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Growth and Architectural Response of Beech Seedlings to Canopy Removal and Soil Compaction from Selective Logging

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Abstract: Logging operations change the forest environment by creating a heterogeneous canopy with a range of different microenvironments that differ mostly in light intensity and level of soil disturbance. In this study, the growth characteristics and architecture of beech (*Fagus orientalis* Lipsky) seedlings grown in three different microenvironments in terms of canopy and soil conditions were investigated. The experimental treatments (microenvironments) included skid trail (removal of canopy and compacted soil), winching corridor (natural canopy and compacted soil), felling gap (removal of canopy and natural soil), and comparison with the control area (canopy and soil in natural state). The results showed that the status of many growth and architectural indicators of seedlings is significantly less favorable than in the control area. These indicators include the length and biomass above and below ground, and the ratio of root length to stem length in the skid trails and winching corridors. The status of these indicators was, however, more favorable in felling gaps than in the control area. The seedling quality index decreased by −12.2% and −4.9% in skid trails and winching corridors, respectively, but increased by 2.4% in felling gaps compared to the control area. The growth characteristics and biomass of seedlings had a significant negative correlation ($p < 0.01$) with soil bulk density and penetration resistance and a significant positive correlation ($p < 0.05$) with soil porosity, moisture, and organic matter content. These results showed that the creation of a gap in the stand canopy due to the cutting of individual trees created a favorable micro-environment for the growth of seedlings, but the soil compaction caused by logging operations created an unfavorable micro-environment for these. Therefore, it is necessary to plan and execute the operation of extracting the cut trees in such a manner as to reduce the extent and severity of soil compaction with the goal of preserving and maintaining the stability of the forest ecosystem.

Keywords: microenvironment; beech seedling; soil compaction; seedling architecture; canopy gap

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Citation: Tavankar, F.; Kivi, A.R.; Naghdi, R.; Latterini, F.; Venanzi, R.; Picchio, R. Growth and Architectural Response of Beech Seedlings to Canopy Removal and Soil Compaction from Selective Logging. *Sustainability* **2024**, *16*, 6162. https://doi.org/10.3390/su16146162

Academic Editors: Anna De Marco, Abolfazl Jaafari and Davood Mafi-Gholami

Received: 23 May 2024
Revised: 14 July 2024
Accepted: 16 July 2024
Published: 18 July 2024

1. Introduction

Successful forest management requires a comprehensive knowledge of how forest ecosystems respond to a variety of stresses [1–3]. Tree canopy removal and soil compaction are the main environmental consequences that occur immediately after logging operations in forest stands [4,5]. The alteration of the stand canopy occurs at the stage of tree felling, as well as during the construction of skid trails. The compaction of the forest soil generally occurs during extraction operations. Therefore, felling gaps, winching corridors, and skid trails are considered to be the main areas of disruption of forest stands caused by logging operations [6].

The canopy is one of the most important factors that control the microclimate of a habitat [7]. Opening the forest canopy in felling gaps and along skid trails can affect plant growth and competition patterns, especially between shade-tolerant and non-shade-tolerant species [8]. Also, soil compaction, which reduces the volume of a certain mass of soil [9,10], is one of the major consequences of the mechanized removal of wood [11]. Timber extraction systems often involve heavy machinery, which results in the compaction of forest soils. The recovery of the compacted soil structure caused by logging machines may be slow and difficult [12].

Soil pore size, water content, aeration, temperature, nutrient availability, and microorganisms are interrelated, and all can be negatively affected by soil compaction and negatively affect plant root growth and performance [13]. The United States Department of Agriculture (USDA) Forest Service has set up a threshold level of forest soil disturbance at 20 percent of the total logging site, considering roads, skid trails, and depots. It is also mentioned that the critical limit of soil compaction is that the bulk density of the upper 20 cm of the soil of the disturbed areas should not increase more than 15% in comparison to the undisturbed soil. However, the threshold level of soil disturbance can be determined by taking into account the climatic conditions, vegetation, topographic, and habitat characteristics of each logging site [14–16].

Several studies have investigated the effect of soil compaction on seedling characteristics. For example, the size and weight of chestnut-leaved oak seedlings have been affected by soil compaction caused by machinery traffic in the forests of northern Iran [17]. A higher seedling mortality rate and reduced growth of *Picea abies* (L.) Karst trees have been reported in compacted soils [18]. According to another study conducted in Italy, it was reported that soil compaction (27% compared to the non-compacted area) reduces the yield of oak seedlings (*Quercus robur* L.) by 26% in height and up to 24% in root growth [19]. In addition, an inverse relationship between seedling root length and soil compaction has been reported in maple [20], oak [17], and beech [21] tree seedlings. In the study of Pinard et al. [22] in Malaysian forests, the highest mortality rate of seedlings was reported after one year from felling, in skid trails, and due to soil compaction and lack of access to soil nutrients for seedlings. However, detailed information about the effects of different degrees of soil disturbance connected to logging operations (skid trails, winching corridors, and felling gaps) on beech seedlings in mixed broadleaved forests managed by selective logging is missing. Furthermore, in the literature, there are several studies reporting an opposing effect of compaction and skid trail establishment on seedling growth [23]. Bigelow et al. (2018) [24] reported higher seedling growth in the compacted soil in the skid trails for longleaf pine (*Pinus palustris* Mill). Also, Jamshidi et al. (2018) [25] showed no influence of machinery-induced soil compaction on the seedling growth for Acer velutinum Boiss and Alnus subcordata C.A.M. in a context similar to our research trial, i.e., Hyrcanian forests in Iran. Therefore, there is still much more to investigate on the topic of the effects of machinery-induced soil compaction on the growth of seedlings, mostly in complex forest ecosystems such as the Hyrcanian forests.

