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# Mechanical Characteristics of the Fine Roots of Two Broadleaved Tree Species from the Temperate Caspian Hyrcanian Ecoregion

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**Abstract:** In view of the important role played by roots against shallow landslides, root tensile force was evaluated for two widespread temperate tree species within the Caspian Hyrcanian Ecoregion, i.e., *Fagus orientalis* L. and *Carpinus betulus* L. Fine roots (0.02 to 7.99 mm) were collected from five trees of each species at three different elevations (400, 950, and 1350 m a.s.l.), across three diameter at breast height (DBH) classes (small = 7.5–32.5 cm, medium = 32.6–57.5 cm, and large =57.6–82.5 cm), and at two slope positions relative to the tree stem (up- and down-slope). In the laboratory, maximum tensile force (N) required to break the root was determined for 2016 roots (56 roots per each of two species x three sites x three DBH classes x two slope positions). ANCOVA was used to test the effects of slope position, DBH, and study site on root tensile force. To obtain the power-law regression coefficients, a nonlinear least square method was used. We found that: 1) root tensile force strongly depends on root size, 2) *F. orientalis* roots are stronger than *C. betulus* ones in the large DBH class, although they are weaker in the medium and small DBH classes, 3) root mechanical resistance is higher upslope than downslope, 4) roots of the trees with larger DBH were the most resistant roots in tension in compare with roots of the medium or small DBH classes, and 5) the root tensile force for both species is notably different from one site to another site. Overall, our findings provide a fundamental contribution to the quantification of the protective effects of forests in the temperate region.

**Keywords:** bioengineering; *Carpinus betulus*; *Fagus orientalis*; tensile force

## 1. Introduction

Worldwide, 24 billion tons of fertile soil are estimated to be lost every year due to erosion and mass wasting [1]. Vegetation, especially in the mountain regions, plays a remarkable role in stabilizing slopes and protecting soil from erosion and landslides [2,3]. Particularly for trees, roots are known to reinforce soil through three mechanisms [4–7]: basal root reinforcement, lateral root reinforcement, and increasing the stiffness of the root–soil composite material. In all of these mechanisms, the contribution of roots is defined by their mechanical properties (strength and elasticity) [4,5,8–10] and their density and spatial distribution [4,6,9,11], although species, environment, root diameter, root branching order, age of the trees, root architecture, and forest structure are known to influence root reinforcement variability [12–14].

A review of the literature reveals an overall lack of agreement regarding the size of the roots that must be considered in root mechanical estimation. On one hand, some authors consider only roots with diameters less than 10 mm, because these fine and thin roots act as tensile fibers during slope failures and provide the major contribution to slope stability [15–17]. On the other hand, a few authors indicated that roots of a size up to 20 mm in diameter contribute the most slope stability [18], although, in rare cases, roots with diameter up to 40 mm are said to play an important role in slope stability [19].

In many studies, root reinforcement was estimated for different vegetation species growing in different regions and environments. The mechanical properties of roots have been studied in several works [20,21] and it is known that the mechanical properties of roots change depending on the species and local conditions, such as the amount of nutrients and water content [21–23]. Generally, roots extend close to the soil surface where the soil has the lowest bulk density and water, oxygen, and nutrients are most available. With increasing soil depth, soil bulk density increases and aeration decreases; consequently, root density and size decline [24]. However, a comprehensive and statistically strong analysis of the influence of factors such as region, species, the diameter at breast height (DBH), and slope position of the roots relative to the tree stem on root mechanical characteristics is lacking in the literature, especially in the Hyrcanian Ecoregion. In Iran, this ecoregion is on the UNESCO World Heritage List from July 2019 because of its biological diversity that provides high economic and social value.

The need for more information about root mechanical characteristics is great. For example, Iran ranks within the top 10 countries for high risk of soil erosion and mass soil movement [25]. Annually, the estimated loss of fertile soil in Iran is one to five billion tons per year [26]. From the period 1996 to 2008, Iran recorded 4900 landslides, and even though these landslides were often shallow in nature [25,27], they caused about 30 billion US dollars of damage [25]. Forestry and natural hazards policies need to be based on the scientific background, which can support the decision makers and forest managers. A simple and reliable quantification of the effect of forests on different types of natural hazards is a key step in order to define a comprehensive and feasible risk mitigation strategy. Such issues still remain largely unsolved globally, especially in temperate forests. Vegetation restoration and forest management are important for the mitigation of such phenomena and preventing hazards, mostly through the impact of the reinforcement exerted by root systems [28,29].

Thus, toward providing a fundamental contribution in the quantification afforded by fine roots against a shallow landslide hazard, our study objective was to assess the most important factors that influence tensile force variability within the roots of the most widespread Iranian tree species in the Caspian Hyrcanian Ecoregion. We explored root tensile force in *Carpinus betulus* L. and *Fagus orientalis* L.; these two species were selected because they are the most common species in the Hyrcanian forests and can be found from Europe to the Caucasus and northern Iran [30]. *F. orientalis* is a shade-tolerant species whereas *C. betulus* is semi-shade tolerant [31]. In the Hyrcanian forests of Iran, more than 80 species can be found on typical sites; *F. orientalis* accounts for about 18% of the total forest area, 30% of the standing volume, and 24% of the stem number whereas *C. betulus* contributes 30% of the standing volume and 30% of the total stem number [30].

## 2. Materials and Methods

### *2.1. Study Site and Species*

Our study site is located in Mazandran Province, northern Iran, within the Hyrcanian Ecoregion along the southern shore of the Caspian Sea. In particular, our sites are in the ~8000 ha Kheyrud Forest (Lat. 36°33′41′′ to 36°33′51′′ N; Long. 50°33′14′′ to 103 50°33′28′′ E; WGS84), classified as temperate deciduous forest [31]. Meteorological records from 1961 to 2015 (Nowshahr Meteorological Station: Lat. 36°38′56′′ N; Long. 51°29′20′′ E; 23 m a.s.l, 7 Km from study area) characterized the mean annual precipitation as 1300 mm, with the heaviest precipitation in fall. October is the wettest month (average 235 mm) and the driest (average 42 mm) is August. The coldest and warmest months are February (7.1 °C) and August (25.1 °C), respectively. The site has a relatively thin soil mantle, and the lithological substrate is mainly calcareous parent material (Jura, Cretaceous) that contains discontinuities and a large number of cracks that can be penetrated by roots [32,33]. The soil in the study site is an Alfisol without any diagnostic horizons [34].

Within the Kheyrud Forest, we collected root samples from three districts (Patom, Namkhane, and Chelir; Figure 1) to compare the effects of different regional environmental factors. These districts, hereafter study sites, range from low elevation (400 m a.s.l.) with the highest mean temperature and lowest annual precipitation (Patom, Lat. 36°36′54′′ N; Long. 51°33′49′′ E) to mid-elevation (950 m; Namkhane, Lat. 36°33′54′′ N; Long. 51°36′09′′ E) to the highest elevation (1300 m) having the lowest mean temperature and greatest annual precipitation (Chelir, Lat. 36°32′02′′ N; Long. 51°40′24′′ E) [35]. These study sites also have different soil properties (Table 1). Soil properties at the three study sites were presented in Table 1 [36]. According to the unified soil classification system [37], the soils on the three study sites were clay with high plasticity (e.g., CH) [36].

