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Root Biomechanical Traits in a Montane Mediterranean Forest Watershed: Variations with Species Diversity and Soil Depth

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Abstract: Plant roots play a key role in stabilizing slopes, particularly in the Mediterranean region, characterized by rough and unstable terrain. However, forest species differ in their stabilizing capacities. The purpose of this study is to fill the gap of knowledge on root biomechanical properties of relevant Mediterranean trees and shrubs in relation to slope stability. Root specimens of typical montane Mediterranean tree and shrub species were sampled in Southern Italy. Root characteristics, such as tensile strength (T_r) and root area ratio (RAR), were assessed from live roots sampled in trenches, while root cohesion was calculated. Power law functions yielded the best fit for the relationship of T_r versus root diameter; however, no significant relationship was found between root strength and root moisture content. RAR varied amongst different tree and shrub species. Roots of *Quercus cerris* L. were the most resistant to breaking under tension, while roots of *Ilex aquifolium* L. had the highest tensile strength among all shrub species. Results provide quantitative information on the role of root systems of montane Mediterranean forest species in stabilizing soils and will improve modeling of landslide susceptibility to the prevention and mitigation of natural hazards in mountain environments.

Keywords: root tensile strength; root area ratio; root cohesion; slope stability; forest management; landslides; Mediterranean species; natural hazards; protection forests; soil bioengineering

1. Introduction

Slope stability and soil erosion are significant environmental and societal issues worldwide, particularly in the Mediterranean region [1,2]. The importance of these geomorphic processes is growing in relation to the intensification of precipitation, as well as in response to the increasing occurrence of extreme rain events in recent years [3], which are predicted to increase even more in the future [4]. In addition to rainfall, earthquakes, storm surges, shallow groundwater-level changes, and streambank erosion can all induce instability in hillslopes, triggering hydrogeomorphic hazards, such as mass movements of rock, debris, and soil [5]. Moreover, factors such as poor land management, forest degradation and conversion, forest fires, road construction, urban sprawl, and climate change can all affect slope stability [6]. In this context, forest conservation and appropriate forest management play significant roles in preventing and mitigating hydrogeomorphic hazards induced or exacerbated by human activities. In fact, the presence of plant roots enhances soil properties (e.g., organic matter content, soil structure, pore size distribution) and significantly increases the shear strength of soils [7–10]. Analyzing landslide inventories clearly shows an increase in landslide frequency and an accelerated displacement of existing landslides after forest harvesting and vegetation removal [11,12]. These studies attribute enhanced landslide occurrence to the reduction in root reinforcement following the removal of forest vegetation. Forest cover has also been suggested to ameliorate slope stability via rainfall interception [13], although other studies have shown that this influence is very limited [14]. Indeed, forests improve the infiltration capacity of the soil, thus reducing the potential for surface erosion [6].

The anchorage of roots into stable substrate and the consequent improvement of slope stability is related to increased soil shear strength [7,15], which also depends on specific properties of the root systems, such as root density and distribution [16] and root tensile strength. The role of vegetation in slope stability has been clearly established [9], whereby root reinforcement mechanisms are particularly dominant in forest soils [17]. In fact, on steep soil slopes, techniques such as restoring woody vegetation cover are applied to prevent shallow failures [18]. Plant roots increase the strength of the soil–root mass by enhancing the confining pressure and the resistance to sliding [19]. Root tensile strength together with root distribution and root area ratio (RAR) are important factors for determining soil reinforcement and contributing to the safety factor of hillslopes [20]. RAR provides a measure of root density within the soil and is defined as the fraction of the soil cross-sectional area occupied by roots [21]. RAR is strongly influenced by local soil and climate characteristics, land management, and associated vegetation. RAR decreases with depth and distance from the tree trunk [22]. Another essential parameter that influences slope stability is root cohesion, which varies according to the species and is highly dependent on root morphology [23]. Zhang et al. [24] showed that root cohesion is produced by the transfer of shear stress in the soil due to tensile resistance in the roots.

Many studies have evaluated mechanical properties of plant roots and their role in soil stability [17,25–27], but there is a lack of such information in Mediterranean environments and vegetation. Furthermore, assessing root cohesion values for different tree and shrub species could improve our understanding of how vegetation affects slope stability and how best to apply phytotechnology for landscape restoration. One aspect which has been rarely taken into account in such investigations is the moisture content in the roots for different species and site characteristics, and its possible effect on mechanical properties [24]. The basic assumption is derived from wood technology studies [28], which report a remarkable effect of moisture content on mechanical properties (including tensile strength) in the wood hygroscopic range from 0 to 30%, where 30% is roughly assumed to be the wood fiber saturation point (FSP) and values above this usually do not influence mechanical properties [28]. The fiber saturation point represents the moisture content at which the maximum water content bonds to cell walls by means of hydrogen bonds and the assumed value of 30% only significantly changes in very degraded wood, such as waterlogged wood [29]. Root biomechanical traits are greatly affected by species and site conditions [30], while they represent relevant properties to be considered for modeling slope stability and landslide initiation. This study aims to investigate the role that important montane Mediterranean forest trees and shrubs play in soil stability and erosion control in largely forested regions of Southern Italy, such as the Sila National Park. In this context, soil erosion and slope stability are critical issues due to geomorphology, ecosystem management, forest fires, and rainfall regimes with irregular but intense events. The purpose of this study was to validate the following objectives:

- Soil–root reinforcement in mountains and hillslopes is highly dependent on forest species biodiversity, particularly in the Mediterranean region;
- Root properties, such as tensile strength and root cohesion, are important biomechanical traits that could be efficiently utilized in nature-based solutions to improve soil stability in the region;
- Root moisture conditions affect root tensile strength.

2. Materials and Methods

2.1. Study Area and Plant Material

The investigation focuses on a mountain catchment in Southern Italy within the Calabria Region. This region is characterized by more than 600,000 ha of forest, corresponding to 40% of the total land surface of the region [31]. According to the Italian National Forest and the Carbon Inventory [31], the main forest types in Calabria are: Chemonstnut (*Castanea sativa* Mill.) (11.3%), Calabrian pine (*Pinus nigra* subsp. *laricio* (Poir.) Maire) (12.2%), and oaks (*Quercus* spp.) (7.6%). The study catchment is located in the Sila Greca mountain range (39°28′50′′ N, 16°30′12′′ E) in proximity to Sila National Park and is named "Bonis" after the stream that crosses through it (Figure 1).