The forests of northern Iran on the southern shores of the Caspian Sea have an area of about 2 million hectares, which are located in the northern parts of the Alborz mountain range from coastal areas to an altitude of 2800 m above sea level. They are the most valuable forest ecosystems in Iran. Among the natural and main features of these forests, we can mention a large number of broad-leaved species, biodiversity, richness of native and endangered species, and a large number of ecological nests. The growth and survival of beech (*Fagus orientalis* Lipsky) seedlings after harvesting operations in the mixed beech forests of northern Iran is of particular importance. Thus, with this research, we want to deepen the scientific knowledge of the complex phenomenon of the natural regeneration of beech forests in the study area, mostly focusing on how logging operations can alter the natural regeneration of the forest stands. With this study, for the first time, a forest management system closely connected to the Continuous Cover Forestry (CCF) was directly linked to forest operations and the disturbances associated, evaluating the connections between edaphic parameters and tree renewal. This aspect, which has transitioned to temperate forests with a prevalence of beech, takes on even more interest, also from the perspective of the sensitivity of these forest ecosystems to climate change.

In this study, we wanted to test the following research hypotheses: (i) soil compaction in the skid trails and winching corridors decreases the growth of natural regeneration; (ii) felling gaps, thanks to higher light availability without alteration of soil, instead create favorable situations for the establishment and growth of seedlings. The main aim was to assess over a period of ten years the effect of active forest management on forest soil and beech renovation with respective connections.

2. Materials and Methods

2.1. Study Area

This study took place in the Nav forest series in the Hyrcanian forests, in watershed number seven in the Guilan province with geographical coordinates between 48°44′36″ and 48°49′58″ east longitude and 37°27′23″ and 37°42′31″ north latitude (Figure 1). The amount of annual precipitation is 924 mm, the average annual temperature is about 10.2 °C, and the climate of the region is humid based on the Dumarten humidity coefficient. The upcoming research was conducted in Parcel 237. The area of this parcel is 41 hectares, the altitude is from 1150 to 1300 m above the sea level, and the general slope aspect is northwest. The silicate is the mother rock type, and the soil is the forest brown soil type with a sandy, loamy texture. The soil of the study area is classified as Luvisols based on the World Reference Basis (WRB) (IUSS Working Group, 2015). The structure of the stand is uneven-aged, while the forest type can be determined as a mixed broadleaved stand with beech predominance.

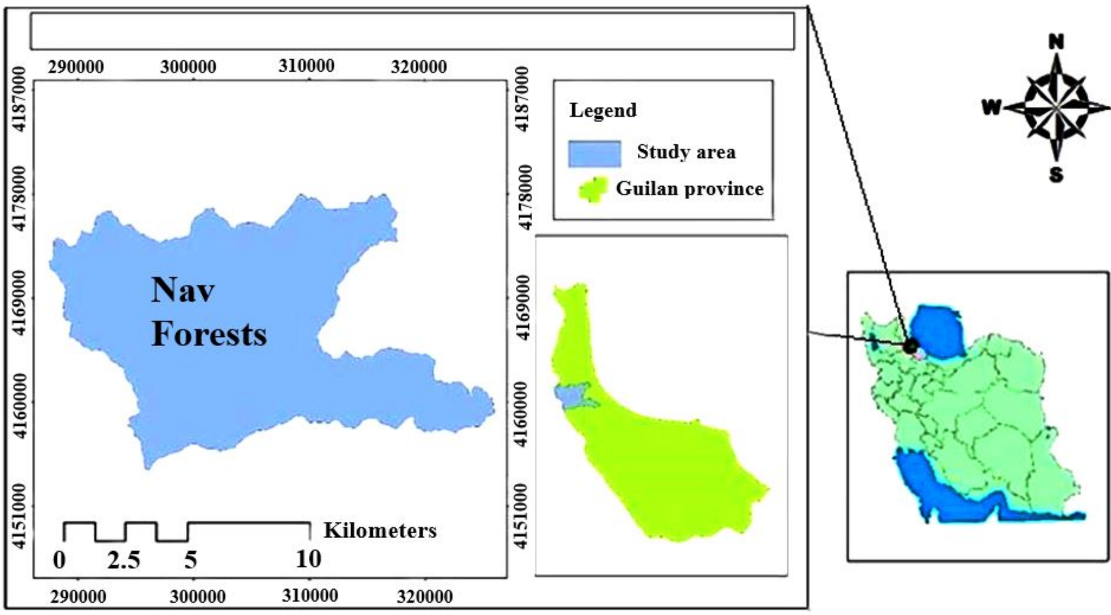

Figure 1. Location of the study area (Nav forests) in Guilan province in northern Iran.

The method of forest management was a single selection cutting, and the applied logging system was ground-based by a cable skidder. The density of the forest roads and skid trails in this parcel was 22.7 and 29.5 m per hectare, respectively. The skid trail network (Figure 2) occupied about 14.6% of the total surface of the parcel. The number of skid trails branching off from the forest road was five, with approximate lengths of 150, 200, 250, 260, and 350 m, with an average longitudinal slope of 22% and a maximum longitudinal slope of 38%. Each of the skid trails had two to five winching corridors (the path of log winching on the skid trail) with a length of 20 to 50 m and a width of two to three meters. We focused our analysis on secondary and tertiary skid trails, experiencing a limited (less than 10) number of machine passes [26]. Thus, we excluded from the analysis the heavily disturbed soil in the primary trails, which was practically absent in the studied parcel, considering that the logging company used the existing forest road network without establishing new primary skid trails.

