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Morphology, Growth and Architecture Response of Beech (*Fagus orientalis* Lipsky) and Maple Tree (*Acer velutinum* Boiss.) Seedlings to Soil Compaction Stress Caused by Mechanized Logging Operations

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Abstract: The Caspian forests of Iran were monitored and evaluated for forest natural regeneration after logging activities for more than a decade. This large area has a substantial ecological, environmental and socio-economic importance. Ground based skidding is the most common logging method in these forests and soil compaction is the most critical consequence of this method. One of the current main topics and important emerging issue in forest research of the last decade are discussed in this study. Soil compaction has major influences on growth and/or mortality rates of forest seedlings. This study has lasted for over ten years so as to have a clear overview related to forest natural regeneration after logging activities. We monitored and evaluated physical soil properties (bulk density, penetration resistance and total porosity) and their effects on maple and beech seedlings on 10-year-old skid trails in the Iranian Caspian forests. Results obtained from evaluating the impact of skid trails within the aforementioned three soil physical parameters were significant; bulk density increased by 12.6% on log skidded routes (between two skidder tires on skid trail) and 36.1% on tire tracks, compared to non-skid trails (1.19 g/cm^3), penetration resistance increased by 68% on log skidded routes and 220% on tire tracks, compared to non-skid trails (0.25 MPa), total porosity decreased by 12.8% on log skidded routes and 30.9% on tire tracks, compared to non-skid trails (54%). Among the morphological parameters, lateral root length (LRL) and root penetration depth (RPD) showed the highest decrease at soil compaction compared to the control (decrease in LRL: 60% in maple and 44% in beech; decrease in RPD: 56% in both maple and beech); the main response of growth parameters to soil compaction was found in roots (decrease in dry mass of 36% both in maple and beech); architectural parameters were also influenced by soil compaction, and the response of both seedling species was more evident in the ratio of main root to stem length (RRS) (reduction in RRS 42% in maple, 33% in beech); the ratio of RPD to main root length (RPL) also showed a great reduction (reduction in RPL 20% in maple 33% in beech). Physical soil properties, changes in other environmental properties of skid trails, created differences in beech and maple seedling growth between the skid trails and non-skid trails. This was closely related to the physiological characteristics of the two species studied. Beech seedlings reacted well to a moderate uncovering but they needed little disturbed soil, even if there was a very mixed bedding. Maple seedlings reacted better than beech seedlings to the uncovering and soil disturbance. The effects of the skid trail on morphology, growth and architecture of maple seedlings in the Hyrcanian beech forests showed that the maple, as a seedling, is a suitable species for maintaining the physical properties of skid trails after logging operations in the beech stands in the Caspian forests of Iran.

Keywords: biomass growth; biomass ratio; root penetration; bulk density; skid trail; root development; timber extraction

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1. Introduction

The use of heavy machinery for logging operations has increased in world forests due to their high productivity rate during last decades [1,2]. Extensive damage to the soil potentially creates a serious threat to the soil ecosystem [3,4]. The United States Department of Agriculture (USDA) Forest Service has cited a critical level of forest soil disturbance at 20% of the total logging area, including roads, skid trails and landings; and compaction standard states that bulk density cannot increase more than 15% from its natural (undisturbed) level in the top 20 cm of soil. However, critical level of soil disturbance can be determined based on the weather conditions, vegetation, topographic and habitat characteristics of each forest area [5]. In recent decades, concerns about the protection of soil during forest operations have been raised. Logging operations cause some degree of soil disturbance [5].

Compaction of forest soils by heavy machinery is a common consequence of logging operations. Compaction negatively alters soil structure increasing soil bulk density and strength; it decreases water and air movement into soil and increases surface runoff and erosion [6–8], by breaking down soil aggregation, and by decreasing porosity, aeration, and infiltration capacity [9,10]. Soil disturbance due to mechanized logging operations in forests influences stand growth and yield by affecting seed germination, seedling survival, root growth [11] and establishment.

Bulk density is usually higher on log landings and skid trails than in undisturbed forest soils [12]. A significantly different bulk density between disturbed and undisturbed areas was found by Marchi et al. [13].

Soil compaction, caused by harvesting operations, limits the effective rooting depth of plants by restricting access to water, nutrients and by reducing gaseous exchange [14]. The physical effects of soil compaction may thus lead to reductions in water, solutes, and gas movements through the soil, reductions in exchange processes such as changes in carbon dioxide efflux from the soil, and reductions in the availability of water and nutrients [15,16]. Reductions in air permeability and soil porosity diminish the penetrability of the soil for roots [16] and limit root extension, elongation, branching, density, and penetration of primary roots as well as root access to, and uptake of, soil moisture and nutrients [15]. Root growth in soil can be limited by physical, chemical, and biological properties of the soil. Naghdi et al. [17] stated germination rate, root length, and stem height of maple seedlings were inversely related to soil compaction.

Higher penetration resistance reduces elongation and penetration of roots, and thus lowers the uptake of water and nutrients [9]. Seedlings with less developed root systems are more sensitive to soil compaction than the adult trees [9]. A higher seedling mortality and reduced tree growth of Norway spruce (*Picea abies* (L.) Karst.) on compacted soils was reported by Gebauer and Martinková [18]. Murphy et al. [19] reported a decreasing height growth of *Pinus radiata* D.Don. due to soil compaction following logging operations and observed that the effects of soil compaction on soil productivity rate can continue for several decades.

According to a study by Pinard et al. [20] in Malaysian forests, the highest mortality rates of established seedlings after one year from the time of logging, were reported on skid trails. This was due to the soil compaction and to the inaccessibility of soil nutrients for seedlings. Jourgholami [21] observed that all morphological and architectural variables of in *Acer cappadocicum* Gled seedlings changed negatively with increasing soil penetration resistance. For the same species Solgi et al. [22] showed that only three skidder passes over the same skid trail produced soil features that were detrimental to seedlings growth and long-term site productivity. Establishing vegetative cover on the skid trails reduces soil erosion and prevents offsite sediment. Tavankar et al. [12] found that soil bulk density of the top 10 cm on the winching area and on skid trails increased 10.7% and 32.1%

more than the controlled area, after using a wheeled skidder for skidding during selection cutting in the north of Iran. Williamson and Neilsen [6] found that a single pass by a rubber-tired skidder increased soil bulk density of the top 10 cm by 22% in the Tasmanian forests. Meek et al. [23] reported a reduction in infiltration rates of 54% when the soil was compacted from 1.6 g/cm^3 to 1.8 g/cm^3. Naghdi et al. [17] studied the influence of ground-based skidding on physical and chemical properties of forest soils and their effects on maple seedling growth in the Caspian forests of Iran. Their results indicated that significant differences between undisturbed areas and machine trail areas, of bulk density (0.75 g/cm^3 vs. 1.26 g/cm^3) and total porosity (70.6% vs. 50.4%) were strongly related to the level of traffic frequency and to the trail gradient. Physical and chemical soil properties are often significantly impacted by skidding operations, depending on trail gradient and traffic frequency, which resulted in the decrease of seedling growth. Jourgholami et al. [24] studied the effects of soil compaction on seedling morphology, growth, and architecture of chestnut-leaved oak (*Quercus castaneifolia* C.A. Mey.) in the Caspian forests of Iran. These results indicated that both above- and below-ground seedling characteristics, including size and biomass, were negatively affected by soil compaction. At the highest intensity of compaction, size and growth were reduced by 50% compared to controls; negative effects were typically more severe on below-ground (i.e., the length and biomass of the root system) than on above-ground responses. Soil compaction reduces macropores and total porosity, infiltration capacity and permeability to water, and increases penetration resistance [9]. Increased soil penetration resistance can reduce, overall, seedling growth performance [24,25]. Tree seedlings tend to be particularly sensitive to the increase of soil penetration resistance [26]. Sustainable timber production of natural high forests needs the continuous establishment of natural tree regeneration and adequate growth of seedlings [27].

The Caspian forests of Iran have an area of about 2 million hectares and are located from the north of the country to the southern coasts of the Caspian Sea in the northern parts of the Alborz mountain belt, from sea level to 2800 m a.s.l. These forests are the most valuable forests in Iran. The main natural characteristics of these forests are the large number of hardwood species, the biological diversity, the richness of endemic and endangered species and the large amount of ecological niches. These forests have been managed by single tree selection cutting silviculture as close-to-nature method since 2015. Since then timber harvesting from these forests has been limited to the harvest of damaged trees, including broken, fallen, uprooted, infested and diseased trees [28,29]. Logging operations in these forests are generally performed using a ground-based skidding system. Chainsaws and cable skidders are two of the main logging machines for wood harvesting. Temporary skid trails with a distance of 120 m from each other are the most common type of forest roads designed and constructed for short-term timber harvesting in the Caspian forests of Iran [30].