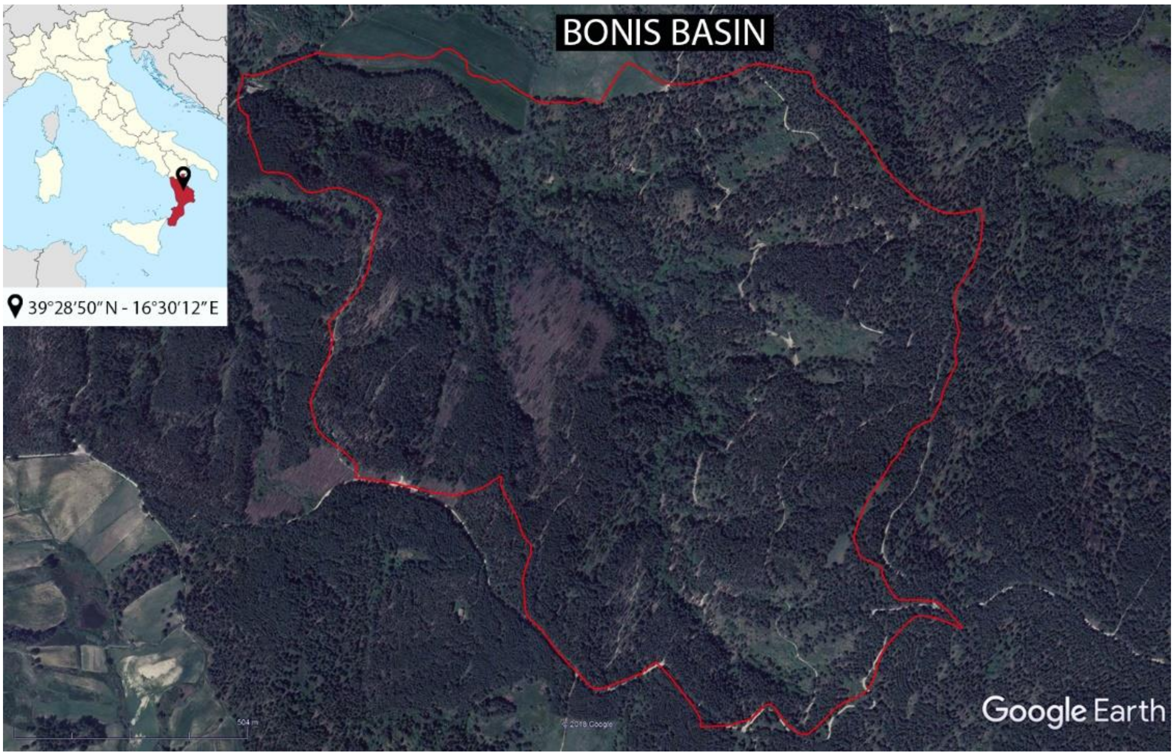


Figure 1. Study site located in South Italy (Calabria Region). Red line marks the "Bonis Basin".

The catchment has a total area of 139 ha, most of which is forested. The area was largely reforested 50 years ago with Calabrian pine plantations, and includes small areas of mixed stands with chestnut and alder (*Alnus glutinosa* (L.) Gaertn) riparian forests. The climate of the Calabria region is Mediterranean, characterized by mild winters and hot summers with little precipitation. However, in mountainous and inland areas, colder winters with snowfall and cooler summers with some precipitation occur [32]. Mean annual precipitation at the Bonis site is 1179 mm and mean annual air temperature is 9 °C [33]. Acidic plutonic rocks [34] underlie two types of soils (*Typic Xerumbrepts* and *Ulpic Haploxeralfs*) in the catchment. The *Typic Xerumbrepts* are variable in thickness, from several centimeters to over a meter, with a dominant sandy texture; the presence of the granite bedrock is common in the most eroded areas. The *Ultic Haploxeralfs* are moderately thick with a silty clay loam texture [34]. The study area is strictly uniform from a geological point of view. The soils have mainly a sandy-silty and sandy-silty clayey texture [33]. The strong sandy component of the soil suggests a low degree of pedogenetic evolution in the area. The measured pH values allow the soils to be classified, regardless of the sampling depth, from ultra-acids (<4.5) to moderate acids (5.1–6.0) [33]. These values are also related to the nature of the granite lithological matrix emerging in the study area [33].

The basin extends from an altitude of 975 to 1300 m a.s.l. (above sea level), with an average elevation of 1131 m a.s.l. The length of the main stream channel is 2.2 km with a median gradient of 43.4%. The catchment was instrumented in 1986 to investigate the hydrological cycle of the area [35]; in 2004, monitoring of carbon and water vapor exchange at the canopy level (eddy covariance technique [36]) was initiated. The catchment is now associated with the ALForLab public–private laboratory (www.alforlab.it). Roots of typical montane Mediterranean tree and shrub species, *Castanea sativa* Mill, *Pinus nigra* subsp. *laricio* (Poir.) Maire, *Alnus glutinosa* (L.) Gaertn., *Quercus cerris* L., *Crataegus monogyna* Jacq., *Cytisus scoparius* L., *Ilex aquifolium* L., and *Spartium junceum* L. (Table 1), were sampled to assess root properties of biomechanical interest, including tensile strength, root area ratio, and root cohesion for each species.

Table 1. Main characteristics of the study tree and shrub species.

Species	Type	Common Name	Mean Height (m)	Mean Age (years)	Geographic Range
Castanea sativa Mill.	Tree	Sweet chestnut	20	350	Southern Europe, Western Europe, and Asia Minor
Alnus glutinosa (L.) Gaertn	Tree	Common alder	25	120	Continental Europe
Quercus cerris L.	Tree	Turkey oak	30	300	South-Eastern Europe and Asia Minor
Pinus nigra subsp. *laricio* (Poir.) Maire	Tree	Calabrian pine	30	400–500	Southern Italy and Corsica
Ilex aquifolium L.	Shrubs	Common holly	5	300	Continental Europe, North Africa, and Asia Minor
Crataegus monogyna Jacq.	Shrubs	Common hawthorn	3	100–150	Continental Europe
Cytisus scoparius L.	Shrubs	Scotch broom	1	80	Southern Europe and North Africa
Spartium junceum L.	Shrubs	Spanish broom	1	50	Southern and Western Europe

The root samples of the study plants were collected in the Bonis catchment at different locations in summer and fall, 2017, by sampling two trees or shrubs for each species. Sample trees were selected according to the mean diameter breast height (DBH) of the population of each selected tree in the forest catchment, while sampled shrubs had a height and size representative of the shrub population of the forest (Table 2).

Table 2. Mean diameter and height of study tree species.