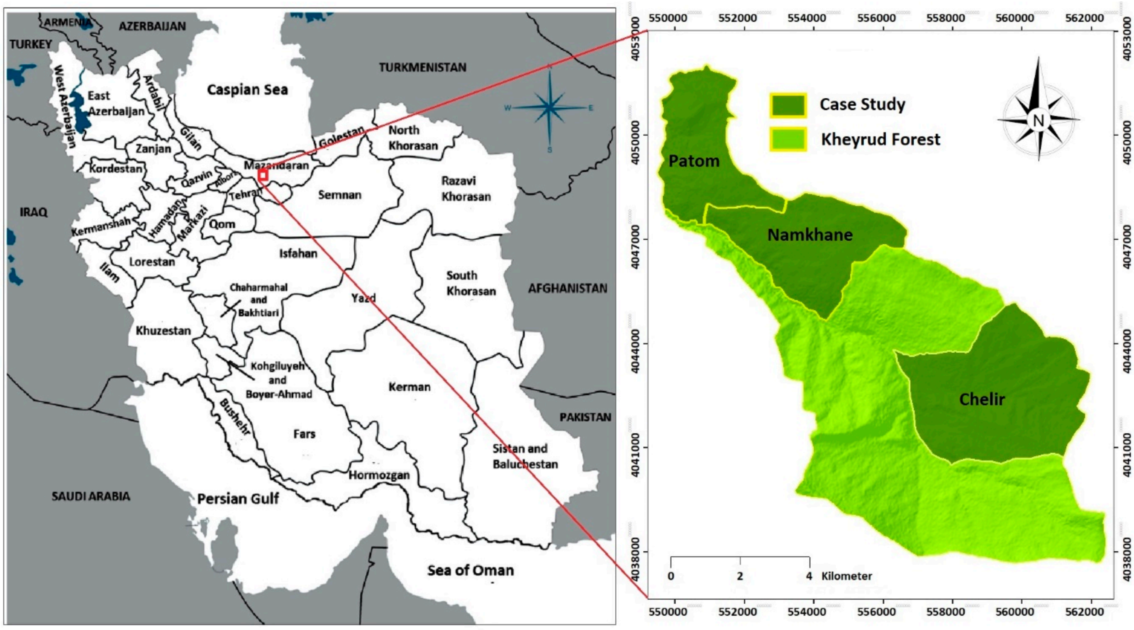


**Figure 1.** Location of the Chelir, Namkhane, and Patom study sites within the Kheyrud Forest of Mazandran Province in northern Iran. This forest is part of the Caspian Hyrcanian Ecoregion.

## 2.2. Sampling Design

Three classes of tree diameter at breast height (DBH) (small = 7.5–32.5 cm, medium = 32.6–57.5 cm, and large = 57.6–82.5 cm) were defined to compare the effects of this parameter [39]. On each of the three study sites and for each of three DBH classes, we randomly selected five trees (with at least 6 m distance between trees) for each species (three sites × three DBH classes × five trees × two species = 90 trees total).

Root samples were collected randomly from the soil (0.5 to 1.5 m from the stem) by excavating pits beside the trees at a depth of about 30 cm below the soil surface and from upslope and downslope of the stem [14]. For each species, site, DBH class, and slope position, we collected about 60 root samples (Table 2). At the end of each day of sampling, a 15% alcohol solution was sprayed on roots in order to prevent mould and microbial degradation [17,40], and treated roots were placed into plastic bags and refrigerated (4 °C) until tested; time between sampling and testing in the laboratory was about 48 h.

**Table 1.** Mean values (± standard error) of soil properties at the three study sites [36].

| Soil Properties | Soil Depth (cm) | Study Site | | |
|---|---|---|---|---|
| | | **Chelir** | **Namkhane** | **Patom** |
| Dry density (g $cm^{-3}$) | 30 | 1.13 (± 0.02) | 1.09 (± 0.02) | 1.16 (± 0.03) |
| Nitrogen (%) | 0–10 | 22.44 (± 3.02) | 24.89 (± 3.02) | 21.19 (± 2.25) |
| | 10–20 | 13.94 (± 1.13) | 14.10 (± 0.80) | 9.19 (± 0.52) |
| Phosphorus (ppm) | 0–10 | 20.98 (± 3.01) | 25.93 (± 3.13) | 23.57 (± 2.11) |
| | 10–20 | 22.00 (± 2.59) | 34.45 (± 1.06) | 28.52(± 2.38) |
| Potassium (ppm) | 0–10 | 1989.2 (± 197.7) | 1253.6 (± 131.6) | 1068.1 (± 91.6) |
| | 10-20 | 1228.0 (± 150.5) | 1458.3 (± 110.5) | 866.7 (± 147.3) |
| Carbon (%) | 0–10 | 2.84 (± 0.3) | 3.12 (± 0.31) | 2.50 (± 0.17) |
| | 10–20 | 1.20 (± 0.10) | 1.48 (± 0.13) | 0.92 (± 0.06) |
| Organic matter (%) | 0–10 | 4.90 (± 0.52) | 5.38 (± 0.59) | 4.31 (± 0.41) |
| | 10–20 | 2.08 (± 0.19) | 2.56 (± 0.25) | 1.59 (± 0.14) |
| pH | 0–10 | 5.54 (± 0.67) | 5.25 (± 0.54) | 5.42 (± 0.49) |
| | 10–20 | 5.28 (± 0.57) | 5.08 (± 0.36) | 5.19 (± 0.40) |
| EC (ds $m^{-1}$) | 0–10 | 0.45 (± 0.02) | 0.45 (± 0.02) | 0.38 (± 0.01) |
| | 10–20 | 0.30 (± 0.01) | 0.30 (± 0.01) | 0.32 (± 0.01) |
| Soil liquid limit [1] | 30 | 85.70 (± 6.85) | 88.52 (± 7.44) | 65 (± 6.21) |
| Soil plastic limit [1] | 30 | 37.70 (± 3.71) | 38.32 (± 4.89) | 26.42 (± 3.05) |
| Soil plasticity index [1] | 30 | 48.00 (± 4.99) | 50.20 (± 4.56) | 38.58 (± 3.80) |
| Soil texture [2] | | Silt loam | Silt loam | Silt loam |
| Unified soil classification | - | CH | CH | CH |

[1] Atterberg limit [38]. [2] USDA soil classification [34].

**Table 2.** Total number of root measurements attempted, and in parentheses, the attempts that yielded valid results, for each tree species, diameter at breast height (DBH) class, slope position relative to the main stem, and study site.

| Site | DBH Classes [1] | *Carpinus betulus* | | *Fagus orientalis* | |
|---|---|---|---|---|---|
| | | **Upslope** | **Downslope** | **Upslope** | **Downslope** |
| Patom | Small | 58 (56) | 57 (56) | 62 (56) | 64 (56) |
| | Medium | 59 (56) | 59 (56) | 61 (56) | 62 (56) |
| | Large | 60 (56) | 61 (56) | 68 (56) | 70 (56) |
| Namkhane | Small | 57 (56) | 57 (56) | 60 (56) | 59 (56) |
| | Medium | 58 (56) | 60 (56) | 61 (56) | 62 (56) |
| | Large | 59 (56) | 59 (56) | 64 (56) | 63 (56) |
| Chelir | Small | 58 (56) | 59 (56) | 58 (56) | 57 (56) |
| | Medium | 59 (56) | 60 (56) | 61 (56) | 59 (56) |
| | Large | 62 (56) | 61 (56) | 63 (56) | 62 (56) |

[1] DBH classes: small = 7.5–32.5 cm; medium = 32.6–57.5; and large = 57.6–82.5 cm.

Tensile tests were performed using a Universal Testing Machine (SMT-5, SANTOM Co., Tehran, Iran), equipped with 500 kg maximum-capacity load cell (Full Scale, F.S. = accuracy of 0.1% of F.S). Roots with a length of 10 cm and diameters ranging from 0.02 mm to 7.99 mm were clamped into position as vertical as possible within the load cell axis. Roots with diameters more than 8 mm could not be tested due to clumping problems [41]. A strain rate of 10 mm/min [42–44] was applied until breakage occurred; breakage near the middle of the root between the clamps was considered a valid test [45], whereas when breakage occurred proximate to the clamps or breakage was due to slippage or crushing by the clamps, the samples were deemed invalid and discarded (Figure 2). The tensile force (N) was taken as the maximum load at the rupture point. Root diameter was measured at three points near the breaking section [40]. For each site, we obtained 336 valid tests for each species (2016 valid root samples; Table 2).

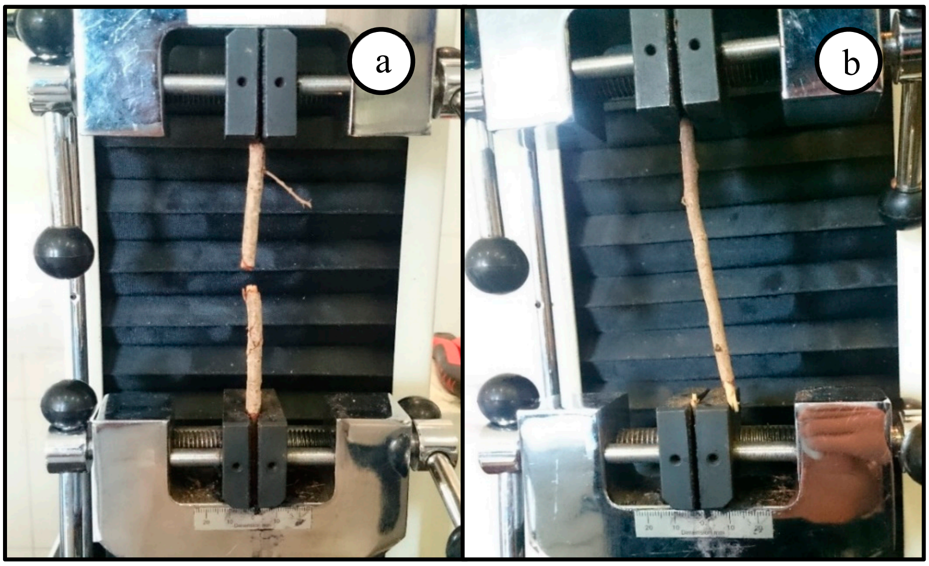


**Figure 2.** Breaking phase of the root in tensile test. A valid test, where the root broke near the middle (**a**), and an invalid test, where the root broke proximate the clamp (**b**).

