Implications of hornbeam and beech root systems on slope stability: from field and laboratory measurements to modelling methods

Azade Deljouei[1]*, Alessio Cislaghi[2], Ehsan Abdi[3], Stelian Alexandru Borz[1], Baris Majnounian[3], Tristram C. Hales[4]

1. Department of Forest Engineering, Forest Management Planning and Terrestrial Measurements, Faculty of Silviculture and Forest Engineering, Transilvania University of Brasov, Şirul Beethoven 1, 500123 Brasov, Romania

2. Department of Agricultural and Environmental Sciences, University of Milan, Milan, Italy

3. Department of Forestry and Forest Economics, Faculty of Natural Resources, University of Tehran, Karaj, Iran

4. School of Earth and Environmental Sciences, Cardiff University, Cardiff, United Kingdom

*** Corresponding author: azade.deljouei@unitbv.ro or a.deljooei@ut.ac.ir (A. Deljouei)**

ORCID of the authors:

- Azade Deljouei: 0000-0003-3453-8530
- Alessio Cislaghi: 0000-0002-4618-818X
- Ehsan Abdi: 0000-0002-3382-7683
- Stelian Alexandru Borz: 0000-0003-4571-7235
- Tristram C. Hales: 0000-0002-3330-3302

Abstract

Purpose This study investigated root distribution and root reinforcement estimated by field and laboratory measurements and modelling methods, in function of species, trees diameter at breast height (DBH), slope position, altitude, vertical and horizontal distances from tree in Hyrcanian temperate ecoregions of Iran.

Method 1080 profile trenches with maximum 1 m depth were excavated on upslope and downslope from trunks of *Carpinus betulus* and *Fagus orientalis* with the DBH of 7.5-32.5, 32.5-57.5, and 57.5-82.5 cm at three altitudes (400, 950, and 1300 m a.s.l.).

Results Root distribution results indicated that: (i) frequency of small roots (2-5mm of diameter) of *C. betulus* and fine roots (0-2 mm) of *F. orientalis* are the highest, whereas the frequency of large roots (>10mm) of both species is the lowest, (ii) the Root Area Ratio (RAR) of *C. betulus* is always higher than *F. orientalis*, (iii) the trees with larger DBH have more roots than those with a smaller DBH, (iv) the RAR of *F. orientalis* in upslope is higher than in downslope; however, the RAR of *C. betulus* for both slopes are similar, (v) the RAR in the 1300 m altitude is the highest, and (vi) the RAR decreases with increasing distance from tree trunk and from soil surface. Furthermore, it is evident that: (i) root reinforcement of *C. betulus* is higher than *F. orientalis*, (ii) altitude has a significant effect on root reinforcement of *C. betulus*, (iii) root reinforcement of large trees is the highest, and (iv) root reinforcement decreases with increasing distance from tree trunks.

Conclusion *C. betulus* is preferable to *F. orientalis* for increasing slope stability. Forest managers should consider this outcome when developing strategies for silvicultural treatment and reforestation projects in mountainous areas.

Keywords: Hillslope stabilization, Root mechanical properties, Root Bundle Model Weibull, Root distribution, Root reinforcement, Soil bioengineering, Iran.

1. Introduction

Forests play a significant role in preventing and mitigating hydrogeomorphic hazards such as shallow landslides, rockfalls, and avalanches. Trees generally provide more protective functions than shrubs and herbs through some hydrological and mechanical processes: rainfall interception (Sadeghi et al. 2020; Lin et al. 2020), soil coverage by rainfall splash (Lin et al. 2020; Williams et al. 2020), buttressing and arching (Gray and Sotir 1996), soil reinforcement by roots in shallower and deeper soil layers (Morgan and Rickson 1995). In detail, trees contribute to regulate water cycle: intercepting rainfall, altering hydraulic conductivity through physical transformation of the soil by roots, and transpiring stored water (Stokes et al. 2014; Vergani et al. 2017a). Moreover, roots contrast the triggering mechanisms of shallow landslides up to 2 m extending and penetrating the soil mantle and sometimes crossing the failure plane, and increasing tensile and shear soil resistance (Norris et al. 2008). On hillslopes, thick roots can act as piles to reinforce the soil, while fine roots act in tension, cross the slip surface and strengthen the soil by adding cohesion. Quantifying the mechanical effects of vegetation on hillslope stabilization remains an unsolved issue and has been frequently investigated since the Sixties (e.g., Endo and Tsuruta 1969; O'Loughlin 1974; Genet et al. 2008). Root systems stabilize the shallower soils by three different mechanisms, called in general root reinforcement: basal root reinforcement, lateral root reinforcement, and root reinforcement under compression (stiffening and buttressing of sliding mass under compression (Giadrossich et al. 2019). When roots cross the shear plane, basal root reinforcement acts as an anchor inside the stable soil layer or bedrock. Lateral root reinforcement is the most effective mechanism in stabilizing landslide-prone slopes, although increasing the landslide size, such contribution declines (Milledge et al. 2014). Finally, the contribution of roots under compression consists in mobilizing an additional resistance across the shear plane, which leads to a complex bending-tensioning of rooted-soil (Schwarz et al. 2015).

Estimating root reinforcement depends by four main factors: root density (i.e. the number of roots into the soil), root spatial distribution into the soil, root diameter (i.e. larger roots are more resistant than fine ones), and root biomechanical properties (i.e., tensile resistance, elasticity, etc.) (Mao 2022). Several parameters individually influence root distribution, including forest stand characteristics (such as tree spatial distribution), diameter at the breast height (DBH), tree age, tree species composition, distance from the trunk, position on the slope, growth conditions (including soil temperature, soil depth, nutrient), and moisture content (Genet et al. 2010; Mao et al. 2012; Cislaghi et al. 2021). Moreover, it is worth noting that the spatial root distribution depends on species morphology and environmental conditions, soil type, soil depth, and availability of water and nutrients (Phillips et al. 2014; Vergani et al. 2017a). For these reasons, investigating the spatial heterogeneity of roots at stand scale and modelling the lateral root distribution is very challenging (Vergani et al. 2017a). A proxy parameter of the spatial distribution of roots is the Root Area Ratio (RAR), computed as the total cross-sectional area of all roots divided by the total soil area, and largely used in the scientific literature (Bischetti et al. 2009; Mao et al. 2012; Arnone et al. 2016). Conversely, most studies have been exclusively focused on fine roots (<2 mm), whereas there is less information on coarse roots, especially roots larger than 10 mm (Giadrossich et al. 2020). In addition, few studies about root distribution as a function of DBH and distance from the tree trunk have allowed modelling the root distribution (Schwarz et al. 2010; Cislaghi et al. 2021). Roots biomechanical properties have been extensively studied compared to root distribution.

Observing data on biomechanical properties and root distribution allowed to develop and improve the use of numerical models that quantify root reinforcement values to be included into slope stability analysis (Ekanayake and Phillips 1999). Numerical models have been generally used since the development of the pioneering model Wu and Waldron (W&W) based on the assumption that roots are elastic fibers extending perpendicular to a shear surface, moreover all roots break at the same time (Wu, 1976; Waldron, 1977). Pollen and Simon (2005) developed the Fiber Bundle Model (FBM) due to the significant overestimation of root reinforcement by W&W model. According to the FBM, all roots assumed to be parallel and have similar elastic properties. When each root breaks, the load is continuously redistributed over the remaining roots until the entire bundle are broken. Besides the already mentioned, the Root Bundle Model Weibull (RBMw) was an interesting improvement since it provides the root reinforcement in function of the observed root distribution at hillslope scales and of the displacement due to a potential triggering mechanism at hillslope scales (Schwarz et al. 2013). RBMw has been used in different environments across the world, including temperate forests of Norway spruce (*Picea abies* (L.) H. Karst.; Bischetti et al. 2007; Schwarz et al. 2013, 2015; Vergani et al. 2014; Moos et al. 2016; Cohen and Schwarz 2017; Cislaghi et al. 2021), jolcham oak (*Quercus serrate* Murray; Yamase et al. 2021), Monterey Pine (*Pinus radiate* D. Don; Giadrossich et al. 2020), black locust (*Robinia pseudoacacia* L.; Zydroń et al. 2019; Zydroń and Gruchot 2021), black poplar (*Populus nigr* L.; Zydroń et al. 2019), common hornbeam (*Carpinus betulus* L.; Zydroń and Gruchot 2021), green alder (*Alnus viridis* (Chaix) D.C.), red willow (*Salix purpurea* L.), goat willow (*Salix caprea* L.), hazel (*Corylus avellana* L.), European ash (*Fraxinus excelsior* L.), and European larch (*Larix decidua* Mill.; Bischetti et al. 2007), silver birch (*Betula pendula* Roth), small-leaved lime (*Tilia cordata* Mill.), English oak (*Quercus robur* L.), and Sweet Cherry (*Prunus avium* L.; Zydroń and Gruchot 2021), sweet chestnut (*Castanea sativa* Mill.; Dazio et al. 2018; Cislaghi et al. 2021), European beech (*Fagus sylvatica* L.; Bischetti et al. 2007; Gehring et al. 2019; Cislaghi et al. 2021), Scots pine (*Pinus sylvestris* L.; Vergani et al. 2017b), and subtropical forest for the white mangrove (*Avicennia marina* (Forssk.) Vierh.; Karimi et al. 2022).

In this context, although it is evident the efforts of scientific community to investigate the implications of forests on slope stability around the world, several scientific gaps remain for some mountainous areas, often prone to landslides, such as the Hyrcanian temperate forests. In this environment, few studies provided useful advances for implementing nature-based solutions such as the forests, to reduce the negative impacts of the shallow landslides. Abdi et al. (2010a) observed that RAR of oriental beech (*Fagus orientalis* Lipsky.), Persian ironwood (*Parrotia persica* (DC.) C.A.Mey.) and *Carpinus betulus* trees decreased with the depth and the maximum RAR values in the upper soil layers. For three pioneer species Caucasian alder (*Alnus subcordata* C.A.Mey), velvet maple (*Acer velutinum* Boiss.), and *Parrotia persica*, Abdi and Deljouei (2019) showed that in shallower depths of the soil, RAR was higher, and in profiles nearer trees, they showed significantly higher RAR than in far trenches. Deljouei et al. (2020) explored the most important parameters that affect fine roots resistance of two common temperate species (*F. orientalis* and *C. betulus*) in the Hyrcanian forest, finding that tree species and DBH make a significant difference in fine roots resistance. Despite, the effect of variability in soil profiles, tree DBH, altitude, and slope positions on the spatial variability of roots and root reinforcement is still underexplored, with only a couple of studies on the topic (Moos et al. 2016; Cislaghi et al. 2021). For these reasons, the present study focuses on spatial and mechanical characteristics of the root systems of the dominant species (*F. orientalis* and *C. betulus*) in the Hyrcanian forest. In such environment, *F. orientalis* forests account for approximately 30% of the standing volume and 23.6% of the stem number, covered large areas at altitude from 300 to 2000 m a.s.l (Sagheb-Talebi et al. 2014). Meanwhile, *C. betulus* species accounts for 30.5% of the standing volume and 30% of the stem number and can be found at altitude from 100 to 1500 m a.s.l in the Hyrcanian forests (Sagheb-Talebi et al. 2014). Both species are representative and valuable study cases not only they cover a vast area of temperate forests in the world but also these species are often located on slopes of mountainous areas where the protection function of forests is significantly important to reduce the landslide susceptibility in proximity of infrastructures and villages.

Recently, a lot of importance has been given to the implications of slope stability and evaluating the potential of trees in stabilizing steep slopes. Some critical challenges in setting a safety factor are understanding how vegetation enhances slope stability and quantifying vegetation's contribution to soil shear strength. The ability to evaluate different areas in terms of their susceptibility to shallow landslides as well as the potential of local trees in stabilizing the hillslopes enables optimization in forestry practices. To the authors' best knowledge, no studies modelling root reinforcement of *C. betulus* and *F. orientalis* in function of DBH, slope position, altitude, soil depth, and distance from the tree trunk. Hence, the main aims of the study consist in: (i) investigating the spatial (root distribution) and mechanical variability of root systems, and (ii) modelling root reinforcement by Root Bundle Model Weibull (RBMw) of two hardwood species in the Hyrcanian forest; (iii) providing a simplified framework for evaluating the effects of trees in terms of slope stabilization. In addition, the study conducted a statistical analysis of the similarities and differences between two main species of Hyrcanian temperate forests and several dendrometric characteristics, altitude, and spatial position on root reinforcement, which forest managers must consider to mitigate shallow landslides.

2. Material and Methods

2.1. Study site

Iran is one of the landslide-prone countries due to its specific geologic, morphologic, climatic, and tectonic conditions, where most landslides are concentrated on the rim of Alborz Mountains. Approximately, 2600 landslides occurred in the year 2000 in the country, which caused 162 deaths, destruction of 176 houses, and damages to 170 roads (Abbaszadeh Shahri and Maghsoudi 2021). One of the regions of Iran in which landslides occur frequently is the Hyrcanian ecoregion, particularly in such circumstances in which the vegetation has been cleared to construct roads. Hyrcanian forests are classified as hilly and mountainous temperate forests, forming a green belt over the northern slopes of the Alborz Mountain. They cover the southern coast of the Caspian Sea spreading on about 1.9 million hectares. The area is abundant in hardwood species, including approximately 50 trees and 80 shrub species. Dominant species are the *Carpinus betulus*, *Fagus orientalis*, *Parrotia persica*, Cappadocian maple (*Acer cappadocicum* Gled.), *Acer velutinum*, common alder (*Alnus glutinosa* (L.) Gaertn), wych elm (*Ulmus glabra* Huds.), and the chestnut-leaved oak (*Quercus castaneifolia* C.A.Mey.). Hyrcanian forests are used for wood production, tourism, environmental protection and supportive services. These forests play an important role in conserving soil and water resources on steep mountain slopes that are vulnerable to landslide. One of the severe problems in Hyrcanian forests is slope failure and shallow landslides, because bare soils are vulnerable during intensive rainstorms, specifically where the trees have been clear cut to make space for forest roads (Abdi et al. 2010a). In this ecoregion, landslides often cause economic losses, property damages and high maintenance costs, as well as injuries or mortality (Pourghasemi et al. 2012).