Tree Species	Number of Trees	Average Diameter at Breast Height (cm)	CI 95 (Confidence Interval)	Average Height (m)	CI 95 (Confidence Interval)
Castanea sativa Mill.	25	25.2	±1.4	19.1	±1.76
Alnus glutinosa (L.) Gaertn	20	24.0	±2.0	16.3	±2.12
Quercus cerris L.	30	28.4	±1.1	20.1	±1.62
Pinus nigra subsp. *laricio* (Poir.) Maire	40	34.1	±2.1	24.1	±2.08

For each woody shrub, 30 × 30 cm trenches were dug 50 cm from the stem. For sample trees, 50 cm wide × 50 cm deep trenches were dug 100 cm from the stem [25,35]. Trenches were dug along the mountain slope contours [37] and root samples were collected along the trench section. To preserve the moisture content of excavated roots, they were stored in sealed plastic bags and transported to the laboratory in a refrigerated box; later, the root moisture content was measured from the root samples. The protocol was adopted because one purpose of the investigation was to determine the original water content of the roots and the related mechanical behavior. It is well known that wood and, in general, lignocellulosic materials lose water in drier conditions because of capillarity and evaporation. Within its hygroscopic field (0–30%), wood exchanges OH^- hydroxyl groups with the environment in the gas phase [28,29]. In the laboratory, the bags were stored in a refrigerated room at a constant temperature of 4 °C for about a week after sampling. Afterwards, 346 total samples of all species (20 cm long) were selected, consisting of about 40 samples for each species. The diameters were measured with a digital caliper (Mitutoyo 500, Lainate, Milano, Italy) (accuracy: ±0.03 mm) at three different positions along their length (at the ends and center). Average diameter was assigned to the entire root and used in data analysis. Roots were grouped into four diameter classes (0–1 mm, 1–2 mm, 2–5 mm, 5–10 mm) [36]. The sampled trees were considered representative of the average conditions of the forest stand.

2.2. Root Tensile Strength

Root terminals of all samples were reinforced with synthetic resin, according to a method proposed by Nilaweera and Nutalaya [38]. After resin application, roots were left for 2 days in a 4 °C cold room for resin thickening. This resin application method enables a better transfer of force from the clamping devices for tensile strength to the root without slipping. The 346 root samples were randomly divided into two subgroups of equal numbers, including each diameter class and each plant species; the first subgroup was utilized for biomechanical measurements with roots at field moisture conditions, whereas the samples of the second subgroup were saturated before biomechanical measurement. Fresh water content (FWC) is defined as the weight of water in plant tissues, expressed as a percentage of the oven-dry weight of the plant sample. Usually, moisture content of roots ranges from about 30% to more than 200% of the weight of an oven-dry plant sample [39]. Root water saturation was reached after soaking the roots in water for 48 h. After 48 h, the samples reached a constant weight. For all steps, weight was carefully measured at an accuracy of 0.001 g. After saturation, the samples were oven-dried for 24 h at 103 °C and reweighed. The temperature of 103 °C is normally used in wood technological analysis because it allows water to evaporate, but it does not cause wood combustion [28,40]. Root fragments used to measure moisture content were discarded and not used for further analysis. The FWC and the maximum water content (MWC) of the root samples was calculated as:

$$\mathrm{FWC} = 100 \times \left(\frac{w_{fc} - w_0}{w_0} \right) \tag{1}$$

$$\mathrm{MWC} = 100 \times \left(\frac{w_{wc} - w_0}{w_0} \right) \tag{2}$$

where w_{fc} is the weight of the root at field moisture condition of the sample collected from the soil, w_{wc} is the weight of the root at water saturated state, and w_0 is the weight of the oven-dry root. Values obtained by Equations (1) and (2) can be related to the expected behavior of roots at the fiber saturation point (FSP), which is a well-known threshold for changing mechanical performance. Each root was tested for tensile stress until failure. When breakage occurred at one of the clamping sites, the result was discarded, and only samples that broke near the middle of the root were accepted for data analysis [41]. A universal testing machine ("ProLine"-Zwick Roell Company, Ulma, Germany, cell load capacity 50 kN) was used to measure root tensile strength ($\mathrm{T_r}$). The machine combines three functions: (1) Traction force generation; (2) measuring load and displacement; and (3) data acquisition (Figure 2).

The samples were subjected to movement at a constant test speed of 10 mm/min. Tensile strength ($\mathrm{T_r}$) was calculated according to Bischetti et al. [42]:

$$\mathrm{T_r} = \frac{\mathrm{F_{max}}}{\left(\frac{\mathrm{D}^2}{4}\right) \times \pi} \tag{3}$$

where $\mathrm{F_{max}}$ is the maximum force needed to break the root and D is the mean root diameter before stretching.

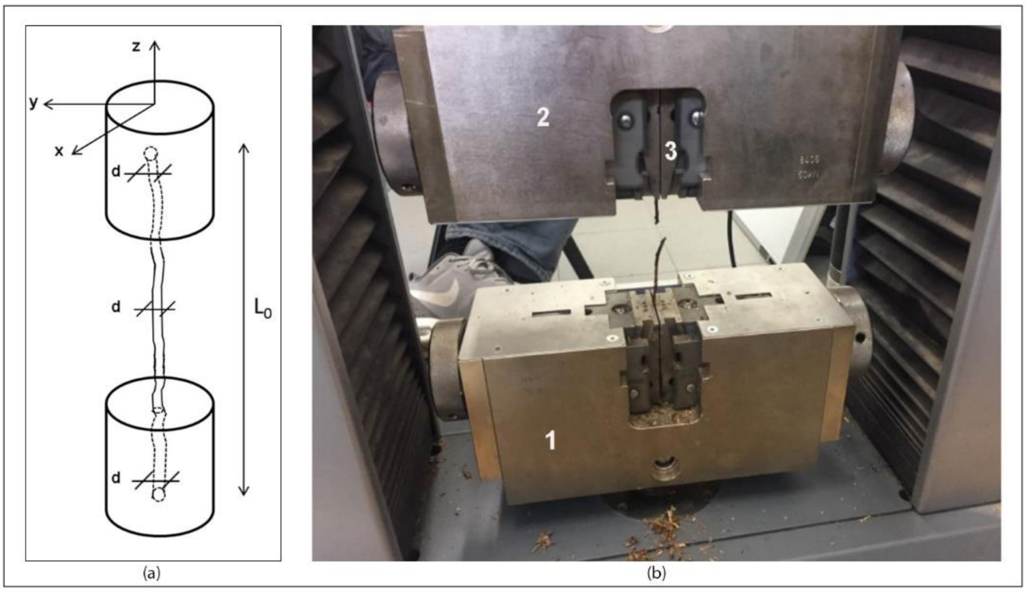


Figure 2. Prepared root samples and tensile strength measurements. (**a**) Root terminals cast in synthetic resin. Tensile force on roots was measured in the z-direction; d = diameter measurement; L_0 = length before test. (**b**) Root secured between clamping jaws before tension test. 1: Wedge tensioner, lower part; 2: Wedge tensioner, upper part; and 3: Vice clamps.

