Original Paper *Journal of Forest Science, 67, 2021 (7): 338–356*

https://doi.org/10.17221/4/2021-JFS

Exploring the variability in elastic properties of roots in Alpine tree species

Alessio Cislaghi[1,2]*

[1]*Department of Agricultural and Environmental Sciences (DiSAA), University of Milan, Milan, Italy*
[2]*Centre of Applied Studies for the Sustainable Management and Protection of Mountain Areas (Ge.S.Di.Mont), University of Milan, Brescia, Italy*

**Corresponding author: alessio.cislaghi@unimi.it*

Citation: Cislaghi A. (2021): Exploring the variability in elastic properties of roots in Alpine tree species. J. For. Sci., 67: 338–356

Abstract: Quantifying the soil reinforcement provided by roots is essential for assessing the contribution of forests to reducing shallow landslide susceptibility. Many soil-root models were developed in the literature: from standard single root model to fibre bundle model. The input parameters of all models are the geometry of roots (diameter and length) and the biomechanical properties (maximum tensile force and elastic modulus). This study aims to investigate the elastic properties estimated by the stress-strain curves measured during tensile tests. A standard procedure detected two different moduli of elasticity: one due to the root tortuosity, and the other due to the woody fibres of roots. Based on a large dataset of tensile tests on different Alpine tree species, the relationships between elastic modulus and root diameter was estimated for each series. Further, the interspecific and intraspecific variability in such relationships was investigated by a statistical analysis. The results showed more intraspecific differences in the elastic modulus vs. root diameter relationships compared to the interspecific ones. This outcome could be an important criterion of discrimination to explain the variability of the elastic properties and to provide representative biomechanical properties for specific environmental conditions.

Keywords: root reinforcement; elastic modulus; biomechanical properties; protection of forests

Forests play a fundamental role in mitigating the shallow landslide susceptibility through mechanical and hydrological mechanisms (Vergani et al. 2017). Forests represent an essential element in risk reduction in mountainous areas (Cislaghi, Bischetti 2019). The most conspicuous contribution provided by forests to stabilizing soil layers is related to the presence of root systems (O'Loughlin 1974a; Burroughs, Thomas 1977). Roots control the water movement into shallower soil layers by forming macropores and by decreasing the soil moisture content (Vergani, Graf 2016). Meanwhile, the root system affects the soil structure by increasing soil aggregation (Burri et al. 2009) and reducing soil erosion (Löbmann et al. 2020). In addition to these processes, roots improve the reinforcement of the shallower soil layer in different ways:

– roots anchor the soil mantle to deeper and more stable layers or bedrock (Gray, Sotir 1996);

– roots tie across planes of weakness and potential slip surface (Gray, Ohashi 1983);

– roots form a binding network within the shallower soil layer minimizing the tension cracks (Schmidt et al. 2001);

– roots increase the tensile strength where crossing the marginal surfaces of an unstable soil mass (Schwarz et al. 2010);

– roots increase the compressive strength of the soil at the toe of a sliding soil mass (Schwarz et al. 2015; Cislaghi et al. 2019a).

This research was an integral part of the project TREE:HERO, acronym of "TREE distribution patterns: HillslopE failuRe prevention through forest management", entirely funded by Fondazione Cariplo (Italy; Ref. 2017-0714) in the framework of "Research dedicated to hydrogeological instability: a contribution to the prevision, prevention and risk mitigation".