## *2.3. Statistical Analysis*

Analysis of covariance (ANCOVA) was used to test the effects of slope position, DBH, and study site on root tensile force. The normality and homogeneity of data were tested before proceeding with the analysis and, as a result, log transformation was necessary to normalize the data. Preliminary use of the ANCOVA revealed that DBH classes and root diameter should be considered as covariate factors, as this model yielded the lowest residuals. Therefore, maximum tensile force was a function of species, slope position, and their interaction. Eta-squared ($\eta^2$) was calculated as a measure of the effect of the parameters on the tensile force.

An analysis of residuals was performed to compare the difference between the fitting curves of each dataset as a function of root diameter. The relationships between tensile force–root diameter were interpreted through a regression, which has been proven to be a power-law function [15,40,46]. To obtain the power-law regression coefficients (i.e., $F_0$ and $\alpha$), a nonlinear least square method was completed using R software (www.r-project.org, R version 3.3.2, University of Auckland, Auckland, New Zealand). In order to visualize whether or not the differences between datasets are significant, $\Delta$Fit and sum of 95% confidence interval (CI) were calculated and compared as shown in Figure 3.

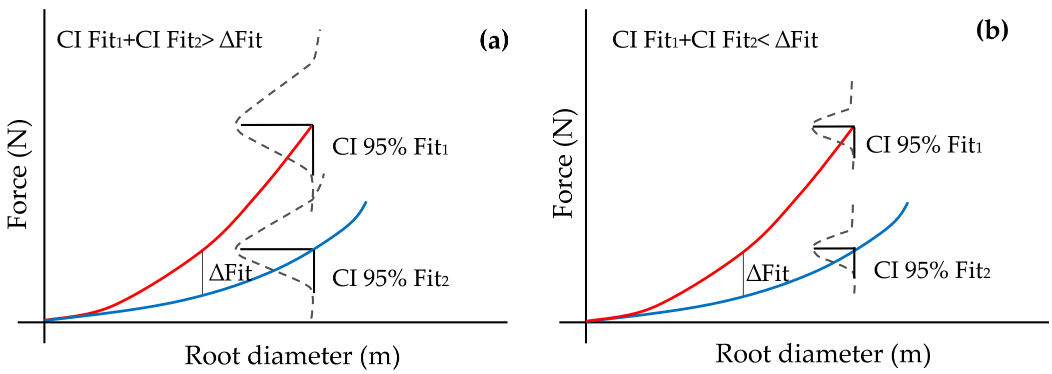


**Figure 3.** Schematic view of the definition of $\Delta$Fit and sum of the confidence interval at 95% (CI-95%), showing an example of overlapping distributions (**a**), and significantly different distributions (**b**).

## 3. Results

### 3.1. ANCOVA

A separate covariate analysis for each site revealed that species, slope position, DBH, root diameter, and the interaction of species and slope position were significant ($p < 0.05$) for the tensile force (N) required to break roots (Table 3), except that the interaction was not significant at Namkhane, only at Chelir and Patom. Regardless of site, F values indicate that tensile force was influenced more by root diameter ($F$=4892) than by species or DBH, and the effect of slope position had the least effect on tensile strength ($F$=23) (Table 3). The eta-squared ($\eta^2$) values indicate that root diameter explains more than 90% of the variance in the studied sites (Table 3).

**Table 3.** Summary of ANCOVA results for each site, showing the effect of species, slope position, diameter at breast height class (DBH), and the species x slope position interaction on tensile force (N) as a function of root diameter.

| Site | Source | df | Sum Square | Mean Square | *F* Value | *P* Value | $\eta^2$ |
|---|---|---|---|---|---|---|---|
| Chelir | Species (S) | 1 | 7.63 | 7.63 | 388.68 | 0.000 * | 0.049 |
| | Slope position (SP) | 1 | 0.43 | 0.43 | 22.15 | 0.000 * | 0.003 |
| | DBH [1] | 1 | 6.13 | 6.13 | 312.01 | 0.000 * | 0.039 |
| | Root diameter [1] | 1 | 140.37 | 140.37 | 7150.01 | 0.000 * | 0.906 |
| | S × SP | 1 | 0.29 | 0.29 | 14.95 | 0.000 * | 0.002 |
| Namkhane | Species (S) | 1 | 2.67 | 2.67 | 99.10 | 0.000 * | 0.019 |
| | Slope position (SP) | 1 | 0.40 | 0.40 | 14.83 | 0.000 * | 0.003 |
| | DBH [1] | 1 | 0.90 | 0.90 | 33.46 | 0.000 * | 0.007 |
| | Root diameter [1] | 1 | 131.95 | 131.95 | 4891.88 | 0.000 * | 0.971 |
| | S × SP | 1 | 0.00 | 0.00 | 0.02 | 0.90 | 0 |
| Patom | Species (S) | 1 | 1.44 | 1.44 | 47.86 | 0.000 * | 0.009 |
| | Slope position (SP) | 1 | 0.33 | 0.33 | 10.83 | 0.001 * | 0.002 |
| | DBH [1] | 1 | 2.44 | 2.44 | 81.41 | 0.000 * | 0.016 |
| | Root diameter [1] | 1 | 146.82 | 146.82 | 4891.64 | 0.000 * | 0.970 |
| | S × SP | 1 | 0.26 | 0.26 | 8.60 | 0.003 * | 0.002 |

[1] Data transformed by log 10 to achieve normality. Significant code: '*' <0.05.

### 3.2. Species

Tensile force values for *F. orientalis* at Chelir, regardless of DBH class, and in the medium DBH class at Patom, were higher than those for *C. betulus* (Figure 4). The slope of regression ($F_0$) is almost the same for *F. orientalis* and *C. betulus* trees in the smallest DBH class at Namkhane and Patom. In the case of trees with the largest DBH at Namkhane and Patom, as well as those with medium DBH at Namkhane, the tensile force values of *C. betulus* are higher than those of *F. orientalis* (Figure 4). The variability of tensile force within a given species is high because of the wide range of root diameters and different soil properties in these study sites. According to Table 4, significant power-law regressions were observed about the relationship between tensile force and root diameter in all scenarios ($p < 0.05$). For *C. betulus*, $F_0$ ranges from 13.75 (Chelir site-small DBH) to 76.75 (Namkhane site-medium DBH). The corresponding values for *F. orientalis* were 28.01 (Chelir site -small DBH) and 53.84 (Chelir site-medium DBH) (Table 4). Our results showed that $\alpha$ fluctuates from 1.12 (Namkhane site-large DBH) to 1.41 (Patom site-small DBH) for *C. betulus*. For *F. orientalis*, $\alpha$ variability is higher than that for *C. betulus*, as the highest and lowest $\alpha$ were 0.96 (Patom site-small DBH) and 1.29 (Chelir site-small DBH), respectively (Table 4).