2.3. Root Area Ratio

Vertical profiles of 50 × 50 cm for trees and 30 × 30 cm for shrubs were used to calculate RAR [43]. Within each trench, root diameter was measured using an electronic caliper; at a later stage, the number of roots in the trench was estimated via high-definition photographs [43]. Before analysis, photographs were corrected to eliminate geometric distortion (Figure 3). For RAR calculation, we subdivided the excavation area into individual 10 cm depth intervals, yielding five depth class intervals for trees and three intervals for shrubs [44].

Figure 3. Trench section area (50 × 50 cm) of a chestnut tree with root sections highlighted.

RAR values at depth increments of 10 cm were calculated by the following equation:

$$\mathrm{RAR} = \frac{\Sigma\pi r^2}{A} \quad (4)$$

where, πr^2 is the total root cross-sectional area in each layer (mm^2) and A is the soil trench area (50 cm × 50 cm) measured in each layer (10 cm in depth and 50 cm wide).

2.4. Root Cohesion

Waldron and Dakessian [45] and Wu et al. [10] were pioneers in modeling relevant soil–root interactions and quantifying the root reinforcement effect on soil. The model developed by these authors assumes that all roots cross the shear plane during slope failure. According to Waldron [45], the primary influence of root reinforcement can be expressed as a cohesion term in the Mohr–Coulomb equation. The Mohr–Coulomb break criterion is a linear equation in main stress space, characterizing the conditions for which an isotropic material will fail [46,47]. To include root reinforcement, the Coulomb equation, which quantifies the resistance to soil sliding, is extended to root-permeated soils (Equation (5)) by considering an increased shear strength as a function also of root cohesion [7]:

$$S_{sr} = c_s' + c_r + (\sigma - u) \times \tan\varphi' \quad (5)$$

where S_{sr} is the soil shear strength against slippage (including root reinforcement), c_s is the effective cohesion of the soil, c_r is the apparent cohesion provided by roots, σ is the normal stress due to the weight of the soil within the sliding mass, u is the soil pore water pressure, and φ′ is the effective internal friction angle of the soil. In this model, c_r (kPa) depends on root tensile strength (T_r (kPa)) and on the cross-sectional area of roots at the shear plane (RAR):

$$c_r = (k' \times k'') \times \sum_{i=1}^{N} \overline{T}_{ri} \times \mathrm{RARi} \quad (6)$$

where i indicates the diameter class and N is the number of classes, k′ represents the random orientations of the roots with respect to the failure plane and depends on the friction angle of the soil and the distortion angle of sheared roots, and k″ is a factor for quantifying non-simultaneous breaking of roots. For a friction angle φ′ = 30°, k varies between 1.03 and 1.13, whereas 0.88 < k′ < 1.02 is used for φ′ = 20° and k′ = 1.2 for φ′ = 40. The values of k′ should be selected according to site conditions, considering a soil friction angle of 30°. Several *k″* values have been defined [45,48,49], and for forest areas, this value was set to 0.56, according to Hammond et al. [49].

The generally accepted form of the relationship between T_r and d is a simple power function [7,9]:

$$T_r = \alpha d^{-\beta} \quad (7)$$

where α and β are empirical constants.

2.5. Statistical Analysis

The Kruskal–Wallis nonparametric multiple comparisons test was used to test for significant differences in tensile strength of FWC and MWC roots of each species and for each of the four root classes. The relationship between root tensile strength (T_r) and root diameter (D) was defined by a power-law regression. Goodness-of-fit models used to assess these two parameters were R^2 and *p*-values, utilizing the log-transformed values of T_r and D; Spearman's rank-order correlation (r_s) between predicted and observed values was also utilized to test statistical significance. The variation of tensile strength values among trees and shrubs was evaluated by ANCOVA analysis, accounting for the diameter as a covariate factor in the linear regression ($\log T_r$-logD) (Supplementary Materials Figure

S1). Least significant difference (LSD) post hoc tests were used to check differences among samples. This ANCOVA procedure was also used to compare the RAR values among tree and shrub species and finally in trees and shrubs in the first three depth classes, considering depth classes as a covariate. In this context, an LSD post hoc test was performed to determine which species in the sample differ. Lastly, differences in RAR values between species in soil layer classes were verified by a two-way ANOVA test. Statistical analyses were conducted using the R software program (www.r-project.org, R version 3.5.3, University of Auckland, Auckland, New Zealand).

3. Results

3.1. Tensile Strength

Fresh water content (FWC) in roots ranged from 73% in *Quercus cerris* L. to 164% in *Pinus nigra* subsp. *laricio* (Poir.) Maire, but variability was large (Table 3). This high variability was particularly evident for *Quercus cerris* L. (coefficient of variation 89%) and *Crataegus monogyna* Jacq. (coefficient of variation 80%). Maximum water content (MWC) ranged from 132% in alder up to 252% in hawthorn and variability for all species was also very high (Table 3).

Table 3. Moisture content for fresh water content (FWC) and maximum water content (MWC) in the studied tree and shrub species.

Species	FWC		MWC	
	Mean (%)	**SD**	**Mean (%)**	**SD**
Castanea sativa Mill.	98.94	78.88	154.52	107.40
Alnus glutinosa (L.) Gaertn	78.15	50.44	132.71	91.84
Quercus cerris L.	73.68	54.78	182.99	171.66
Pinus nigra subsp. *laricio* (Poir.) Maire	164.36	91.04	244.73	169.66
Ilex aquifolium L.	125.89	10.33	241.51	100.09
Crataegus monogyna Jacq.	163.72	131.58	252.06	184.64
Cytisus scoparius L.	104.96	66.13	220.68	127.80
Spartium junceum L.	135.95	89.60	251.61	179.50

Kruskal–Wallis H tests indicated no statistically significant differences in tensile strength of the roots related to their water content (both FWC and MWC) for all species and roots classes (*Castanea sativa* Mill. $\chi^2(1) = 0.337$, $p = 0.561$; *Alnus glutinosa* (L.) Gaertn $\chi^2(1) = 0.198$, $p = 0.655$; *Quercus cerris* L. $\chi^2(1) = 0.016$, $p = 0.898$; *Pinus nigra* subsp. *laricio* (Poir.) Maire $\chi^2(1) = 3.347$, p = 0.067; *Ilex aquifolium* L. $\chi^2(1) = 1.471$, $p = 0.225$; *Crataegus monogyna* Jacq $\chi^2(1) = 1.928$, $p = 0.164$; *Cytisus scoparius* L. $\chi^2(1) = 0.007$, $p = 0.932$; *Spartium junceum* L. $\chi^2(1) = 0.355$, $p = 0.551$), hence, all samples of the same species (FWC and MWC) were grouped together for the purpose of this study. Tensile strength (T_r) decreased with increasing diameter (D), according to a power law curve (Figure 4). The parameters of the root strength–diameter power law relationship are reported in Table 4. In total, 346 root trials were performed. Diameter of the tested roots varied between 0.31 and 7.59 mm, while the minimum and maximum tensile strength values were 1.44 and 107.91 MPa, respectively (Table 4). Power law functions for different species had R^2 values ranging from 0.27 (*Pinus nigra* subsp. *laricio* (Poir.) Maire) to 0.84 (*Cytisus scoparius* L.), but for all species, the relationships were highly significant ($p < 0.001$; Table 5).