Due to steep slopes of the Caspian forests, most of the skid trails are built by excavator. Although oriental beech (*Fagus orientalis* Lipsky) forest sites are highly suitable for timber production [31], these sites are also located in steep mountainous terrain on marls (35% lime and 65% clay) which have low infiltration capacity and are susceptible to intense runoff and erosion after heavy rainfall [32]. Seedling growth and survival following skidding, are of particular concern in the Caspian oriental beech forests. Mixed and pure beech stands occupy about 20% of these forests and produce more than 35% of the total wood stock volume of the Caspian forests [33]. Maple tree (*Acer velutinum* Boiss.) is one of the first woody species that establishes naturally a few years after selective logging and grows on the skid trails in the Caspian forests [17].

Timber or biomass extraction and forest logging affect forest soil, and natural renovation is particularly crucial for the maintenance of biodiversity. Monitoring the effects of forest operations is a requirement for sustainable forest management.

Beech is the most frequent species in mixed forest and the forestry interventions are aimed at its affirmation both in pure and mixed stands. The maple tree and beech are both of commercial interest in these forests. The seedlings of the maple tree and beech were selected as experiment objects in this study. Maple is a pioneer and shade intolerant species, suitable for restoring compacted soils, hence it is the preferred species for revegetating machine operating trails and landings in the Caspian forests. Beech is the shade tolerant tree, with a significant economic importance.

The aims of this study were: (1) To determine soil physiochemical properties after 10 years from machinery logging operation, (2) to determine the effects of soil compaction on seedling morphology, growth and architecture, (3) to identify the growth variable most responsive to soil compaction level, and (4) to obtain models of growth variables of seedlings in natural sites.

2. Materials and Methods

2.1. Study Area

The study was conducted in the Iranian Caspian forests. The study area is located in the Nav forests (latitude: 37°38′34′′ to 37°42′21′′ N; longitude: 48°48′44′′ to 48°52′30′′ E) in the Guilan province, north of Iran. The elevation in the study area is approximately 1450 m a.s.l. and the site is oriented towards the north. The mean annual precipitation is approximately 950 mm and the mean annual temperature is 9.1 °C.

According to the United States Department of Agriculture (USDA) soil taxonomy, the soils are Alfisols (brown forest soil) and the soil texture is sandy clay loam. The bedrock type is siltstone and limestone, which belong to the upper Jurassic and lower Cretaceous periods. The average depth of soil to the bedrock ranged from 60 cm to 90 cm, which is well-drained.

Forest type is uneven-aged mixed hardwood species, dominated by beech (45%), and hornbeam (*Carpinus betulus* L.) (20%). Other tree species are Caucasian alder (*Alnus subcordata* C.A. Mey.) (13%), Maple (*Acer velutinum* Boiss.) (11%), Cappadocian maple (*Acer cappadocicum* Gled.) (6%), Wych elm (*Ulmus glabra* Huds.) (2%), Lime tree (*Tilia begonifolia* Stev.) (2%), other Spp. (1%). Canopy cover is 90%. Tree density is 311 stem ha^{-1}, standing volume is 274 m^3 ha^{-1}, basal area of trees is 19.8 m^2 ha^{-1}. Skid trail density in the study area is 30 m ha^{-1} [12].

During December and January of 2007, marked trees (10.7 trees/ha) were felled using motor-manual felling, topped at merchantable height of 20 cm DUB (Diameter Under Bark). Due to the high soil moisture in winter and to prevent future damage to the soil, during May and June of 2007 the logs were winched on the constructed skid trails and were skidded in the shape of long logs to roadside landings using a Timberjack 450C wheeled skidder. The weight of the skidder was 9.8 Mg (55% on the front and 45% on the rear axle), and its width and length were 3.8 m and 6.4 m, respectively, with engine power of 177 hp (132 kW). It is equipped with a blade for light pushing of obstacles and stacking of logs. The skidder was fitted with size 24.5–32 tires inflated to 220 kPa on both front and rear axles.

2.2. Sampling Design and Data Collection

In June 2017 (10 years after logging), about 100 m of skid trails were selected to compare physical soil properties and beech (*Fagus orientalis* Lipsky) and maple (*Acer velutinum* Boiss.) seedling characteristics between the skid trail and the near undisturbed forest area (control). The sampled skid trails represented about the 30% of the total trail length, and they had an average longitudinal gradient of 35%. Five sample plots (10 m × 4 m) with random starting points and regular distance of 5 m intervals were taken on the skid trails. Actually, sample plots were placed to cover the width of the skid trail (4 m) and 10 m along the skid trail. For each skid-trail sample, three samples (2 m × 2 m) were taken at a 50 m distance from the skid trail in the undisturbed interior stand as control plots. Three main physical soil properties were measured in plots: bulk density, penetration resistance and total porosity (Figure 1).

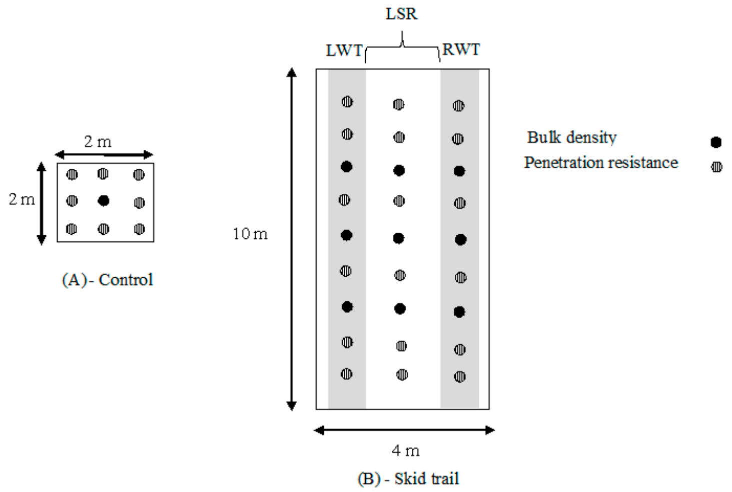

Figure 1. Sample plots on control (**A**) and skid trail (**B**), and bulk density and penetration resistance on plot, LWT: Left wheel track, RWT: Right wheel track, LSR: Log skidded route.

On each skid-trail sample, 9 soil core samples (3 samples on the left wheel tracks, 3 samples on the right wheel tracks, and three core samples on log skidded routes, between the two wheel tracks) were taken to measure soil bulk density. Also, one core sample from the center of the control plot was taken. In total, 30 soil core samples were taken from wheel tracks, 15 soil core samples from log skidded routes, and 15 soil core samples from undisturbed (control) sites.

Soil parameters were derived using ASTM soil laboratory measurements standards. The soil samples of 10 cm in deep were collected with a soil hammer and rings (diameter 5 cm, length 10 cm), put in polyethylene bags, and immediately labeled. Surface litter and duff were removed before sampling. The soil samples were dried in an oven under 105 °C for 24 h to obtain dry bulk density [34].

Sample volumes and weights were corrected for large roots, wood, or gravel. The dry bulk density was calculated from the Equation (1):

$$\rho_d = \frac{(W_d - W_c)}{V_c} \tag{1}$$

where, ρ_d is the soil dry bulk density (g/cm^3), W_d is dry weight of the sampler complete of the soil sample (g), W_c is weight of the cylinder sampler (g) and V_c is volume of the cylinder sampler (cm^3).

On each skid-trail sample, the soil penetration resistance (PR) was measured in 18 points (6 points on left wheel track, 6 points on right wheel track, and 6 points on log skidded routes, between the two wheel tracks) by a hand-held penetrometer (Eijkelkamp, Zevenaar, The Netherlands) at depths of 0 cm, 5 cm, and 10 cm. Also, PR was measured in 8 points for each control plot. Totally, the number of measured PR on the wheel tracks, log skidded routes and control areas, were 60, 30 and 120, respectively.

The total soil porosity was calculated as Equation (2):

$$AP = 1 - \left(\frac{\rho_d}{2.59}\right) \times 100 \tag{2}$$

where AP is the total porosity (%), ρ_d is the dry bulk density (g /cm^3), and 2.59 g /cm^3 is the particle density measured by a pycnometer on the same soil samples used to determine the bulk density [1].

Soil pH was determined using an Orion Model 901 pH meter (Orion Research, Cambridge, MA, USA) in a 1:2.5, soil/water solution, soil organic C (OC) was determined using the Walkley-Black technique, and total N (TN) using a semi-micro-Kjeldahl technique [1].

Seedling response to different soil properties was measured by several variables. The traditional measure is height growth. Forms of below-ground growth and biomass are also significant measure growth responses [35]. On each area treated (wheel track, log skidded, and control) 27 normal seedlings of maple tree (nearest to the soil bulk density samples) with stem lengths between 30 cm–60 cm and

7 years age of were selected. Seedling age was determined by phyllotaxy, and the following parameters were measured for each seedling:

Morphological parameters: Stem length (SL), stem diameter (SD), main root length (MRL), main root diameter (MRD), lateral root length (LRL), and root penetration depth (RPD). Growth parameters: Total dry biomass (TDB), stem dry biomass (SDB), and root dry biomass (RDB). Architectural parameters: Ratio of lateral to main root length (RLM), root mass ratio (RMR; ratio of RDB to TDB), stem mass ratio (SMR, ratio of SDB to TDB), ratio of main root length to stem length (RRS), and ratio of root penetration to main root length (RPL).

