 ^{Ba}	3.52 ^{Cb}	2.50 ^{Dc}	2.35 ^{Ec}
	SB1 (0.0–0.5 m)	6.82 ^{Aa}	6.61 ^{Aa}	5.65 ^{Ab}	5.11 ^{Bb}	6.73 ^{Aa}	5.77 ^{Bb}	5.24 ^{Cbc}	4.40 ^{Dc}
	SB2 (0.5–1.0 m)	6.93 ^{Aa}	6.79 ^{Aa}	6.72 ^{Aa}	5.67 ^{ABb}	6.74 ^{Aa}	6.58 ^{Aa}	5.60 ^{Bb}	5.07 ^{Cb}
	SB3 (1.0–1.5 m)	6.88 ^{Aa}	6.83 ^{Aa}	6.80 ^{Aa}	6.78 ^{Aa}	6.77 ^{Aa}	6.83 ^{Aa}	6.65 ^{Aa}	5.49 ^{Bb}
	SB4 (1.5–2.0 m)	6.98 ^{Aa}	6.95 ^{Aa}	6.78 ^{Aa}	6.82 ^{Aa}	7.1 ^{Aa}	6.87 ^{Aa}	6.81 ^{Aa}	6.68 ^{Aa}

In undisturbed areas, the average N content was measured as 0.29% (ranging from 0.28 and 0.29%) and decreased significantly by traffic intensity, slope gradient, distance from skid trail, as well as the interaction of traffic intensity × distance from skid trail, slope gradient × distance from skid trail, and traffic intensity × slope gradient × distance from skid trail. The higher the traffic intensity and the slope gradient the lower the N content. The most significant reduction in N content occurred after 30 cycles on the steepest slope class (Table 7). In comparison with the undisturbed area, the decrease in N values in the slope class >20% for all distance zones ranged from 1.4 to 40%, 2.4 to 65%, 2.4 to 88.2%, and 6.6 to 89.9% after 3, 8, 15, and 30 skidding cycles, respectively (Table 8).

Table 7. Effect of traffic and slope on mean values of N (%) at various distances from skid trail edge. ST: skid trail. Different letters show significant differences ($p < 0.05$): capital letters highlight statistically significant differences among distance zones (skid trail and four buffer strip distances) (column). Lower case letters refer to the comparison made among four classes of traffic intensity on each slope class and buffer strip distance zone (row).

	Passes	Slope (%)							
		<20				>20			
		3	8	15	30	3	8	15	30
Distance Zone (m)	Undisturbed	0.29 ^{Aa}				0.28 ^{Aa}			
	ST	0.238 ^{Ba}	0.173 ^{Bb}	0.098 ^{Cc}	0.084 ^{Dc}	0.198 ^{Ba}	0.101 ^{Bb}	0.034 ^{Dc}	0.029 ^{Ec}
	SB1 (0.0–0.5 m)	0.279 ^{Aa}	0.273 ^{Aa}	0.240 ^{Bb}	0.207 ^{Cc}	0.275 ^{Aa}	0.255 ^{Aa}	0.213 ^{Cb}	0.181 ^{Dc}
	SB2 (0.5–1.0 m)	0.282 ^{Aa}	0.275 ^{Aa}	0.277 ^{Aa}	0.242 ^{Bc}	0.274 ^{Aa}	0.268 ^{Aa}	0.235 ^{Bb}	0.198 ^{Cc}
	SB3 (1.0–1.5 m)	0.280 ^{Aa}	0.282 ^{Aa}	0.279 ^{Aa}	0.278 ^{Aa}	0.280 ^{Aa}	0.278 ^{Aa}	0.273 ^{Aa}	0.226 ^{Bb}
	SB4 (1.5–2.0 m)	0.282 ^{Aa}	0.284 ^{Aa}	0.279 ^{Aa}	0.282 ^{Aa}	0.282 ^{Aa}	0.281 ^{Aa}	0.281 ^{Aa}	0.269 ^{Aa}

Table 8. Average changes in soil chemical properties (%) compared to undisturbed area following 3, 8, 15, and 30 skidding passes for various distance from the edge of skid trail and the two slopes categories.