ANCOVA analysis indicated significant differences in root tensile strength among species ($F_{(7,730)} = 33.96$, p-value < 0.001) (root diameter as covariate). Indeed, analysing $T_r(D)$ log-transformed values, we found that the angular coefficients were different among the species, resulting in non-parallel curves (Figure 4).

The ANCOVA analysis confirms that the tensile strength depends on diameter and that the slope of the regression between Tr and D is species-specific. The LSD test divided the tested species into four significantly different groups based on tensile strength: 1—*Quercus cerris* L.; 2—*Ilex aquifolium* L. and *Cytisus scoparius* L.; 3—*Spartium junceum* L.; 4—*Crataegus monogyna* Jacq., *Castanea sativa* Mill., *Pinus nigra* subsp. *laricio* (Poir.) Maire, and *Alnus glutinosa* (L.) Gaertn. *Quercus cerris* L. had the largest values of Tr and therefore greater root resistance. Moreover, considering plant type (trees versus shrubs) the two series are parallel (ANCOVA, $F_{(1,342)} = 0.11$, p-value = 0.73) and significantly different (ANCOVA, $F_{(1,342)} = 2.72$, p-value < 0.1). The LSD post hoc test highlighted that shrubs have a significantly higher root tensile strength than trees and, therefore, the shrubs have a higher resistance to tension stress.

Table 4. Descriptive statistics for diameter and tensile strength of the tested roots of different species.

Species	Samples	Diameter (mm)				Tensile Strength (MPa)			
		Mean	CI 95	Min	Max	Mean	CI 95	Min	Max
Castanea sativa Mill.	38	2.61	±0.53	0.31	7.59	13.49	±3.71	1.44	53.22
Alnus glutinosa (L.) Gaertn	39	2.58	±0.42	0.96	6.71	10.23	±2.14	3.50	37.91
Quercus cerris L.	63	1.63	±0.29	0.39	5.61	40.45	±6.21	9.96	107.91
Pinus nigra subsp. *laricio* (Poir.) Maire	65	2.21	±0.31	0.63	6.47	11.28	±1.51	2.81	33.10
Ilex aquifolium L.	45	2.23	±0.36	0.68	6.17	24.42	±3.99	4.40	48.76
Crataegus monogyna Jacq.	26	2.30	±0.41	0.80	4.92	13.10	±2.58	5.81	28.43
Cytisus scoparius L.	36	1.78	±0.43	0.49	5.82	21.58	±5.43	3.03	63.67
Spartium junceum L.	34	1.77	±0.34	0.59	5.60	20.66	±4.86	5.67	76.85

Table 5. Coefficients of the power law equation, with statistical parameters and coefficient of correlation.

Species	α	β	*R*-Squared	*p*-Value	r_s
Castanea sativa Mill.	17.98	0.79	0.45	<0.001	0.69
Alnus glutinosa (L.) Gaertn	14.35	0.57	0.30	<0.001	0.50
Quercus cerris L.	42.51	0.80	0.82	<0.001	0.91
Pinus nigra subsp. *laricio* (Poir.) Maire	13.68	0.48	0.27	<0.001	0.46
Ilex aquifolium L.	40.80	1.07	0.50	<0.001	0.58
Crataegus monogyna Jacq.	19.28	0.66	0.47	<0.001	0.69
Cytisus scoparius L.	24.76	1.08	0.84	<0.001	0.93
Spartium junceum L.	26.61	0.95	0.63	<0.001	0.85

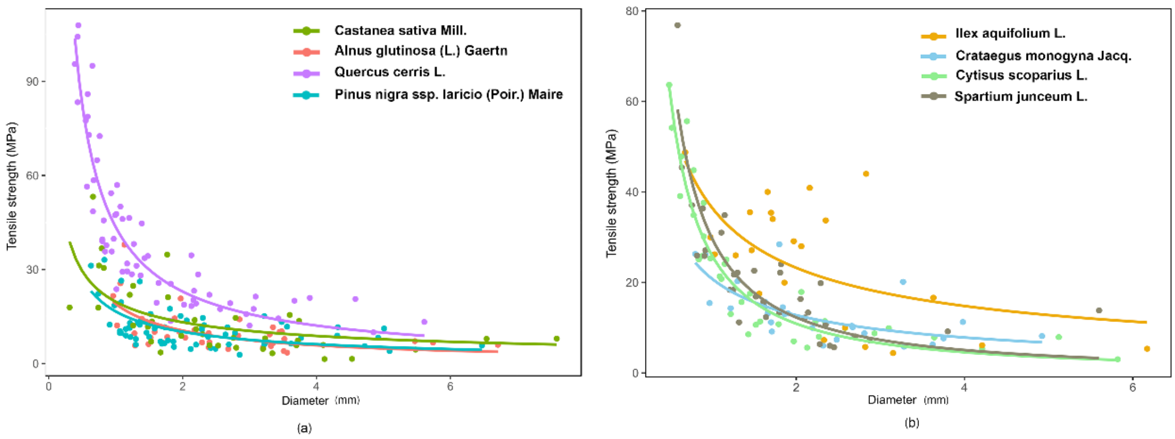


Figure 4. Tr and D relationships for eight different species fitted to a power law function: (**a**) Trees, (**b**) shrubs.

Young modulus could add interesting information to predicting root reinforcement [50]. Nevertheless, the stress strain curves of many samples show a shape quite tortuous, as in agreement with Commandeur and Pyles [50] too. Indeed, in order to measure the Young modulus, several traits of stress strain curve must be selected, applying for each trait a different model to determine the root's real behavior. This part of the research needs a focused investigation. The results of the modulus of elasticity, processed by testing machine "ProLine"-Zwick Roell" for each species, were: *Castanea sativa* Mill. 63.3 MPa ± 1.49, *Alnus glutinosa* (L.) Gaertn 256.4 MPa ± 0.49, *Quercus cerris L.* 77.2 MPa ± 1.61, *Pinus nigra* subsp. *laricio* (Poir.) Maire 118.2 MPa ± 0.186, *Ilex aquifolium* L. 250.2 MPa ± 0.261, *Crataegus monogyna* Jacq. 136.2 ± 0.206, *Cytisus scoparius* L. 143.5 ± 0.625, and *Spartium junceum* L. 177.2 MPa ± 0.486. The measured values are comparable with Commandeur and Pyles [50] and Wu et al. [51].