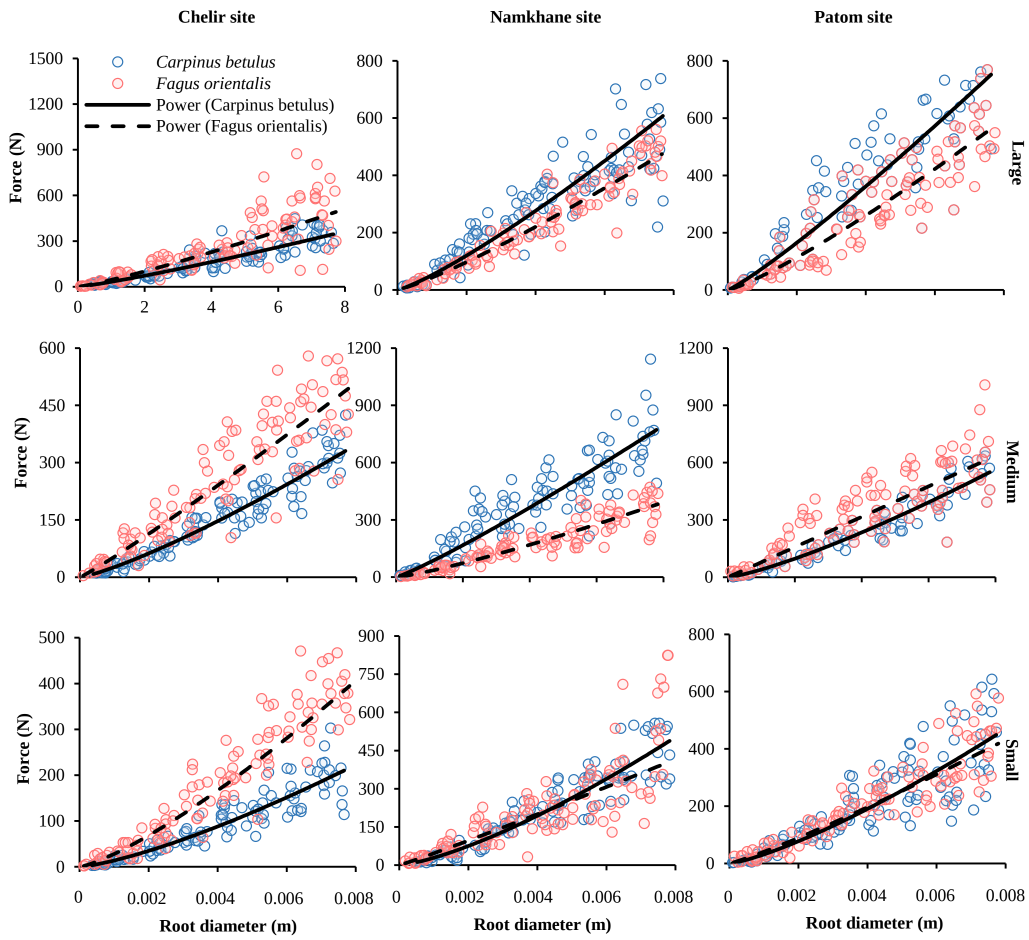


**Figure 4.** Tensile force at failure point versus root diameter for *Carpinus betulus* (blue circles) and *Fagus orientalis* (red circles) within three classes of diameter at breast height (DBH; small = 7.5–32.5 cm; medium = 32.6–57.5; and large = 57.6–82.5 cm) at three sites (Chelir, Namkhane, Patom). Solid (*C. betulus*) and dashed (*F. orientalis*) lines show power-law regression curves fitted to the data.

**Table 4.** Coefficients and statistical parameters of the power-law regressions for tensile force–root diameter compared by diameter at breast height (DBH) classes.

| Site | Species | DBH [1] | $F_0$ | α | *P* Value | SE |
|---|---|---|---|---|---|---|
| Chelir | *Carpinus betulus* | Large | 32.44 | 1.16 | 0.000 | $1.235 \times 10^4$ |
| | | Medium | 26.54 | 1.24 | 0.000 | $1.625 \times 10^4$ |
| | | Small | 13.75 | 1.34 | 0.000 | $2.307 \times 10^4$ |
| | *Fagus orientalis* | Large | 44.92 | 1.17 | 0.000 | $7.444 \times 10^4$ |
| | | Medium | 53.84 | 1.08 | 0.000 | $2.224 \times 10^4$ |
| | | Small | 28.01 | 1.29 | 0.000 | $7.143 \times 10^4$ |
| Namkhane | *Carpinus betulus* | Large | 51.87 | 1.21 | 0.000 | $3.191 \times 10^4$ |
| | | Medium | 76.75 | 1.12 | 0.004 | $5.326 \times 10^4$ |
| | | Small | 28.98 | 1.37 | 0.000 | $1.278 \times 10^5$ |
| | *Fagus orientalis* | Large | 42.88 | 1.18 | 0.000 | $5.439 \times 10^4$ |
| | | Medium | 31.51 | 1.21 | 0.000 | $3.827 \times 10^4$ |
| | | Small | 46.42 | 1.05 | 0.000 | $5.166 \times 10^4$ |
| Patom | *Carpinus betulus* | Large | 75.22 | 1.33 | 0.000 | $2.250 \times 10^4$ |
| | | Medium | 40.21 | 1.27 | 0.000 | $2.190 \times 10^4$ |
| | | Small | 24.25 | 1.41 | 0.000 | $5.236 \times 10^4$ |
| | *Fagus orientalis* | Large | 40.66 | 1.12 | 0.000 | $2.528 \times 10^4$ |
| | | Medium | 30.94 | 1.19 | 0.000 | $1.087 \times 10^4$ |
| | | Small | 51.37 | 0.96 | 0.000 | $1.903 \times 10^4$ |

[1] DBH: small = 7.5–32.5 cm; medium = 32.6–57.5; and large = 57.6–82.5 cm.

For tensile force (N), the ANCOVA revealed that at least one species was significantly different on one of the sites (Table 3). With the data for both species combined, we observed that tensile force was not significantly different for trees with large DBH at all three sites and the medium DBH trees at Patom (as evidenced by the overlap of the ΔFit values and sum of the single tail CI-95% values across the range of root diameter classes; Figure 5). Moreover, it was also not significantly different for trees with small DBH at Namkhane and Patom (i.e., ΔFit values are well below the CI-95% values). In contrast, we found a significant difference in tensile force for trees in the small and medium DBH classes at Chelir and in the medium DBH class at Namkhane (i.e., ΔFit values exceed the CI-95% values).