Kheyrud Forest, which covers an area of ~8000 ha, was selected as the study location (Fig. 1). The climate of the area is humid, and the temperature fluctuations are relatively limited. The average annual precipitation is 1300 mm, falling mainly as rain. The mean summer and winter temperatures are estimated to be 25.1 and 7.1 °C, respectively. Field sampling was carried out in three districts of the Kheyrud Forest (Fig. 1), namely Patom, Namkhane, and Chelir. Altitude of the study sites ranges from 400 m a.s.l. in Patom, with the highest mean temperature and lowest annual precipitation, to 950 m a.s.l. in Namkhane, and 1300 m a.s.l. in Chelir, the latter exhibiting the lowest mean temperature and the highest yearly precipitation. According to the unified soil classification system, the soils on the three study sites were clays with high plasticity (i.e., CH). The mean values (± SD) of the Atterberg limits of the soils (soil liquid limit (Casagrande cup method), soil plastic limit (rolling and thread method), and soil plasticity index) from the study sites were estimated at 65% (± 6.2%), 26.4% (± 3.1%), 38.6% (± 3.8%) in Patom district, 88.5% (± 7.4%), 38.3% (± 4.9%), 50.2% (± 4.6%) in Namkhane district, and 85.7% (± 6.9%), 37.7% (± 3.7%), 48.0% (± 5.0%) in Chelir district, respectively.

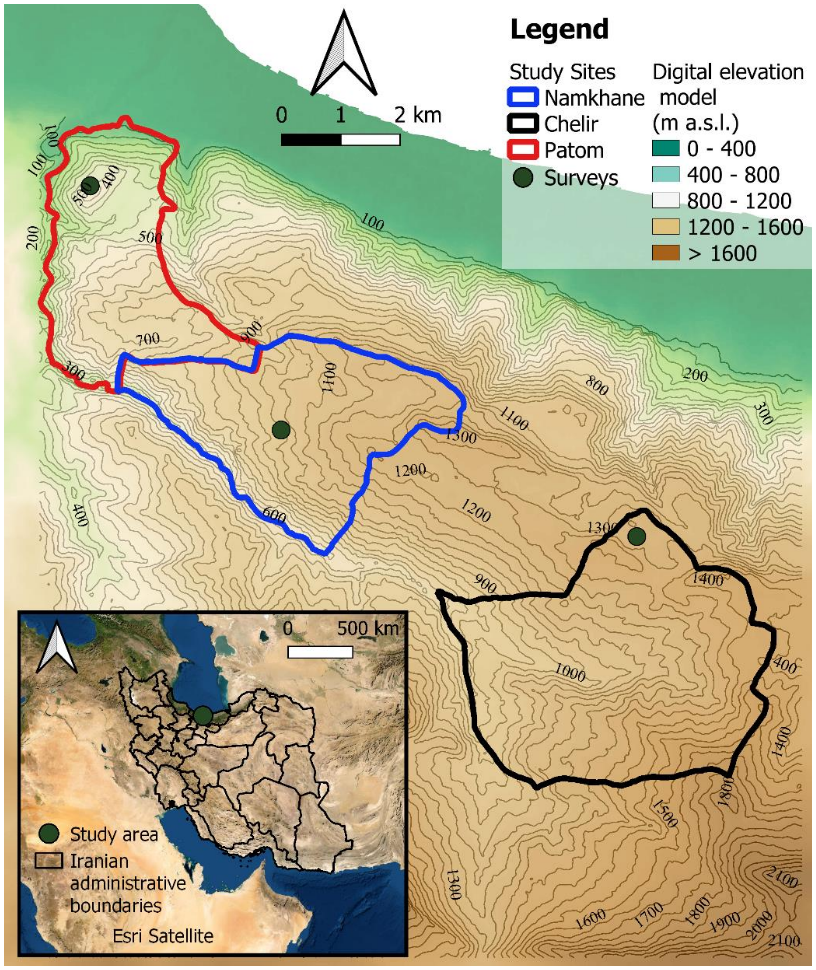

Fig. 1 Study location: map of Iran showing the general location of the study and districts taken into study

2.2. Measuring root distribution

Root distribution was measured for 5 sample trees of each of the two investigated species (*C. betulus* and *F. orientalis*), for each study site (Patom, Namkhane, and Chelir) at altitude of 400, 950, and 1300 m a.s.l., respectively, and for each DBH class (small = 7.5-32.5 cm, medium = 32.5-57.5 cm, and large = 57.5-82.5 cm). Hence, 90 trees were randomly selected (3 altitudes × 3 DBH classes × 2 species × 5 trees) and used as a sampling reference in this study. Six trenches with a width of 0.5 m and a length of 1 m were excavated manually to the maximum rooting depth (1 m soil depth); located on the downslope and upslope at distances of 1, 1.5, 2, 2.5, 3.5, and 4 m from the tree (Fig. S1). The profile trenching method was used to characterize the root distribution (Böhm 1979; Fig. S1). Layers of 10 cm were marked on the vertical profile walls using pins and string (Fig. S1). The number of roots, diameter, and maximum depth were measured in both downslope and upslope trenches. The diameters of roots intersecting the soil profile were measured with a digital calliper. Based on their diameter, the roots were included in four classes, namely fine roots (0-2 mm), small roots (2-5 mm), medium roots (5-10 mm), and large roots (>10 mm). The field measurements lasted between August and October 2016. All the steps of collecting data are shown in Fig. 2.

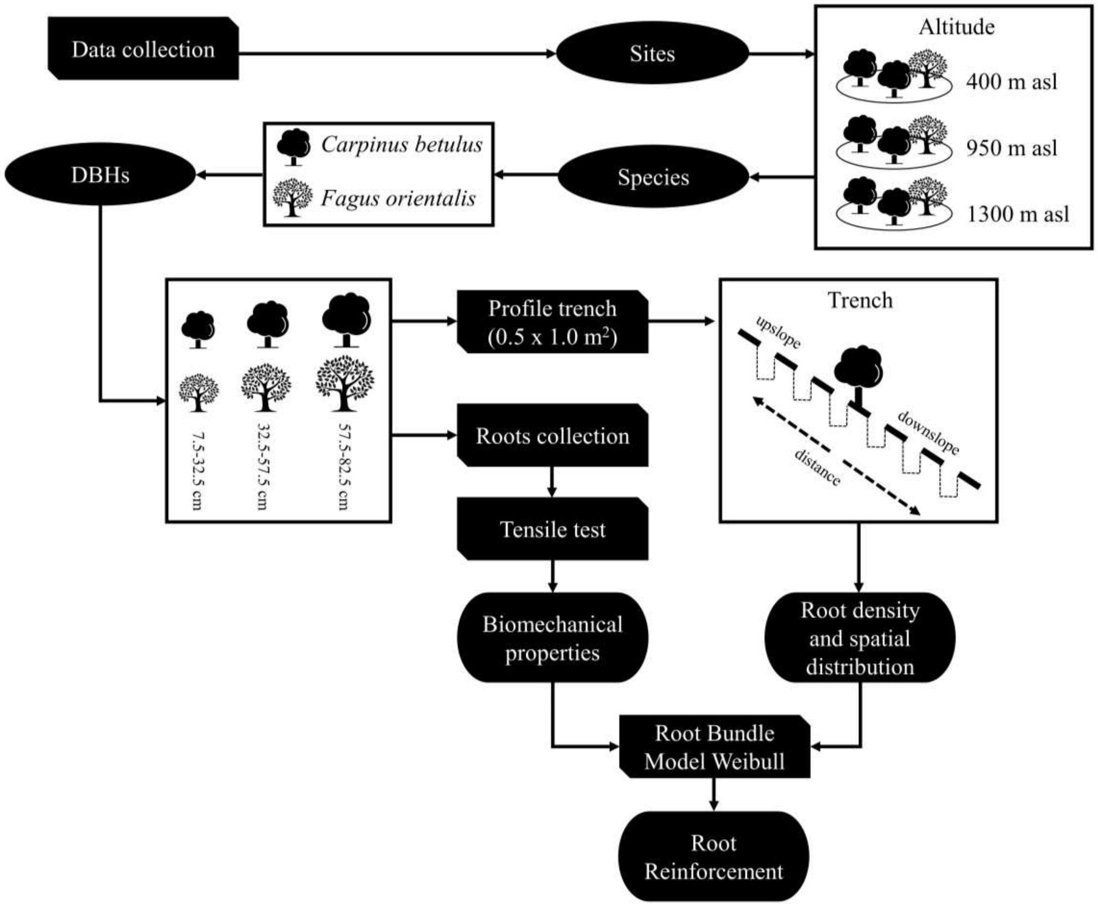

Fig. 2 Flowchart describing the steps for quantifying root reinforcement: selecting study sites at different altitudes (400 m, 950 m, 1300 m a.s.l), selecting *Carpinus betulus* and *Fagus orientalis* samples with different DBH classes (small: 7.5-32.5 cm, medium: 32.5-57.5 cm, large: 57.5-82.5), evaluating root density and spatial distribution at downslope and upslope at six distances from tree trunk (1, 1.5, 2, 2.5, 3.5, and 4 m), investigating roots biomechanical properties and quantifying root reinforcement by Roor Bundle Model Weibull

2.3. Measuring biomechanical properties

Root samples were collected randomly from downslope and upslope at a depth of about 30 cm from the surface (Mao et al. 2012). To prevent mould and microbial degradation, a 15% alcohol solution was sprayed on the roots, then the treated roots were placed into plastic bags and refrigerated (4 °C) until tested (time between sampling and testing in the laboratory was of about 48 h) (Vergani et al. 2012). Roots with a length of 15 cm were placed in the clamps of the Universal Testing Machine (SANTAM Co./SMT-5, Tehran, Iran), and mechanical tests were conducted at a speed of 10 mm min^{-1} until rupture occurred. Only specimens that broke near the middle of the root segment were considered. Then, the relationships between the root diameter and biomechanical properties (i.e., maximum tensile force, Young's modulus, maximum elongation) were calculated through power-law functions, as follows:

$$F_{max} = F_0 \phi^{\xi} \quad (1)$$

$$E = E_0 \phi^{\beta} \quad (2)$$

$$L = L_0 \phi^{\alpha} \quad (3)$$

where F_{max} is maximum tensile force (in N), ϕ is root diameter (in mm), E is root elasticity (MPa), and L is root elongation (in mm). F_0, E_0, and L_0 are constant coefficients (in N, MPa, and mm, respectively), ξ, β, and α are exponents (dimensionless).

2.4. Root Bundle Model weibull (RBMw)

Root reinforcement was calculated using the Root Bundle Model Weibull (RBMw; Schwarz et al. 2013). RBMw is a strain-step fiber bundle model, developed to include the failure probability of roots due to variability in root mechanical properties. RBMw calculates force-displacement behaviour of a root bundle based on root distribution in diameter classes and on a series of power-distributed relationships (Eqs. 1-3). Root reinforcement c_r (in kPa) is calculated by summing up the force contributions F (in N) for each root per unit of area (m^2) multiplied by the Weibull survival function S (dimensionless), as follows:

$$c_r = \sum_{i=1}^{N} F(\phi_i, \Delta x) S(\Delta x^*) \quad (4)$$

Where Δx is the displacement unit in mm and S is a function of the normalized displacement Δx^* (dimensionless). The following equation calculates the $S(\Delta x^*)$:

$$S(\Delta x^*) = \exp\left[-\left(\frac{\Delta x^*}{\lambda}\right)^{\omega}\right] \quad (5)$$

In equation (5), λ is the scale Weibull parameter (dimensionless) and ω is the shape Weibull parameter (dimensionless).

The ratio between the displacements is estimated by each single tensile tests and the corresponding displacement values are calculated using fitted values of tensile forces.

$$F(\phi_i, \Delta x) = \frac{\pi E_0}{4 L_0} \phi_i^{2+\beta-\alpha} \qquad F(\phi_i, \Delta x) < F_{max}(\phi_i) \quad (6)$$

All input parameters (F_0, E_0, L_0, ξ, β, and α) were calculated from the tensile tests.

2.5. Evaluation of the hillslopes stability using a Monte Carlo approach

The majority of distributed slope-stability models that predict shallow landslides overlook the forces acting on landslide scars. Based on back calculations and observations in the field, most shallow landslides are controlled by lateral root strength (Casadei et al. 2003). The infinite slope analysis is a rather simplistic and well-known method, being used to assess slope stability; however, it assumes that the plane of failure is parallel to the slope (Taylor 1948).