These mechanical effects have been widely investigated and discussed during the last four decades since the end of the 1960s until now (e.g., Endo, Tsuruta 1969; Waldron 1977; Abe, Ziemer 1991; Naghdi et al. 2013; Abdi, Deljouei 2019; Pourmalekshah et al. 2019) and have been defined as root reinforcement. Yet following the pioneering works, the root reinforcement (c_r) is considered as an additional cohesion term (in Pa) and is included in the Mohr-Coulomb failure criteria (O'Loughlin 1974b). Despite the scientific efforts, quantifying remains a challenge because of the limited knowledge of the root systems in the soil (Waisel et al. 1991). The prevailing approaches to estimate are the standard single root method (Waldron 1977; Waldron, Dakessian 1981) and the fibre bundle model (Pollen, Simon 2005; Cohen et al. 2009; Schwarz et al. 2010). Whichever model is considered, c_r is a function of root distribution and biomechanical properties of roots (mainly tensile resistance and elastic modulus) (Dias et al. 2017). Root distribution can vary according to the position inside a forest stand, the soil depth and the local growth condition (Mattia et al. 2005; Stokes et al. 2007; Ji et al. 2012; Mao et al. 2013; Giadrossich et al. 2020). Concerning the material properties of tree roots, many authors focused on quantifying the root tensile strength and on investigating how tree characteristics, soil properties and topographic attributes can influence it (Hathaway, Penny 1975; Schmidt et al. 2001; Genet et al. 2008; Sun et al. 2008; Hales et al. 2009). In particular, the root tensile strength significantly differs among different tree species (Bischetti et al. 2009; Burylo et al. 2011; Abdi, Deljouei 2019) or even whithin the same tree species (Vergani et al. 2012). On the contrary, few works estimated the elastic properties of roots since the calculation is more complex, subjective and time consuming (Commandeur, Pyles 1991; Operstein, Frydman 2000; Fan, Su 2008). Moreover, even fewer studies explored their variability in relation to tree species or environmental factors (Fan, Su 2008; Thomas, Pollen-Bankhead 2010; Sanchez-Castillo et al. 2017; Meijer et al. 2018a; Zavala-González et al. 2019). Nonetheless, the few available data of root elastic properties show a huge variability in magnitude without clear evidences not explained by a specific external factor, either within the same tree species or within the same forest stand. For these reasons, many authors ignored this parameter preferring simple root reinforcement models that request a parsimonious number of input parameters (i.e., tensile strength properties and cumulative root distribution) (Abdi 2014; Zhou, Qi 2019; Ettbeb et al. 2020). However, in this way, some aspects of root mechanics, such as root elongation and progressive mobilization of tensile resistance, remain neglected (Schwarz et al. 2013).

In this context, the objectives of the present study are:

– to apply a standard approach for calculating the elastic properties of a root;

– to detect the tensile behaviour by analysing the shape of the stress-strain curve;

– to fit the elastic moduli vs. root diameter relationships for different tree species of the European Alps;

– to statistically analyse the variability of such mechanical properties looking for intraspecific and interspecific differences.

Finally, this study provides a new large dataset and discusses useful criteria to explain and generalize differences and similarities in the elastic modulus vs. root diameter relationship, an essential parameter in root reinforcement modelling.

MATERIAL AND METHODS

Study sites. Thirty-six study sites are located in different spots of the European Southern Alps (North Italy, Figure 1). A huge variability of ecological and climatic features distinguishes each site, when they belong to fluvial, hill and mountainous areas (Table S1 in Electronic Supplementary Material (ESM)). The average altitude ranges between 67 and 1 701 m a.s.l. whereas the slope gradient varies from 0° to 52°. The local stand forest characteristics are analysed in different features such as tree species, tree density, tree age, and average tree diameter (from 0.06 m to 0.55 m). The study focused on 16 tree species, widely spread in Northern Italy (Table 1). High forest management is the predominant silvicultural system for conifers, whereas the coppice system is used for broadleaves. According to the geological map of Northern Italy, soils and texture classes are extremely variable due to the large size of selected study area. Table 1 in ESM includes the soil types according to the WRB soil classification (FAO 2014) and the texture composition according to the USDA soil classification (Schoeneberger 2002).

Collection and tensile tests. A minimum of 50 roots not less than 150 mm in length were collected by carefully digging trenches without damaging