3.2. Root Area Ratio—RAR

In the trenches, tree roots were measured at depth increments of 10 cm and divided into 3 depth classes for shrubs and 5 depth classes for trees. The percentage of roots varied according to soil depth and species (Figure 5 and Table 6).

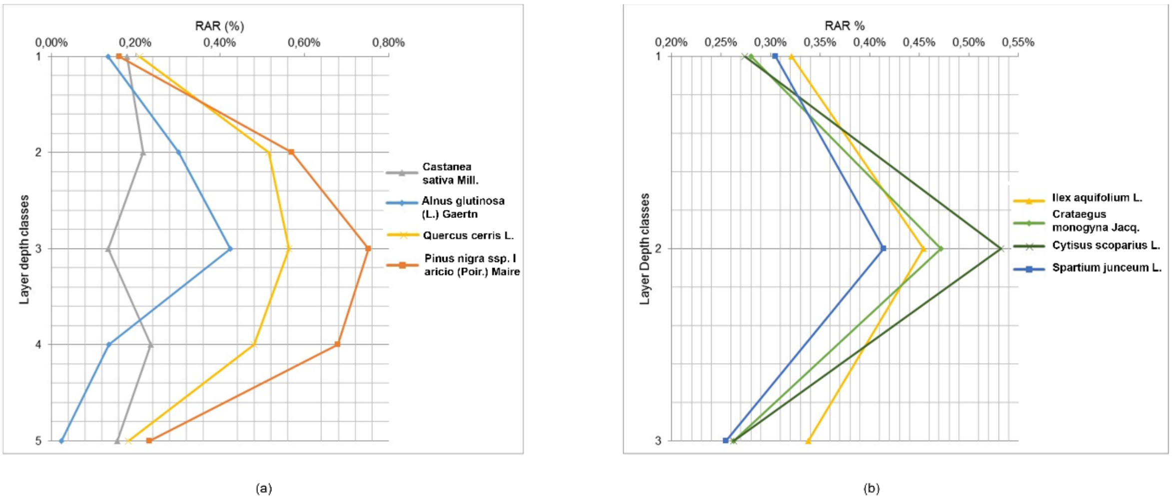


Figure 5. RAR distributions of the tree (**a**) and shrub species (**b**). Class 1 (0.00–10.0 cm), Class 2 (10.0–20.0 cm), Class 3 (20.0–30.0 cm), Class 4 (30.0–40.0 cm), and Class 5 (40.0–50.0 cm).

Table 6. Mean and standard deviation values of Root Area Ratio (RAR) for each species.

Species	Root Area Ratio (%)									
	0.0–10.0 cm		10.0–20.0 cm		20.0–30.0 cm		30.0–40.0 cm		40.0–50.0 cm	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Castanea sativa Mill.	0.18	0.0001	0.22	0.0008	0.13	0.0008	0.24	0.00042	0.16	0.0009
Alnus glutinosa (L.) Gaertn	0.13	0.0001	0.30	0.0002	0.42	0.00006	0.14	0.0001	0.02	0.0002
Quercus cerris L.	0.21	0.0006	0.52	0.002	0.56	0.00002	0.48	0.0012	0.18	0.00005
Pinus nigra subsp. *laricio* (Poir.) Maire	0.16	0.0007	0.57	0.003	0.75	0.0002	0.68	0.0009	0.23	0.002
Ilex aquifolium L.	0.32	0.001	0.45	0.0012	0.34	0.0007				
Crataegus monogyna Jacq.	0.28	0.0007	0.47	0.00009	0.26	0.002				
Cytisus scoparius L.	0.27	0.001	0.53	0.004	0.26	0.0001				
Spartium junceum L.	0.30	0.00004	0.41	0.000	0.25	0.00003				

For trees, RAR values in the first layer (0–10 cm depth) ranged from 0.13% (*Alnus glutinosa* (L.) *Gaertn*) to 0.21% (*Quercus cerris* L.); in the second layer (10–20 cm), these values range from 0.22% (*Castanea sativa* Mill.) to 0.57% (*Pinus nigra* subsp. *laricio* (Poir.) Maire); in the third layer (20–30 cm), the values range from 0.13% (*Castanea sativa* Mill.) to 0.75% (*Pinus nigra* subsp. *laricio* (Poir.) Maire); in the fourth layer (30–40 cm), these range from 0.14% (*Alnus glutinosa* (L.) Gaertn) to 0.68% (*Pinus nigra* subsp. *laricio* (Poir.) Maire); and in the deepest layer (40–50 cm), the values range from 0.02% (*Alnus glutinosa* (L.) Gaertn) to 0.23% (*Pinus nigra* subsp. *laricio* (Poir.) Maire). Shrub species revealed similar trends, although roots did not extend as deep as tree roots. In this context, RAR values in the first layer (0–10 cm depth) ranged from 0.27% (*Cytisus scoparius* L.) to 0.32% (*Ilex aquifolium* L.); in the second layer (10–20 cm), these values varied from 0.41% (*Spartium junceum* L.) to 0.53% (*Cytisus scoparius* L.); and in the deepest layer (20–30 cm), the values ranged from 0.25% (*Spartium junceum* L.) to 0.34% (*Ilex aquifolium* L.). The variability of root density with depth among different species was also quite large; root systems of trees were concentrated in the 20–30 cm layer, while shrub roots were concentrated in the 10–20 cm layer.