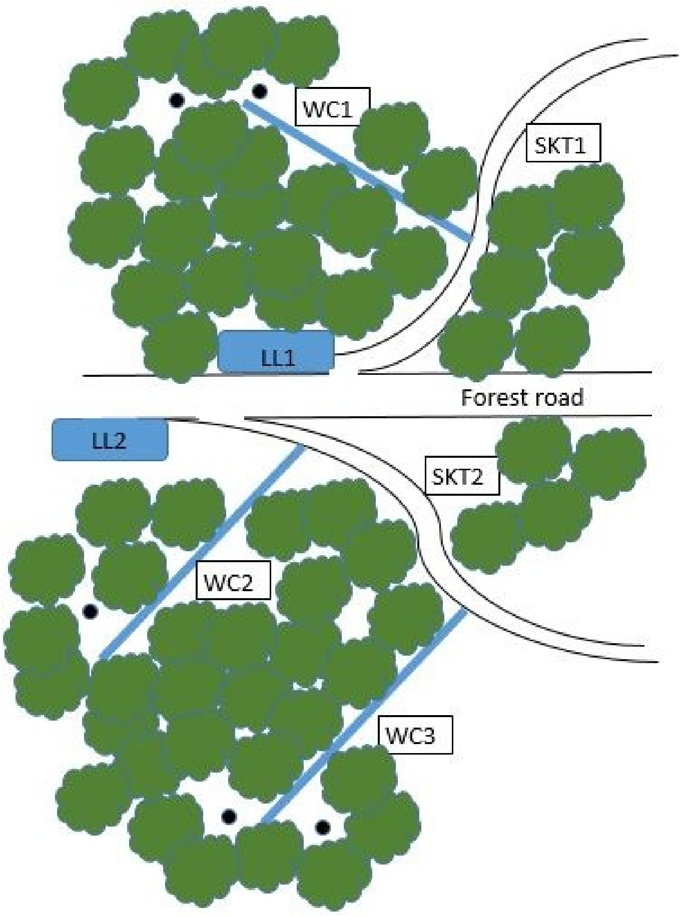

Figure 2. Schematic map of forest road, skid trails (SKT), winching corridors (WC), and log landings (LL) in the study area. The black circles represent the felled tree stumps.

The number and volume of trees cut and removed from this parcel in the third period of operation (winter 2011) were 248 trees and 822 m^3, respectively. Selected trees were cut and bucked by a chainsaw, and the trunks and logs were extracted using a Timberjack C450 rubber wheeled skidder. The weight of the skidder was 9.8 tons, the engine power was 177 horsepower, and its length and width were 6.4 and 3.8 m, respectively. The length of the extracted logs was 5.2 and 7.8 m, and the maximum length of the winching cable was 50 m (Nav FMP, 2008).

2.2. Data Collection

The growth and architectural indices of beech seedlings and some physical and chemical characteristics of the soil in four different microenvironments (experimental treatments) were investigated in summer 2021, ten years after logging operations. These physical and chemical characteristics were the result of the implementation of single-selection cuttings and ground-based logging operations in the forest under study. Microenvironments were identified and separated based on the canopy and soil conditions (Table 1). Seven-year-old healthy beech seedlings and soil samples were collected from three different microenvironments and from the control area.

Three skid trails and three winching corridors were randomly selected in the studied parcel. In order to eliminate the influence of variables such as machine traffic intensity and longitudinal slope of the skid trails on soil and seedling characteristics, the middle third of each skid trail and winching corridor, which had a longitudinal slope of 10 to 15%, was considered for collecting seedling and soil samples. Also, five logging gaps of a medium size (50 to 113 m^2) were randomly selected [27]. Beech seedlings and soil samples were collected from a distance of 50 m from the skid trails, winching corridors, and felling gaps to compare seedling growth and architecture indicators. Soil conditions were observed in research treatments in areas without soil compaction and a natural canopy (control treatment).

Table 1. Canopy and soil characteristics of the experimental treatments.

Treatment	Canopy and Soil Condition	Canopy Closure (%)
Skid trail	Removed canopy + compacted soil	5–10
Winching corridor	Natural canopy + compacted soil	80–100
Felling gap	Removed canopy + un-compacted soil	5–10
Control	Natural canopy + un-compacted soil	80–100

From each of the considered microenvironments and the control area, a total of five seven-year-old healthy seedlings were completely removed from the soil, including aerial and underground organisms, and then placed in plastic bags and transferred to the laboratory. The age of the seedlings was determined by the phyllotaxy method [28]. A soil sample was taken from a distance of 50 cm from each extracted seedling using a sampling cylinder with an inner diameter of 5 cm and a height of 10 cm from the upper surface of the soil after removing the litter. The amount of soil penetration resistance was measured using a pocket penetrometer, model Eijkelkamp, Zevenaar, Netherlands, at 0.5, and 10 cm soil depths at a distance of 0.5 m from each seedling in four repetitions (one sampling from each geographical direction).

The following variables were measured for each seedling: physical characteristics, including seedling height (SH), stem length (SL), stem diameter (SD), main root length (MRL), main root diameter (MRD), lateral root length (LRL) and root penetration depth (RPD); growth characteristics including total biomass (TB), above-ground biomass (AGB), and below-ground biomass (BGB); and architectural characteristics including root length to stem length ratio (RL/SL), lateral root to main ratio length (LRL/MRL), root biomass ratio (RDB/TDB), and seedling quality index. Root and stem diameters were measured using a vernier caliper (Insize Model 1205, Grieskirchen, Austria) five centimeters above and below the surface of the soil. A metal ruler was used to measure the root penetration depth, i.e., the vertical distance from the root tip to the soil surface. After drying at 70 °C until a steady weight was established, the seedlings' dry weight was determined [20]. The seedling quality index was subsequently calculated through Equation (1):

$$SQI = TB/[(SH/SD) + (AGB/BGB)] \tag{1}$$

The soil bulk density is the ratio of the dry weight of the soil to the volume of the soil sample (after drying the soil in an oven for 24 h at 105 °C). Equation (2) [29], the percentage of soil moisture by weight method [29], the total soil porosity from Equation (3) [30], the soil acidity (pH) in a 1:1 ratio of water to soil, the amount of soil organic matter using the Walkley and Black method [29], and the soil nitrogen were measured by the Kjeldahl method [30] in the laboratory.

$$BD = WD/VC \tag{2}$$

$$TP = [1 - (BD/2.65)] \times 100 \tag{3}$$

In Equation (1), BD is bulk density in g/cm^3, WD is the dry weight of soil in g, and VC is the volume of a cylinder of soil sample in cm^3. In Equation (3), TP is the total porosity of the soil in percent, BD is the soil bulk density in g/cm^3, and 2.65 is the density of soil particles (g/cm^3) determined in the same soil samples that were used to calculate the bulk density using a pycnometer [29].

It is worth highlighting that we focused on soil compaction as the major factor that generally influences root growth [31]. Further parameters that could be assessed are rutting and soil displacement. However, since our analysis focused on secondary and tertiary trails, the levels of rutting and soil displacement were negligible. Obviously, this is even more valid for the winching corridors. As a consequence, the soil disturbance, which was observed in the skid trails and winching corridors, affected only the removal of the litter layer and the organic horizon.