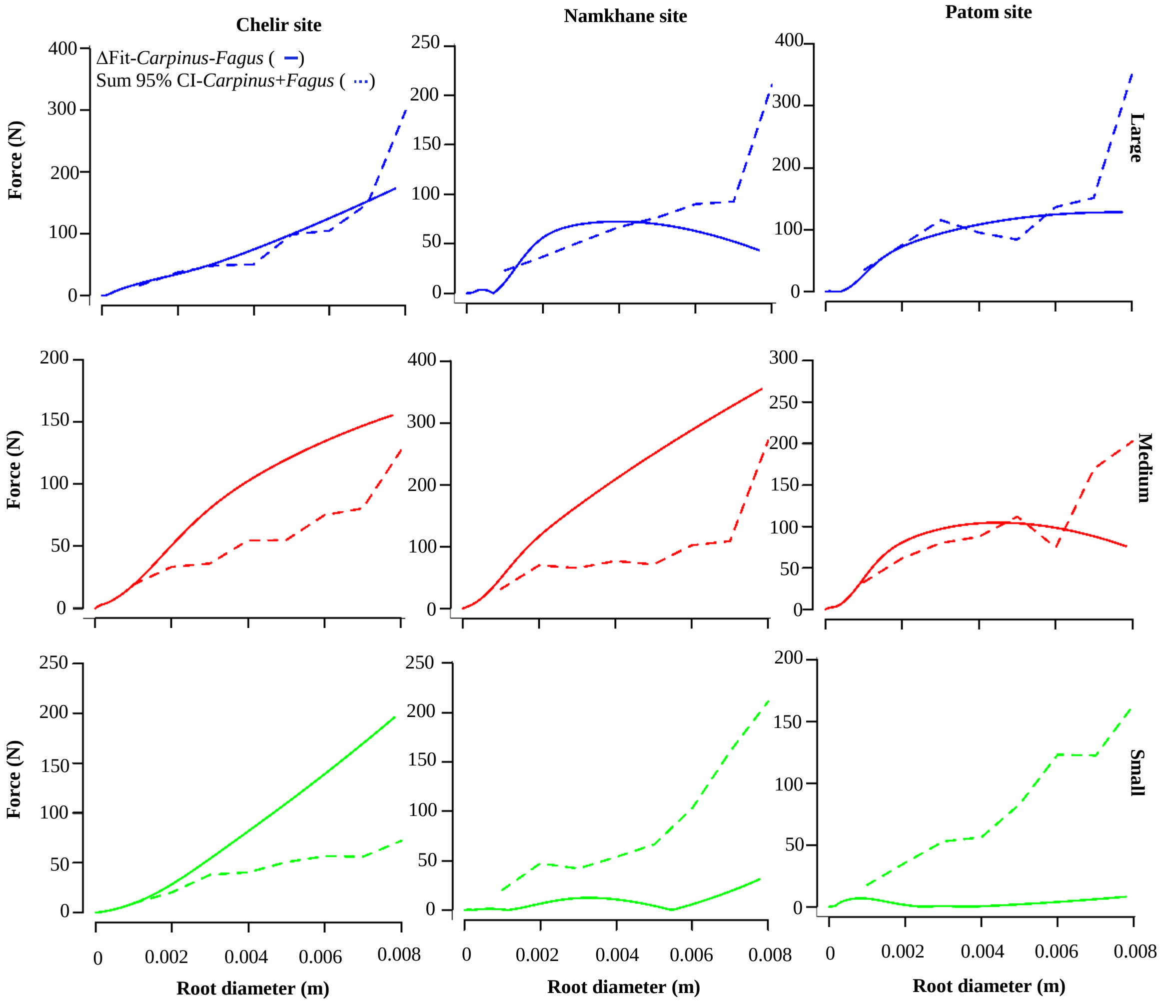


**Figure 5.** Calculation of difference between the fitting curves of tensile force vs. root diameter for *Carpinus betulus* and *Fagus orientalis* within three classes of diameter at breast height (DBH; small = 7.5–32.5 cm; medium = 32.6–57.5; and large = 57.6–82.5 cm) at three study sites (Chelir, Namkhane, Patom).

### *3.3. Slope Position*

For both species, and across sites and DBH classes, the slope of regression ($F_0$) for tensile force by increasing root diameter ranged from 19.66 to 47.01 downslope and 26.88 to 54.84 upslope, and $\alpha$ ranged from 1.08 to 1.29 downslope and 1.12 to 1.24 upslope (Table 5). $F_0$ is slightly higher in the upslope position than in the downslope position at Chelir and Namkhane for *C. betulus* and at Namkhane and Patom for *F. orientalis* (Figure 6 and Table 5). Regression slopes for upslope and downslope positions were similar at Patom for *C. betulus* and for *F. orientalis* at Chelir (Figure 6 and Table 5). Moreover, significant power-law regressions were observed for the relationship between tensile force and root diameter in all scenarios ($p < 0.05$; Table 5). Downslope, $\alpha$ is higher than that for upslope for both species across three study sites, and it ranged from 1.23< α <1.29 and 1.08< α <1.20 for *C. betulus* and *F. orientalis*, respectively (Table 5).

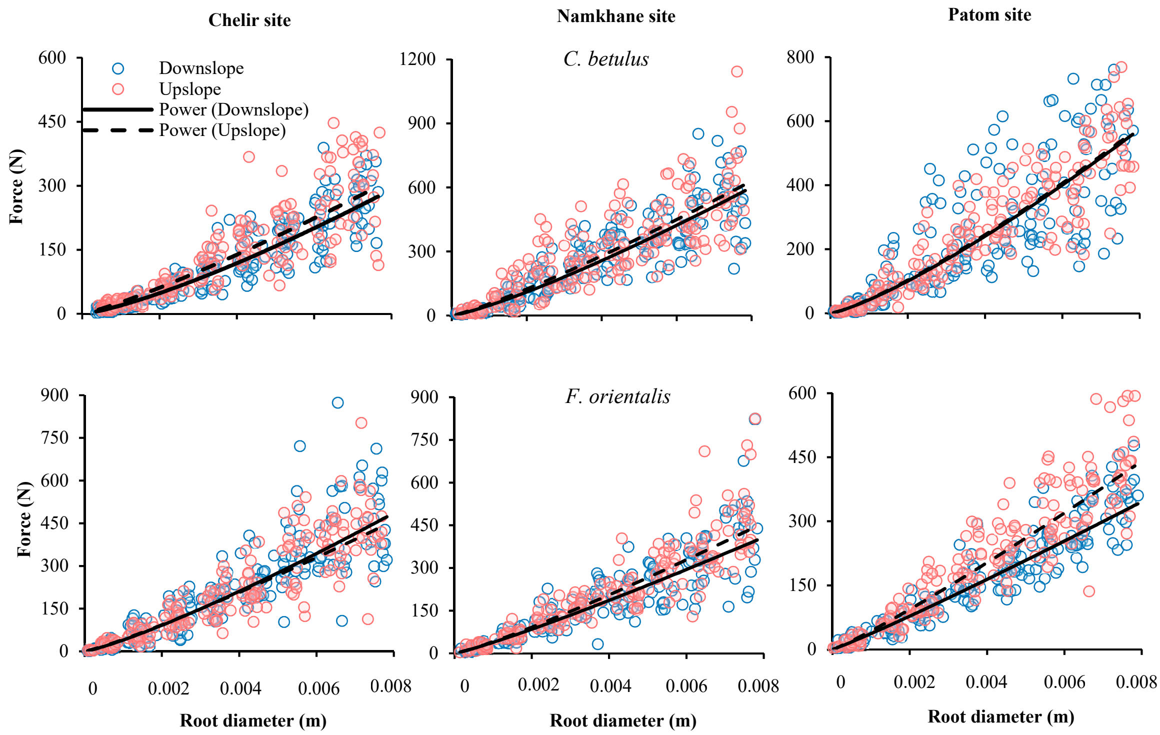


**Figure 6.** Tensile force at failure point versus root diameter for upslope (red circles) and downslope (blue circles) positions relative to the tree stem at three sites for *Carpinus betulus* and *Fagus orientalis*. Solid (downslope) and dashed (upslope) lines show power-law regression curves fitted to the data.

**Table 5.** Coefficients and statistical parameters of the power-law regressions for tensile force–root diameter based on a comparison of upslope versus downslope position.

| Site | Species | Slope Position | $F_0$ | α | *P* Value | SE |
|---|---|---|---|---|---|---|
| Chelir | *Carpinus betulus* | Down | 19.66 | 1.29 | 0.000 | $1.436 \times 10^3$ |
| | | Up | 26.88 | 1.18 | 0.000 | $1.246 \times 10^4$ |
| | *Fagus orientalis* | Down | 39.72 | 1.20 | 0.000 | $6.109 \times 10^4$ |
| | | Up | 42.06 | 1.15 | 0.000 | $3.540 \times 10^4$ |
| Namkhane | *Carpinus betulus* | Down | 47.01 | 1.23 | 0.000 | $3.198 \times 10^4$ |
| | | Up | 54.84 | 1.17 | 0.000 | $4.205 \times 10^4$ |
| | *Fagus orientalis* | Down | 38.59 | 1.13 | 0.000 | $5.875 \times 10^4$ |
| | | Up | 41.07 | 1.16 | 0.000 | $4.001 \times 10^4$ |
| Patom | *Carpinus betulus* | Down | 42.08 | 1.26 | 0.000 | $2.556 \times 10^4$ |
| | | Up | 43.63 | 1.24 | 0.000 | $3.198 \times 10^4$ |
| | *Fagus orientalis* | Down | 36.94 | 1.08 | 0.000 | $2.065 \times 10^4$ |
| | | Up | 43.11 | 1.12 | 0.000 | $2.188 \times 10^4$ |

In general, the one-tail confidence intervals (CI) overlap by more than 2.5%, indicating that the differences in the measured maximum tensile forces upslope and downslope were low (Figure 7). For five combinations of species and site (Carpinus-Chelir; Carpinus-Namkhane; Carpinus-Patom; Fagus-Chelir; Fagus-Namkhane), slope position had no significant effect on tensile force by root diameter class (i.e., ΔFit values are well below the CI-95% values) (Figure 7).