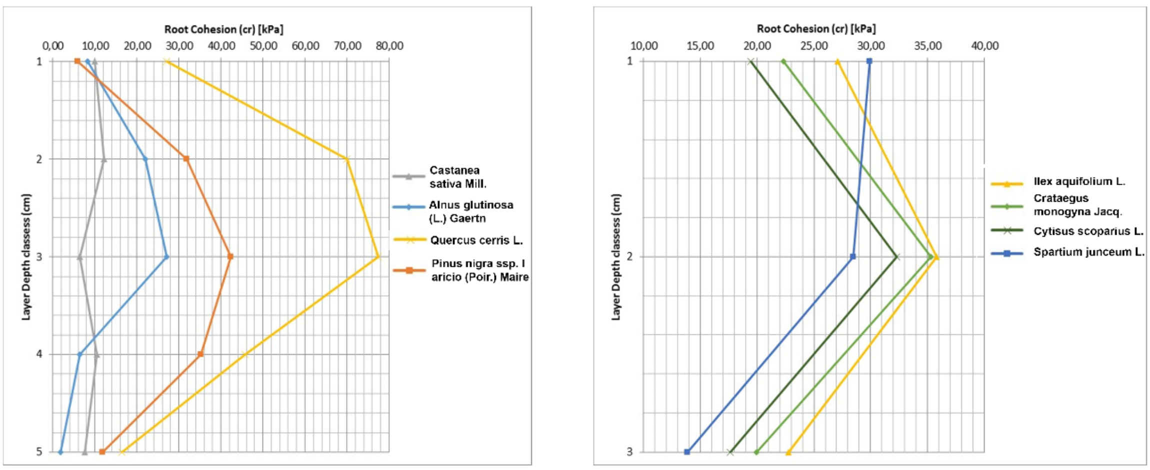
For tree species, results of the ANCOVA showed that RAR is significantly different among species $F_{(4,35)} = 4.26$, *p*-value < 0.0065 (depth as covariate). The post hoc LSD test showed that *Pinus nigra* subsp. *laricio* (Poir.) Maire and *Quercus cerris* L. had significantly higher RAR values than the other tree species. This result is confirmed by the ANOVA test, in fact, the main effect of species was significant, $F_{(3,20)} = 17.31$, *p* value < 0.0001, as was the main effect of layer depth classes, $F_{(4,20)} = 14.06$, *p*-value < 0.0001. Furthermore, the interaction of these two factors was significant, $F_{(12,20)} = 2.59$, *p*-value = 0.029. The post hoc LSD test showed that the RAR values in the 10–20 cm, 20–30 cm, and 30–40 cm depth classes were significantly different with respect to the other classes (0–10 cm and 40–50 cm). For shrubs, results of the ANCOVA confirmed that the RAR is not significantly different among species $F(_{4,19}) = 0.075$, *p*-value = 0.99 (depth as covariate). This result is confirmed by the ANOVA test, in which the main effect of species was not significant, $F(_{3,12}) = 0.09$, *p* value = 0.96, nor was the main effect of layer depth classes, $F(_{2,12}) = 3.08$, *p*-value = 0.08. The interaction of these two factors was also not significant, $F(_{6,12}) = 0.11$, *p*-value = 0.99. The ANCOVA for tree and shrub categories in the first three depth classes showed that the RAR is not significantly different among categories ($F_{(2,45)} = 2.34$, *p*-value = 0.10).

3.3. Root Cohesion

Equation (5) for estimating soil reinforcement by roots was applied and the results were highly variable for both species and depth. Values of c_r ranged from 1.90 kPa for *Alnus glutinosa* (L.) Gaertn to 77.53 kPa for *Quercus cerris* L., while for shrubs, the highest c_r was for *Ilex aquifolium* L. (35.80 kPa) and the lowest for *Spartium junceum* L. (13.86 kPa) (Table 7 and Figure 6). Root cohesion in the 10–20 cm depth was highest in all species. For trees, the second and third depth layer had elevated c_r values. Below this depth, c_r declined similarly to other studies [9,30,41,43,52,53]

Table 7. Mean and standard deviation values of root cohesion for each species.

Species	Root Cohesion (c_r) (kPa)									
	0.0–10.0 cm		10.0–20.0 cm		20.0–30.0 cm		30.0–40.0 cm		40.0–50.0 cm	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Castanea sativa Mill.	9.92	0.12	12.09	3.90	6.33	4.86	10.49	4.42	7.51	6.26
Alnus glutinosa (L.) Gaertn	8.30	1.84	22.03	0.34	27.05	0.87	6.34	4.46	1.90	0.08
Quercus cerris L.	27.14	7.28	70.06	41.24	77.53	12.98	45.83	13.32	16.38	2.79
Pinus nigra subsp. *laricio* (Poir.) Maire	5.97	0.20	31.81	20.50	42.36	5.57	35.15	3.71	11.85	9.15
Ilex aquifolium L.	27.10	19.74	35.80	3.88	22.77	3.77				
Crataegus monogyna Jacq.	22.32	0.45	35.32	4.15	19.95	19.16				
Cytisus scoparius L.	19.48	9.21	32.27	16.85	17.62	6.58				
Spartium junceum L.	29.92	2.99	28.48	7.04	13.86	6.54				



(a) (b)

Figure 6. Root cohesion distributions of the tree (**a**) and shrubs species (**b**).

4. Discussion

The analysis of the root systems of important montane Mediterranean tree and shrub species indicates significant differences in their strength characteristics. A total of 346 undamaged roots with diameters smaller than 1 cm and a constant root length of 20 cm were tested for tensile strength. In general, the root tensile strength (T_r) decreased with increasing root diameter (D). The generally accepted form of the relationship between T_r and D is a simple power function [7,9]. Many studies have confirmed the validity of this relationship [41,45], while the influence of root diameter on tensile properties has been studied from the perspective of chemical components [23]. ANCOVA tests showed that species are the most important factor determining root tensile strength, as also shown by previous studies [41]. Furthermore, root diameter acts together with species characteristics to affect root tensile strength. Differences in tensile strengths between trees and shrubs were not statistically significant. Tensile strength values of *Quercus cerris* L. roots were the highest among the species tested; *Alnus glutinosa* (L.) Gaertn and *Pinus nigra* subsp. *laricio* (Poir.) Maire had the lowest tensile strength values, while other species showed an intermediate behavior. The tensile strength values of *Pinus nigra* subsp. *laricio* (Poir.) Maire are comparable with the other Pinus species [24,54]. Generally, roots of deciduous trees have higher tensile strengths than conifers [54] and this is confirmed in our study, except for *Alnus glutinosa* (L.) Gaertn, which could be explained by its wood density being similar to the density of pine trees. The values of tensile strength obtained in all the hardwoods and shrubs fall within ranges reported by other studies [24,27,41,55], especially with regard to *Quercus cerris* L. [26]. However, in many studies, most of the species showed large variability in tensile strength [56]. This variability can arise from different conditions in the growing environment [26], including soil moisture content and physical characteristics, and other factors, such as the methods used for preserving roots prior to measurements, the time elapsed before testing, and differences in machines used to conduct tensile strength tests [41].