2.3. Data Analysis

Data analysis was performed using the SPSS version 20 software (Chicago, IL, USA). The normality of data distribution was checked using the Kolmogorov–Smirnov test ($\alpha = 0.05$) [31]. The homogeneity of variance between treatments was tested and confirmed using Levene's test ($\alpha = 0.05$) [32]. The effect of treatments (skid trail, winching corridors, felling gap, and control area) on soil properties and seedling characteristics was investigated using a one-way ANOVA [33]. Duncan's test was used to find the difference between treatment means at the $\alpha \leq 0.05$ level [34]. The Pearson correlation test was used to ascertain the association between the parameters of the soil and the seedlings.

3. Results

The results showed that all the physical and chemical properties of soil were affected by the experimental treatments (Figure 3). The soil from skid trails had the highest amount of soil bulk density and soil penetration resistance and the lowest amount of porosity, moisture, organic matter, and nitrogen. All the physical and chemical properties of the soil from skid trails were significantly different from the soil of the control area. The soil from winching corridors was also significantly different from the soil from the control area in all physical and chemical properties. The bulk density and penetration resistance of the soil from the winching corridors were higher than in the control area, while the porosity, humidity, organic matter, and nitrogen were lower than in the control area. The soil from felling gaps was not significantly different from the soil from the control area in terms of bulk density, porosity, penetration resistance, and acidity, but the amount of moisture, organic matter, and nitrogen was lower than in the control area.

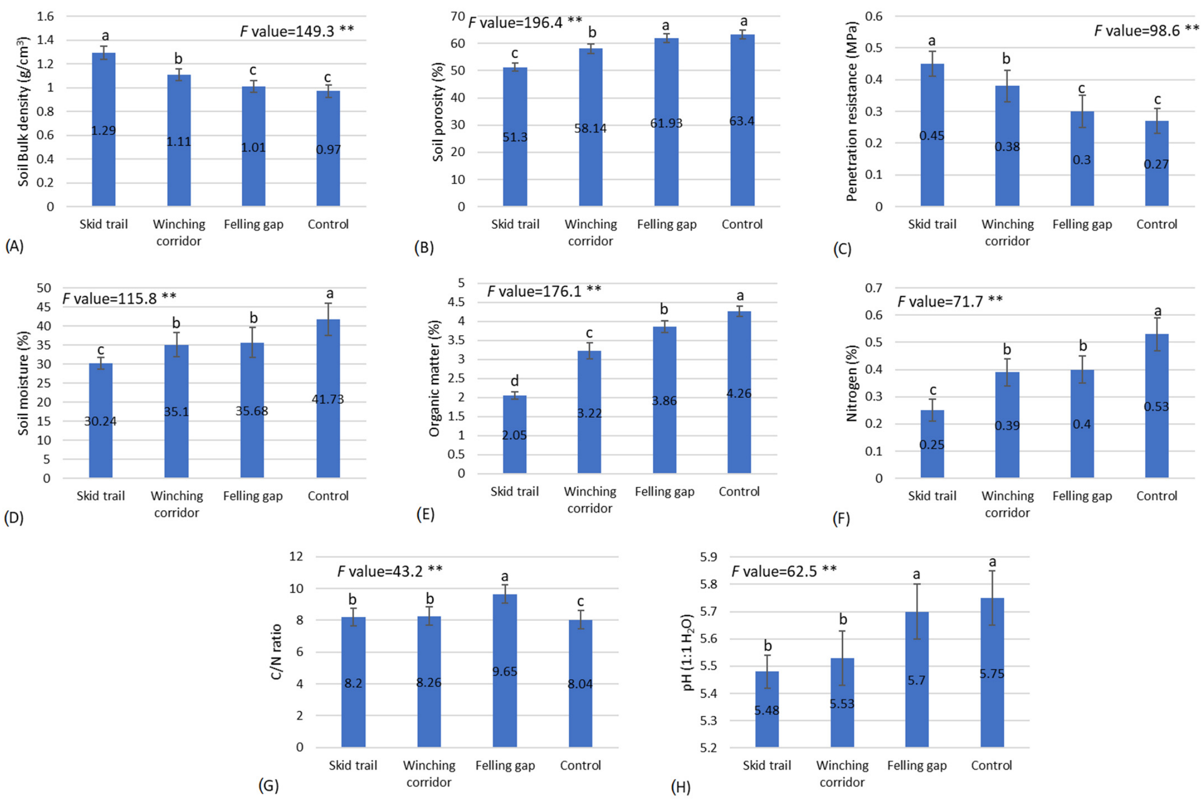

Figure 3. Physical and chemical characteristics of the soil of studied treatments. ** indicates significant differences at $\alpha = 0.01$; different lowercase letters indicate significant differences through Duncan's test at the $\alpha = 0.05$ level. Note that for all the sub figures (**A**–**H**) the soil characteristics showed are detailed in y axis.

The results of the analysis of variance showed that the treatments had a significant effect on all growth characteristics of beech seedlings (Figure 4). The average of all growth characteristics of beech saplings grown in skid trails and winching corridors was significantly lower than the control area. The average of all the growth characteristics of the beech seedlings grown in the felling gaps was higher than the control area, except for the length of the lateral root and the depth of root penetration, which was not significantly different from the control area.

Based on the results of the analysis of variance, the treatments had a significant effect on the biomass of beech seedlings (Table 2). The highest biomass of the beech seedlings was observed in the felling gaps and the lowest in the skid trails. The average biomass of beech seedlings in the skid trails and winching corridors was significantly lower than that of the felling gaps and control area.