Slope (%)	Distance Zone (m)	Passes															
		3				8				15				30			
		OC	N	P	K	OC	N	P	K	OC	N	P	K	OC	N	P	K
<20	ST	−23.9	−17.4	−16.1	−11.3	−38.0	−39.9	−34.4	−28.1	−50.7	−66.0	−46.0	−47.0	−52.1	−70.8	−49.6	−51.3
	SB1 (0.0–0.5 m)	−4.2	−3.1	−1.7	−2.9	−7.0	−5.6	−3.3	−4.8	−21.1	−16.7	−13.1	−9.1	−28.2	−28.1	−23.7	−19.9
	SB2 (0.5–1.0 m)	−2.8	−2.1	−2.5	−2.3	−4.2	−4.5	−1.8	−3.9	−5.6	−3.8	−3.5	−4.4	−19.7	−16.0	−12.1	−8.6
	SB3 (1.0–1.5 m)	−2.8	−1.4	−0.8	−1.9	−4.2	−2.1	−0.7	−3.0	−4.2	−3.1	−2.2	−3.5	−4.2	−3.5	−3.1	−4.6
	SB4 (1.5–2.0 m)	−1.4	−2.1	0	−0.2	−1.4	−1.4	−0.5	−0.8	−4.2	−3.1	−0.8	−1.8	−4.2	−2.1	−0.4	−1.2
>20	ST	−31.0	−40.0	−24.7	−22.0	−50.7	−65.0	−40.5	−43.7	−64.8	−88.2	−52.3	−55.3	−67.6	−89.9	−54.0	−56.4
	SB1 (0.0–0.5 m)	−5.6	−5.6	−2.6	−4.1	−18.3	−11.5	−10.1	−6.9	−26.8	−26.0	−21.6	−19.0	−38.0	−37.2	−34.0	−27.2
	SB2 (0.5–1.0 m)	−5.6	−4.5	−2.0	−3.2	−4.2	−6.9	−3.9	−39	−21.1	−18.4	−12.7	−9.6	−28.2	−31.2	−21.9	−19.5
	SB3 (1.0–1.5 m)	−4.2	−2.1	−0.8	−2.6	−4.2	−3.5	−2.3	−3.2	−7.0	−5.2	−3.7	−4.5	−22.5	−21.5	−13.1	−10.6
	SB4 (1.5–2.0 m)	0	−1.4	−0.2	−1.0	−2.8	−2.4	−0.4	−1.5	−4.2	−2.4	−0.5	−2.1	−5.6	−6.6	−3.3	−2.7

The average P content in the undisturbed area was 46.32 (ppm). After skidding, average value decreased to 21.27 (ppm) and was significantly affected by traffic intensity, slope gradient, distance from skid trail, as well as the interaction of traffic intensity × slope gradient, traffic intensity × distance from skid trail, and traffic intensity × slope gradient × distance from skid trail. The greatest reduction in P content occurred in the first buffer strip distance (0.0–0.5 m from skid trail edge) an on slope gradient >20% following 30 skidding cycles (Table 9). Significant differences with the undisturbed area in P content started on slope <20 in SB1 after 15 passes and were recorded also in SB2 after 30 passes. On slope >20%, significant differences were determined: in SB1 after eight passes; SB1 and SB2 after 15 passes; SB1, SB2, and SB3 after 30 passes. Table 8 summarizes the percentage differences in P values among the distance treatments compared to the undisturbed area.

Table 9. Effect of traffic and slope on mean P content (ppm) at various distances from skid trail edge. ST: skid trail. Different letters show significant differences ($p < 0.05$): capital letters highlight statistically significant differences among distance zones (skid trail and four buffer strip distances) (column). Lower case letters refer to the comparison made among four classes of traffic intensity on each slope class and buffer strip distance zone (row).