In comparison, the physical-based 3D slope stability approach overcomes the limitations of infinite slope analysis and incorporates the root reinforcement effectively. By applying the limit equilibrium theory, slope stability can be expressed using the Factor of Safety (FoS) as proposed by Casadei et al. (2003) and modified by Chiaradia et al. (2016), equation 7:

$$FoS = \frac{S}{T} = \frac{c_s + c_{r-b} + \frac{A_l}{A_b} c_s + \frac{A_l}{A_b} c_{r-l} + \{[(D - D_w)\gamma_s + (\gamma_{sat} - \gamma_w) D_w + q_0]\cos\alpha\}\tan\varphi'}{[(D - D_w)\gamma_s + \gamma_{sat} D_w + q_0]\sin\alpha} \quad (7)$$

where S is the resisting force, T is the shear force, c_s is the soil cohesion (kPa), c_{r-b} and c_{r-l} are the contributions of plant roots to slope stability (root reinforcement) along the basal and lateral surfaces (in kPa), A_b and A_l are basal and lateral area of the sliding volume (in m^2), D is the average depth of the sliding surface (in m), γ_s is the unit weight of dry soil, D_w is the average height of the seepage in respect to the sliding surface, γ_w is the unit weight of water, q_0 is the tree surcharge per unit area (in kPa), α is the slope steepness, φ' is the effective friction angle (°), and γ_{sat} is the unit weight of saturated soil.

Based on a mathematical formula, Monte Carlo Simulation is an effective method for calculating distributions for the FoS. It identifies independent and random sets of possible values for each input parameter to determine the FoS for each pass. The Monte Carlo approach was applied to overcome the variability and uncertainties of each input parameter. The slope angle varies from 20 ° to 60 °. The soil bulk density is normally distributed around 13.5 kNm^{-3} (Abdi and Deljouei 2019). The internal friction angle is uniformly distributed between 26 ° and 35 °, and the soil cohesion is normally set around the average value of 15.3 kPa (Abdi and Deljouei 2019). The A_l/A_b ratio can be approximated by a value of 0.50 (Milledge et al. 2014). Trees surcharge for different DBH classes was considered as 140 Nm^{-2}, 220 Nm^{-2}, and 320 Nm^{-2} for small, medium and large *C. betulus* trees, and corresponding values for *F. orientalis* were 100 Nm^{-2}, 230 Nm^{-2}, and 400 Nm^{-2}, respectively (Chiaradia et al. 2016; Hayati et al. 2017). C_{r-l} is the RBMw-calculated root reinforcement in function of the most critical conditions i.e. distance of 4 m and upslope position. The mean, minimum, and maximum values of C_{r-l} are 3.46, 0.06, and 53.24 kPa, respectively. C_{r-b} is a percentage of C_{r-l} in function of RAR and soil depth which depends on slip failure. To summarise, the parameters for Monte Carlo Simulation are reported in Table 1. For this analysis, Monte Carlo simulation is replicated 1000 times; furthermore, to reduce the effects of random selection (Hammond et al. 1992).

Table 1. The parameters for Monte Carlo Simulation in function of species, altitude and DBH classes, considering the upslope position and the far distance from the trunk (i.e. 4 m). The parameters were specified using a range and the distribution function.

Parameter	**Unit**	**Range**	**Distribution function**	**Reference**
A_b	m^2	μ=104 σ=2.63	Normal	Milledge et al. 2014
L/W *	-	μ=1.42 σ=0.20	Normal	Milledge et al. 2014
D	m	[0.5; 1.5]	Uniform	Hammond et al. 1992
D_w/D	-	μ=1.42 σ=0.20	Normal	Schwarz et al. 2010

γ_s	kN/m³	μ=13.5 σ=1.00	Normal	Abdi and Deljouei 2019
φ'	°	[26; 35]	Uniform	Abdi and Deljouei 2019
c_s	kPa	μ=13.5 σ=2.00	Normal	Abdi and Deljouei 2019
ω_c **	-	μ=0.20 σ=0.01	Normal	Abdi and Deljouei 2019

* $w = \sqrt{A_b \cdot \frac{w}{L}}$

** $\gamma_{sat} = \gamma_s(1 + \omega_c)$

2.6. Statistical analysis

Statistical analysis was used to check the differences in root distribution and root reinforcement by considering the species, DBH, slope position, altitude, and distance from the trees. The Shapiro–Wilk and Levene's tests were used to check the normality and homogeneity of the data, respectively. Since the datasets were found to violate the normality and homogeneity assumptions, a nonparametric Kruskal-Wallis test (H) was used to compare the RAR and soil reinforcement of different root diameter classes within DBH classes, slope positions, and study sites for *C. betulus* and *F. orientalis* trees (Tables S1-S5). When the residuals were normal and variance was heterogeneous, parametric Welch t-tests were used to compare between two independent groups. Finally, when the residuals were normal and variance was homogenous, One-way ANOVA (analysis of variance) was used to compare the means of two or more groups for one dependent variable. All statistical analyses were implemented using the R software (https://www.r-project.org). Confidence intervals were set for a probability level of 0.05.

3. Results

3.1. Variability of root distribution

3.1.1. Root distribution as a function of species

RAR was measured by considering a number of 1080 profile trenches. Figure 3 showed the total RAR for fine (0-2 mm), small (2-5mm), medium (5-10mm), and large roots (>10mm) as a function of species. Root distributions were remarkably different in regard to the diameter classes. As a fact, for *C. betulus*, small roots had the highest RAR value whereas the value of large was the lowest among all the root diameter classes (Fig. 3). Furthermore, fine roots of *F. orientalis* had a higher frequency compared with that from the rest of diameter classes (Fig. 3). The Kruskal-Wallis test indicated that RAR values of *C. betulus* was significantly higher than those of *F. orientalis* (H_1 = 65.13, H_1 = 140.65, H_1 = 177.01, H_1 = 117.44; p< 2.2e-16 to p<1e-15; for fine, small, medium, and large roots, respectively; Fig. 3 and Table S2). The total RAR (H_1 = 191.37, p< 2.2e-16; Fig. 4 and Table S2) and total roots per unit area (H_1 = 99.60, p< 2.2e-16; Fig. 4 and Table S2) of *C. betulus* and *F. orientalis* demonstrated a significant difference, in which *F. orientalis* had fewer roots. The minimum, maximum and mean value of RAR for *C. betulus* were of 0.0010%, 0.0040%, and 0.0020%, respectively, while for *F. orientalis* the same statistics accounted for 0.0005%, 0.0020%, and

0.0010%, respectively. The results showed that *C. betulus* had more roots in all root diameter classes, in which the total number of roots per unit area for *C. betulus* was 38987 and for *F. orientalis* was 26079 (Fig. 4).

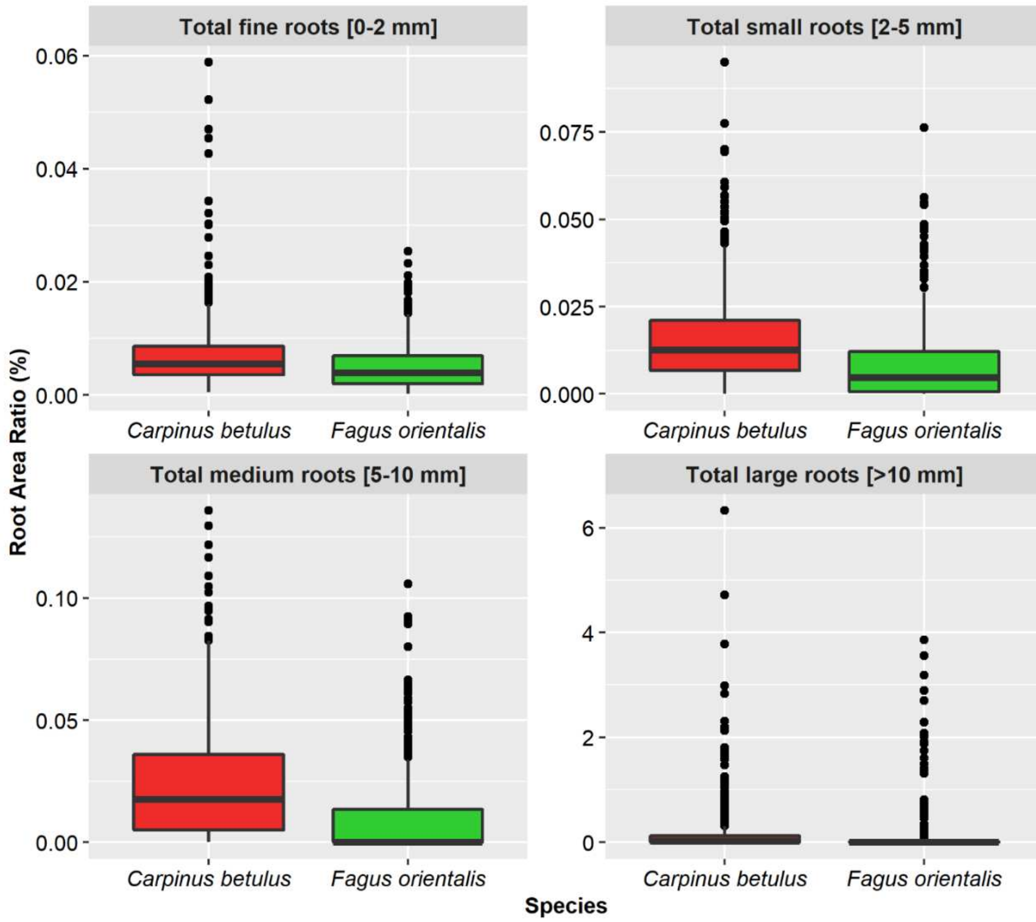

Fig. 3 Root Area Ratio (RAR, in %) of fine roots (0-2 mm), small roots (2-5 mm), medium roots (5-10 mm), and large roots (>10 mm) as a function of species: *Carpinus betulus* and *Fagus orientalis*

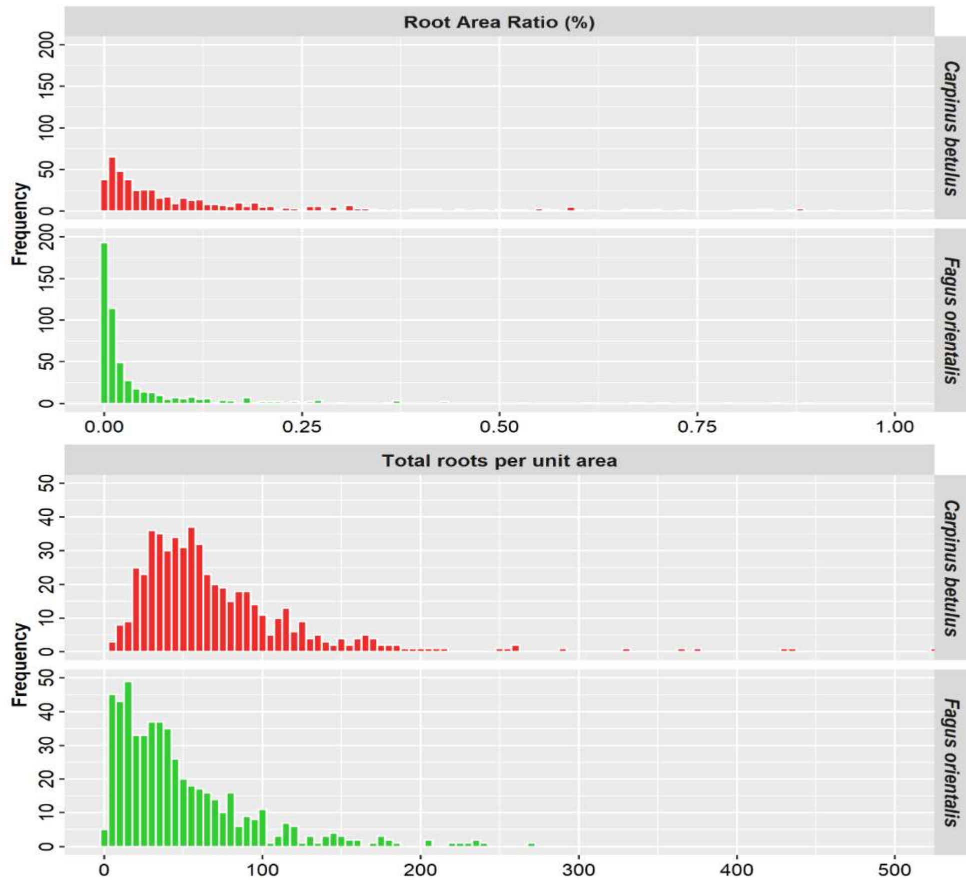

Fig. 4 Total Root Area Ratio (RAR, in %) and total roots per unit area as a function of tree species: *Carpinus betulus* and *Fagus orientalis*

3.1.2. Root distribution as a function of DBH

Kruskal-Wallis test was conducted to verify the differences in RAR as a function of DBH for *C. betulus* ($H_2 = 111.01$) and *F. orientalis* ($H_2 = 112.80$) in which significant differences were found to be caused by DBH classes of both species ($p < 2.2e\text{-}16$; Table S3). On average, the largest DBH tree class of both species had the highest RAR value compared to the other DBH classes (Fig. 5). The mean values of RAR for large trees was 0.0050% and 0.0030%, for *C. betulus* and *F. orientalis*, respectively (Fig. 5). Mean values of RAR for medium and small trees of *C. betulus* and *F. orientalis* were of 0.0010% and 0.0004%, 0.0006% and 0.0001%, respectively (Fig. 5).