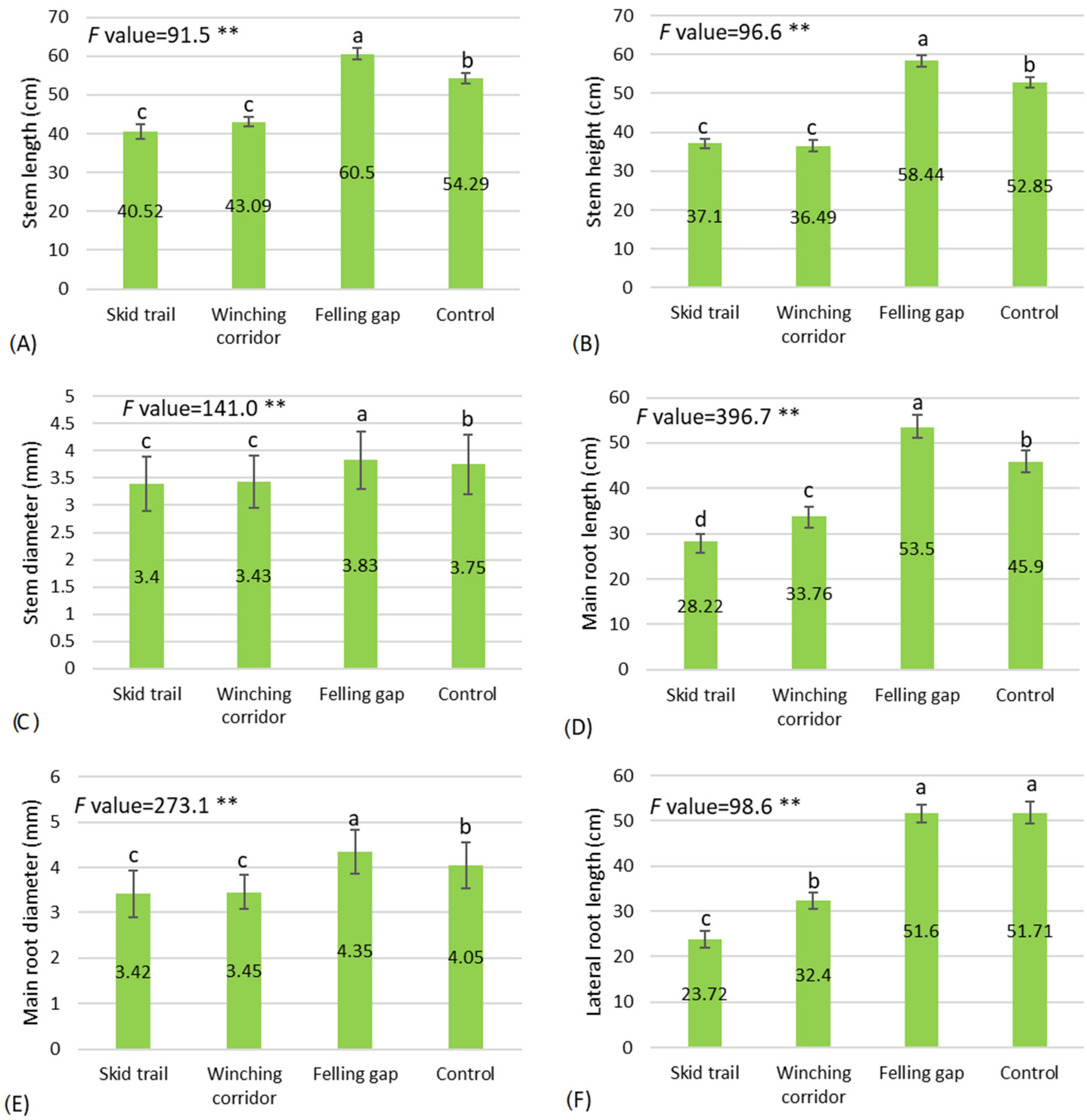

Figure 4. Growth characteristics of beech seedlings in the studied treatments. ** indicates significant differences at $\alpha = 0.01$; different lowercase letters indicate significant differences through Duncan's test at the $\alpha = 0.05$ level. Note that for all the sub figures (**A**–**F**) the seedlings growth characteristics showed are detailed in y axis.

Table 2. Biomass of beech seedlings in the studied treatments (mean ± standard deviation).

Growth Characteristics	Skid Trail	Winching Corridor	Felling Gap	Control Area	*F* Value
Above ground (gr)	21.32 ± 1.02 c	22.50 ± 1.05 c	31.77 ± 1.11 a	28.20 ± 1.08 b	89.2 **
Below ground (gr)	11.92 ± 0.95 d	14.61 ± 0.94 c	22.85 ± 1.17 a	19.74 ± 1.03 b	96.6 **
Whole of seedling (gr)	33.25 ± 1.07 d	37.11 ± 1.18 c	54.62 ± 1.40 a	47.94 ± 1.35 b	141.0 **

** indicates significant differences at α = 0.01; different lowercase letters in each row indicate significant differences through Duncan's test at the α = 0.05 level.

The changes made in the characteristics of the beech seedlings in the skid trails and winching corridors were lower (negative values) compared to the control area but higher (positive values) in the felling gap compared to the control area (Figure 5). The length of the lateral root, the biomass of the belowground, and the length of the main root in the skid trails had the highest growth reduction with values of 54.1%, 39.6%, and 38.6%, respectively. Also, on the skid trails, the total biomass decreased by 30.7%, the stem height decreased by 29.7%, the stem length decreased by 25.4%, and the above-ground biomass decreased by 24.5%. The decrease in the growth characteristics of beech seedlings in winching corridors was less than that of the skid trails. The greatest decrease in growth in the winching corridors was related to the decrease in the length of the lateral root by 37.3% and the decrease in the height of the stem by 30.8%. Also, in the winching corridors, the length of the main root and the height of the underground organs showed a significant decrease compared to the control area, with a value of 26.1% and 25.9%, respectively. Unlike the skid trails and winching corridors, the length of the main root and the biomass of the underground organs in the felling gaps were increased by 16.6% and 16.3%, respectively, compared to the control area. The total biomass and length of the stem were also increased by 14.2% and 11.4%, respectively, in the felling gaps compared to the control area.