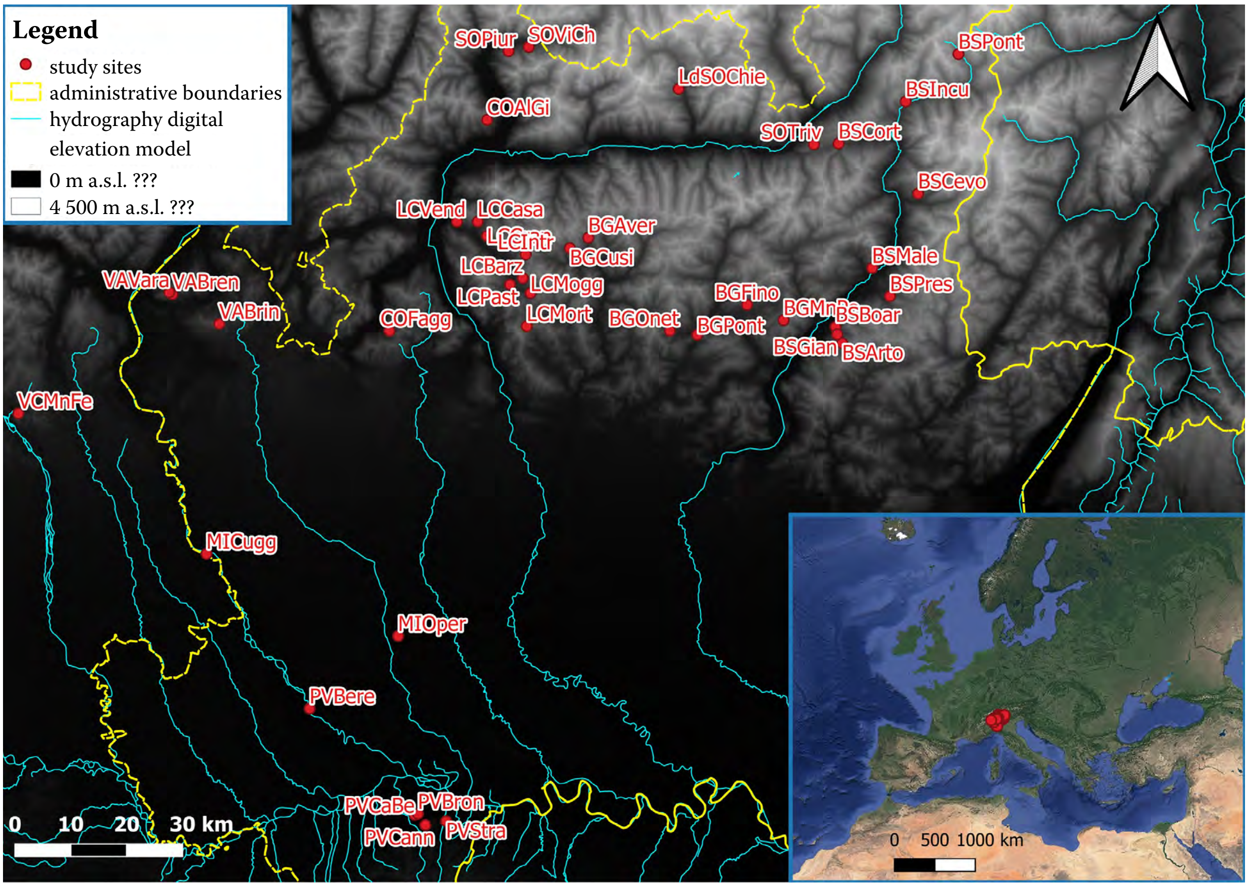

Figure 1. Samples of roots were collected in 36 study sites located in North Italy; the study sites are abbreviated in the map with a code composed by 6 letters (2 letters abbreviate the administrative province and 4 abbreviate the municipalities)

the tree root system as little as possible (Böhm 1979). Because of extreme difficulty to identify the Alpine tree species (Cutler et al. 1987; Rewald et al. 2012; Giupponi et al. 2018), all trenches were generally dug at a distance of around 1–1.5 m from the nearest stem belonging to a specific tree species and at a soil depth of 0.30 m at least. To maintain the biomechanical properties and to prevent the cellulose deterioration after root collection, the storage and handling of roots are fundamental (Bischetti et al. 2005; Hales et al. 2013). The common preservation method consists in conserving the collected roots in plastic containers with a 15% alcohol solution for a maximum period of two weeks from the sampling date (Meyer, Gottsche 1971). The quantification of the biomechanical properties of roots was conducted analysing the stress-strain curve performed by laboratory tensile tests, usually carried out within 1 week from sampling. The tensile tests were conducted using a device consisting of a strain apparatus controlled by an electrical motor (Bischetti et al. 2005; Deljouei et al. 2020) (Figure 2). Two clamps hold in position the tested root and a series of gears exerts the tensile force at a rate of 10 mm·min^{-1}. To monitor the tensile force, a load cell with a limit of 500 N and an accuracy of 0.1% was used. The acquisition system connected to the tensile test device records both tensile force (in N) and cumulative displacement (in mm). The diameter of tested roots ranged from 0.2 mm to 8 mm and the span is around 60 mm. Roots larger than 8 mm in diameter could cause measurement errors because of the device limits (De Baets et al. 2008; Giadrossich et al. 2017). Otherwise, thin roots less than 0.5 mm in diameter were more fragile and generally difficult to manipulate carrying out a tensile test (Vergani et al. 2012).