	Passes	Slope (%)							
		<20				>20			
		3	8	15	30	3	8	15	30
Distance Zone (m)	Undisturbed	46.38 ^{Aa}				46.26 ^{Aa}			
	ST	38.86 ^{Ba}	30.37 ^{Bb}	25.03 ^{Cc}	23.35 ^{Dc}	34.86 ^{Ba}	27.54 ^{Cb}	22.08 ^{Db}	21.27 ^{Eb}
	SB1 (0.0–0.5 m)	45.75 ^{Aa}	44.80 ^{Aa}	40.25 ^{Bb}	35.33 ^{Cc}	45.13 ^{Aa}	41.66 ^{Bb}	36.29 ^{Cc}	30.61 ^{Dd}
	SB2 (0.5–1.0 m)	46.16 ^{Aa}	45.48 ^{Aa}	44.70 ^{Aa}	40.70 ^{Bb}	45.39 ^{Aa}	44.51 ^{Aa}	40.44 ^{Bb}	36.18 ^{Cc}
	SB3 (1.0–1.5 m)	46.01 ^{Aa}	46.01 ^{Aa}	45.30 ^{Aa}	44.87 ^{Aa}	45.92 ^{Aa}	45.26 ^{Aa}	44.59 ^{Aa}	40.23 ^{Bb}
	SB4 (1.5–2.0 m)	46.31 ^{Aa}	46.07 ^{Aa}	45.97 ^{Aa}	46.13 ^{Aa}	46.24 ^{Aa}	46.11 ^{Aa}	46.09 ^{Aa}	44.80 ^{Aa}

The average K content in the undisturbed area was 13.15 (ppm). After skidding operations over all treatment plots, the average K content decreased to 5.73 (ppm) being significantly affected ($p < 0.005$) by traffic frequency and slope gradient (Table 10). The first 0.5 m interval on a slope >20% after 30 skidding cycles (Table 8) were the conditions that carried to the greatest reduction of K mean values. Related data are shown in Table 8, where it is evident that the highest reductions in K values were concentrated on steep slopes, rather than the gentle slopes. Finally, K mean values were significantly different up to 1 and 1.5 m buffer strip zones for a slope gradient >20% after 15 and 30 skidding passes, respectively.

Table 10. Effect of traffic and slope on mean values of K (ppm) at various distances from skid trail edge. ST: skid trail. Different letters show significant differences ($p < 0.05$): capital letters highlight statistically significant differences among distance zones (skid trail and four buffer strip distances) (column). Lower case letters refer to the comparison made among four classes of traffic intensity on each slope class and buffer strip distance zone (row).

	Passes	Slope (%)							
		<20				>20			
		3	8	15	30	3	8	15	30
Distance Zone (m)	Undisturbed	13.19 ^{Aa}				13.11 ^{Aa}			
	ST	11.67 ^{Ba}	9.45 ^{Bb}	7.03 ^{Cc}	6.41 ^{Dc}	10.26 ^{Ba}	7.41 ^{Cb}	5.88 ^{Dc}	5.73 ^{Ec}
	SB1 (0.0–0.5 m)	12.84 ^{Aa}	12.52 ^{Aa}	11.95 ^{Ba}	10.53 ^{Cb}	12.61 ^{Aa}	12.24 ^{Ba}	10.65 ^{Cb}	9.57 ^{Dc}
	SB2 (0.5–1.0 m)	12.95 ^{Aa}	12.64 ^{Aa}	12.57 ^{Aa}	12.02 ^{Ba}	12.73 ^{Aa}	12.64 ^{Aa}	11.89 ^{Ba}	10.58 ^{Cb}
	SB3 (1.0–1.5 m)	13.02 ^{Aa}	12.75 ^{Aa}	12.69 ^{Aa}	12.54 ^{Aa}	12.89 ^{Aa}	12.73 ^{Aa}	12.56 ^{Aa}	11.76 ^{Bb}
	SB4 (1.5–2.0 m)	13.10 ^{Aa}	12.85 ^{Aa}	12.81 ^{Aa}	12.99 ^{Aa}	12.94 ^{Aa}	12.87 ^{Aa}	12.62 ^{Aa}	12.79 ^{Aa}