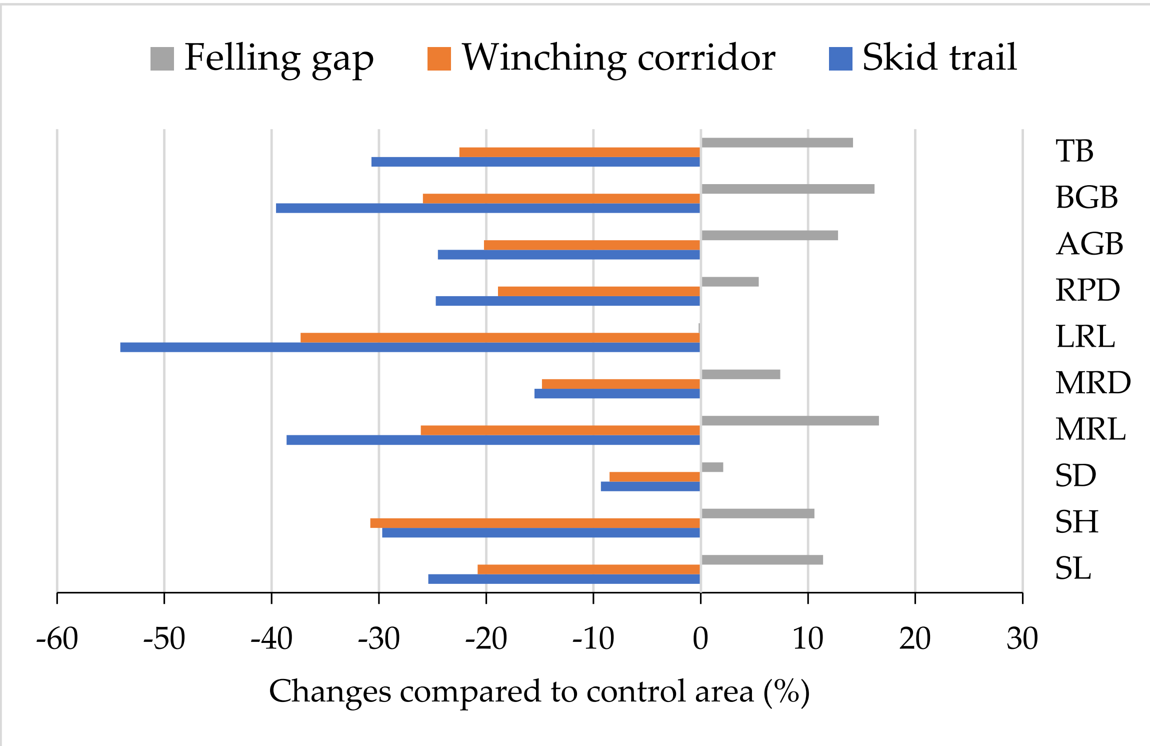

Figure 5. Average changes in the characteristics of beech seedlings in skid trails, winching corridors, and felling gaps compared to the control area (SL: Stem length, SH: stem height, SD: stem diameter, MRL: main root length, MRD: main root diameter, LRL: lateral root length, RPD; root penetration depth, AGB: above-ground biomass, BGB: below-ground biomass, and TB: total biomass).

The results of correlation tests showed that all the characteristics of the beech seedlings had a significant negative correlation with soil bulk density and penetration resistance and a significant positive correlation with soil porosity, moisture, and soil organic matter (Table 3). Lateral root length, root penetration depth, below-ground biomass, and total biomass had a positive significant correlation with soil nitrogen content. The length of the main root, the length of the lateral root, and the biomass below ground also had a positive significant correlation with soil acidity (pH value). The highest correlation coefficient value (R^2) was obtained between the characteristics of beech seedlings and soil penetration resistance.

Table 3. Correlation (R-value) between soil properties and beech seedling growth characteristics (SL: stem length, SH: stem height, SD: stem diameter, MRL: main root length, MRD: main root diameter, LRL: lateral root length, RPD: root penetration depth, AGB: above-ground biomass, BGB: below-ground biomass, TB: total biomass, BD: bulk density, SP: soil porosity, PR: penetration resistance, SM: soil moisture, OM: organic matter, TN: total N, pH: acidity value).

Soil Properties	SL (cm)	SH (cm)	SD (mm)	MRL (cm)	MRD (mm)	LRL (cm)	RPD (cm)	AGB (gr)	BGB (gr)	TB (gr)
BD (g/cm^3)	−0.49 **	−0.48 **	−0.50 **	−0.81 **	−0.55 **	−0.57 **	−0.69 **	−0.57 **	−0.69 **	−0.66 **
SP (%)	0.48 **	0.46 **	0.43 **	0.70 **	0.54 **	0.81 **	0.82 **	0.66 **	0.75 **	0.73 **
PR (MPa)	0.67 **	0.53 **	0.55 **	0.79 **	0.72 **	0.84 **	0.91 **	0.51 **	0.88 **	0.81 **
SM (%)	0.41 *	0.40 *	0.42 *	0.43 *	0.40 *	0.43 *	0.43 *	0.39 *	0.51 **	0.48 **
OM (%)	0.43 *	0.40 *	0.37 *	0.45 *	0.41 *	0.53 **	0.55 **	0.47 **	0.55 **	0.53 **
TN (%)	0.15 N.S.	0.20 N.S.	0.21 N.S.	0.14 N.S.	0.18 N.S.	0.39 *	0.39 *	0.24 N.S.	0.41 *	0.40 *
pH (1:1 H_2O)	0.10 N.S.	0.09 N.S.	0.11 N.S.	0.39 *	0.13 N.S.	0.40 *	0.25 N.S.	0.22 N.S.	0.43 *	0.23 N.S.

** indicates significant correlation at α = 0.01; * indicates significant correlation at α = 0.05; N.S.: not significant.

The results of the analysis of variance showed that the architectural indices of beech seedlings were influenced by the research treatments (Table 4).

Table 4. The results of the analysis of variance of the effects of treatments on the architectural indices of beech seedlings.

Seedling Architectural Indices	Root Length Ratio (MRL/SL)	Lateral Root Length Ratio (LRL/MRL)	Root Penetration Ratio (RPD/MRL)	Root Biomass Ratio (RB/TB)
F-value	76.9	102.5	98.3	3.08
p-value	0.001 **	0.000 **	0.000 **	0.045 *

** indicates significant differences at α = 0.01. * indicates significant differences at α = 0.05.

The root length ratio (MRL/SL) was the highest in the felling gap and control area and the lowest in the skid trails (Figure 6A). The lateral root length ratio (LRL/MRL) was the highest in the control area and the lowest in the skid trails (Figure 6B). The root biomass ratio (RB/TB) was the highest in the felling gap and control area and the lowest in the skid trails (Figure 6C). The seedling quality index in the felling gaps and control area was significantly higher than in the winching corridors and skid trails (Figure 6D).