Background on the modulus of elasticity. The elastic modulus or modulus of elasticity or Young's modulus (E) is the slope of stress-strain curve in the near-linear portion called elastic region. E is expressed as the relationship between stress (in MPa) and strain (dimensionless) well known

https://doi.org/10.17221/4/2021-JFS

Table 1. Abbreviations and scientific names of the tree species selected for the present study

Tree species	Abbreviation	Scientific name
European silver fir	Aa	*Abies alba* Mill.
Norway maple	Ar	*Acer platanoides* L.
Sycamore maple	Ap	*Acer pseudoplatanus* L.
Grey alder	Ai	*Alnus incana* L.
Sweet chestnut	Cs	*Castanae sativa* Mill.
Common hazel	Ca	*Coryllus avellana* L.
European beech	Fs	*Fagus sylvatica* L.
European ash	Fe	*Fraxinus excelsior* L.
Flowering ash	Fo	*Fraxinus ornus* L.
European larch	Ld	*Larix decidua* Mill.
Hop hornbeam	Oc	*Ostrya carpinifolia* Scop.
Norway spruce	Pa	*Picea abies* L.
English oak	Qr	*Quercus robur* L.
Pubescent oak	Qp	*Quercus pubescens* Willd.
Black locust	Rp	*Robinia pseudoacacia* L.
Field elm	Um	*Ulmus minor* Mill.

as Hooke's law (Askeland et al. 2011). The tensile test is a widely adopted method to measure the stress-strain curve of tree roots and to subsequently calculate the value of E (Giadrossich et al. 2017). Such experiments showed that a marked elastic variability characterises the root fibres, especially affected by the root size.

Such uncertainty is exacerbated by the complexity of identifying the non-linear elastic portion of the stress-strain curve. For this reason, Comman-