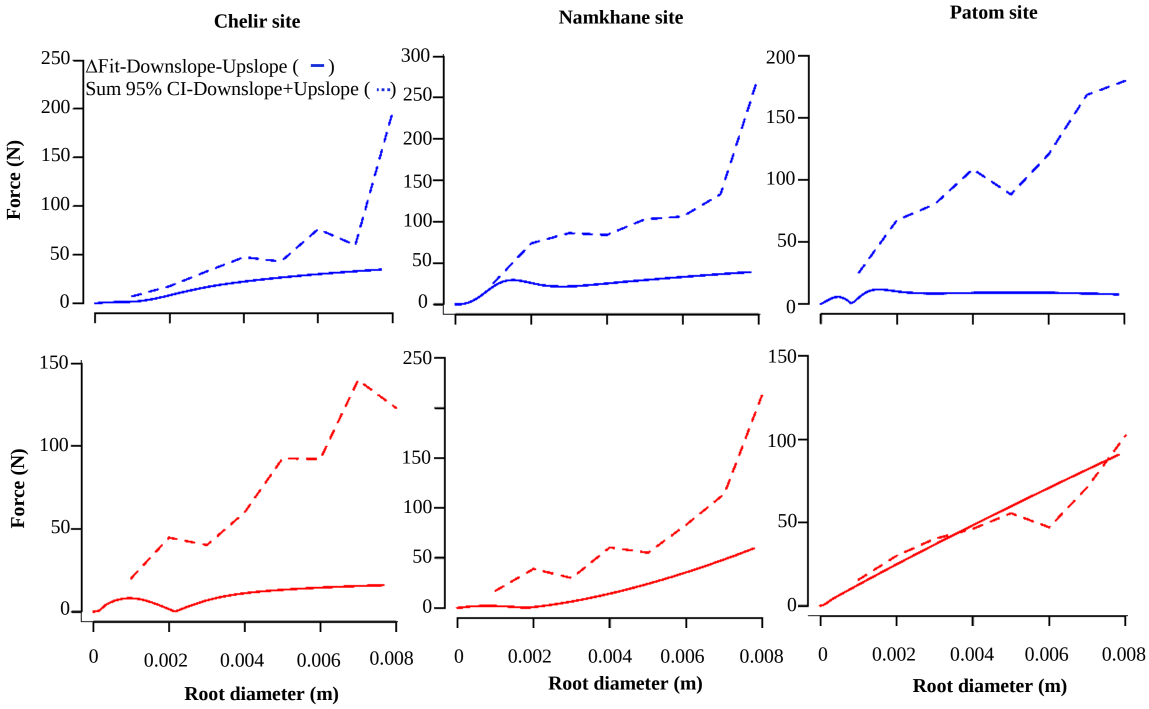


**Figure 7.** Calculation of difference between the fitting curves of tensile force vs. root diameter for the *Carpinus betulus* (blue line) and *Fagus orientalis* (red line) at three study sites (Chelir, Namkhane, Patom).

### *3.4. DBH*

Significant power-law regressions were found observed for the relationship between tensile force and root diameter for all DBH classess (Table 4). At the three study sites, and for both species, unknown trends were observed for $F_0$ values; the exception was for small DBH classes of *C. betulus* that had the lowest $F_0$ values for this species (Table 4). The $F_0$ of large trees increased slightly at all sites except Namkhane for *C. betulus* and for *F. orientalis* at Chelir (Figure 8). For *C. betulus*, $\alpha$ value within a small DBH class is higher than other DBH classes, whereas no obvious trends were observed for *F. orientalis* (Table 4).

Figure 9 shows the differences between the fitting curves of tensile force vs. root diameter for both species with the three DBH classes on the three study sites. The fitting curves for small and medium, small and large, and medium and large DBH classes were significantly different at all three sites for *C. betulus*, except at Chelir site, where the curves for medium and large were not significantly different (Figure 9). Furthermore, the curves for small and large and medium and large measurements at Namkhane site and small and medium at Patom site overlap for most of the root diameter classes with a probability lower than 2.5% (Figure 9). The fitting curves for small and medium, small and large, and medium and large DBH classes of *F. orientalis* at Chelir and Namkhane sites are not significantly different (Figure 9). Small and medium and small and large measurements at Chelir, and medium and large at Namkhane site, overlap for most of the root diameters, although, in the case of Patom site, ΔFit is higher than sum of single tail CI-95% (Figure 9). Results of the ANCOVA test showed that the effect of DBH classes on tensile force was significant (Table 3). F values of ANCOVA test among DBH classes ranged from 33.46 (Namkhane site) to 312.01 (Chelir site) (Table 3).

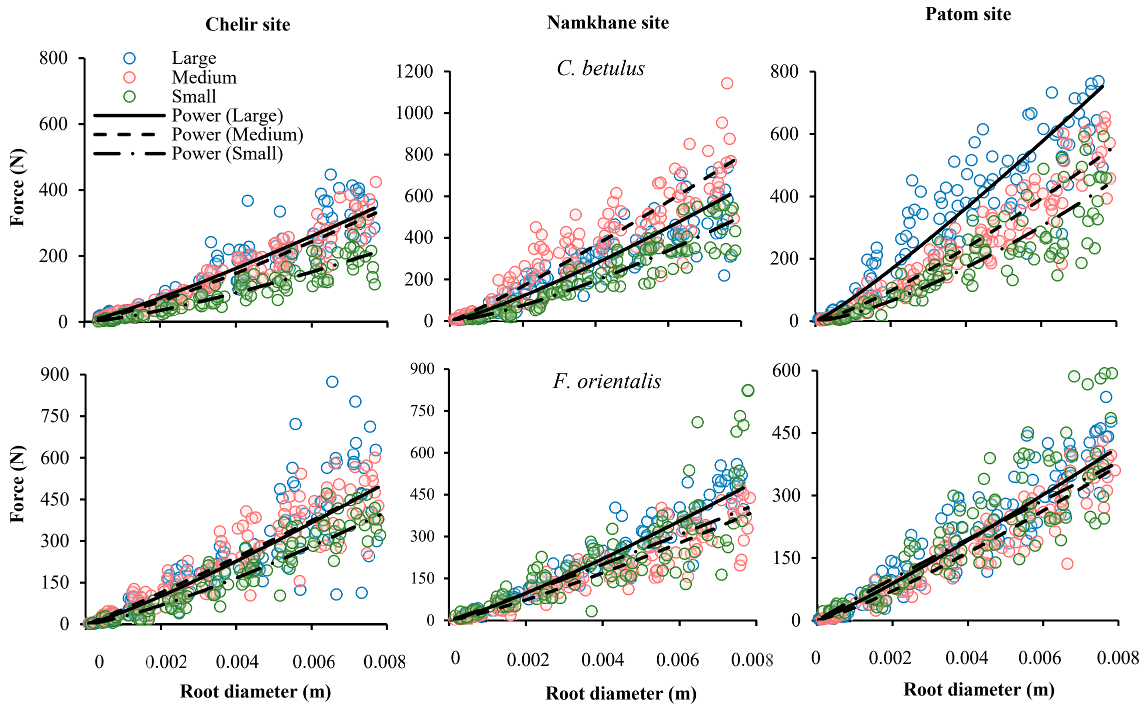


**Figure 8.** Tensile force at failure point versus root diameter for diameter at breast height (DBH; small = 7.5–32.5 cm; medium = 32.6–57.5; and large = 57.6–82.5 cm) at three study sites (Chelir, Namkhane, Patom) for *Carpinus betulus* and *Fagus orientalis*. Solid (large), dashed (medium), and long dash dot (small) lines show power-law regression curves fitted to the data.