3.3. Survival and Growth

The germination rate in the undisturbed areas was 48.53% (ranging between 48.49 and 48.65%) and did not significantly differ among the different slope gradients. After skidding, the germination rate decreased to 24.17% and was significantly affected by traffic intensity, slope gradient, distance from skid trail, as well as the interaction of slope gradient × distance from skid trail, and traffic intensity × distance from skid trail. The higher the number of passes, the lower the germination rate; however, with increasing distance from the wheel ruts, these values increased. In comparison with undisturbed soil, decreases in germination rate values were significant only in ST, SB1, and SB2 on slope <20%, while significant declines were found up to SB3 on slopes >20% (Table 11).

Table 11. Effect of traffic and slope on mean values of germination rate (%) at various distances from skid trail edge. ST: skid trail. Different letters show significant differences ($p < 0.05$): capital letters highlight statistically significant differences among distance zones (skid trail and four buffer strip distances) (column). Lower case letters refer to the comparison made among four classes of traffic intensity on each slope class and buffer strip distance zone (row).

	Passes	Slope (%)							
		<20				>20			
		3	8	15	30	3	8	15	30
Distance Zone (m)	Undisturbed	48.65 Aa				48.49Aa			
	ST	42.79 Ba	34.32 Bb	28.97 Cc	25.83 Dc	38.62 Ba	30.08 Cb	24.38 Dc	24.17 Ec
	SB1 (0.0–0.5 m)	46.21 Aa	45.25 Aa	43.26 Bb	39.77 Cc	46.47 Aa	45.63 Ba	39.21 Cb	34.61 Dc
	SB2 (0.5–1.0 m)	46.73 Aa	46.54 Aa	46.57 Aa	44.11 Bb	46.49 Aa	46.03 Aa	44.01 Bb	38.87 Cc
	SB3 (1.0–1.5 m)	46.96 Aa	46.62 Aa	46.50 Aa	46.44 Aa	46.56 Aa	46.63 Aa	46.39 Aa	43.79 Bb
	SB4 (1.5–2.0 m)	48.45 Aa	48.37 Aa	47.70 Aa	47.60 Aa	48.26 Aa	47.65 Aa	47.15 Aa	46.90 Aa

Average root length was 34.05 cm in the undisturbed area. The relation between compaction after skidding and the root length of maple seedling is inverse. The average root length was always lower on skid trails than the control area (Table 12). The reduction in the average root length on the skid trails ranged from 30% with three passes and a slope <20% to 66% with 30 passes and a slope >20% compared with the undisturbed area (Table 12). In the first 0.5 m interval for a slope gradient >20%, after 30 skidding passages, mean values of root length encountered the highest levels of reduction in comparison with control plots (Table 13).

Table 12. Effect of traffic and slope on mean values of root length (cm) at various distances from skid trail edge. ST: skid trail. Different letters show significant differences ($p < 0.05$): capital letters highlight statistically significant differences among distance zones (skid trail and four buffer strip distances) (column). Lower case letters refer to the comparison made among four classes of traffic intensity on each slope class and buffer strip distance zone (row).

	Passes	Slope (%)							
		<20				>20			
		3	8	15	30	3	8	15	30
Distance Zone (m)	Undisturbed	34.24 Aa	34.24 Aa	34.24 Aa	34.24 Aa	33.86 Aa	33.86 Aa	33.86 Aa	33.86 Aa
	ST	23.82 Ba	18.76 Bb	14.15 Cc	13.09 Dc	20.71 Ba	15.38 Cb	12.52 Dc	11.67 Ec
	SB1 (0.0–0.5 m)	31.54 Aa	31.02 Aa	25.14 Bb	21.25 Cc	31.28 Aa	27.35 Bb	22.19 Cc	18.93 Dd
	SB2 (0.5–1.0 m)	32.19 Aa	31.71 Aa	31.72 Aa	26.70 Bb	31.75 Aa	31.07 Aa	25.54 Bb	21.38 Cc
	SB3 (1.0–1.5 m)	32.36 Aa	31.92 Aa	31.60 Aa	31.81 Aa	31.87 Aa	31.87 Aa	31.27 Aa	25.65 Bb
	SB4 (1.5–2.0 m)	33.67 Aa	33.01 Aa	32.54 Aa	32.90 Aa	33.14 Aa	32.87 Aa	31.95 Aa	32.19 Aa

Table 13. Average changes in survival and growth (%) compared to undisturbed area following 3, 8, 15, and 30 skidding passes for various distance from edge of skid trail and slopes categories. GR = germination rate; RL = root length; SH = stem height.