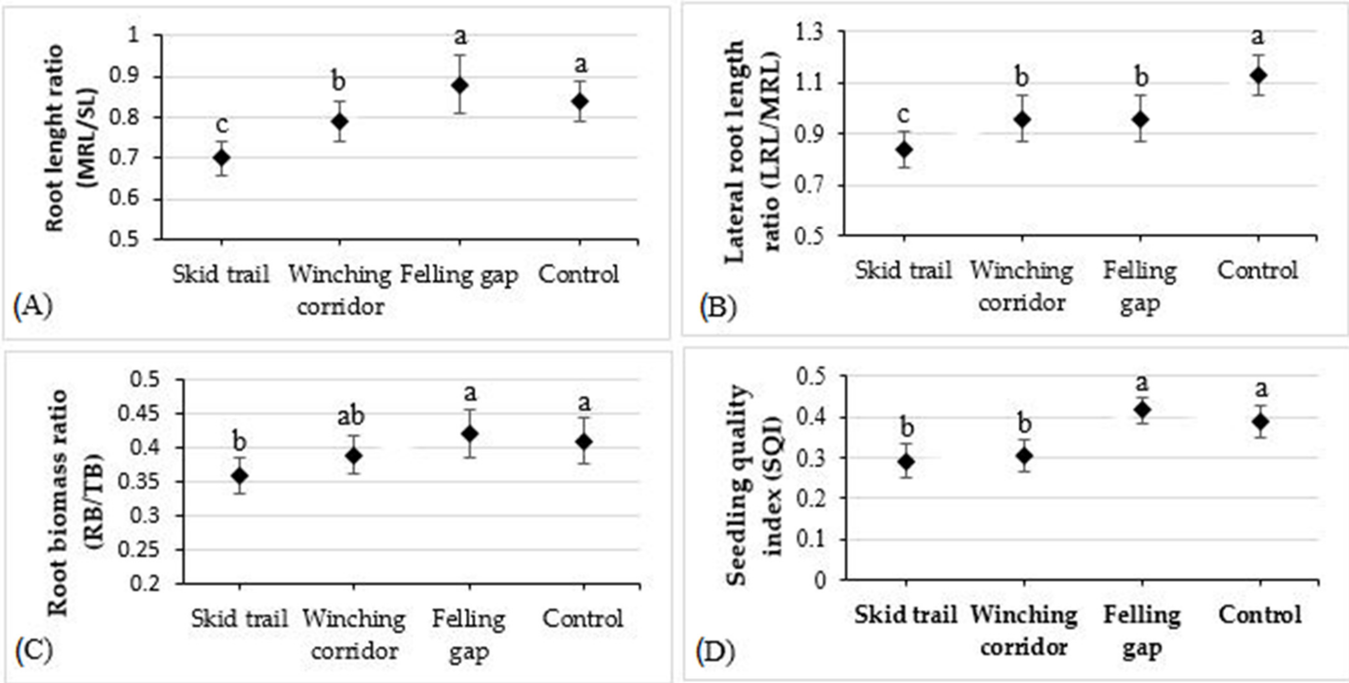

Figure 6. Average architectural indices of beech seedlings in the studied treatments: (**A**) Root length ratio, (**B**) Lateral root length ratio, (**C**) Root biomass ratio, (**D**) Seedling quality index. Error bars indicate ± SD. Different lowercase letters indicate significant differences through Duncan's test at the $\alpha = 0.05$ level.

4. Discussion

The results of this study showed that the physical and chemical properties of the soil were influenced by various disturbances caused by logging operations in the studied forest, leading to the confirmation of both research hypotheses. Even though ten years had passed since the operation, the soil bulk density and soil penetration resistance of skid trails and winching corridors were still significantly higher than that of the control area, and the amount of porosity, moisture, organic matter, and nitrogen of their soil was lower than that of the control area. Skidders used in logging operations usually have a large mass and can cause significant damage to the forest soil, which often has a very poor bearing capacity [11,32,33]. The highest levels of soil disturbance are generally found in the case of repeated machine passage on steep slopes (>20%) [34]. Of course, appropriate technical options can be used to reduce this type of soil damage and restore it [16,35,36].

Compacted soils are less able to store water because of their decreased porosity [37]. Soil water content has been reported to be a limiting factor for western beech (*Fagus sylvatica* L.) seedling survival [38,39]. Several studies emphasize the effects of forest operations on soil and forest regeneration [40]. Because compacted soil from forest harvesting activities restricts plant roots' access to nutrients and water and lowers air pollution, it is crucial in slowing down plant root growth [41,42]. According to Pinard et al. (2000) [22], who studied the topic in Malaysian forests, the density and richness of woody plants in the skid trails was lower than in the control site after 17 years [43].

Tan et al. (2005) [42] investigated the effects of soil compaction and forest floor removal on soil microbial properties and N transformations in a boreal forest. They found that nitrification rates were lowered in both the forest floor and the mineral soils and that soil compaction decreased soil microbial biomass N (MBN) but increased the microbial C:N ratio in the mineral soil. Short-term N transformation rates were not adversely affected by the removal of the forest floor, yet N export from the removed organic matter was comparatively high.

Two major objectives of organic matter management in the boreal forests are to preserve the organic matter and nutrient capitals on the site to promote long-term site productivity and to manipulate the organic matter to increase rates of decomposition and nutrient mineralization, improve seedbeds and reduce competing vegetation to enhance short-term productivity, such as seedling growth [43].

Štraus et al. (2023) [44] studied plant–soil feedback among boreal forests for four tree seedling species (*Alnus glutinosa* (L.) Gaertn., *Betula pendula* Roth., *Picea abies* (L.) H. Karst., and *Pinus sylvestris* L.). They reported that Ectomycorrhizal fungi (EMF) enhanced the growth of most seedlings, Actinomycetota supported alder and birch growth, and fungal plant pathogens hampered pine growth. Increased growth was linked to the ability of trees to recruit specific EMF and root-associated fungi in heterospecific soils.