Stem and root diameter were measured by a vernier caliper (Insize Model 1205, INSIZE, Queensland, Austria), 5 cm above and below of the soil surface, respectively. The vertical distance from the tip of the root to the soil surface was measured by a metal ruler as the root penetration depth. Dry weights (biomass) of seedlings were obtained after drying at 70 °C until a constant weight was reached.

Quality indicators of seedlings included sturdiness quotient (SQ) and root-shoot ratio (RS). The SQ and RS were calculated by Equation (3) [36], and Equation (4) [37], respectively:

$$SQ = \frac{SH(cm)}{RCD(mm)} \tag{3}$$

$$RS = \frac{RDB\ (g)}{SDB\ (g)} \tag{4}$$

2.3. Data Analysis

The means of soil bulk density bulk density (BD), AP and PR, and the means of seedling parameters in three treatment areas were compared by one-way analysis of variance (ANOVA) and Duncan test at significance level of 0.05. The relationship between bulk density (BD) and stem length (SL), stem diameter (SD), main root length (MRL), lateral root length (LRL), root penetration depth (RPD) and total dry biomass (TDB); between seedling stem length (SL) and MRL, LRL, RPD, RDB, and TDB; and the relationship between MRL and RPD, were analyzed by correlation and regression in the three treatment areas. The nMDS (Non-metric multidimensional scaling) approach was used to analyze the differences of the main indicators of the seedling performance tested among the three areas. All analyses were performed using SPSS 19 (IBM, New York, NY, USA).

3. Results

3.1. Soil Environment

Impact of skidding on the three physical soil parameters was significant, with a higher level of impact in the wheel track and slightly lower in log skidded compared to Control (Table 1). Moreover, ten years later the larger number of tractor passes increased bulk density from 12.6% to 36.1% and penetration resistance from 68.0% to 220.0%, while porosity declined from 12.8% to 30.9% in winching corridors and tire track (Table 1). Amount of organic C and total N in the tire track and winching corridor were significantly lower than the control. The pH value on the control was significantly lower than the tire track and winching corridor.

Table 1. Soil physiochemical properties on three areas and ANOVA and Duncan test results (Mean ± SD).

Soil Physiochemical Properties	(A) Control	(B) Log Skidded	(C) Tire Track	*F*-Value	*p*-Value
Bulk density (g/cm^3)	1.19 ± 0.06 a	1.34 ± 0.08 b	1.62 ± 0.08 c	104.8	0.000
Penetration resistance (MPa)	0.25 ± 0.05 a	0.42 ± 0.07 b	0.80 ± 0.08 c	730.2	0.000
Total porosity (%)	54.0 ± 2.22 c	47.1 ± 3.02 b	37.3 ± 3.24 a	359.9	0.000
Organic C (%)	3.51 ± 0.28 a	2.24 ± 0.24 b	1.36 ± 0.20 c	488.5	0.000
Total N (%)	0.44 ± 0.04 a	0.15 ± 0.02 b	0.10 ± 0.04 c	596.1	0.000
pH	5.82 ± 0.29 c	6.12 ± 0.30 b	6.51 ± 0.32 a	32.5	0.000

Data followed by different letters within a column differ significantly according to Tukey's test ($p < 0.05$) .

3.2. Effect of Soil Compaction on Seedling Morphology, Growth Biomass and Architecture

3.2.1. Morphology

Considering the growth mode and the plagiotropic behavior of the seedlings in beech, both stem length and height were measured. However, seedlings of both beech and maple did not show statistical differences from the control area (Table 2) referring to height or stem length, while for all other parameters clear statistical differences were found. Length and diameter of the main root were significantly reduced by soil compaction, lateral root length in the compacted soils was significantly shorter than control, root penetration length decreased from control area to wheel track.

In the skid trail soil, root penetration depth decreased by 56% compared to forest soil, this for both beech and maple seedlings. A lower reduction was observed in the winching corridor, 41% and 39% respectively, compared to the control.

Soil compaction had a significant effect on diameter reduction of stem (B = −10.70%, C = −18.51%) and root (B = −10.06%, C = −17.77%) (Table 2) in beech seedlings, while stem diameter (B = +8.12%, C = +21.07%) and main root diameter (B = +5.28%, C = +25.28) of maple seedlings increased in wheel track compared to winching corridors and tire track.

3.2.2. Growth (Biomass)

Soil compaction had a significant effect on the reduction of stem and dry root biomass of beech (Table 2 Beech). Seedling biomass in the compacted soils (B = −24.2% and C = −35.0%) was significantly lower than the control (A). Dry stem biomass in the tire track (C) and winching corridor (B) was 34.3% and 20.8% lower, respectively, than the control (C). Dry root biomass in the tire track (C) and winching corridor (B) was 36.1% and 29.3% lower, respectively, than the control (A).

Regarding maple seedling growth (Table 2 Maple), only dry root biomass showed a statistical difference; the value decreased from the control area to the wheel track (C = −35.7%), with an intermediate value in the area of log skidded (B = −20.26), in accordance with main root length, lateral root length and root penetration length decrease. Dry stem biomass (B = +4.5%, and C = +5.4%) did not show an effective statistical difference from the control area, while total dry biomass with the *p*-value of 0.081 was considered as border line, with value that decreased from the control area to the wheel track (C = −15.55), with an intermediate value in log skidded (B = −7.3%), but without statistical significance.

3.2.3. Architecture (Allocation Rates)

Soil compaction had a significant effect on all the seedling architecture parameters of beech. Root penetration/main root length (RPL) showed that at a higher compaction level main root suffers difficulties in penetrating. Both main root/stem length (RRS) and root penetration/main root length (RPL) showed differences in each different soil impaction, as the Duncan test highlighted.

Referring to the seedling architecture of maple, all the characteristics showed clear statistical differences from the control area, in particular, a decreasing trend was shown for RLM, RMR, RRS and RPL from the control area to the wheel track, with an intermediate value in log skidded, while for SMR there was an increasing trend.

Table 2. Effect of soil compaction on maple (Ma) and beech (Be) seedling morphology, growth and architecture (Mean ± SD) in three areas and ANOVA and Duncan test results.

Seedling Characteristic		Area			One-Way ANOVA	
	Species	A- Control	B- Log Skidded	C- Wheel Track	F-Value	p-Value
Morphology (size)						
Stem height (cm)	Ma	40.4 ± 6.8 a	39.1 ± 7.9 a	41.1 ± 8.6 a	0.406	0.835
	Be	53.5 ± 3.64 a	52.7 ± 5.20 a	52.8 ± 3.48 a	0.278	0.758
Stem length (cm)	Ma	46.5 ± 7.33 a	42.8 ± 8.19 a	45.1 ± 7.30 a	1.509	0.228
	Be	56.8 ± 3.92 a	55.6 ± 4.93 a	55.7 ± 3.25 a	0.660	0.520
Stem diameter (mm)	Ma	3.94 ± 0.61 b	4.26 ± 0.80 b	4.77 ± 0.76 a	8.083	0.001
	Be	4.86 ± 0.28 a	4.34 ± 0.76 b	3.96 ± 0.28 c	20.55	0.000
Main root length (cm)	Ma	49.3 ± 7.90 a	39.7 ± 10.1 b	27.3 ± 4.52 c	53.071	0.000
	Be	47.5 ± 2.83 c	38.3 ± 4.24 b	31.3 ± 3.93 a	118.89	0.000
Main root diameter (mm)	Ma	3.60 ± 0.67 b	3.79 ± 0.82 b	4.51 ± 0.88 a	9.793	0.000
	Be	4.67 ± 0.26 a	4.20 ± 0.93 b	3.84 ± 0.29 c	19.760	0.000
Root collar diameter (mm)	Ma	3.84 ± 0.78 b	4.21 ± 0.81 b	4.82 ± 0.90 b	19.084	0.000
	Be	4.85 ± 0.26 a	4.34 ± 0.72 b	4.00 ± 0.27 c	20.733	0.000
Lateral root length (cm)	Ma	72.1 ± 11.4 a	42.6 ± 9.90 b	28.5 ± 5.00 c	158.21	0.000
	Be	53.5 ± 3.80 c	43.2 ± 4.60 b	30.2 ± 3.84 a	203.43	0.000
Root penetration depth (cm)	Ma	30.1 ± 6.5 a	21.6 ± 4.02 b	13.2 ± 3.73 c	80.530	0.000
	Be	32.6 ± 2.08 a	19.2 ± 2.40 b	14.3 ± 1.95 c	484.45	0.000
Growth (biomass)						
Total dry biomass (g)	Ma	46.8 ± 10.1 a	43.4 ± 11.9 a	40.0 ± 11.1 a	2.592	0.081
	Be	51.7 ± 2.49 a	39.2 ± 3.21 b	33.6 ± 3.76 c	210.40	0.000
Stem dry biomass (g)	Ma	24.1 ± 5.63 a	25.2 ± 7.66 a	25.4 ± 7.90 a	0.269	0.765
	Be	31.2 ± 1.66 a	24.7 ± 2.59 b	20.5 ± 1.93 c	165.36	0.000
Root dry biomass (g)	Ma	22.7 ± 5.02 a	18.1 ± 4.7 b	14.6 ± 3.71 c	22.010	0.000
	Be	20.5 ± 1.94 a	14.5 ± 2.26 b	13.1 ± 2.22 b	84.006	0.000
Architecture (allocation rates)						
Lateral/main root length (RLM)	Ma	1.47 ± 0.16 a	1.08 ± 0.10 b	1.05 ± 0.13 b	87.408	0.000
	Be	1.13 ± 0.09 b	1.14 ± 0.16 b	0.97 ± 0.13 a	12.933	0.000
Root mass ratio (RMR)	Ma	0.49 ± 0.03 a	0.42 ± 0.04 b	0.37 ± 0.04 c	58.615	0.000
	Be	0.40 ± 0.03 a	0.37 ± 0.05 b	0.39 ± 0.03 b	3.648	0.031
Stem mass ratio (SMR)	Ma	0.51 ± 0.03 c	0.58 ± 0.04 b	0.63 ± 0.04 a	58.615	0.000
	Be	0.60 ± 0.03 b	0.63 ± 0.05 a	0.61 ± 0.03 ab	3.648	0.031
Main root/stem length (RRS)	Ma	1.06 ± 0.08 a	0.92 ± 0.11 b	0.62 ± 0.12 c	123.59	0.000
	Be	0.84 ± 0.04 a	0.69 ± 0.04 b	0.56 ± 0.06 c	206.64	0.000
Root penetration/main root length (RPL)	Ma	0.61 ± 0.07 a	0.57 ± 0.10 a	0.49 ± 0.12 b	10.928	0.000
	Be	0.69 ± 0.05 a	0.50 ± 0.07 b	0.46 ± 0.04 c	119.27	0.000