Slope (%)	Distance Zone (m)	Passes											
		3			8			15			30		
		GR	RL	SH	GR	RL	SH	GR	RL	SH	GR	RL	SH
<20	ST	−11.8	−30.0	−23.5	−29.3	−44.9	−44.1	−40.3	−58.4	−58.2	−46.8	−61.6	−60.6
	0.5	−4.8	−7.4	−7.7	−6.7	−8.9	−10.8	−10.8	−26.2	−20.3	−18.1	−37.6	−32.2
	1	−3.7	−5.4	−5.4	−4.1	−6.9	−6.2	−4.0	−6.8	−6.7	−9.1	−21.6	−18.4
	1.5	−3.2	−5.0	−4.2	−3.9	−6.2	−5.6	−4.2	−7.2	−7.0	−4.3	−6.6	−6.8
	2	−0.16	−1.1	−1.7	−0.33	−3.0	−1.1	−1.7	−4.4	−2.0	−1.9	−3.4	−2.4
>20	ST	−20.4	−39.2	−34.5	−38.0	−54.8	−56.5	−49.8	−63.2	−65.8	−50.2	−65.7	−68.8
	0.5	−4.2	−8.1	−9.1	−6.0	−19.7	−16.7	−19.2	−34.8	−34.4	−28.7	−44.4	−43.2
	1	−4.2	−6.7	−6.2	−5.2	−8.8	−10.3	−9.3	−25.0	−19.1	−19.9	−37.2	−32.8
	1.5	−4.0	−6.4	−3.1	−3.9	−6.4	−7.1	−4.4	−8.2	−5.8	−9.8	−24.7	−17.6
	2	−0.56	−2.7	−2.8	−1.7	−3.5	−3.3	−2.8	−6.2	−3.1	−3.4	−5.5	−4.6

Stem height averaged 23.54 cm in undisturbed control areas and ranged between 23.15 and 15.41 cm after three passes of the skidder, 23.27–10.25 cm after eight skidder passes, 23.06–8.06 cm after 15 skidder passes, and 22.97–7.35 cm after 30 passes (Table 14). A consistent decrease of stem height was registered with increasing the number of passages and increasing slope gradient (Table 13). The analyses of data showed that stem height values increased considerably with increasing distance from skid trail within all skidding cycles (Table 13).

Table 14. Effect of traffic and slope on mean values of stem height (cm) at various distances from skid trail edge. ST: skid trail. Different letters show significant differences ($p < 0.05$): capital letters highlight statistically significant differences among distance zones (skid trail and four buffer strip distances) (column). Lower case letters refer to the comparison made among four classes of traffic intensity on each slope class and buffer strip distance zone (row).

	Passes	Slope (%)							
		<20				>20			
		3	8	15	30	3	8	15	30
	Undisturbed	23.63 Aa				23.45 Aa			
Distance Zone (m)	ST	18.01 Ba	13.15 Bb	9.83 Cc	9.27 Dc	15.41 Ba	10.25 Cb	8.06 Dc	7.35 Ec
	SB1 (0.0–0.5 m)	21.73 Aa	20.99 Aa	18.76 Bb	15.97 Cc	21.39 Aa	19.62 Bb	15.44 Cc	13.38 Dd
	SB2 (0.5–1.0 m)	22.26 Aa	22.08 Aa	21.97 Aa	19.20 Bb	22.07 Aa	21.11 Aa	19.04 Bb	15.82 Cc
	SB3 (1.0–1.5 m)	22.55 Aa	22.23 Aa	21.89 Aa	21.94 Aa	22.76 Aa	21.88 Aa	22.18 Aa	19.39 Bb
	SB4 (1.5–2.0 m)	23.15 Aa	23.27 Aa	23.06 Aa	22.97 Aa	22.89 Aa	22.76 Aa	22.80 Aa	22.45 Aa