The results showed that all characteristics of beech seedlings grown in skid trails and winching corridors were lower than the control area, while the characteristics of beech seedlings grown in felling gaps were higher than the control area. One of the basic requirements of sustainable forest management in mixed broadleaf stands is to provide suitable conditions for the natural regeneration of trees. These conditions include but are not limited to, the abundance, quality, and composition of seedling species [45,46].

The results of this research showed that the average biomass of beech seedlings in skid trails and winching corridors was significantly lower than that of the felling gaps and control area. Root biomass indicates the ability of the root system to absorb water and nutrients, which ensures better seedling survival [47]. According to the present study, Jourgholami et al. [17] investigated how the morphology, development, and architecture of oak saplings in the northern Iranian woodlands were affected by soil compaction. Their findings support ours, demonstrating that soil compaction had an impact on seedling traits, including size and biomass.

The growth characteristics of beech seedlings were negatively correlated with soil bulk density, while they were positively correlated with soil porosity. According to our findings, thinner roots, shorter lateral roots, and a lower root penetration depth were all related to higher soil bulk density. Similar results have been found by Mósena and Dillenburg [48], Jourgholami [49], and Picchio et al. [20]. This finding was also confirmed by Naghdi et al. (2016) [30], who showed that the root length of maple seedlings has a negative relationship with soil bulk density. The growth characteristics of beech seedlings were positively correlated with soil moisture, organic matter, and nitrogen content. Beech root biomass has been reported to be positively related to water availability [50]. According to the current results, Jourgholami [49] revealed that there was a negative correlation between bulk density and soil penetration resistance and a positive correlation between stem and main root length, total stem and root dry mass, and soil porosity. Low root biomass ratio seedlings may be more vulnerable to water deficit stress under natural conditions. According to the results of this research, Cambi et al. [19] showed that high soil compaction (+27%) reduces the yield of oak seedlings (*Quercus robur* L.) in terms of height (−26%) and root growth (−24%).

The results showed that the architecture of beech seedlings was affected by disturbances caused by forest harvesting operations. Roots grow mainly downwards, and compacted soils are more resistant than those with lower bulk density [50,51]. High resistance to penetration changes the shape of the root system from the normal pattern [52–54]. Increasing soil strength (resistance to infiltration) may change the proportional growth allocation between aboveground and belowground parts of seedlings (root length ratio) [17,55,56].

Summarizing, this study confirmed that the major driver of disturbance to the establishment and growth of natural regeneration after single-selection intervention is soil compaction, which occurs along the skid trails and winching corridors. Thus, the careful planning of the skid trail network becomes a fundamental issue in reducing the negative consequences of logging operations on the forest soil. Furthermore, the application of Best Management Practices to reduce soil compaction, for example, placing brush mats on the trails and using snatch blocks while winching, can be an effective measure to decrease the effects of soil compaction in both skid trails and winching corridors [57–59]. We, therefore, recommend that these solutions should become part of the local regulations concerning forest interventions and be routinely applied to ensure the sustainability of logging operations. However, as a future research direction, we recommend specifically testing the efficacy of such Best Management Practices in the study context, in order to be able to shape effective and evidence-based management recommendations for the valuable forest ecosystems in the Hyrcanian forests.

5. Conclusions

Forest soil maintenance is a key factor in maintaining productive forests. The growth of natural seedlings of good quality is one of the important goals of forest management in mixed uneven-aged stands. Mechanized forest operations can have destructive effects on the physical and chemical properties of the soil and the regeneration of forest stands. In the present research, the growth and architectural response of beech seedlings to soil and canopy disturbances caused by logging operations, including four microenvironments of logging road, winching corridor, felling gap, and control area in mixed beech forests, were investigated. The study shows that the skid trails and winching corridors had a negative effect on the quantitative and qualitative characteristics of beech seedlings, while the beech seedlings established in felling gaps had better growth characteristics, architecture, and quality than the control area. The results showed that skid trails caused a decrease in AGB of −24.5%, BGB of −39.6%, root penetration depth of −24.7%, and seedling quality index of −12.2% compared to their values in the undisturbed area (control). Also, winching corridors caused a decrease in AGB of −20.2%, BGB of −25.9%, root penetration depth of −18.9%, and seedling quality index of −4.9% compared to their values in the control. The felling gaps caused an increase in the AGB of +12.8%, BGB of +16.2%, root penetration depth of +5.4%, and seedling quality index of +2.4% compared to their values in the control. Seedlings biomass (boss AGB and BGB) had a significant negative correlation ($p < 0.01$) with soil bulk density and penetration resistance and a significant positive correlation ($p < 0.05$) with soil porosity, moisture, and organic matter content. In general, it can be concluded that beech seedlings are sensitive to soil compaction, and their growth is greatly reduced in compacted soils. The conditions of canopy opening without soil compaction, such as felling gaps, created suitable conditions for the establishment and quality growth of beech seedlings. Therefore, the goal of managing these forests should be primarily to reduce the intensity of soil compaction and also to minimize the disturbed soil surface under the influence of skidder traffic. In this context, the standard design and construction of skid trails play an essential role. Also, the bioengineering operation after the completion of logging operations is very important and decisive in order to have a faster recovery of the physical, chemical, and biological properties of compacted soils. Microbial and fungal factors of the soil may have an effect on the amount of growth of beech seedlings through symbiosis with the roots, which were not investigated in the present research and can be of interest in future research.

Author Contributions: Conceptualization, F.T., A.R.K., R.N.; methodology, F.T., A.R.K., R.N.; formal analysis, F.T., A.R.K., R.N.; writing—original draft preparation, F.T., A.R.K., R.N.; writing—review and editing, F.T., F.L., R.V., R.P.; supervision, R.P. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the Italian Ministry for Education, University and Research (MIUR) for financial support (Law 232/2016, Italian University Departments of Excellence 2023–2027) project "Digitali, Intelligenti, Verdi e Sostenibili (D.I.Ver.So)—UNITUS-DAFNE WP3".

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data are available from the corresponding author upon reasonable request.

Conflicts of Interest: The authors declare no conflicts of interest.

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