Data followed by different letters within a column differ significantly according to Tukey's test ($p < 0.05$) .

3.3. Relationship between Bulk Density and Seedlings Morphology and Biomass

The effect of soil bulk density increase on root and stem parameter was tested (Table 3). A negative statistic correlation was observed between bulk density and root length (for beech: $F = 340.84$, $p < 0.000$; $R^2 = 0.7437$; for maple: $F = 185.60$, $p < 0.000$, $R^2 = 0.5451$) (Figure 2); the lateral roots suffered more than main roots from the increase in soil compaction. In beech seedlings a negative statistical correlation was also observed between bulk density and diameter of root (F = 29.65, p < 0.000, R^2 = 0.4516) and stem (F = 65.77, p < 0.000, R^2 = 0.474) (Figure 2); both root and stem diameter decreased at bulk density increase. While, root and stem diameter of maple seedlings increased by increasing bulk density, although these relationships were not statistically significant. Root penetration depth was significant correlated with soil bulk density (for beech: F = 356.12, p < 0.000, R^2 = 0.8299; for maple: F = 301.14, p < 0.000, R^2 = 0.7432) (Figure 2), at higher bulk density values root penetration decreased. A negative statistical correlation was observed between bulk density and seedling biomass (Figure 2). In both seedlings species total biomass was negatively correlated with bulk density (for beech: F = 166.05, p < 0.000, R^2 = 07847; for maple: F = 110.47, p < 0.000, R^2 = 0.4717) (Figure 2).

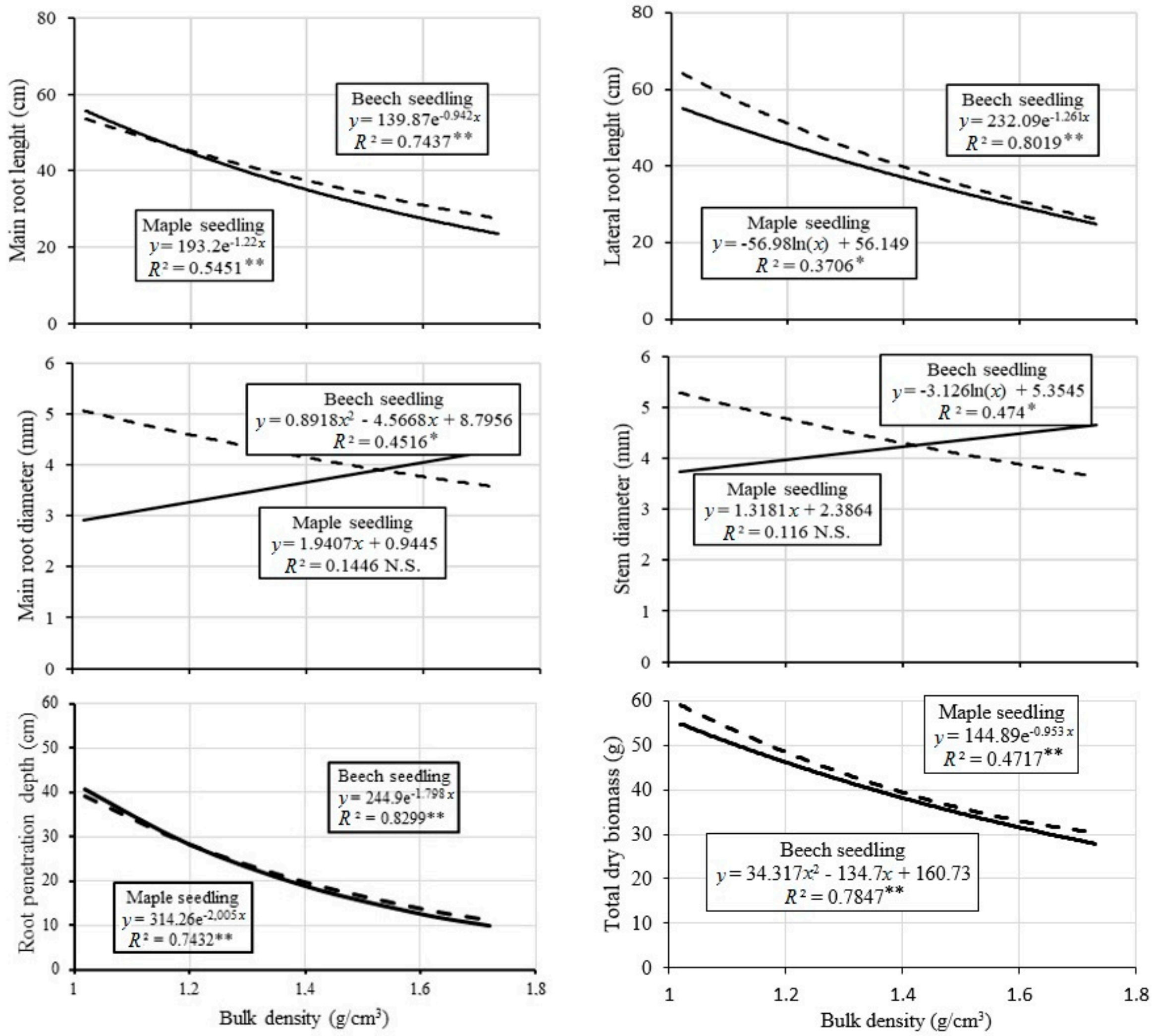

Figure 2. Relationship between bulk density and seedlings morphology and biomass; continuous line indicates maple behavior, and discontinuous line indicates beech behavior.

Table 3. Values of R^2 adjusted, standard error (SE), F, and t for relationship between bulk density and seedlings morphology and biomass that shows in Figure 2.

Variables	Species	R^2 Adjusted	SE	F	t
BD-MRL	Be	0.740	0.10	340.84	15.451
	Ma	0.539	0.21	185.60	7.666
BD-LRL	Be	0.799	0.12	295.41	13.635
	Ma	0.360	0.28	30.42	−7.037
BD-MRD	Be	0.436	0.43	29.65	−1.033 * 0.564
	Ma	0.141	0.74	3.49	1.867
BD-SD	Be	0.467	0.45	65.77	−8.110
	Ma	0.104	0.68	9.578	3.095
BD-RPD	Be	0.828	0.15	356.12	10.496
	Ma	0.732	0.22	301.14	7.192
BD-TDB	Be	0.779	3.88	166.05	−3.393 * 2.418
	Ma	0.464	0.19	110.47	8.476

BD: Bulk density, MRL: Main root length, LRL: Lateral root length, MRD: Main root diameter, SD: Stem diameter, RPD: Root penetration depth, TDB: Total dry biomass, Be: Beech; Ma: Maple; *: The first number is t value for x^2, and second number is t value for x in relationship models.

3.4. Beech Seedling Performance

In beech seedlings, the ratio of lateral root length to main root length (RLM) showed a trend that is first increasing and then decreasing, but the R^2 value was low, while the ratio of main root length to stem length (RRS) and the ratio of root penetration to main root length (RPL) showed a negative trend, at increasing bulk density (Figure 3).