4. Discussion

In the last decade, several studies highlighted that many factors can negatively affect soil characteristics and the magnitude of these effects depends on many aspects. The most important characteristics of soil that normally influence the susceptibility of soils to disturbances are texture, moisture content, and organic matter content. Regarding forest operations, machine type, traffic level, slope of trails, tire pressure, vibrations transmitted by vehicles, and work organization (affected by the experience and the expertise of operators) are important factors that can aggravate or reduce the impacts on soil. [4,6,20,25,35–37]. However, a lack of knowledge still exists about the effects of soil compaction in the surrounding areas of the skid trail.

Our study addressed this knowledge gap. In comparison with undisturbed areas, our results confirmed the increase of dry bulk density and decrease of porosity, as well as soil OC content and the concentrations of N, P, and K, after skidding operations. More importantly, we also highlighted the effect of the changes in physical and chemical properties on skid trail and four buffer strip distances from its edge on early seedling growth parameters (including germination rate, stem, and root growth).

This approach allowed us to highlight the effect of compaction on seedling early growth and to assess their potential long-lasting consequences for stand regeneration, plant growth, and forest productivity.

Dry bulk density of the soil located in the trafficked skid trail was considerably higher than the dry bulk density of the undisturbed area. Three skidder passes over the same skid trail were sufficient to produce soil conditions close to critical threshold values that have been shown to be detrimental to future plant growth and long-term site productivity. In fact, in accordance with the findings of Ampoorter et al. [19] and Naghdi et al. [10], about 50% of the total impact, both in terms of soil bulk density and total porosity, occurred after three passes. An important consequence of increased soil compaction is the change in soil porosity. Our results highlighted that compaction lead to a reduction in total porosity, likely due to the reduction of macroporosity that was strongly reduced for some treatments in our study. Changes in pore size distribution toward a decrease in macroporosity and an increase in microporosity were highlighted in other studies [7,8,29]. When air filled (macro-) porosity falls below 10% of the total soil volume, as recorded in our study at the highest traffic intensity and slope gradient air diffusion, microbial activity and root proliferation can be severely limited in most soils and site productivity may decline [19,38]. Ampoorter et al. [16] reported that soil disturbance due to harvesting operations can have strong effects on chemical and physical characteristics of forest soils together with a reduction of forest renovation capacity.

Soil chemical properties were also strongly affected by logging [1,39]. The incidence of traffic frequency and skid trail slope on soil chemical properties were clearly shown by our results. Usually, due to machine trafficking and log dragging, much of the changes in soil chemical properties associated with skidding operation are related to the displacement of forest floor biomass and surface organic and mineral soil top layers, as well as soil mixing [1,4]. In our study, the comparison of soil chemical properties on different distance from wheel rut showed that organic matter-related properties increased with increasing the distance from the wheel rut.

The effects of machine trafficking on soil physical and chemical properties led to a significant decrease in seedling emergence and growth. The reduction of the average germination rate from 48.53% to 24.17% in undisturbed (control) area and skid trail, respectively, supports previous reports of reductions in germination rates due to soil disturbance or compaction [8,11,40]. Research in [11] reported the negative influence of compaction on tree regeneration by inhibiting seed germination, reducing seedling growth and inducing seedling mortality. The reduction in root length was significant in all the buffer strip distance classes for traffic intensities higher than 30 and for the higher slope class. Soil compaction typically reduces the rate of root lengthening [8]. The results obtained in this study clearly show the relation between reduction of root length and increasing bulk density. Moreover, growth reductions can be observed even before the assumed threshold is reached (1.40–1.55 g cm^{-3}) [41,42], which is in accordance with findings of [43] who found that compaction have adverse effects on root growth.