The comparison between tensile strength measured in fresh roots (FWC), as collected in the field, and water-saturated roots (MWC) requires more discussion. Apparently, by choosing the wettest conditions, the test should represent the minimum strength value of a particular root and, more likely, the strength of the root in conditions of root failure during landslide initiation caused by soil water saturation [54]. The role of moisture content in roots is controversial because an increase in moisture has been shown to induce a decrease in mechanical strength [54,57]. Yang et al. [54] showed that the quadratic equation was the most applicable model for explaining the relationship between root moisture content and tensile strength. A comparable result was obtained by [58], who also took into account decreasing root diameter due to water content loss [58,59] and, consequently, root strength. However, in our study, the variation of water content in the roots, from ambient soil moisture conditions to maximum water content, did not significantly affect tensile strength performance. This can be related to the fact that moisture content values were generally higher than the wood fiber saturation point (about 30%), above which the physical–mechanical properties usually did not change significantly [56]. In any case, in relation to the high variability of soil moisture content, soil properties, climate conditions, root structure (especially diameter [54]), species (hardwood or conifers), and tree physiological status [57] (vegetative season or dormant period), fresh root water content needs to be further investigated, as it would be preferable to make experiments on the real fiber saturation point at different conditions.

Our findings confirm the trend of decreasing RAR with soil depth that has been associated with reduced availability of nutrients, decrease in soil aeration, and the presence of more compact layers [60]. RAR patterns were investigated separately for trees and shrubs and assessed to depths of 0.50 m and 0.30 m, respectively. Our method only considered roots typically smaller than those of second- and third-order roots. Furthermore, the effects of different root system structures for various species were not considered. For example, we found that *Pinus nigra* subsp. *laricio* (Poir.) Maire, *Quercus cerris* L., and *Alnus glutinosa* (L.) Gaertn have a similar RAR distribution trend with very deep taproots and well-developed radical structures, whereas *Castanea sativa* Mill. had the highest

RAR value in the second and fourth depth class layer and roots expanded more laterally than in depth [61]. For woody shrubs, RAR values were very similar for all four species, while the largest number of roots were present in the 10 to 20 cm soil depth interval. Significantly, because of our mountainous site, more lateral roots were located below the upper 10 cm soil depth; plants growing on relatively flat sites typically have more abundant lateral roots in the upper 10 cm of soil compared to hillslopes [62]. RAR trends for shrub and tree profiles in our study can be compared with previous results [63]. Lombardi et al. [62] found that the number of fine roots of *Spartium junceum* L. was highest in the upper 10 cm and decreased with soil depth. In our study, RAR values were generally higher compared to the values obtained in other Mediterranean and alpine sites [27,41], except for values of chestnut, which are comparable with the results obtained by Bischetti et al. [41].

The model reported by Wu et al. [10] was used to calculate root cohesion. The choice of the coefficients k' and k'', as reported in Equations (5) and (6), play a crucial role in estimating root cohesion. Many authors have demonstrated that k'' can assume values much smaller than 1.0, dramatically affecting the value of root reinforcement [45,48]. Hammond et al. [49] proposed a k'' factor of 0.56 for forest vegetation. Moreover, the value of root cohesion varies as a function of the RAR distribution patterns, although some discrepancies can be associated with the dependency on root tensile strength and root diameter distribution. Usually, estimated root cohesion values are significantly higher in the upper soil layers (10–40 cm) and decline with soil depth. Furthermore, our results show that the investigated plant species have comparable reinforcement to previously studied tree and shrub species [22,60]. Maximum root cohesion occurred from 10 to 20 cm depth in all species examined in our study. The type of vegetation affects the value of root cohesion as well as the land use. Schmidt et al. [30] noted lower root cohesion values in intensively managed clear-cut forests compared to natural forests. The root cohesion values obtained in the Bonis basin were very similar to those found by Schmidt et al. [30] for unharvested natural forests and those reported by Greenway [22] (average root cohesion up to 40 kPa for trees).

5. Conclusions

Our findings contribute to knowledge about the root tensile strength, RAR, and the cohesion model of some typical trees and wood shrubs in the Mediterranean region. The results could significantly increase knowledge to improve natural hazard prevention and mitigation in Mediterranean forest environments. The results related to tensile strength, RAR, and cohesion are not all comparable with values obtained in previous studies, indicating the significant role of site features, such as soil type and management history of forest stands. While *Quercus cerris* L. maintained the strongest role in soil reinforcement, pioneer shrub species like *Spartium junceum* L., with root tensile strengths comparable or even higher than some tree species, have important stabilizing roles. Shrubs can increase soil shear strength considerably without having the more complex effects attributed to wind stress or static surcharge of the trees. Furthermore, retaining woody shrubs with high root strength via forest cable logging operations could benefit soil stability, compared to harvesting operations that damage the understory layer [64]. Increases in soil shear strength are mostly attributed to roots ($1 < D < 10$ mm) that often exert their maximum tensile strength during soil displacement [43]. Our results confirmed the very important role of small roots, which increase soil shear strength by anchoring the soil mantle and by forming a binding network within the soil profile. The role played by *Pinus nigra* subsp. *laricio* (Poir.) Maire, which has been used extensively in reforestation throughout Europe and in other continents, was quite important. Although the tensile strength of *Pinus nigra* subsp. *laricio* (Poir.) Maire is modest, root cohesion is quite high, as displayed by maximum values of RAR. Thus, *Pinus nigra* subsp. *laricio* (Poir.) Maire can significantly contribute to soil slope stabilization and, providing that appropriate forest management practices are used, could also allow for recolonization by other late-successional trees and woody shrubs, further stabilizing the soil, considering that diverse tree root types greatly contribute to slope stability [65]. Knowledge of the behavior of root systems can be helpful for designing and using bioengineering techniques [16,56,66] and can be useful for mapping slope stability in wooded areas, particularly in Mediterranean environments. Moreover, the results of our experimental data can be used in slope stability models, opening up new research scenarios, especially by including root cohesion in models of mountain stability [6,67]. Root properties such as tensile strength and root morphology are important biomechanical traits that could be efficiently utilized in nature-based solutions to improve soil stability in the region. In this context, forest management in sustainable ways could play a key role in improving slope stability [68] and enhance the ecosystem services associated with forests [69]. Therefore, managing forests against mass wasting hazards is one of the most important ecosystem services provided in mountain regions [68,70].

Supplementary Materials: The following are available online at http://www.mdpi.com/1999-4907/10/4/341/s1; Figure S1: Tr(D) log-transformed values for the study species.

Author Contributions: Conceptualization, F.V.M., M.M. and G.S.M.; Methodology, F.V.M.; Software, F.V.M., M.M.; Validation, F.V.M., M.M., M.R.; Formal Analysis, F.V.M., M.M.; Investigation, F.V.M., M.M. and M.R.; Resources, G.S.M., G.M.; Data Curation, F.V.M., M.M., G.S.M. and M.R.; Writing—Original Draft Preparation, F.V.M., M.M., M.R., G.M., G.S.M. and R.C.S.; Writing—Review & Editing, G.S.M. and R.C.S.; Visualization, F.V.M., M.M. and G.S.M.; Supervision, G.S.M.; Project Administration, G.S.M.; Funding Acquisition, G.M. and G.S.M.

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