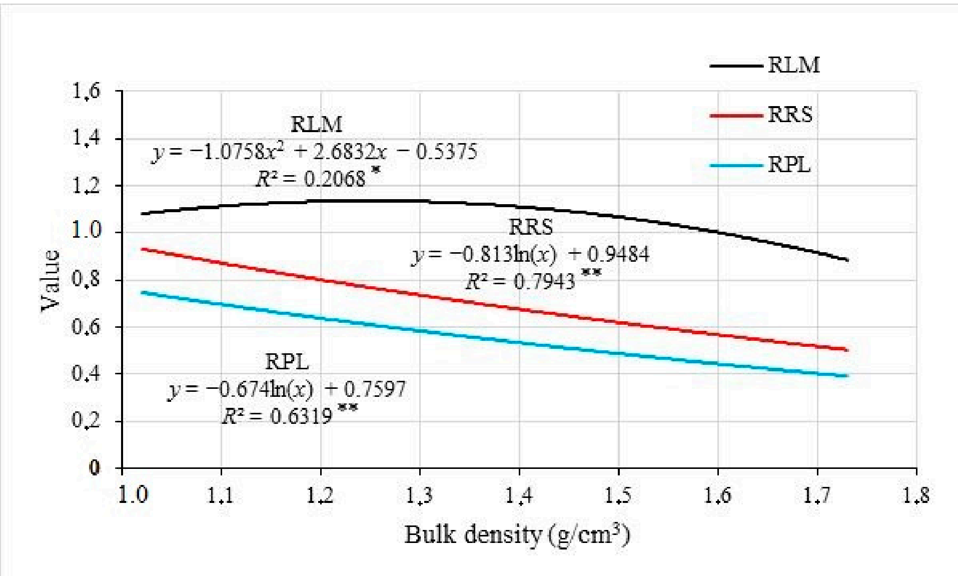

Figure 3. Relationship between RLM (ratio of lateral to main root length, RRS ratio of main root length to stem length, and RPL ratio of root penetration to main root length of beech seedlings with soil bulk density.

3.5. Maple Seedling Performance

The relationship between stem length and main root length was tested for the three areas. In this case, only for area C the regression analysis was statistically not significant, and R^2 value was very low (Figure 4). In area A (control) and B (log skidded) the regression analysis was statistically significant with a positive relationship between the two variables, with a high R^2 value of about 0.8.

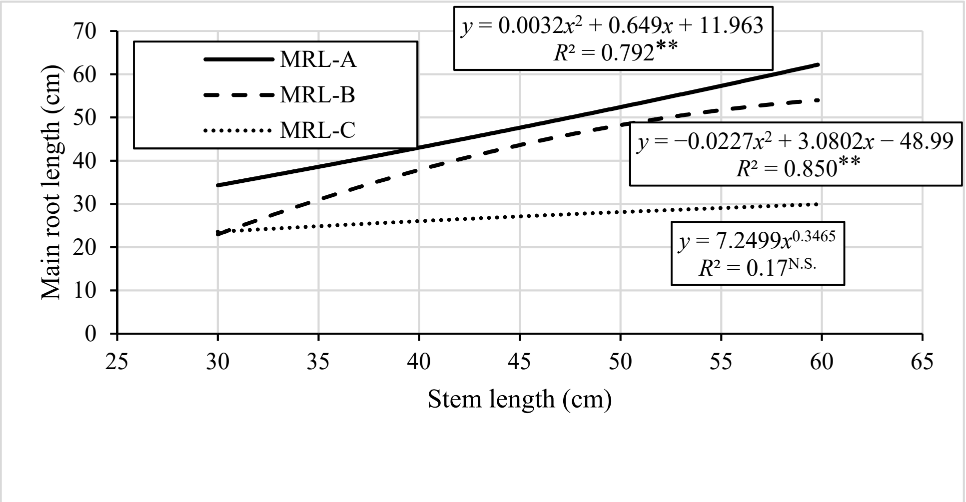

Figure 4. Relationship between stem length and main root length of maple seedlings in three areas (MRL: main root length; A: control area; B: Log skidded area; C: Tire track area).

The relationship between stem length and lateral root length was tested for the three areas. In this case, for all the three areas the regression analysis was statistically significant, and R^2 value was low only for area C (Figure 5). In area A and B, the regression showed a positive relationship between the two variables, with a good R^2 value of about 0.8.

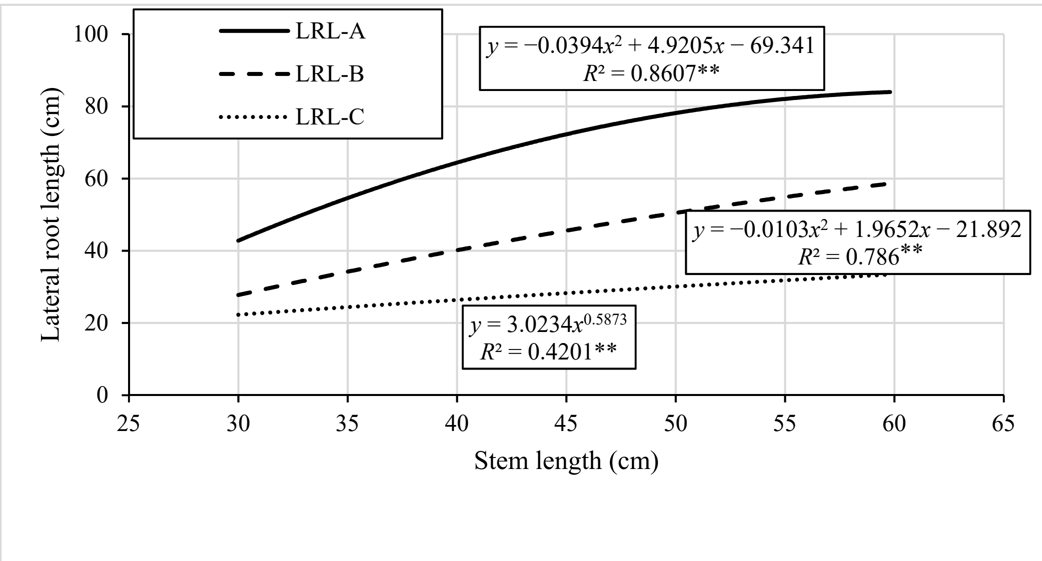

Figure 5. Relationship between stem length and lateral root length of maple seedlings in three areas (LRL: lateral root length; A: control area; B: Log skidded area; C: Tire track area).

The relationship between stem length and main root penetration depth was tested for the three areas (Figure 6), and in this case, for all the three areas the regression analysis was statistically significant, but R^2 value was low. In areas A and B, the regression showed a slightly positive relationship between the two variables, with R^2 value low, ranging from 0.35 to 0.69.

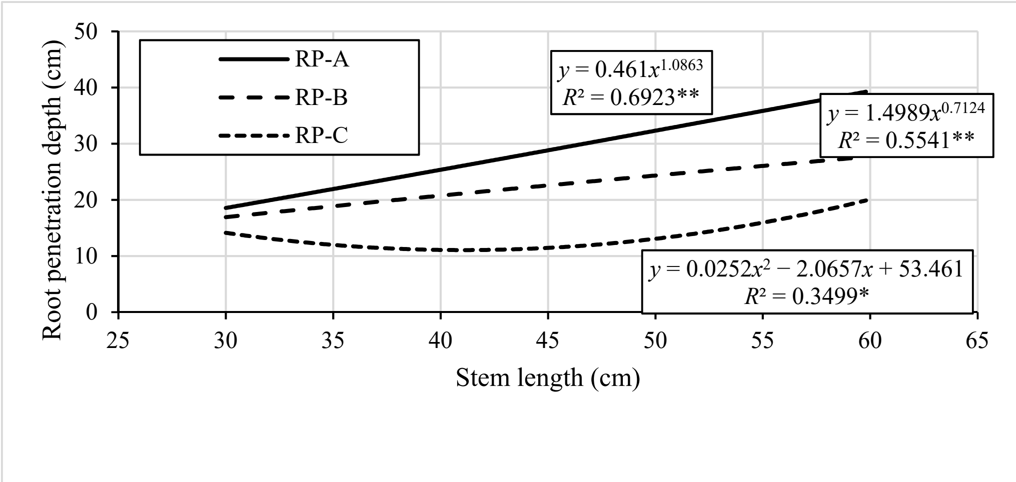

Figure 6. Relationship between stem length and main root penetration depth of maple seedlings in three areas (RP: main root penetration depth; A: control area; B: Log skidded area; C: Tire track area).

The relationship between stem length and main dry root biomass was tested for the three areas. In this case, for all the three areas the regression analysis was statistically significant with R^2 value of about 0.7 and the regression showed a slightly positive relationship between the two variables (Figure 7).