Growth of seedlings in height is also significantly reduced by soil compaction in areas affected by traffic of forest machines. This result is confirmed by other previous studies [44–46]. Moreover, our results, showed that the effect of trafficking may affect the skid sides until a distance range of 0.5 to 1.5 m in relation with number of passes and terrain steepness (i.e., up to SB3 buffer strip class of our study). The effect of soil disturbance on seedling growth can be negative or positive. Gomez et al. [47] reported that considering different texture and water content in soil, the effects of compaction on the same species (in this case, *Pinus ponderosa*) could be negative, neutral or positive. This has been obtained also in other cases [48], confirming that texture and soil depth influence the effect of soil compaction on tree growth.

Finally, results showed that disturbance on soil is included in a surrounding area of 1.5 m from wheel ruts, while increasing the distance from disturbed surface, the effects rapidly decrease, as demonstrated by results in control areas. These results agree with the findings of Williamson and Neilsen [49], Defossez and Richard [50], and Ampoorter et al. [19]. Solgi et al. [23] found that maximum compaction occurs within 2 m from wheel ruts. Helms and Hipkin [51] also reported 18% increases in dry bulk density on the areas adjacent to machine operating trails compared to control areas. An increase in traffic intensity caused increased compaction up to 1 m intervals from the wheel ruts for slopes less than 20%. This was most pronounced for slopes greater than 20%, up to 1.5 m into the forest. When a skidder passes more slowly on steeper trails, the top soil is vibrated more and therefore compacted more than on gentle skid trails that are traversed with higher speeds [52]. Furthermore, the increase of dry bulk density on steeper skid trails may be associated with changes in the machine weight distribution. On steep skid trails, driving uphill, the rear axle has a higher load than in flat terrain, and the wheels could slip. In this case, soil particles are pushed together closer than normal, and consequently soil compaction increases [10]. This finding is in line also with studies carried out in agriculture [53], confirming the phenomenon of wheel slip as an important factor in increasing soil compaction.

The soil compaction at the side of skid trails is influenced by lateral movement of soil particles from the maximum compression point to the external points with lower pressure. Moreover, some additional effects, like shear forces that tend to loosen the soil, appear during turns, when the operator rotates the tires [54,55]. In conclusion, soil compaction is affected to both static and dynamic forces—including engine vibrations, tools, and wheel slippage [56].

5. Conclusions

This work investigated the magnitude of changes in soil physical and chemical properties and seedling growth parameters and extent of soil disturbance along the margin of a skid trail at four levels of skidder traffic and two trail gradients. It is confirmed that traffic of heavy machines on skid trails causes consistent impacts on soil, especially increasing the number of passages. However, this impact is often limited to the close surroundings of skid trails, while the negative effects of compaction decrease increasing the distance from trails. Within the limits of experimental conditions, some statements can be made, supported by demonstrable results, to improve the efficiency and reduce impacts on soil during forest operations:

Chemical properties are strongly influenced by traffic. On skid trails, these changes are already evident after three passages, and continue to increase increasing the number of passages. The effects in the surrounding of skid trail are considerable after 15 passages up to 0.5 m from skid trail, and also at 1 m after 30 passages. Slope is an aggravating factor, increasing the effects of traffic on chemical properties of soil.

1. The same trend of chemical properties is valid for physical characteristics. In fact, traffic causes compaction and consequently an increase of bulk density (close to redouble on skid trails after 30 passages on slope) and a decrease of porosity.
2. These changes in soil properties have an effect on tree regeneration. Resulting in negative effects, mainly on steep skid trails, in terms of germination rate (up to −50%), root length (up to −66%), and stem height (up to −70%). Negative percentages are indeed better at short distances from skid trails.

Finally, the results that emerged in this study highlight once more the importance of detailed planning in forest harvesting. In fact, being aware that the impacts of skidding exist, it is important to reduce negative effects through a preliminary detailed planning of interventions. Fundamental precaution is the best planning of skid trails, to reduce their density (m*ha^{-1}) and consequently the negative effects on soil, guaranteeing the efficiency of operations. Moreover, it is important to have competent and expert operators able to apply the planned operations.

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