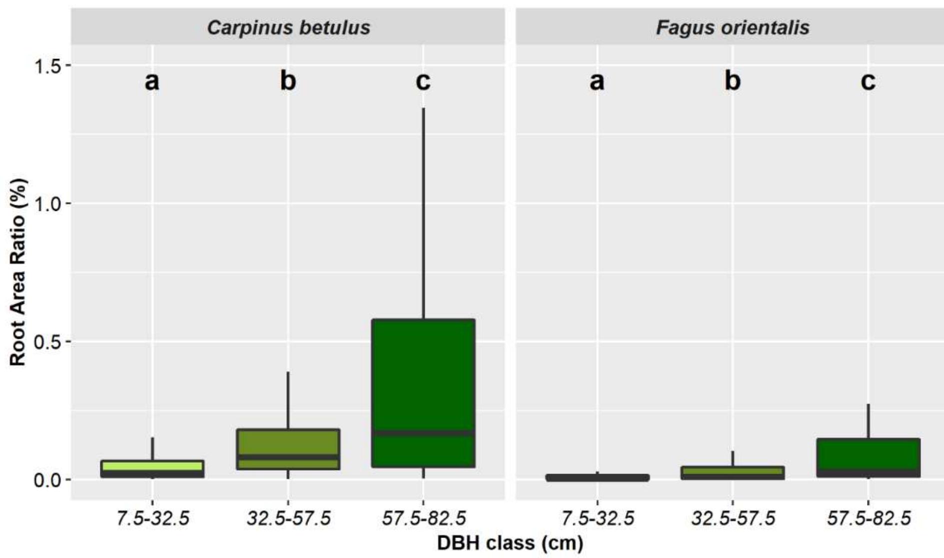

Fig. 5 Root Area Ratio (RAR in %) for *Carpinus betulus* and *Fagus orientalis* as a function of DBH class: Small (7.5-32.5 cm), Medium (32.5-57.5 cm), and Large (57.5-82.5 cm). Boxes with the similar lowercase letters are not significantly different

3.1.3. Root distribution as a function of slope position

A synthesis of the RAR as a function of slope position is shown in Figure 5. RAR values of downslope and upslope were not significantly different for *C. betulus* (H_1 = 2.86, p = 0.09; Table S4). However, while the RAR values of *F. orientalis* were significantly higher for downslope (H_1 = 7.01, p = 0.01; Table S4). The mean value of RAR for downslope and upslope of *C. betulus* was estimated to be 0.0020%, while the mean value of RAR for *F. orientalis* was of 0.0020% and 0.0007% for downslope and upslope, respectively (Fig. 6).

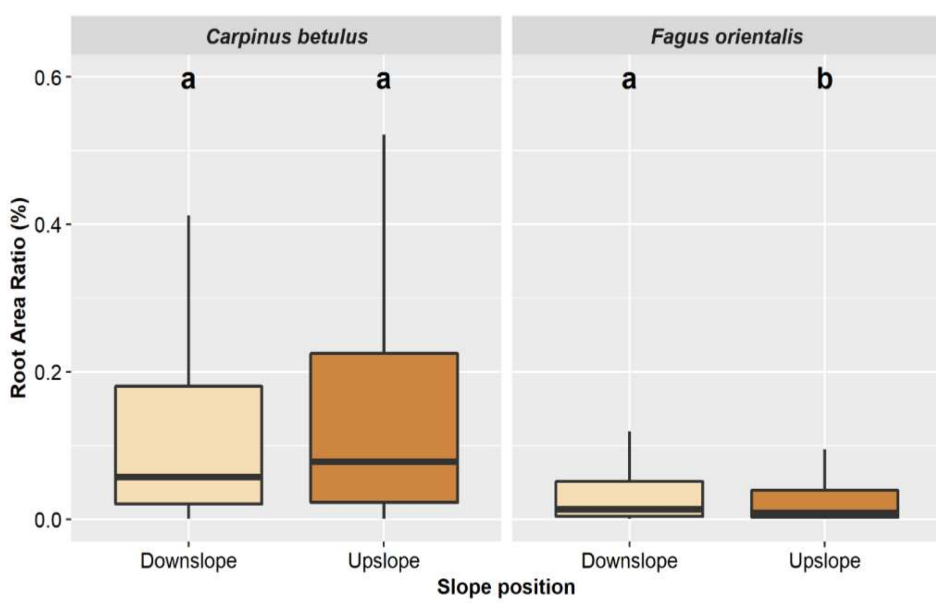

Fig. 6 Root Area Ratio (RAR in %) for *Carpinus betulus* and *Fagus orientalis* in function of slope position: Downslope and Upslope. Boxes with the similar lowercase letters are not significantly different

3.1.4. Root distribution as a function of altitude

RAR values varied among altitudes: 400, 950, and 1300 m of *C. betulus* (H_2 = 32.73, p<1e-7; Table S5) and *F. orientalis* (H_2 = 6.46, p=0.04; Table S5). Figure 7 showed the statistical differences brought by the altitude on the RAR of the two species. For *C. betulus*, the highest mean value of RAR was found in 1300 m (0.0020%) and it was followed by 950 m (0.0010%) and 400 m (0.0030%). For *F. orientali*s, RAR values in 1300 and 950 m were larger than in 400 m (Fig. 7). According to the altitude, mean RAR for *F. orientali*s was reported as 0.0010% for 1300 m and 950 m; furthermore, it was recorded as 0.0009% for 400 m (Fig. 7).

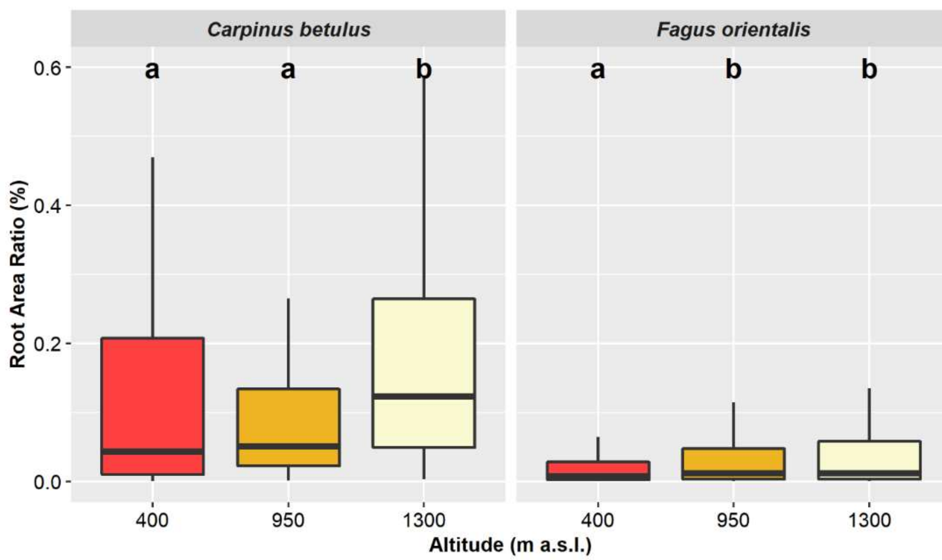

Fig. 7 Root Area Ratio (RAR in %) for *Carpinus betulus* and *Fagus orientalis* as a function of altitude: 400, 950, and 1300 m. Boxes with the similar lowercase letters are not significantly different

3.1.5. Root distribution as a function of vertical and horizontal directions

In the case of both species, the predominant number of roots was found in the subsurface soil layers to a depth of up to 30 cm after which the root frequency decreased (Fig. 8). For both *C. betulus* and *F. orientalis*, RAR decreased monotonically with distance to tree beyond a 2 m (Fig. 8). The highest RAR values were found closest to the tree trunk with greater concentrations at 1-1.5 m from the tree trunk for both species (Fig. 8). The mean RAR at 1 m distance was calculated 0.07% and 0.06% for *C. betulus* and *F. orientalis*, respectively. It was recorded that mean RAR at 1.5 m distance was 0.03% for *C. betulus* and 0.01% for *F. orientalis* (Fig. 8). Indeed, roots were detected for the 49.21% at the 1 m distance for *C. betulus* and 82.93% for *F. orientalis*. Only 20.80% and 10.76% of roots were distributed at 1.5 m distance for *C. betulus* and *F. orientalis*. It was noted that mean values of RAR at the 0-10 cm soil depth were 0.11 and 0.08% for *C. betulus* and *F. orientalis*, respectively (Fig. 8). In the case of 10-20 cm soil depth, it was estimated 0.06% for *C. betulus* and 0.02% for *F. orientalis* (Fig. 8). Approximately, in the case of *C. betulus*, 50% of roots distributed at the 0-10 cm soil depth and 69% for *F. orientalis*. Furthermore, at a depth of 10-20 cm, root distribution was reported 25.55% and 19.77% for *C. betulus* and *F. orientalis*, respectively. Overall, root distribution decreases with increasing soil depth and distance from the tree trunk. Moreover, root distribution was found higher on *C. betulus* than *F. orientalis*.

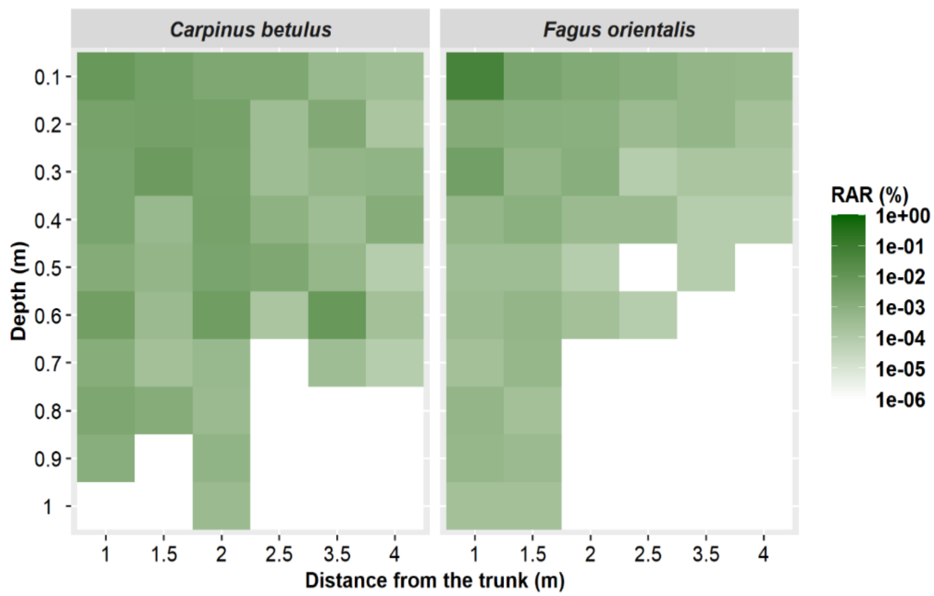

Fig. 8 Spatial distribution of Root Area Ratio (RAR in %) as a function of vertical and horizontal direction of *Carpinus betulus* and *Fagus orientalis*

3.2. Variability of the mechanical properties of roots

3.2.1. Variability of RBMw parameters

The main input parameters, including the relationship between root tensile force and root diameter, the regression coefficients for Young's modulus, root elongation, and the Weibull survival function are shown in Figures S2, S3, S4, S5, S6, S7, and Table S7. The results of the root tensile tests indicated strong relations between the mechanical and geometrical characteristics of the roots (root diameter) by power-law regression (Figures S2- S7). Variability of Root Bundle Model Weibull (RBMw) parameters including constant coefficients F_0, E_0, L_0 and exponents ξ, β, α, λ, ω coefficients were shown in Fig. 9. F_0 ranged between 12.41 and 124.18 N, E_0 ranged between 1.39E+07 and 1.27E+08 MPa, and L_0 ranged between 12.56 and 98.07 mm (Fig. 9). The minimum values of ξ, β, α, λ, ω were 0.94, -1.17, -0.48, 1.04, and 1.59, respectively. The maximum values of these exponents were 1.38, -0.64, -0.18, 1.39, and 4.29, respectively (Fig. 9).