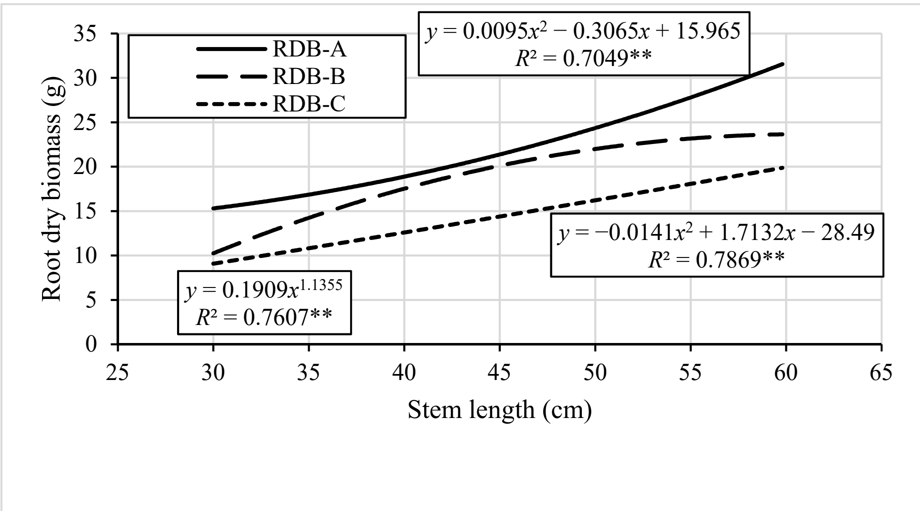

Figure 7. Relationship between stem length and main root dry biomass of maple seedlings in three areas (RDB: main root dry biomass; A: control area; B: Log skidded area; C: Tire track area).

The relationship between stem length and total dry biomass was tested for the three areas: For all the three areas the regression analysis was statistically significant with a very good R^2 value of about 0.9 and the regression showed a positive relationship between the two variables (Figure 8).

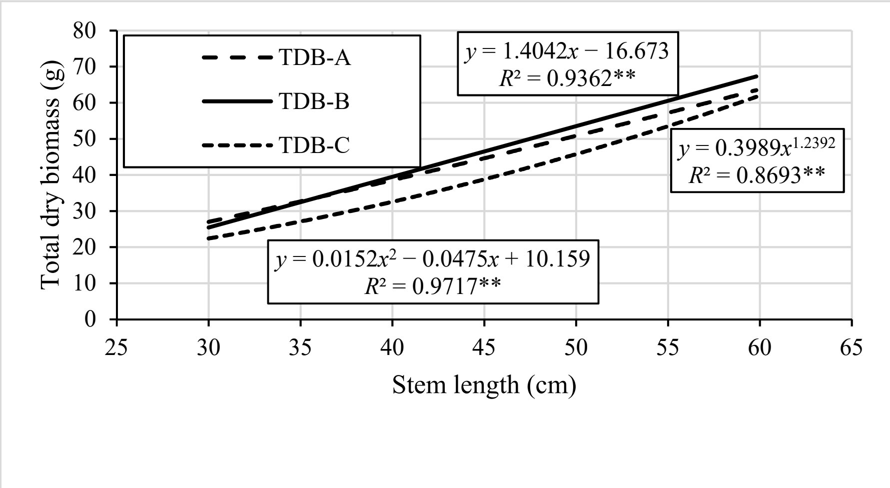

Figure 8. Relationship between stem length and total dry biomass of maple seedlings in three areas (TDB: total dry biomass; A: control area; B: Log skidded area; C: Tire track area).

The relationship between main root length and root penetration depth was tested for the three areas, and only for area C the regression analysis was statistically not significant, and R^2 value was very low (Figure 9). In areas A and B, the regression analysis was statistically significant, with a positive relationship between the two variables, with good R^2 value, ranging from 0.6 to 0.8.

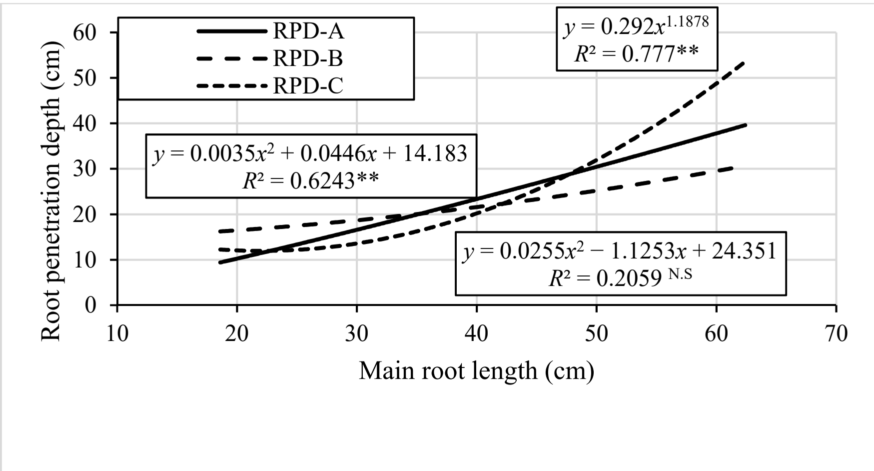

Figure 9. Relationship between main root length and root penetration depth of maple seedlings in three areas (RPD: root penetration depth; A: control area; B: Log skidded area; C: Tire track area).

Finally, the relationship between stem length and R/S biomass was tested: for area B the regression analysis was statistically not significant, and R^2 value was very low (Figure 10). In areas A and C, the regression analysis was statistically significant with a negative relationship between the two variables.

The nMDS diagram of the main indicators of the maple seedling performance matrix (Figure 11) showed a negative relationship between seedling characteristics, functionality and soil disturbance: The most impacted (and thus most compacted) soils showed an abnormal growth in the root diameter of the seedlings, a stiff growth in height and a limited length and distribution of the root system. The main variability was expressed from stem mass ratio (SMR) and root mass ratio (RMR), while root penetration/main root length (RPL) showed a clear differentiation between the groups A and B, and area C.

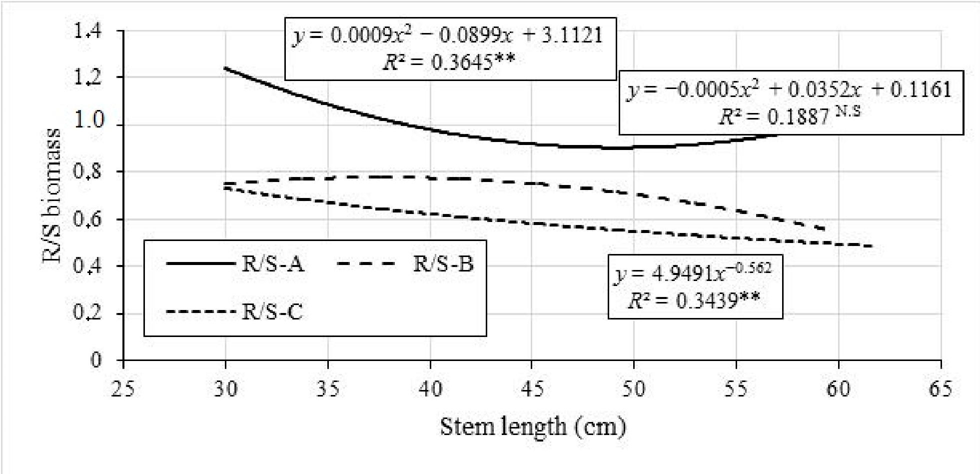

Figure 10. Relationship between stem length and R/S biomass of maple seedlings in three areas (R/S: ratio between dry biomass of root and stem; A: control area; B: Log skidded area; C: Tire track area).

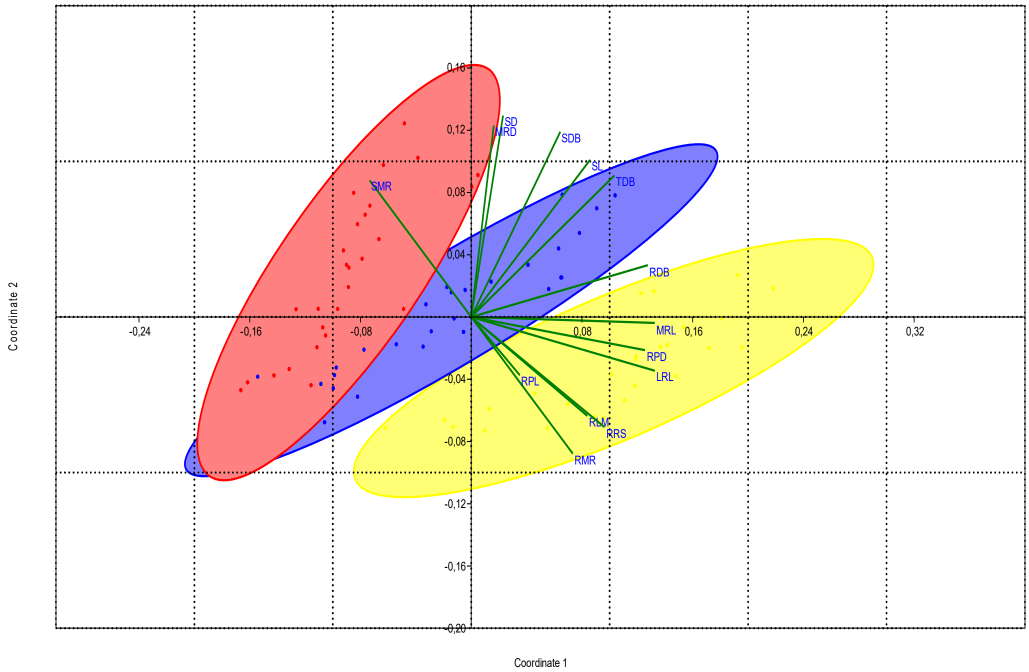

Figure 11. nMDS analysis of the main indicators of the maple seedlings performances (SL: Stem length; SD: Stem diameter; MRL: Main root length; MRD: Main root diameter; LRL: Lateral root length; RP: Root penetration; SDB: Stem dry biomass; RDB: Root dry biomass; TDB: Total dry biomass; RLM: Ratio of lateral length to main root length; RMR: Root mass ratio; SMR: Stem mass ratio; RRS: Ratio of main root length to stem length; RPL: Ratio of root penetration to main root length), difference tested among the three areas (yellow: Area A; blue: Area B; red: Area C).