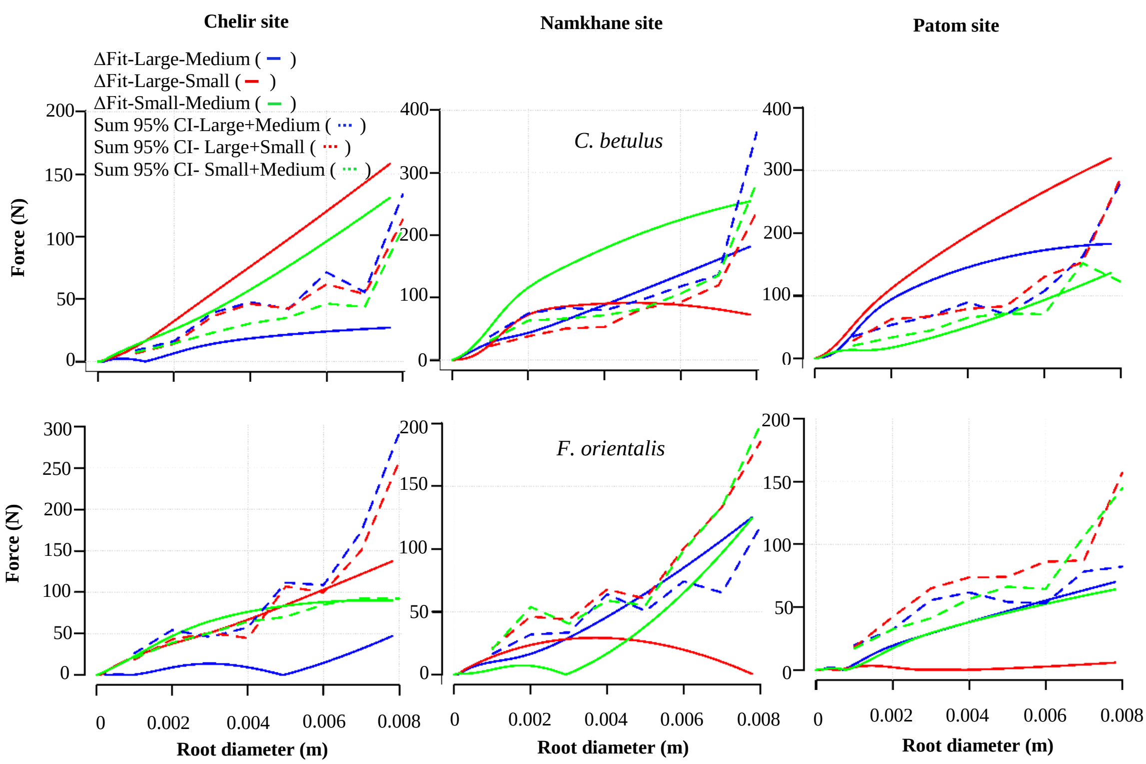


**Figure 9.** Calculation of difference between the fitting curves of tensile force vs. root diameter for the *Carpinus betulus* and *Fagus orientalis* within three classes of diameter at breast height (DBH; small = 7.5–32.5 cm; medium = 32.6–57.5; and large = 57.6–82.5 cm) at three study sites (Chelir, Namkhane, Patom).

### 3.5. Study Sites

To evaluate the influence of site on the tensile force–root diameter relationship within each species, data from the different sites were plotted and compared, revealing that tensile force increased slightly at different study sites (Figure 10). Significant power-law regressions were observed about the relationship between tensile force and root diameter across study sites ($p < 0.05$; Table 4). For *C. betulus*, $F_0$ at Patom site is higher than other sites, while no obvious trends were found for *F. orientalis* (Table 4). For *C. betulus*, the α value observed at the Patom site was greater than that observed on the Chelir and Namkhane sites (Table 4). For *F. orinetalis*, the α value at Namkhane site was greater than that at other sites, except within the small DBH class (Table 4).

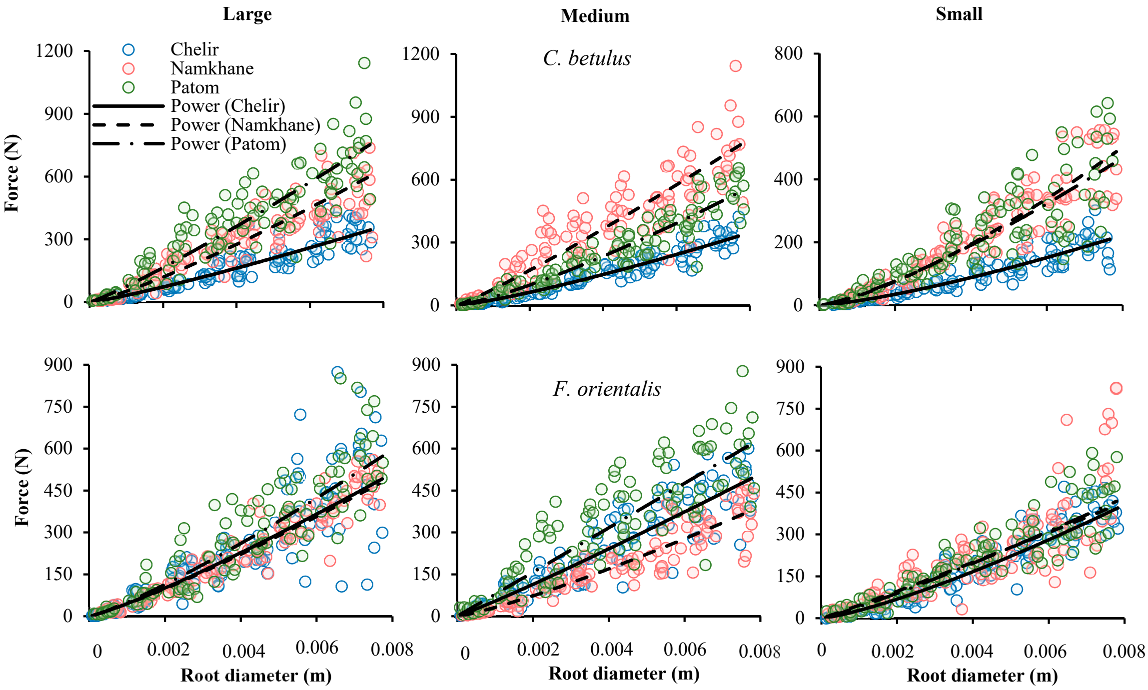


**Figure 10.** Tensile force at failure point versus root diameter for diameter at breast height (DBH; small = 7.5–32.5 cm; medium = 32.6–57.5; and large = 57.6–82.5 cm) at three study sites (Chelir, Namkhane, Patom). Solid (Chelir), dashed (Namkhane), and long dash dot (Patom) lines show power-law regression curves fitted to the data.

For *C. betulus*, we observed that tensile force was significantly different among Chelir and Namkhane, Chelir and Patom, within all DBH classes (i.e., ΔFit values exceed the CI-95% values), whereas tensile force was not significantly different for large, medium (as evidenced by the overlap of the ΔFit values and sum of the single tail CI-95% values across the range of root diameter classes), and small (i.e., ΔFit values are well below the CI-95% values) trees of Patom and Namkhane (Figure 11). Within the data for *F. orientalis*, tensile force within the medium DBH class at Patom and Namkhane was significant (Figure 11). No significant differences were observed, however, between large and small diameter trees at all sites, medium trees at Chelir and Namkhane, or any trees at Chelir and Patom (Figure 11).

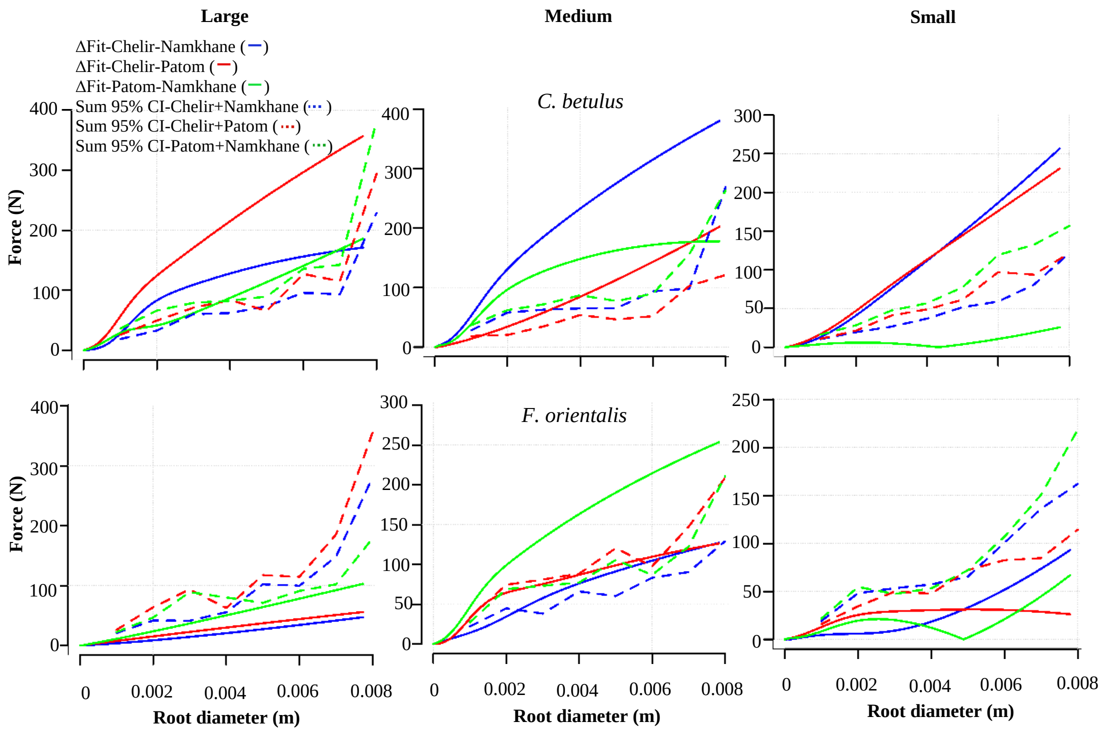


**Figure 11.** Calculation of difference between the fitting curves of tensile force vs. root diameter of three classes of diameter at breast height (DBH; small = 7.5–32.5 cm; medium = 32.6–57.5; and large = 57.6–82.5 cm) for *Carpinus betulus* and *Fagus orientalis* at three study sites (Chelir, Namkhane, Patom).