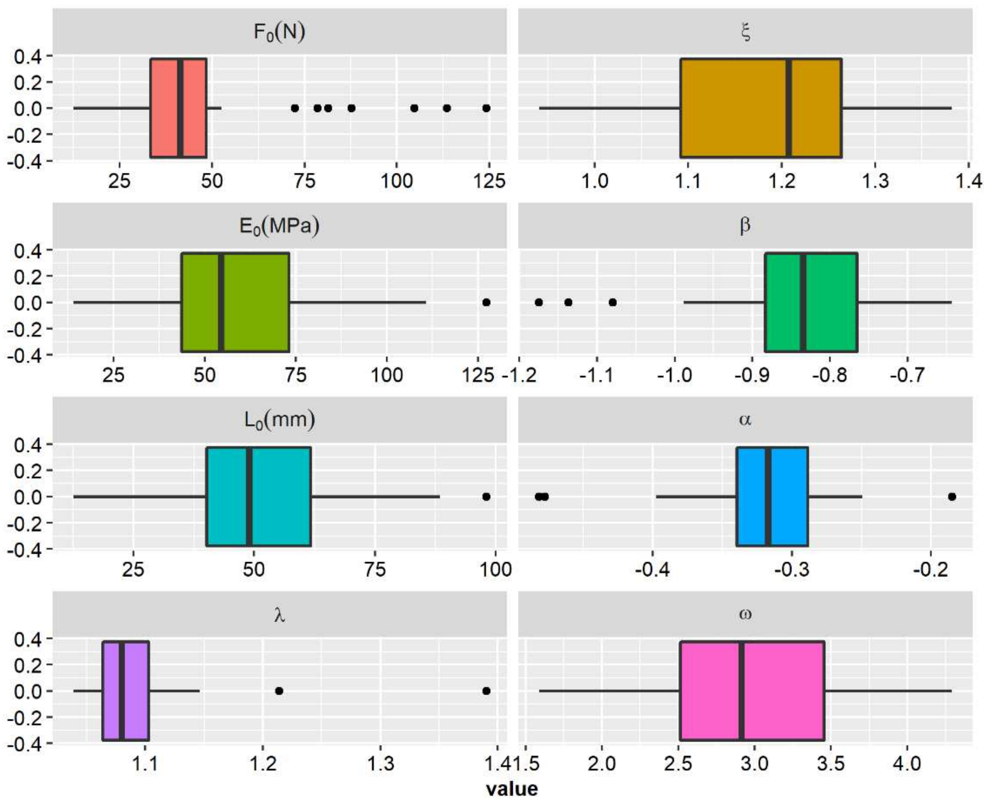

Fig. 9 Variability of Root Bundle Model Weibull (RBMw) parameters: constant coefficients F_0, E_0, L_0 and exponents ξ, β, α, λ, ω coefficients (dimensionless)

3.2.2. Species-specific root reinforcement using RBMw model

The mean values of root reinforcement for *C. betulus* and *F. orientalis* were of 16.08 and 7.69 kPa, respectively. Figure 10 showed that root reinforcement of *C. betulus* distributed more and higher than *F. orientalis*, whereas the Kruskal-Wallis test showed a statistically significant difference in root reinforcement between the species (H_1 = 168.22, $p < 2.2e\text{-}16$; Table S6). The minimum and maximum values of root reinforcement for *C. betulus* calculated as 0.23 and 216.95 kPa, respectively which is concentrated in shallower soil layers and nearer to tree trunk. Root reinforcement for *F. orientalis* varied from 0.07 to 145.39 kPa.

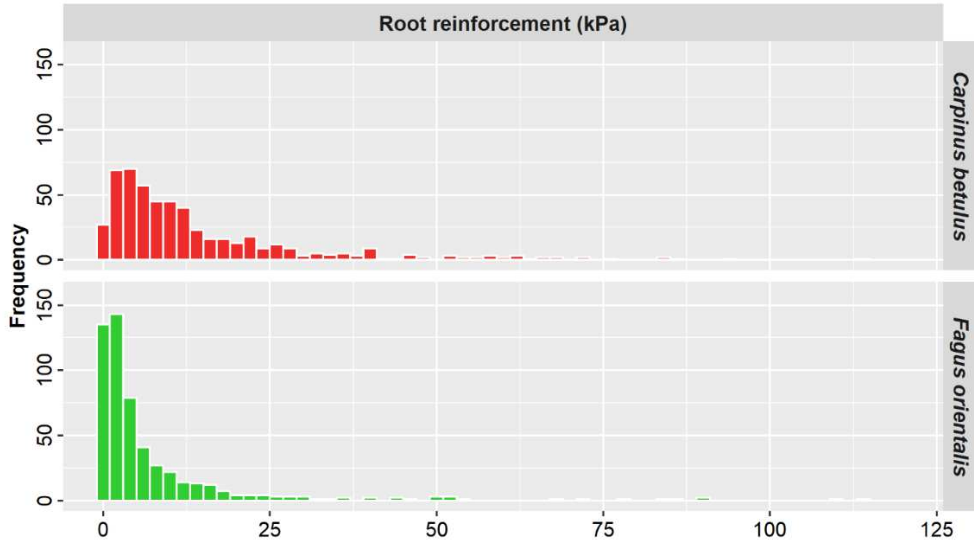

Fig. 10 Root reinforcement in function of species (*Carpinus betulus* and *Fagus orientalis*)

3.2.3. Impacts of environmental factors on RBMw-calculated root reinforcement

Applying RBMw, the root reinforcement of *C. betulus* was the highest in 400 and 950 m compared with 1300 m. The mean values of c_r showed larger variation, including 23.89, 12.95, and 11.41 kPa at 400, 950, and 1300 m, respectively. Conversely, the mean value of c_r for *F. orientalis* reported 5.65, 9.58, and 7.85 kPa at the same altitudes, respectively. The results showed that c_r declined by decreasing DBH for both species (Fig. 11). Mean values of c_r reached 29.12, 14.29, and 4.82 kPa for large, medium and small trees of *C. betulus*, respectively; however, for the same DBH classes, the mean values of c_r for *F. orientalis* were of 15.52, 5.30, and 2.26 kPa, respectively. Furthermore, the c_r decreased with increasing distance from the tree trunk (Fig. 11). The highest mean value of c_r for *C. betulus* was of 38.55 kPa at 1 m distance from the tree, whereas it was of 26.99 kPa for *F. orientalis* at the same distance (Fig. 11). The lowest mean values of c_r were of 5.85 and 0.78 kPa, and they were found at distances of 4 m for *C. betulus* and *F. orientalis*, respectively (Fig. 11).

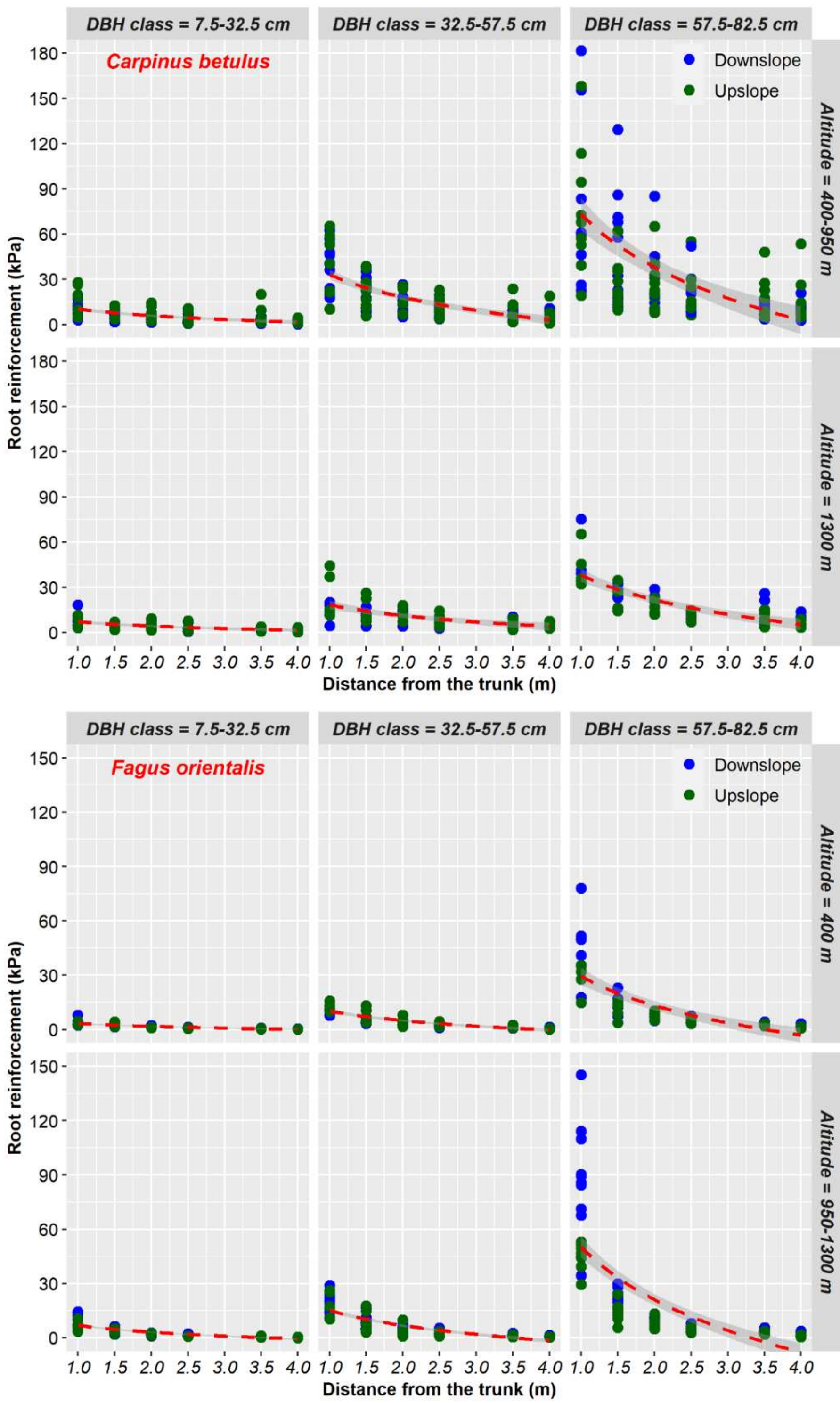

Fig. 11 Root reinforcement of *Carpinus betulus* and *Fagus orientalis* as a function of DBH class (Small: 7.5-32.5 cm, Medium: 32.5-57.5 cm, and Large: 57.5-82.5 cm), altitudes (400, 950, and 1300 m), and distance from tree (1, 1.5, 2, 2.5, 3.5, and 4 m)

3.3. Slope stability analysis

Including both basal and lateral reinforcement, the results of slope stability analysis (Eq. 7) suggested that the most stabilizing species is *C. betulus* in a mature growth (DBH= 57.5-82.5 cm) at the distance of 4 m. In fact, at 400, 950, and 1300 m a.s.l trees of *C. betulus* maintained an instability probability near 22.7%, 29.2%, and 35.3% for very steep conditions, respectively (Fig. 11). Instability probability for small trees at same altitudes varied from 40.9% to 43.3%. These values for medium trees of *C. betulus* reported between 31.9% and 35.6% (Fig. 12). In contrast, the instability probabilities of the *F. orientalis* was higher, reaching up to approximately 46.0% for all DBH classes at 400, 950, and 1300 m a.s.l (Fig. 12). The instability probabilities was less than 10% until 40 ° for *F. orientalis* at the distance of 4 m (Fig. 12). In the areas without forest with very steep conditions instability probability for *C. betulus* and *F. orientalis* was 46.17% (Fig. 12).

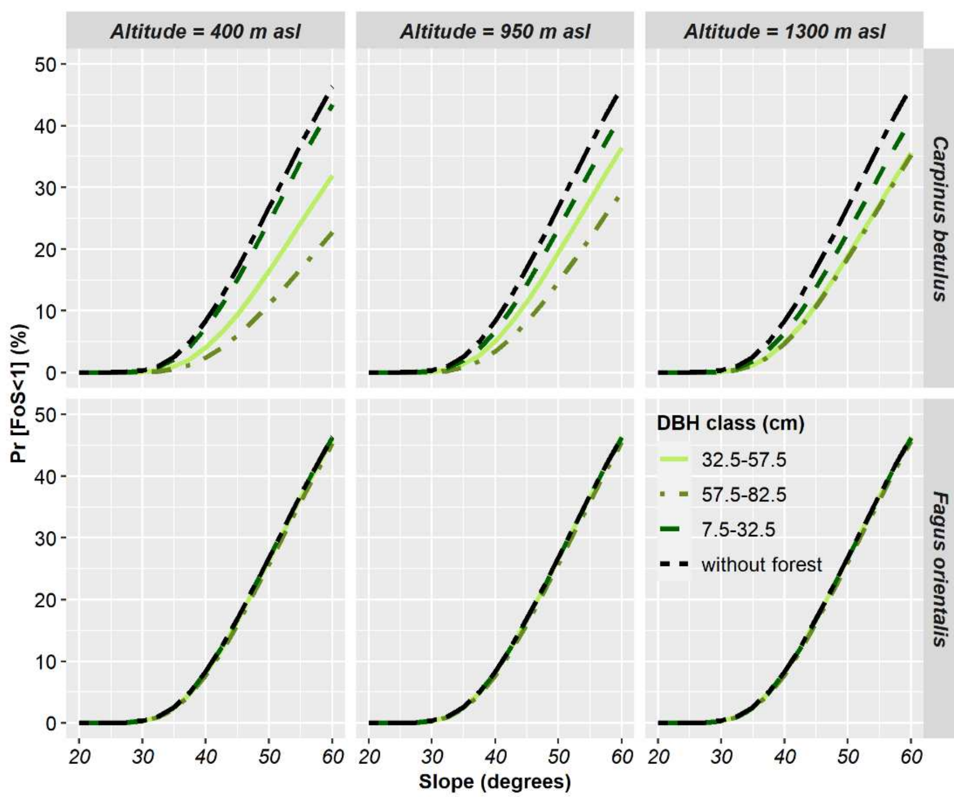

Fig. 12 Factor of safety (FoS), probability of failure (Pr(FoS < 1)), in function of species (*Carpinus betulus* and *Fagus orientalis*), altitude (400, 950, and 1300 m), and DBH classes (small: 7.5-32.5 cm, medium: 32.5-57.5 cm, and large: 57.5-82.5 cm) considering the upslope position and the far distance from the trunk (i.e. 4 m). In all the case, the contribution to slope stability by the vegetation is evaluated as the sum of both basal and lateral root reinforcement values

4. Discussion

4.1. Root distribution

The scientific literature often used RAR to quantify, first, root distribution into the soil and, second, the root reinforcement. In this study, the root density, observed though total roots per unit area and RAR, was significantly different in of the two investigated species. In fact, it was evident that root density of *C. betulus* was higher than that of *F. orientalis*. In parallel to our findings, previous literature showed that root density is affected by tree species (Bischetti et al. 2007; Phillips et al. 2014; Vergani et al. 2017a; Moresi et al. 2019; Gholami-Derami et al. 2021). For example, Bischetti et al. (2007) found differences among European alpine species, including *Alnus viridis*, *Fagus sylvatica*, *Salix purpurea*, *Salix caprea*, *Corylus avellana*, *Fraxinus excelsio*, *Picea abies*, and *Larix decidua* in which root density varies significantly for the same species within a same locality. Gholami-Derami et al. (2021) compared RAR of *C. betulus* with that of *Alnus subcordata* and among two non-native tree species (*Pinus sylvestris* and *Robinia pseudoacacia*) with similar habitat conditions in Northern Iran. They found that RAR value in exotic species is higher than native species. A study in New Zealand reported that willow roots were more numerous than poplar (Phillips et al. 2014). Several reasons can relate to differences between species, above all else is heterogeneity in environmental factors (Burylo et al. 2011), such as soil bulk density (Goodman and Ennos 1999), and soil moisture and fertility (Taub and Goldberg 1996; Hodge 2004).