3.6. Effect on Seedling Quality

The morphological features of the seedlings were used to compute the quality parameters in order to compare the three cases (Table 4). Sturdiness quotient (SQ) of seedlings on the tire track (for maple: SQ = 10.7, for beech: SQ = 13.1) and log skidded (for maple: SQ = 9.3, for beech: SQ = 12.3) were significantly higher than on the un-compacted soils (A control) (for maple: SQ = 8.5, for beech: SQ = 11.1). Root-shoot ratio (RS) of maple seedlings on the control (RS = 0.96) was significantly higher than the tire tracks (RS = 0.60) and log skidded (RS = 0.73). On the contrary, the root-shoot ratio (RS) in beech seedlings did not show statistically significant differences in the three areas.

Table 4. Quality of maple (Ma) and beech (Be) seedlings on tire track, log skidded, and un-compacted (control) soils; and ANOVA and Duncan test results.

Quality	Species	(A) Tire Track	(B) Log Skidded	(C) Control	F-Value	*p*-Value
SQ	Ma	10.7 ± 1.49 a	9.3 ± 0.59 b	8.5 ± 0.47 c	30.045	0.000
	Be	13.1 ± 0.81 a	12.3 ± 1.46 b	11.1 ± 0.76 c	27.130	0.000
RS	Ma	0.60 ± 0.11 c	0.73 ± 0.12 b	0.96 ± 0.14 a	57.819	0.000
	Be	0.64 ± 0.08 a	0.60 ± 0.11 a	0.66 ± 0.07 a	2.705	0.074

Data followed by different letters within a column differ significantly according to Tukey's test ($p < 0.05$) .

4. Discussion

In this research, the long-term effects of skidding were investigated on physical and chemical properties of soil (bulk density, penetration resistance total porosity, organic C, total nitrogen and pH), on morphology, growth and architectural characteristics of beech and maple seedlings, in the Caspian forests of Iran.

4.1. Soil Environment

The results of our research demonstrated that 10 years after the operation skid trails and winching corridors still showed a significant difference in physical and chemical properties compared to undisturbed soils.

On winching corridors soil disturbance was due to dragging the logs on trails to skidder and logs. Higher value of bulk density signed the compacting action of the trunk load and the coupled load of trunk and vehicle. Jourgholami et al. [38] observed that bulk density significantly increased with the number of vehicle passes, in a mixed forest characterized by a brown forest soil (Alfisols) and well-drained in Iran. Similar results were obtained in other studies in the Hyrcanian forest [22,39,40]. Important soil structural characteristics were modified and physical parameters worsened more in higher disturbed soil than in the winching corridor. USDA Forest Service suggested that a bulk density increase of more than 15% is detrimental for the soil ecosystem [41]. Compaction alters the moisture regime of the soil and can impede the growth of roots; hence the tree is not able to draw water or nutrients at depth; poor root development can also make mature trees more susceptible to wind-throw [42]. Dickerson [43] found that wheel-rutted soils required about 12 years to recover and log-disturbed soils about 8 years after tree-length skidding. A research by Naghdi et al. [44] showed that 20 years after skidding operations, the micromorphological properties of compacted soil on the skid trails had not yet recovered. They were significantly different compared to the control thus needing more time for a complete recovery in the Caspian forests of Iran. However, some authors reported lower soil damage improving harvesting methods and providing training for the operators [13,45].

Soil penetration resistance after 10 years on log skids and tire tracks dramatically increased compared to the undisturbed areas. Whalley et al. [46] found that plant root growth slowed down at a penetration resistance of 2 MPa and stopped when resistance values exceeded 3 MPa.

As bulk density and penetration resistance increased, porosity decreased. Total soil porosity observed after 10 years has maintained a negative relative variation compared to the undisturbed of about 13% in the winching corridor and 30% in the tire track. This is consistent with previous observations [2,8,11,14,47–49]. Naghdi et al. [44] reported that the soil porosity on the skid trails (35.8%) was significantly lower than the untouched soils (54.9%) after 20 years from compaction (skidding operation) in the Hyrcanian forests of Iran. These results were quite similar to those observed in our research. Reduction in soil porosity and air permeability reduces the soil penetrability for roots [50] and limit root extension, elongation, branching, density, and penetration of primary roots as well as root access to, and uptake of soil moisture and nutrients [15]. Seedling root growth is also reduced when oxygen concentration drops beneath the 6% to 10% range [51].

Generally, pH seems less susceptible to variations in the case of forest soils, even if disturbed [3,4,11], but in our case it increased at the different disturbance intensity. Naghdi et al. [17] observed that the pH was significantly influenced by the number of passes of a rubber-tired skidder in the Sorkhekolah forest, North Iran.

Organic Carbon content decreased as disturbance increased, as well as nitrogen. The soil disturbed by the coupled Timberjak movement and trunk load showed a considerably lower organic matter content, as observed in other cases studied in different forest areas, management, treatment and soil type [3,4,17,52]. Rut and soil displacement, causing layers of lesser fertility to emerge [22,40] is still indicated 10 years after the forest operation by the difference in chemical characteristics compared to the undisturbed control, such as the reduction in organic carbon and nitrogen, and the increase in pH. It is very interesting to note that 10 years after the recovery processes are still in progress, although the areas considered were colonized by forest vegetation. The lowering of chemical parameters seems to be ascribed to the microbiological activity decline [3,53,54] due to displacement of dead wood and forest litter and to mixing and removal of topsoil, coupled with the reduced soil porosity [49]. The lowering of porosity may result in decreased water fluxes and gas diffusion with adverse effects on roots of trees [55,56] and seedlings [57], soil bacterial community [58] and more in general soil biota community [59].

4.2. *Effect of Soil Compaction on Beech and Maple Seedling*

After 10 years morphological parameters of beech and maple seedlings were affected as soil compaction increased. Only stem length and seedling height of both beech and maple were similar in the different soil compaction [25]. The difference in height and length of beech seedling is not dramatic, as plagiotropic stem behavior can be frequently observed in beech [60].

Both root and stem diameter of beech were adversely affected by bulk density, decreasing at its increasing. On the contrary in maple they were positively influenced, increasing at soil compaction increase.

Seedlings with a larger stem diameter were better able to survive than the smaller diameter [61]. Jacobs et al. [62] noted that seedlings with a greater initial height at planting could better survive. Therefore, it can be argued that after 10 years, the smaller seedlings in each soil compaction type were subjected to environmental selection. Furthermore, the beech seedlings observed have not yet been subjected to neighborhood competition and were not yet discriminated for water and light (similar height of seedling and length of stem).

The relationship analysis of maple seedling morphology indicated that main root, lateral root length and dry biomass, and root penetration depth were increased by increasing stem length in all three treatments. These results indicate that although soil compaction decreases the root growth, roots have a good growth, and a good penetration depth in the heavily compacted soils, with increasing stem length.

The root system of beech and maple seedlings was significantly reduced by increased soil compaction. The effects of skid trails on reduction of root length was higher on lateral root length than on main root length.

Root length decreasing with increasing soil compaction was noted for many plant species [63], including trees [9,64]. Higher soil bulk density was associated with thinner root, shorter lateral roots and lower penetration depth. Similar results were found by Mosena and Dillenburg [65]. According to our results on beech and maple seedlings unfavorable effects were observed in other hardwood species [11,25,26,66]. Hildebrand [57] indicated a bulk density threshold in 1.25 g/cm^3 for the development of fine roots of beech seedlings in loess loam soil; beech seedlings grown at a bulk density of 1.34 g/cm^3 exhibited a heavy suppression of fine roots; at bulk density 1.46 g/cm^3 the fine roots were arranged around the main root shaped like a brush and therefore showed poor penetration of the soil. Naghdi [17] observed a 44% reduction of maple seedlings root length in soils heavily trafficked. In *Acer cappadocicum* Bunge. seedlings, grown in greenhouse condition, Jourgholami [21] detected a decrease of 43% in stem lengths, 36% in stem diameters, 49.8% in main root lengths, and an increase of 101% in lateral root lengths when comparing the un-compacted class (control, bulk density 1.08 ± 0.03 g/cm^3) to the highest compaction (bulk density 1.38 ± 0.03 g/cm^3). Von Wilpert and Schäffer [67] indicated that deficiencies in soil gas permeability reduce fine root formation. The lowest fine root density and rooting depth were found below the wheel tracks due to compaction in nearly stone-free loamy soils (Luvisols) and fine root distribution was interpreted as a very sensitive indicator for the soil aeration status [67]. The results of previous research indicate that soil compaction effects are related to soil type [14], species [68] and forestry intervention system [52,69].