## 4. Discussion

To the best of our knowledge, existing research in the Caspian Hyrcanian Ecoregion on root mechanical characteristics consists of case studies with small datasets focused only on the effects of different species on root mechanical characteristics. The novelty of our research is the broadening of the scope and relevance of root mechanical characteristics. This was achieved through a robust sample of roots (2016 samples) across a variety of DBH classes, elevational gradients, and slope positions of the roots of two common species.

Deciduous broadleaf species characterized by an intensive development of fine roots in the upper soil layer instantly linked to different factors such as climate, age, DBH, and stand composition [47]. Root reinforcement has been noticed as one of the key factors when dealing with slope stability issues and landslides safety, thereby becoming one of the criteria in managing forests against natural hazards [10,11]. Large roots anchor the soil, especially across planes of weakness, and fine roots provide an extensive network that increases soil shear strength [6,48,49]. While coarse roots (>10 mm) have a higher impact on root reinforcement than fine roots [6,7], fine roots are more numerous and occupy a larger area around the tree on slopes than do coarse roots [50], playing a key role in slope stability. Most of the scientists consider that fine and thin roots (<10 mm), which act as tensile fibers during slope failures, provide the major contribution to slope stability [15–17,51]. Large numbers of fine roots could limit the number of cracks occurring on the surface soil, thereby stabilizing the shallow soil more effectively than a small number of coarse roots, which can slip out of the soil upon soil mass sliding [13,52,53].

In older models of root reinforcement, maximum tensile strength of roots was used to describe their mechanical characteristics [54]. Maximum tensile strength is calculated using root diameter and maximum tensile force (the force required to break roots), the later also being calculated in relation to root diameter. Recently, mechanical tensile force has been used independent of tensile strength to describe the mechanical characteristics of roots [7,55]. In our study, our models also focused solely on the tensile force of fine roots to examine their potential contribution to soil reinforcement. We did so to alleviate using the root diameter twice for each observation, which can add uncertainty to the models because of the difficulty involved in accurately determining the very small diameters we studied [40,44]. In this study, roots larger than 8 mm were not tested, therefore, the results of the maximum tensile force will be different if coarse roots are considered in the analysis.

We found a significant relationship between root diameter and tensile force, confirming that root tensile force strongly depends on root size, and similar to the findings of many researchers [15,40,44,46,51,56,57]. This supports the necessity to take the root diameter into account as a covariate for root tensile force analyzing [9,20,40,58]. Moreover, our results show that root tensile force increases with rising root diameter regardless of species, DBH class, or elevation, similar to the results of other studies [6–8,43,57].

In most cases, *F. orientalis*, with higher root resistance than *C. betulus*, may be preferred in soil bioengineering systems. Perhaps this type of effect is related to species-specific tree longevity. Alidadi [59] showed that *F. orientalis* had a significantly higher longevity than *C. betulus*, and Abdi [60] observed that *F. orientalis* roots were stronger than those of *C. betulus* of unspecified DBH in the Kheyrud forest. Our results, which included discrete DBH classes, were similar. Moreover, our comparisons of tensile force vs. root diameter for these two species are similar to those observed in other studies (*F. sylvatica* [22,40,61]; *C. betulus* [40]).

We did not, however, note any differences in root-system mechanical resistance on the basis of slope position. This contrasts with the results of Stokes [62], where resistance was greater in the upslope position compared to the downslope position but concurs with Khuder et al. [63] and Genet et al. [64], who observed that no differences occur in the mechanical properties of the roots in different positions around the root system. Commonly, it is believed that no general rule exists to explain the differences in root growth and mechanical properties on the slope, similar to our results. Although earlier studies examined a variety of parameters on root tensile force (e.g., slope position, species, soil types) [9,10,42,51,53,56,58,62]; to the best of our knowledge, we are the first to attempt to examine the interactions of these parameters. Our finding of an interaction between species and slope positions on two of three sites (i.e., Chelir and Patom) suggests that the effective parameters on root tensile force are various and complex.

In general, we found that the roots of the trees with larger DBH were more resistant in tension compared with the roots of the medium or small DBH classes, which concurs with [11]. This may be explained by the report of [65], who showed that root resistance was lower in the early growth stage and increased in older plants.

For the same root diameter, the force needed to break a root was found to decrease with increasing elevation above sea level [64]. Whenever the tensile strength of the roots decreases, the root system may adapt based on the situation, and therefore tree anchorage is not comprised [64]. Adaption of the root system architecture to external stimuli in response to mechanical force was recently shown as the initiation of new coarse roots [66]. This potential of adaptation based on the environmental conditions is termed “morphoplasticity” [67] or “phenotypic plasticity” and results in asymmetric root distribution [66–70]. Our results showed that for *C. betulus* and *F. orientalis* the root tensile force is notably different from one site to another site, although further assessment on root system architecture is necessary to determine whether any decrease in root resistance associated with increasing elevation was compensated by morphological adaptation. These findings are similar to those of other studies performed on a single species [64] or in a small area [71]. These authors attributed site differences to elevation and the position of the sampling on hillslope. Genet et al. [65], found a significant difference for the same species sampled at different locations, but the elevation between their locations was much greater than those in our study. However, in contrast with the results of Genet et al. [65], the maximum tensile force of roots of *Castanea sativa* Mill. did not differ between the two sites under consideration [7]. The mechanical properties of roots between sites with different soil water content regimes differed significantly [23]. Vergani et al. [40] clarified that the comparisons of sites’ relationships for different species remarkably are a consequence of varying conditions of the growing sites and environment. It is discussed that alterations in root mechanical resistance with increasing elevation were due to modification in soil's chemical and physical properties [64]. On our sites, however, the physical characteristics are almost the same in different sites, although chemical properties showed differences in nitrogen, phosphorus, potassium, carbon, nitrogen, and organic matter (Table 1), making it difficult to reach any conclusion. Different levels of soil compaction did not significantly affect the root resistance in the woody plants *Acacia senegal* L. and *Prosopis juliflora* DC. [72]. Goodman and Ennos [73] demonstrated, however, that the roots of two annual plants, *Zea mays* L. and *Helianthus annuus* L., either became stiffer or were unchanged, respectively, when growing in soil with low bulk density Moreover, Jourgholami et al. [74] investigated the ratio of lateral to main root length, which is significantly reduced in high intensity compaction in comparison with control treatment, although the ratio of lateral to main root biomass was not significant among different soil compaction treatments. Accordingly, to prove if soil physical characteristics affect root resistance and mechanical properties, further studies are required.

The increased tensile force with increasing root diameter, slope position, tree age and longevity, and elevation has been attributed to a greater cellulose content as a function of root size, environmental stimuli, or genetics [22,41,42,65,71,75,76]. Consequently, analyzing the cellulose content of roots for different size, DBH, slope position, and age classes would be a valuable addition to the literature.

## 5. Conclusions

This study provides a comprehensive analysis of root tensile force variation of two common species, *Carpinus betulus* and *Fagus orientalis*, across differing DBH classifications, slope positions, and study site elevations within a temperate deciduous forest. Our results identified that the main factors affecting variability in fine root tensile force are the tree species and the DBH of the sampled tree. Study site location had an effect on root tensile force only for *C. betulus*. No differences in tensile force were found for roots growing upslope or downslope of the tree stem. This information is useful for scientists and forest land managers in order to evaluate the variability in root reinforcement due to different factors, and to account for this uncertainty when evaluating the effectiveness of slope stabilization using biological engineering measures. The selection of a species in a region can cause changes in soil reinforcement and slope stability. Understanding the relationship between tree species and soil bioengineering and the impact of different DBH classes on these processes can be useful for forest management and the selection of appropriate species for reforestation projects. In the Caspian Hyrcanian Ecoregion, *F. orientalis*, with a higher fine root resistance than *C. betulus*, may be preferred in soil bioengineering systems.

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