For both studied species, our results revealed that a tree with larger DBH has more roots than a tree with a smaller diameter, and this finding is in line with previous studies (Bischetti et al. 2009; Schwarz et al. 2010; Mehtab et al. 2021), and is consistent with Abdi et al. (2010b) who showed that a significant effect of DBH on total RAR in three hardwood species in Hyrcanian forests (*F. orientalis*, *C. betulus*, and *Parrotia persica*). In accordance, John et al. (2001), comparing three stands of 6, 15, and 23 years old, showed that root distribution increases by tree age. Additionally, it was reported that in the older stands, fine roots (0-2mm) declined as they were converted into coarse roots (>10 mm) to provide more structural support. As a result, coarse root mass increased substantially compared to fine roots (John et al. 2001). McQueen (1968) reported that fine roots peak at the early ages of the stands and are relatively maintained constant after that. Our findings indicate that larger trees maintain their anchorage, with increasing root numbers and RAR values. In fact, nutrient availability increases lateral root extension as well as causes changes in lateral roots anatomy by supplying nutrients (Goss et al. 1993). Also, Ford and Deans (1977) reported a higher concentration of fine roots because of increased nutrient availability. Furthermore, in this study, moisture content has been highlighted as a key factor in the distribution of roots. So, greater root mass could be attributed to the higher nutrient content and better aeration of the surface soil (Ford and Deans 1977). Overall, root growth can be affected by a variety of environmental factors such as soil texture, soil structure, aeration, moisture, temperature, and competition with other plants (Kramer and Boyer 1995).

The slope influences root distribution with the roots-oriented upslope, assisting soil anchorage (Vergani et al. 2017a), as observed in this study for *F. orientalis* species. RAR distribution of *F. orientalis* in downslope is greater than upslope; however, in the case of *C. betulus*, the RAR values of both slopes were similar. Mechanical function of the root system in downslope and upslope is different based on the specific type of root system architecture (i.e., asymmetry of the cross-sectional area; Chiatante et al. 2003). It was stated that mechanical stress is one reason for large cross-sectional areas (Di Iorio et al. 2005), therefore, the higher RAR value of *F. orientalis* in upslope is a kind of adaptability in response to the environment. Burylo et al. (2011) reported that the heterogeneity in soil properties, natural obstacles, and interactions between vegetation such as competition makes a high variability of RAR. Stokes et al. (2008) found that this variability was related to the interactions of genetic and environmental factors. In the case of *C. betulus*, RAR values of downslope and upslope were not significantly different, probably implying that trees are thickening the roots instead of increasing the number in the reaction of the mechanical stresses (Abdi et al. 2010a). Our results highlighted that RAR values fluctuate among different altitudes, and RAR in the 1300 m is higher than 950 and 400 m. One possible reason is the variation among the meteorological parameter and altitude above sea level. These altitudes range from low altitude (i.e., 400 m a.s.l.) with the highest mean temperature and lowest annual precipitation to mid- altitude (i.e., 950 m a.s.l) to the highest altitude (i.e., 1300 m a.s.l.) having the lowest mean air temperature and greatest annual precipitation with the most proportion of snowfall (Azaryan et al. 2015; Deljouei et al. 2020). Bischetti et al. (2009) showed that for *F. sylvatica*, RAR distributions were statistically more in a site with highest altitude than lowest altitude (altitude ranges from 1100 to 1454 m a.s.l.). Mao et al. (2012) found similar results for *P. abies*, *Abies alba*, and *F. sylvatica* growing at 1400 m a.s.l. and 1700 m a.s.l. The use of altitude gradients is considered an excellent way to examine vegetation responses to environmental change (Sundqvist et al. 2013; Weemstra et al. 2021). Higher altitudes in temperate regions typically have longer growing seasons and more seasonality, and their vegetation is adapted to the extreme variations in climate they can experience (Körner 1999; Sundqvist et al. 2013). In most cases, high-altitude soils are more heterogeneous in terms of soil nutrient availability (Holtmeier and Broll, 2005) and less fertile (Sveinbjörnsson et al. 1995), since the cooler temperatures slow down microbial activity (Loomis et al. 2006; Mayor et al. 2017), leaf and root litter decomposition rates (Moore 1986; Loomis et al. 2006; See et al. 2019), and mineralization rates (Sveinbjörnsson et al. 1995). This means that changes in climate and soil properties along an altitude gradient can profoundly influence intraspecific root trait variation (Weemstra et al. 2021). Another significant factor is the distance from the trunk. In fact, root distribution decreases with increasing distance from tree trunk and soil depth for both species. Seventy percent of *C. betulus* roots and 94% *F. orientalis* roots were distributed at 1.5 m of distance from the tree trunk. Furthermore, the maximum RAR values (50% of *C. betulus* roots and 69% of *F. orientalis* roots) were situated in the surface soil, i.e. 1-10 cm of soil depth and approximately were smaller in deeper soil. Species or genetics, climate characteristics determined root distribution throughout the soil profiles, and soil type (Bischetti et al. 2005); for instance, changes in nutrient content, water availability and aeration will affect root distribution, whereas the most available nutrients are detected in the topsoil and cause a reduction in vertical root distribution (Bischetti et al. 2005; Abdi et al. 2010a; Mao et al. 2012; Bordoni et al. 2019; Moresi et al. 2019). It was pointed out that root development might depend mainly on the quantity of organic matter in the soil (Bordoni et al. 2019). In addition, deeper layers due to compacted soil layers and bedrock caused the roots to grow horizontally (Coppin and Richards 1990; Zydroń et al. 2019). The decreasing pattern of RAR values in this study is similar to the values reported by other researchers for various species and in other locations such as the Mediterranean (Moresi et al. 2019), subtropical (Genet et al. 2008), temperate (Bischetti et al. 2005; Abdi et al. 2010a; Abdi and Deljouei 2019), arid (Abdi et al. 2019) climate zones.

4.2. Root reinforcement

Root reinforcement is fundamentally determined by combining root distribution and mechanical properties (Schwarz et al. 2013). Mechanical properties of roots are well-known by root maximum tensile force and stiffness. Several researchers indicated that different parameters affect root resistance, including species (Abdi and Deljouei 2019), root size and age (Loades et al. 2013; Gilardelli et al. 2017; Boldrin et al. 2017), tree age (Genet et al. 2008), root length (Zhang et al. 2012), DBH (Deljouei et al. 2018), cellulose and lignin content (Hales et al. 2009; Abdi et al. 2014), root moisture content (Moresi et al. 2019), root dehydration (Ekeoma et al. 2021), season (Makarova et al. 1998; Abdi and Deljouei 2019), living or decaying roots (Vergani et al. 2014), altitude (Genet et al. 2011), slope position (Stokes 2002; Abdi et al. 2010a), soil moisture content (Tsige et al. 2020), and elastic modulus as a root reinforcement input parameter (Cislaghi 2021).

The root system may be adapted according to the environmental conditions and tree location, where roots resistance will be varied by different altitudes (Genet et al. 2011). If altitude causes a variation in root cellulose content, as a result, we can expect that root resistance will be altered. Consequently, environmental conditions might help researchers to understand the mechanisms of root reinforcement better and use these data in modelling slope stability, however, such information about the effect of altitude on root systems remains largely unsolved and further investigation on root morphological adaptation is required. Root reinforcement of *C. betulus* at 400 m a.s.l. higher than 1300 m a.s.l, i.e. root reinforcement decreased significantly with increasing altitude, which means it was required more force for root failure. These findings are similar to other studies performed on root reinforcement of different altitudes (Hales et al. 2009; Genet et al. 2011; Vergani et al. 2012). It was investigated that the differences in site interactions for various species result from several conditions of growing sites and environment (Vergani et al. 2012). It is clarified that soil's chemical and physical properties are a consequence of changes in root resistance and root reinforcement with increasing altitude (Genet et al. 2011).

The quantity of root reinforcement assessed by the contribution of different species might indicate the impact of roots in reducing shallow landslides and slope instabilities. Root numbers of *C. betulus* were more numerous than *F. orientalis*, so root reinforcement of *C. betulus* is higher than *F. orientalis*. Also, root resistance has differed between altitudes, and roots of *C. betulus* have shown higher resistance in terms of force than *F. orientalis* (see Deljouei et al. 2020).

Root reinforcement of large trees is the highest among all the tree DBH classes, concurs with Cohen and Schwarz (2017). The roots of the oldest trees were the most resistant in tension compared to the middle age and young trees (Genet et al. 2006). It could be defined by the differences in the root structure of trees in the early growth stage and older trees, as large DBH trees may possess a higher amount of cellulose (Genet et al. 2006). As a result, investigating cellulose content in roots of large, medium, and small trees would be interesting in future research.

Root reinforcement decreases with increasing distance from tree trunks and varies considerably, even at the same distance from trees, and similar results were found in past research (Moos et al. 2016). Therefore, we highlighted that considering uniform cohesion value for vegetation in landslide models may not be appropriate to represent the effect of trees on slope stability.

4.3. The implications on slope stability and possible countermeasures of forest management

According to our results, species, trees DBH, slope position, distance from the tree trunk, and altitude strongly influence tree roots' stabilizing effect. Hence, the addition of a uniform cohesion term for vegetation in physicallybased landslide models (e.g., CHASM model (Wilkinson et al. 2002), TRIGRS model (Baum et al. 2008), SOSlope (Cohen and Schwarz 2017), PRIMULA model (Cislaghi et al. 2018), and SLIP model (Montrasio and Valentino 2008)) may not be appropriate to represent the trees impacts on slope stability. The variable value for root reinforcement based on species, trees DBH, slope position, distance from the tree trunk, and altitude shows to be a good approximation for root reinforcement models. These findings indicated that specific root reinforcement should be considered due to various species, tree DBH, etc. Due to the high cost and time involved in investigating root reinforcement may be of great relevance to the large-scale model application. Based on a large database about root properties and root reinforcement in beech and hornbeam species in the temperate forests of Europe and Iran (Bischetti et al. 2005, 2007, 2009; Abdi et al. 2010b; Chiaradia et al. 2016; Abdi and Deljouei 2019; Deljouei et al. 2020; Cislaghi, 2021; Cislaghi et al. 2021), modelling root reinforcement can be applied for various environmental conditions.

By comparing the performance of various species in terms of additional root reinforcement, the species most likely to increase slope stability were identified. Also, our result can be used for nature-based solutions targeting root reinforcement, like the effect of different forest stand structures on slope stability (Moos et al. 2016; Dazio et al. 2018), and forest management scenarios (Kumar et al. 2021). Over a long period, *C. betulus* is preferable to *F. orientalis* when promoting one species over another to increase (or maintain) slope stability. Forest managers should consider this outcome when developing strategies for large forests in mountainous areas. Certainly, factors including inter-and intraspecific competition affect the performance of species concerning slope stability (Chiaradia et al. 2016). As shown in this paper, this performance can be considered by using a large, widely distributed dataset and evaluating the probabilistic function used to describe the values in the field survey. By clarifying the higher prevention power's behaviour from large DBH *C. betulus* trees, it is possible to propose forest management that keep this tree species with a large diameter in landslide-prone areas. Using both basal and lateral reinforcement, the results suggest that the most stabilizing species is *C. betulus*. Importantly, our findings imply tree diameter and species may be appropriate for assessing FoS by common tree species in Hyrcanian temperate forests. Future studies can be conducted on the available landslide inventory data with back analysis.

5. Conclusions

This study conducted a total of 1080 profile trenches for widely species in temperate forests of Iran and European countries (i.e., *C. betulus* and *F. orientalis*) at various altitudes (i.e., 400, 940, and 1350 m a.s.l). Root distribution and mechanical properties of trees with 7.5-32.5, 32.5-57.5, and 57.5-82.5 cm DBH were used as input parameters of RBMw. This study highlighted quantitative information about the impact of roots mechanical properties and distribution in DBH classes, slope position, altitude, and vertical and horizontal distance from tree trunk of *C. betulus* and *F. orientalis* on root reinforcement and slope stability is the practical conjunction for forest management. Our results reported that altitude, DBH classes, and slope position significantly affect root reinforcement in Hyrcanian temperate forests. Slope stabilization is decreased in further distances (more than 1 m) from the tree trunk; furthermore, it is entirely different for both species in which *C. betulus* shows better root reinforcement than *F. orientalis*.