Root dry mass is an indicator of the root system capability to absorb water and nutritive elements [61] that assure better survival for seedling. The negative effect on the dry mass of stem and root agrees with data and correlations observed in other species [11,25,66,70]. It is interesting to note that total dry biomass difference in the compacted area was driven by stem rather than root biomass in beech and by root rather than stem in maple. This suggests primarily the difference of species behavior. Moreover, after 10 years a selection of seedling was performed on disturbed areas based on capability to obtain sufficient natural resources to grow. After 10 years, dry root biomass was lesser decreasing than other parameters, probably due to the environmental selection in beech. The root system assures seedling survival exploring soil for water supply and nutrients, supporting mycorrhizal symbiosis [71]. Under a threshold related to the transpiring area (shoot) and to the water absorbing area (roots) the seedlings have no future.

Root penetration depth was dramatically affected by increasing bulk density in both beech and maple seedlings. The growth inhibition of the roots system and limitation of the maximum depth of penetration was observed in *Quercus petraea* Matt. seedlings [70]. Furthermore, a modest increase in soil density has led to negative effects on plant growth. Root penetration depth and lateral root length were the parameters mainly affected by soil compaction in our study. These evidences confirmed that the impact on soil properties have a long-term detrimental effect on the seedling root system [18,57,61,66,67].

The architecture of the seedlings describes the allocation of biomass to the root and the stem. As noted above, the bulk density affects the morphology and growth of the seedling. Likewise, as soil compaction increases, the seedling architecture is also affected. The main root length (MRL) and the root penetration depth (RPD) are different root morphological indicators. Therefore, the index of RPL is a root architectural indicator as a root growth performance indicator. The morphological plasticity of the root system in response to soil compaction is clearly exposed by the RPL. The parameters describing the seedling architecture confirm the observation on the morphology and the growth of seedlings both beech and maple. Beech and maple seedling showed that the ratio of lateral to main root length (RLM), root mass ratio (RMR), main root/stem length ratio (RRS) and root penetration/main root length ratio (RPL) on compacted soil were lower than the undisturbed control. Conversely, the stem mass ratio (SMR) of maple and beech on the log skids and tire tracks was higher than the undisturbed area.

Roots grow mainly downwards [72] and compacted soils oppose greater resistance than ones with lower bulk density. A high penetration resistance modified the root system shape from the typical pattern [73]. Increased soil strength (penetration resistance) may change the proportional growth allocation between above and below ground portions of seedlings [24,64,74] decrease the proportion of roots [9]. RRS typically increases with decreasing water availability [75,76], but as result of soil compaction, R/S responses were highly variable. Following soil compaction, RRS increased in *P. contorta* Dougl. ex Loud. in dry soils, but not in moist or wet soils [77], while it decreased in the cases of *Q. coccifera* L. and *Q. faginea* Lam., and remained unchanged in the cases of *Q. ilex* L., *Q. canariensis* Willd., and *Q. pyrenaica* Willd. [74]. Compacted soils exhibit lower water storage capacity due to lower porosity [32]. Madsen [78] observed a limiting factor in soil water content for survive of beech seedling. Specifically, the root biomass of beech is positively conditioned by the availability of water [72]. In natural conditions, seedlings with low root shoot ratio may be more susceptible to water deficit stress [79]. Similarly, to what was previously observed for growth parameters, the biomass of both the root and the stem was observed after 10 years of forest operations and the seedlings sampled had at least the opportunity to acquire minimal survival features.

4.3. Effect of Soil Compaction on Seedling Quality

Seedling sturdiness quotient expresses the vigor and robustness of the seedling, and it reflects the stocky and spindly nature of the seedlings, being the ideal value less than six [37]. It is good indicator of seedling ability to withstand physical damage such as exposure to severe wind. The parameters that characterize the seedlings grown in the natural context compared with seedlings produced in controlled systems showed a great difference. In our study the sturdiness quotient depicted tall and thin beech and maple seedlings, in each compaction situation, although the seedlings in the control were better shaped. The morphological, growth and architectural parameters are only generally the same compared to what was observed in controlled contexts [61,80].

Seedling root-shoot ratio (RS) indicate a measure of balance between the transpiration area and water absorbing area. A root-shoot ratio between one and two is considered as optimal [37]. Our results indicated that all means of RS values for both beech and maple seedlings were lower than one. The maximum RS value was obtained in the control for maple seedlings (RS = 0.96). The RS values of maple seedlings on the tire track and log skidded were higher than RS values of beech seedlings in these areas.

Nevertheless, the SQ and RS values are incomparable with indexes obtained in the nursery. The seedlings examined in our study were older. Natural regeneration is a much more complex process and the scenario is different.

Several studies underline the effects on soils and forest regeneration of forest operations [81,82]. Compacted soil caused by forest harvesting has an important role in the reduction of root growth of plants by restricting access to water and nutrients and by reducing air diffusion [14]. In a study by Pinard et al. [20] in the Malaysian forests, it was concluded that after 17 years, the density and richness of woody plants on skid trails are less than the adjacent forests. Krause [83] reported that compaction from harvesting equipment can reduce water infiltration and air permeability which is detrimental to the establishment and growth of regenerating species.

On the other hand, skid trails, which are often constructed by excavation, are one of the most important elements for close-to-nature forestry, in order to enable selective cutting methods in areas provided by optimal forest road network [84]. For this reason, the rehabilitation of skid trails has become more important in recent years. D'Oliveira [85] suggests artificial regeneration on the skid trails of the Brazilian forests, and based on his research, native species have grown well and survived after 5 years. The rehabilitation of skid trails after finishing skidding operations by drainage construction are essential to reduce the quantity of runoff and to minimize then soil erosion [7,86] and the installation of water bars and brush barriers on skid trails is necessary to control and capture runoff and ensure soil stabilization. The cross drains should be spaced less than 25 m apart on skid trails sloping 10–15 degrees [87]. Post-harvest operations such as installation of water bars and brush barriers on skid trails, construction of drains across skid trails and seeded to grass, replanting and fertilization of severely compacted soils are procedures for the specific purpose of maintaining forest biodiversity. The forest management plan should include these operations in order to maintain both short and long term management goals and to ensure forest productivity. Forest soil maintenance is a key factor to sustain productive forests [88]. Plant coverage is a main ecological factor to limit soil erosion on the skid trails.

The forest service must be competent in managing soil disturbance, in order to maintain a sustainable production of natural resources [89].

Physical soil properties and changes in other environmental properties of skid trails can create differences in beech and maple seedling growth between the skid trail and non-skid trail, such as chemical soil properties, wind speed, air temperature, and light intensity.

5. Conclusions

Post-harvest operations are necessary to limit soil erosion and to maintain plant species diversity in these forests.

All the data gathered, both physical and chemical on the features of the soil in the different conditions of impacts, demonstrated that vehicle passages and loads provoke damage. The physical soil properties analyzed for the skid trails showed a clear impact in comparison to the undisturbed areas. In particular, the impact was more relevant in the tire tracks with dangerous values, while on the log skids the impact was limited. The increase in soil bulk density restricted root and stem growth, reduced root penetration and modified the architecture of beech and maple seedlings, probably limiting the access and the absorption of nutrients and water in different magnitudes.

Although all forest logging systems have the potential to negatively affect forest soil, a more sustainable approach to forest harvesting is needed. Monitoring soil damage and recovery are useful in order to evaluate and improve sustainable forest management while maintaining fertility.

Harvesting systems that require vehicle passage on the tracks must be prioritized so as to reduce forest soil degradation, ensuring an environment favorable to the establishment and growth of natural regeneration.

The careful planning of interventions, the rational opening of forest tracks, the choice of the best system for the environmental conditions, the adequate training of workers and the correct management of forest operations are essential elements if a sustainable and respectful forest management of natural resources is to be pursued.

Physical soil properties and changes in other environmental properties of the skid trail created differences in beech and maple seedling growth between the skid trail and the non-skid trail. This was closely related to the physiological characteristics of the two species studied. Beech seedlings reacted well to a moderate uncovering, but they needed little disturbed soil, even if very mixed bedding. Maple seedlings reacted better than beech seedlings to the uncovering and soil disturbance. The effects of the skid trail on morphology, growth and architecture of maple seedlings in the Hyrcanian beech forests showed that the maple as a seedling is a suitable species for maintenance of the physical properties of skid trails after logging operations in the beech stands in the Caspian forests of Iran. Stem and main root diameter increased, while main root and lateral root length, and root penetration depth decreased. Ratio of lateral to main root length, root mass ratio, stem mass ratio, ratio of root penetration to main root length were significantly reduced. The relationship analysis of seedling morphology indicated that, although soil compaction reduces root growth, roots have a good growth, and good penetration depth in the heavily compacted soils, with increasing stem length.

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