Furthermore, the most stabilizing species is mature *C. betulus* at all altitudes, which maintained an instability probability near 29% for very steep conditions. Overall, we could highlight that vegetation's impact on soil slope stability depends on various parameters, and considering the constant value of soil reinforcement via tree roots in soil stabilization modelling is incorrect. As far as slope stabilization is concerned, there are no specific species suitable for all ecological conditions since its suitability depends not only on its root reinforcement characteristics but also on the species ability to grow and support healthy forest cover. Protecting slopes from long-term instability is dependent on the forest's ability to withstand disturbances and its ability to recover after disturbances.

References

Abbaszadeh Shahri A, Maghsoudi Moud F (2021) Landslide susceptibility mapping using hybridized block modular intelligence model. Bull Eng Geol Environ 80:267–284. https://doi.org/10.1007/s10064-020-01922-8

Abdi E, Azhdari F, Abdulkhani A, Mariv HS (2014) Tensile strength and cellulose content of Persian ironwood (*Parrotia persica*) roots as bioengineering material. J For Sci 60:425–430. https://doi.org/10.17221/44/2014-JFS

Abdi E, Deljouei A (2019) Seasonal and spatial variability of root reinforcement in three pioneer species of the Hyrcanian forest. Austrian J For Sci 136:175–198

Abdi E, Majnounian B, Genet M, Rahimi H (2010a) Quantifying the effects of root reinforcement of Persian Ironwood (*Parrotia persica*) on slope stability; a case study: Hillslope of Hyrcanian forests, northern Iran. Ecol Eng 36:1409–1416. https://doi.org/10.1016/j.ecoleng.2010.06.020

Abdi E, Majnounian B, Rahimi H, Zobeiri M, Mashayekhi Z, Yosefzadeh H (2010b) A comparison of root distribution of three hardwood species grown on a hillside in the Caspian forest, Iran. J For Res 15: 99–107. https://doi.org/10.1007/s10310-009-0164-2

Abdi E, Saleh HR, Majnounian B, Deljouei A (2019) Soil fixation and erosion control by *Haloxylon persicum* roots in arid lands, Iran. J Arid Land 11:86–96. https://doi.org/10.1007/s40333-018-0021-2

Arnone ED, Caracciolo D, Noto LV, Preti F, Bras RL (2016) Modeling the hydrological and mechanical effect of roots on shallow landslides. Water Resources Research 52:8590–8612. https://doi.org/10.1002/2015WR018227

Azaryan M, Marvie-Mohadjer MR, Etemaad V, Shirvany A, Sadeghi SMM (2015) Morphological characteristics of old trees in Hyrcanian forest (Case study: Pattom and Namkhaneh districts, Kheyrud). J For Wood Prod 68:47–59. https://doi.org/10.22059/JFWP.2015.53977

Baum RL, Savage WZ, Godt JW (2008) TRIGRS: a Fortran program for transient rainfall infiltration and grid-based regional slope-stability analysis. US Geological Survey open-file report 424:38.

Bischetti GB, Chiaradia EA, Simonato T, Speziali B, Vitali B, Vullo P, Zocco A (2005) Root strength and root area of forest species in Lombardy. Plant Soil 278:11–22. https://doi.org/10.1007/978-1-4020-5593-5_4

Bischetti GB, Chiaradia EA, Epis T, Moriotti E (2009) Root cohesion of forest species in the Italian Alps. Plant Soil 324:71–89. https://doi.org/10.1007/s11104-009-9941-0

Bischetti GB, Chiaradia EA, Simonato T, Speziali B, Vitali B, Vullo P, Zocco A (2007) Root strength and root area ratio of forest species in Lombardy (Northern Italy). In: Stokes A, Spanos I, Norris JE, Cammeraat E (eds) Eco-and Ground Bio-Engineering: The Use of Vegetation to Improve Slope Stability. Developments in Plant and Soil Sciences, vol 103. Springer, Dordrecht. https://doi.org/10.1007/978-1-4020-5593-5_4

Boldrin D, Leung AK, Bengough AG (2017) Correlating hydrologic reinforcement of vegetated soil with plant traits during establishment of woody perennials. Plant Soil 416: 437–451. https://doi.org/10.1007/s11104-017-3211-3

Bordoni M, Vercesi A, Maerker M, Ganimede C, Reguzzi MC, Capelli E, Wei X, Mazzoni E, Simoni S, Gagnarli E, Meisina C (2019) Effects of vineyard soil management on the characteristics of soils and roots in the lower Oltrepò Apennines (Lombardy, Italy). Sci Total Environ 693:133390. https://doi.org/10.1016/j.scitotenv.2019.07.196

Burylo M, Hudek C, Rey F (2011) Soil reinforcement by the roots of six dominant species on eroded mountainous marly slopes (Southern Alps, France). Catena 84: 70–78. https://doi.org/10.1016/j.catena.2010.09.007

Böhm W, (1979) Methods of studying root systems, Ecological Studies. Springer, Berlin, Germany

Casadei M, Dietrich WE, Miller N (2003) Controls on shallow landslide size. In: Proceedings of the 3rd International Conference on Debris-Flow Hazards Mitigation: Mechanics, Prediction, and Assessment. Davos, Swizerland.

Chiaradia EA, Vergani C, Bischetti GB (2016) Evaluation of the effects of three European forest types on slope stability by field and probabilistic analyses and their implications for forest management. For Ecol Manag 370:114–129. https://doi.org/10.1016/j.foreco.2016.03.050

Chiatante D, Sarnataro M, Fusco S, Di Iorio A, Scippa GS (2003) Modification of root morphological parameters and root architecture in seedlings of *Fraxinus ornus* L. and *Spartium junceum* L. growing on slopes. Plant Biosyst 137:47–55. https://doi.org/10.1080/11263500312331351321

Cislaghi A (2021) Exploring the variability in elastic properties of roots in Alpine tree species. J For Sci 67: 338–356. http://dx.doi.org/10.17221/4/2021-JFS

Cislaghi A, Rigon E, Lenzi MA, Bischetti GB (2018) A probabilistic multidimensional approach to quantify large wood recruitment from hillslopes in mountainous-forested catchments. Geomorphology 306:108–127. https://doi.org/10.1016/j.geomorph.2018.01.009

Cislaghi A, Alterio E, Fogliata P, Rizzi A, Lingua E, Vacchiano G, Bischetti GB, Sitzia T (2021) Effects of tree spacing and thinning on root reinforcement in mountain forests of the European Southern Alps. For Ecol Manag 482:118873. https://doi.org/10.1016/j.foreco.2020.118873

Cohen D, Schwarz M (2017) Tree-root control of shallow landslides. Earth Surf Dynamics 5(3):451-477. https://doi.org/10.5194/esurf-5-451-2017

Coppin NJ, Richards IG (1990) Use of vegetation in civil engineering. Butterworth, London

Dazio EPR, Conedera M, Schwarz M (2018) Impact of different chestnut coppice managements on root reinforcement and shallow landslide susceptibility. Forest Ecology and Management 417:63–76. https://doi.org/10.1016/j.foreco.2018.02.031

Deljouei A, Abdi E, Schwarz M, Majnounian B, Sohrabi H, Dumroese RK (2020) Mechanical characteristics of the fine roots of two broadleaved tree species from the Temperate Caspian Hyrcanian Ecoregion. Forests 11:345. https://doi.org/10.3390/f11030345

Deljouei A, Sadeghi SMM, Abdi E, Bernhardt-Römermann M, Pascoe EL, Marcantonio M (2018) The impact of road disturbance on vegetation and soil properties in a beech stand, Hyrcanian forest. Eur J For Res 137:759–770. https://doi.org/10.1007/s10342-018-1138-8

Di Iorio A, Lasserre B, Scippa GS, Chiatante D (2005) Root system architecture of *Quercus pubescens* trees growing on different sloping conditions. Ann Bot 95:351–361. https://doi.org/10.1093/aob/mci033

Ekanayake JC, Phillips CJ (1999) A method for stability analysis of vegetated hillslopes: an energy approach. Can Geotech J 36:1172–1184. https://doi.org/10.1139/t99-060

Ekeoma EC, Boldrin D, Loades KW, Bengough AG (2021) Drying of fibrous roots strengthens the negative power relation between biomechanical properties and diameter. Plant Soil 1–14. https://doi.org/10.1007/s11104-021-05150-1

Endo T, Tsuruta T (1969) Effects of tree root upon the shearing strengths of soils. Annual Report of the Hokkaido Branch, Tokyo Forest Experiment Station 18:168–179

Ford ED, Deans JD (1977) Growth of a sitka spruce plantation: spatial distribution and seasonal fluctuations of lengths, weights and carbohydrate concentration of fine roots. Plant Soil 47:463–485. https://doi.org/10.1007/BF00011504

Gehring E, Conedera M, Maringer J, Giadrossich F, Guastini E, Schwarz M (2019) Shallow landslide disposition in burnt European beech (Fagus sylvatica L.) forests. Sci Rep 9:8638. https://doi.org/10.1038/s41598-019-45073-7

Genet M, Kokutse N, Stokes A, Fourcaud T, Cai X, Ji J, Mickovski S (2008) Root reinforcement in plantations of *Cryptomeria japonica* D. Don: effect of tree age and stand structure on slope stability. Forest Ecol Manag 256:1517–1526. https://doi.org/10.1016/j.foreco.2008.05.050

Genet M, Stokes A, Fourcaud T, Norris JE (2010) The influence of plant diversity on slope stability in a moist evergreen deciduous forest. Ecological Engineering 36:265–275. https://doi.org/10.1016/j.ecoleng.2009.05.018

Genet M, Li M, Luo T, Fourcaud T, Clément-Vidal A, Stokes A (2011) Linking carbon supply to root cell-wall chemistry and mechanics at high altitudes in *Abies georgei*. Ann Bot 107: 311–320. https://doi.org/10.1093/aob/mcq237

Genet M, Stokes A, Fourcaud T, Hu X, Lu Y (2006) Soil fixation by tree roots: changes in root reinforcement parameters with age in *Cryptomeria japonica* D. Don. plantations. In Interpraevent 25–27

Gholami-Derami A, Akbari H, Nasiri M, Foshat M (2021) Comparison of bioengineering characteristics of native and non-native tree species. J Wood For Sci Technol 27:67–80. https://doi.org/10.22069/JWFST.2021.18253.1884

Giadrossich F, Cohen D, Schwarz M, Ganga A, Marrosu R, Pirastru M, Capra GF (2019) Large roots dominate the contribution of trees to slope stability. Earth Surf Process Landf 44:1602–1609. https://doi.org/10.1002/esp.4597

Giadrossich F, Schwarz M, Marden M, Marrosu R, Phillips C (2020) Minimum representative root distribution sampling for calculating slope stability in *Pinus radiata* D. Don plantations in New Zealand. N Z J For Sci 50. https://doi.org/10.33494/nzjfs502020x68x

Gilardelli F, Vergani C, Rodolfo G, Bonis A, Chanteloup P, Citterio S, Chiaradia EA (2017) Root characteristics of herbaceous species for topsoil stabilization in restoration projects. Land Degrad Dev 28:2074–2085. https://doi.org/10.1002/ldr.2731

Goodman AM, Ennos AR (1999) The effects of soil bulk density on the morphology and anchorage mechanics of the root systems of sunflower and maize. Ann Bot 83:293–302. https://doi.org/10.1006/anbo.1998.0822

Goss MJ, Miller MH Bailey LD, Grant CA (1993) Root growth and distribution in relation to nutrient availability and uptake. Eur J Agron 2:57–67. https://doi.org/10.1016/S1161-0301(14)80135-4

Gray DH, Sotir RB (1996) Biotechnical and soil bioengineering slope stabilization: a practical guide for erosion control. John Wiley & Sons, New York, USA.

Hales TC, Ford CR, Hwang T, Vose JM, Band LE (2009) Topographic and ecologic controls on root reinforcement. J Geophys Res 114. https://doi.org/10.1029/2008JF001168

Hammond C, Hall D, Miller S, Swetik P (1992) Level I Stability Analysis (LISA) Documentation for Version 2.0. US Department of Agriculture, Forest Service, Intermountain Research Station

Hayati E (2017). Monitoring of forest slope hydrological changes for applying in hydrological and slope stability models. PhD thesis, University of Tehran, Karaj, Iran.

Hodge A (2004) The plastic plant: root responses to heterogeneous supplies of nutrients. New phytol 162: 9–24. https://doi.org/10.1111/j.1469-8137.2004.01015.x

Holtmeier FK, Broll G (2005) Sensitivity and response of northern hemisphere altitudinal and polar treelines to environmental change at landscape and local scales: Treeline and environmental change. Glob Ecol Biogeography 14(5):395–410. https://doi.org/10.1111/j.1466- 822X.2005.00168.x

John B, Pandey HN, Tripathi RS (2001) Vertical distribution and seasonal changes of fine and coarse root mass in *Pinus kesiya* Royle Ex. Gordon forest of three different ages. Acta Oecologica 22:293–300. https://doi.org/10.1016/S1146-609X(01)01118-3

Karimi Z, Abdi E, Deljouei A, Cislaghi A, Shirvany A, Schwarz M, Hales TC (2022) Vegetation-induced soil stabilization in coastal area: An example from a natural mangrove forest. Catena, 216:106410. https://doi.org/10.1016/j.catena.2022.106410

Körner C (1999) Alpine plant life: Functional plant ecology of high mountain ecosystems. Springer.

Kramer JP, Boyer SJ (1995) Water Relations of Plants and Soils. Academic Press, San Diego, New York

Kumar P, Debele SE, Sahani J, Rawat N, Marti-Cardona B, Alfieri SM, Basu B, Basu AS, Bowyer P, Charizopoulos N, Gallotti G (2021) Nature-based solutions efficiency evaluation against natural hazards: Modelling methods, advantages and limitations. Science of the Total Environment 784:147058. https://doi.org/10.1016/j.scitotenv.2021.147058

Lin M, Sadeghi SMM, Van Stan JT (2020) Partitioning of rainfall and sprinkler-irrigation by crop canopies: A global review and evaluation of available research. Hydrology, 7(4):76. https://doi.org/10.3390/hydrology7040076

Loades KW, Bengough AG, Bransby MF, Hallett PD (2013) Biomechanics of nodal, seminal and lateral roots of barley: Effects of diameter, waterlogging and mechanical impedance. Plant Soil 370:407–418. https://doi.org/10.1007/s11104-013-1643-y

Loomis PF, Ruess RW, Sveinbjörnsson B, Kielland K (2006) Nitrogen cycling at treeline: latitudinal and elevational patterns across a boreal landscape. Ecoscience 13(4):544-556. https://doi.org/10.2980/1195-6860(2006)13[544:NCATLA]2.0.CO;2

Makarova OV, Cofie P, Koolen AJ (1998) Axial stress– strain relationships of fine roots of beech and larch in loading to failure and in cyclic loading. Soil Tillage Res 45:175–187. https://doi.org/10.1016/S0933-3630(97)00017-2

Mao Z, Saint-André L, Genet M, Mine FX, Jourdan C, Rey H, Courbaud B, Stokes A (2012) Engineering ecological protection against landslides in diverse mountain forests: Choosing cohesion models. Ecol Eng 45:55–69. https://doi.org/10.1016/j.ecoleng.2011.03.026

Mao Z (2022) Root reinforcement models: classification, criticism and perspectives. Plant Soil. https://doi.org/10.1007/s11104-021-05231-1

Mayor JR, Sanders, NJ, Classen AT, Bardget RD, Clément JC, Fajardo A, Lavorel S, Sundqvist MK, Bahn M, Chisholm C, Cieraad E, Gedalof Z, Grigulis K, Kudo G, Oberski DL, Wardle DA (2017) Elevation alters ecosystem properties across temperate treelines globally. Nature 542(7639):91–95. https://doi.org/10.1038/nature21027

McQueen DR (1968) The quantitative distribution of absorbing roots of *Pinus sylvestica* in a forest succession. Oecol. Plant 3:83–99

Mehtab A, Jiang YJ, Su LJ, Shamsher S, Li JJ, Mahfuzur R (2021) Scaling the Roots Mechanical Reinforcement in Plantation of Cunninghamia R. Br in Southwest China. Forests 12:33. https://doi.org/10.3390/f12010033

Milledge DG, Bellugi D, McKean JA, Densmore AL, Dietrich WE (2014) A multidimensional stability model for predicting shallow landslide size and shape across landscapes: predicting landslide size and shape. J. Geophys. Res. Earth Surf. 119:2481–2504. http://dx.doi.org/10.1002/2014JF003135

Montrasio L, Valentino R (2008) A model for triggering mechanisms of shallow landslides. Nat. Hazards Earth Syst Sci 8:1149–1159. https://doi.org/10.5194/nhess-8-1149-2008

Moore AM (1986) Temperature and moisture dependence of decomposition rates of hardwood and coniferous leaf litter. Soil Biol. Biochemis 18(4):427-435. https://doi.org/10.1016/0038-0717(86)90049-0

Moos C, Bebi P, Graf F, Mattli J, Rickli C, Schwarz M (2016) How does forest structure affect root reinforcement and susceptibility to shallow landslides?: A Case Study in St. Antönien, Switzerland. Earth Surf Process Landf 41:951–960. https://doi.org/10.1002/esp.3887

Moresi FV, Maesano M, Matteucci G, Romagnoli M, Sidle RC, Scarascia Mugnozza G (2019) Root biomechanical traits in a montane Mediterranean forest watershed: variations with species diversity and soil depth. Forests 10:341. https://doi.org/10.3390/f10040341

Morgan RP, Rickson RJ (1995) Slope stabilization and erosion control: a bioengineering approach. Second edition. Chapman and Hall, 293 p

Norris JE, Iorio AD, Stokes A, Nicoll BC, Achim A (2008) Species selection for soil reinforcement and protection. In Slope stability and erosion control: ecotechnological solutions. Springer, Dordrecht

O'Loughlin CL (1974) A study of tree root strength deterioration following clear felling. Canadian Journal of Forest Research 4:107–113. https://doi.org/10.1139/x74-016

Phillips CJ, Marden M, Lambie S (2014) Observations of root growth of young poplar and willow planting types. N Z J For Sci 44:15. https://doi.org/10.1186/s40490-014-0015-6

Pollen N, Simon A (2005) Estimating the mechanical effects of riparian vegetation on stream bank stability using a fiber bundle model. Water Resour. Res. 41:W07025. https://doi.org/10.1029/2004WR003801

Pourghasemi H, Pradhan B, Gokceoglu C, Moezzi KD (2012) Landslide susceptibility mapping using a spatial multi criteria evaluation model at Haraz Watershed, Iran. In: Pradhan B, Buchroithner M (eds) Terrigenous mass movements. Springer, Berlin, pp. 23–49. https://doi.org/10.1007/978-3-642-25495-6_2

Sadeghi SMM, Gordon DA, Van Stan II JT (2020) A global synthesis of throughfall and stemflow hydrometeorology. In Precipitation partitioning by vegetation (pp. 49-70). Springer, Cham. https://doi.org/10.1007/978-3-030-29702-2_4

Sagheb-Talebi K, Sajedi T, Pourhashemi M (2014) Euxino-Hyrcanian Province: Caspian and Arasbaran Regions. In: Forests of Iran. Plant and Vegetation, vol 10. Springer, Dordrecht. https://doi.org/10.1007/978-94-007-7371-4_2

Schwarz M, Giadrossich F, Cohen D (2013) Modeling root reinforcement using a root-failureWeibull survival function. Hydrol Earth Syst Sci 17:4367–4377. https://doi.org/10.5194/hess-17-4367-2013

Schwarz M, Lehmann P, Or D (2010) Quantifying lateral root reinforcement in steep slopes: from a bundle of roots to tree stands. Earth Surf Process Landf 35:354–367. https://doi.org/10.1002/esp.1927

Schwarz M, Rist A, Cohen D, Giadrossich F, Egorov P, Buttner D, Stolz M, Thormann JJ (2015) Root reinforcement of soils under compression. J. Geophys. Res. Earth Surf. 120:2103–2120. https://doi.org/10.1002/2015JF003632

See CR, McCormack LM, Hobbie SE., Flores-Moreno H, Silver WL, Kennedy PG (2019) Global patterns in fine root decomposition: Climate, chemistry, mycorrhizal association and woodiness. Ecology Letters 22(6):946–953. https://doi.org/10.1111/ele.13248

Stokes A, Norris JE, van Beck LPH, Bogaard T, Cammeraat E, Mickovski SB, Jenner A, Iorio AD, Fourcaud T (2008) How vegetation reinforces the soil on slopes. Slope stability and erosion control: Ecotechnological solutions. Springer, Dordrecht

Stokes A (2002) The biomechanics of tree root anchorage. Plant Roots, The Hidden Half, Plenum Publishing, New York

Stokes A, Douglas GB, Fourcaud T, Giadrossich F, Gillies C, Hubble T, Kim JH, Loades KW, Mao Z, McIvor IR, Mickovski SB (2014) Ecological mitigation of hillslope instability: ten key issues facing researchers and practitioners. Plant Soil 377:1–23. https://doi.org/10.1007/s11104-014-2044-6

Sundqvist MK, Sanders NJ, Wardle DA (2013) Community and ecosystem responses to elevational gradients: processes, mechanisms, and insights for global change. Ann Review Ecol Evol Systematics 44(1): 261-280. https://doi.org/10.1146/annurev-ecolsys-110512-135750

Sveinbjörnsson B, Davis,J, Abadie W, Butler A (1995) Soil carbon and nitrogen mineralization at different elevations in the Chugach Mountains of south-central Alaska, USA. Arctic Alpine Resear 27(1):29-37. https://doi.org/10.2307/1552065

Taub DR, Goldberg D (1996) Root system topology of plants from habitats differing in soil resource availability. Funct Ecol 258–264. https://doi.org/10.2307/2389851

Taylor DW (1948) Fundamentals of soil mechanics. Soil Sci. 66:161

Tsige D, Senadheera S, Talema A (2020) Stability analysis of plant-root-reinforced shallow slopes along mountainous road corridors based on numerical modeling. Geosciences 10:19. https://doi.org/10.3390/geosciences10010019

Vergani C, Chiaradia EA, Bischetti GB (2012) Variability in the tensile resistance of roots in Alpine forest tree species. Ecol Eng 46:43–56. https://doi.org/10.1016/j.ecoleng.2012.04.036

Vergani C, Giadrossich F, Buckley P, Conedera M, Pividori M, Salbitano F, Rauch HP, Lovreglio R, Schwarz M (2017a) Root reinforcement dynamics of European coppice woodlands and their effect on shallow landslides: A review. Earth Sci Rev 167:88–102. https://doi.org/10.1016/j.earscirev.2017.02.002

Vergani C, Werlen M, Conedera M, Cohen D, Schwarz M (2017b) Investigation of root reinforcement decay after a forest fire in a Scots pine (*Pinus sylvestris*) protection forest. Forest Ecology and Management 400:339–352. https://doi.org/10.1016/j.foreco.2017.06.005

Vergani C, Schwarz M, Cohen D, Thormann JJ, Bischetti GB (2014) Effects of root tensile force and diameter distribution variability on root reinforcement in the Swiss and Italian Alps. Can J For Res 44:1426–1440. https://doi.org/10.1139/cjfr-2014-0095

Waldron LJ (1977) The shear resistance of root-permeated homogeneous and stratified soil. Soil Sci. Soc. America J. 41:843–849.

Weemstra M, Freschet GT, Stokes A, Roumet C (2021) Patterns in intraspecific variation in root traits are species-specific along an elevation gradient. Functional Ecol 35(2):342-356. https://doi.org/10.1111/1365-2435.13723

Wilkinson PL, Anderson MG, Lloyd DM, Renaud JP (2002) Landslide hazard and bioengineering: towards providing improved decision support through integrated numerical model development. Environ Model Softw 17:333–344. https://doi.org/10.1016/S1364-8152(01)00078-0

Williams CJ, Pierson FB, Kormos PR, Al-Hamdan OZ, Johnson JC (2020) Vegetation, ground cover, soil, rainfall simulation, and overland-flow experiments before and after tree removal in woodland-encroached sagebrush steppe: the hydrology component of the Sagebrush Steppe Treatment Evaluation Project (SageSTEP). Earth System Science Data, 12(2):1347-1365. https://doi.org/10.5194/essd-12-1347-2020

Wu TH (1976) Investigation on landslides on Prince of Wales Island, Alaska. Geotech Rpt. No 5, Dpt. of Civil Engineering, Ohio State University, Columbus, USA.

Yamase K, Todo C, Torii N, Tanikawa T, Yamamoto T, Ikeno H, Ohashi M, Dannoura M, Hirano, Y (2021) Dynamics of soil reinforcement by roots in a regenerating coppice stand of *Quercus serrata* and effects on slope stability. Ecol Eng 162:106169. https://doi.org/10.1016/j.ecoleng.2021.106169

Zhang C, Chen L, Jiang J, Zhou S (2012) Effects of gauge length and strain rate on the tensile strength of tree roots. Trees 26:1577–1584. https://doi.org/10.1007/s00468-012-0732-5

Zydroń TA, Gruchot A (2021) Influence of root systems of deciduous trees on soil reinforcement. A case study from the Carpathians, Poland. Environ Eng Manag J 20. https://doi.org/10.30638/eemj.2021.042

Zydroń TA, Gruchot A, Kluba M (2019) Spatial Variability of Reinforcement Provided by Juvenile Root Systems of Black Locust and Black Poplar. Pol J Environ Stud 28:4027–4037. https://doi.org/10.15244/pjoes/96260

Statements & Declarations

Funding

The authors declare that no funds, grants, or other supports were received during the preparation of this manuscript.

Competing Interests

The authors have no competing interests to declare that are relevant to the content of this article.

Author Contributions

Conceptualization: Azade Deljouei, Alessio Cislaghi, Ehsan Abdi; **Methodology:** Azade Deljouei, Alessio Cislaghi; **Formal analysis and investigation:** Azade Deljouei, Alessio Cislaghi; **Writing - original draft preparation:** Azade Deljouei, Alessio Cislaghi; **Writing - review and editing:** Ehsan Abdi, Stelian Alexandru Borz, Baris Majnounian, Tristram C. Hales; **Resources:** Azade Deljouei, Ehsan Abdi; **Supervision:** Ehsan Abdi, Baris Majnounian