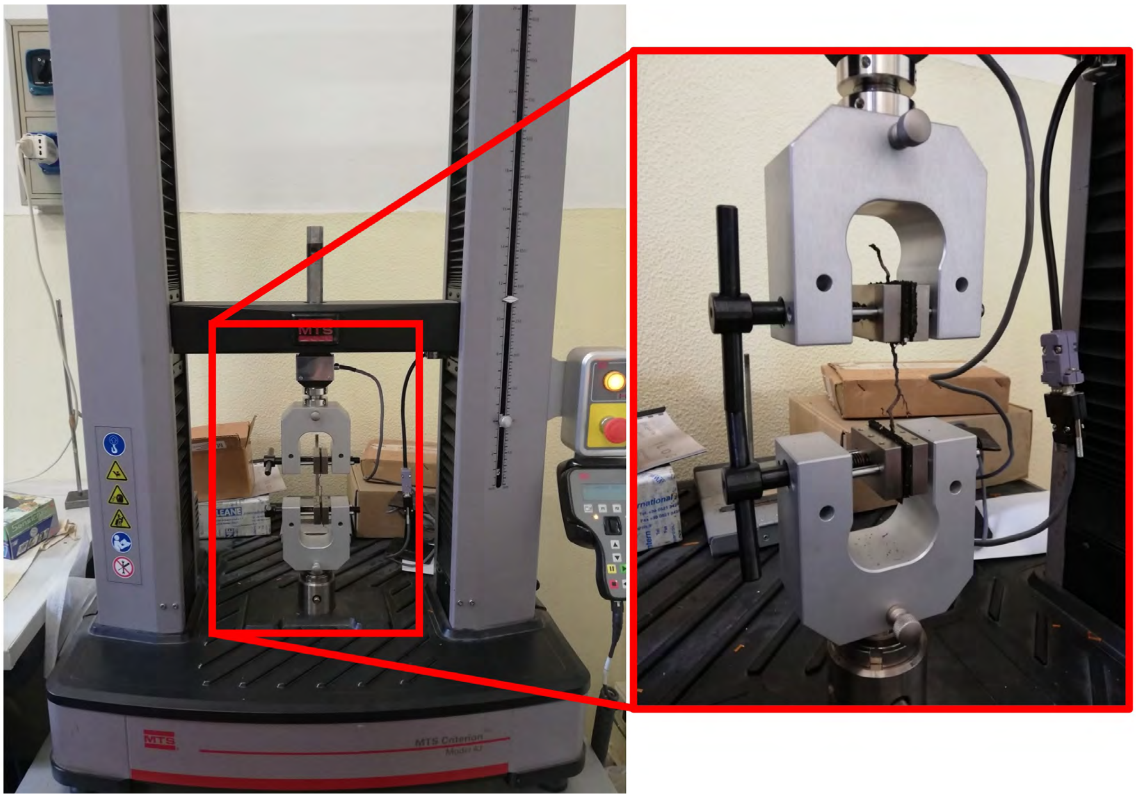

Figure 2. Universal testing machine equipped with clamps for tensile tests

deur and Pyles (1991) investigated the tensile process and showed how the root tortuosity influences the macroscopic elastic behaviour. They detected two different shapes of stress-strain curve: (*i*) the hyperbolic type (Figure 3A) and (*ii*) the sigmoid type (Figure 3B). The hyperbolic type is characterized by a stress-strain curve with the initial straight-line portion before the plastic behaviour and the ultimate rupture (Watson et al. 1997), where the tangent slope of the initial portion is the "material" elastic modulus (E_{mat}). Otherwise, the sigmoid type displays two distinguishable straight-line portions with two different slopes. The first slope is the "form" modulus of elasticity (E_{form}) influenced by root tortuosity and by pre-stretching, whereas the second slope is the E_{mat} comparable to that estimated in the hyperbolic type. Both shapes of stress-strain curve showed a natural elastic-plastic behaviour (Chen et al. 2014).

Evaluating the elastic moduli. To evaluate the elastic moduli (E_{mat} and E_{form}), a standard procedure was proposed and summarized in the following key steps:

– interpolating the stress-strain curve for each measured point with a 9-degree polynomial;

– calculating the first derivative of the polynomial interpolation;

– detecting two inflection points where the third derivative of the polynomial interpolation is 0;

– dividing into three parts the stress-strain curve delimited by the inflection points;

– calculating E_{form} as the maximum relative value of the stress-strain gradient between the origin and the first inflection point, where the second derivative of the polynomial interpolation is 0;

– calculating E_{mat} as the maximum value of the elastic modulus between the two inflection points, where the second derivative of the polynomial interpolation is 0.

If the stress-strain curve belongs to the hyperbolic type, only one of the two inflection points is detected and, consequently, the modulus of elasticity is unique (i.e., E_{mat}).

Statistical analysis. In the present study, a series of statistical analyses was performed. The one-way non-parametric Mann-Whitney-U (MWU) test was used to statistically determine the presence of main effects on the shape of stress-strain curve. A regression analysis was conducted to calculate the relationships between the elastic properties and the root diameter using Fisher's test (FT) and its statistical parameters: test statistic *F*, standard error (SE), *P*-value and coefficient of determination (R^2). Linearization is necessary and could be obtained through a logarithmic transformation of root diameter and elastic moduli (E_{form} and E_{mat}). Furthermore, the analysis of covariance (ANCOVA) was used to explore the variability of the elastic modulus vs. root diameter relationships within the same tree species and within the same study site. To adopt this statistical methodology, it is necessary to verify the ANCOVA's assumptions:

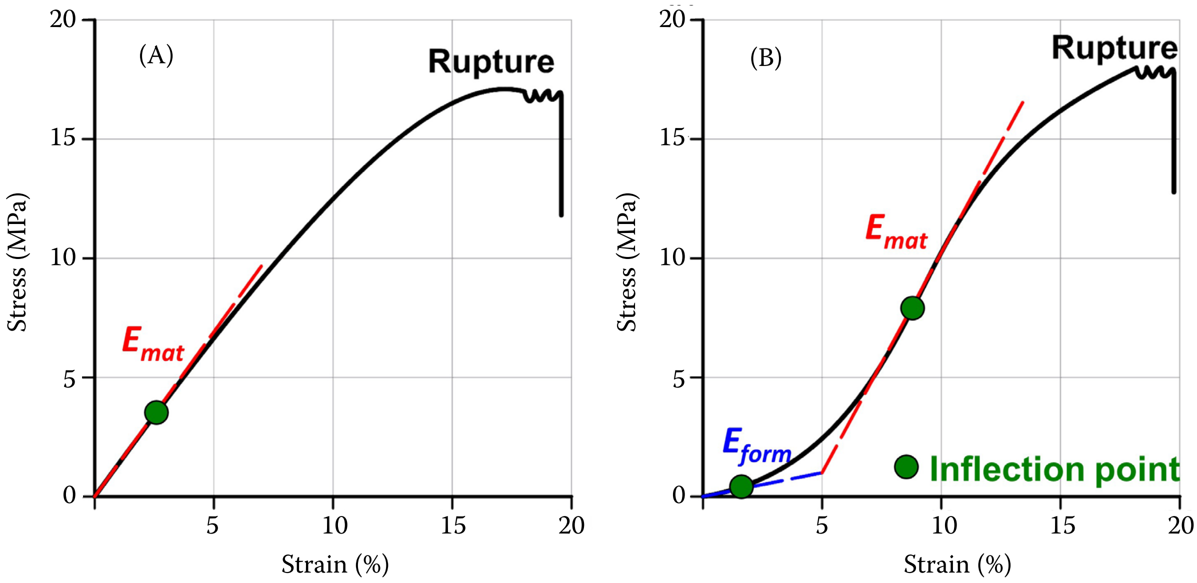

Figure 3. Shapes of stress-strain curve: (A) hyperbolic type and (B) sigmoid type; the dotted lines indicates the tangent slopes to the stress-strain curve (blue line indicates the "form" modulus of elasticity and red line the "material" modulus of elasticity)

https://doi.org/10.17221/4/2021-JFS

(*i*) the residuals of linear regression are normally distributed; (*ii*) the homogeneity of variance of the independent variable; and (*iii*) the covariate factor (in our case, the root diameter) and the factor variable (i.e. tree species, etc.) are independent of each other. To verify these three assumptions, a series of statistical tests was conducted: the Shapiro-Wilk test of normality (SW) (Shapiro, Wilk 1965), Levene's test (LT) (Levene 1960) and the analysis of variance (ANOVA), respectively. ANCOVA's results show differences in the slope and intercept of the regression lines. When the samples to compare are more than two, I also performed a pairwise comparison through the post-hoc analysis using Tukey's honest significant difference test (THSD). The significance level for all tests was set to 0.01. All statistical analyses were performed using R software (https://www.r-project.org).

Exploring the variability of elastic modulus. To investigate the differences in the relationships between root diameter and elastic properties of roots, the dataset was subdivided in function of tree species and geographical area, before performing the statistical analysis. Tree species represents the biological factor that can influence the elastic moduli vs. root diameter relationships, whereas the geographical area includes more external factors such as climate, geomorphology, geology and lithology. Firstly, to explore the intraspecific variability, the dataset, despite containing measurements of tensile tests conducted on roots of 16 tree species, was subdivided into only 10 groups (Aa, Ar, Ap, Cs, Fs, Fe, Ld, Oc, Pa and Rp; see Table 1) because it was collected in at least three different geographical areas. Secondly, the dataset was again subdivided into 7 groups according to the geographical area (Figure 4): (a) Valcuvia; (b) Alpe Gigiai; (c) Valsassina; (d) Valseriana; (e) Upper Valcamonica; (f) Lower Valcamonica; and (g) Lower Oltrepò Pavese. The 7 groups included at least 3 different tree species.

RESULTS AND DISCUSSION

Elastic moduli. The dataset of 56 series composed of 2 989 stress-strain curves showed

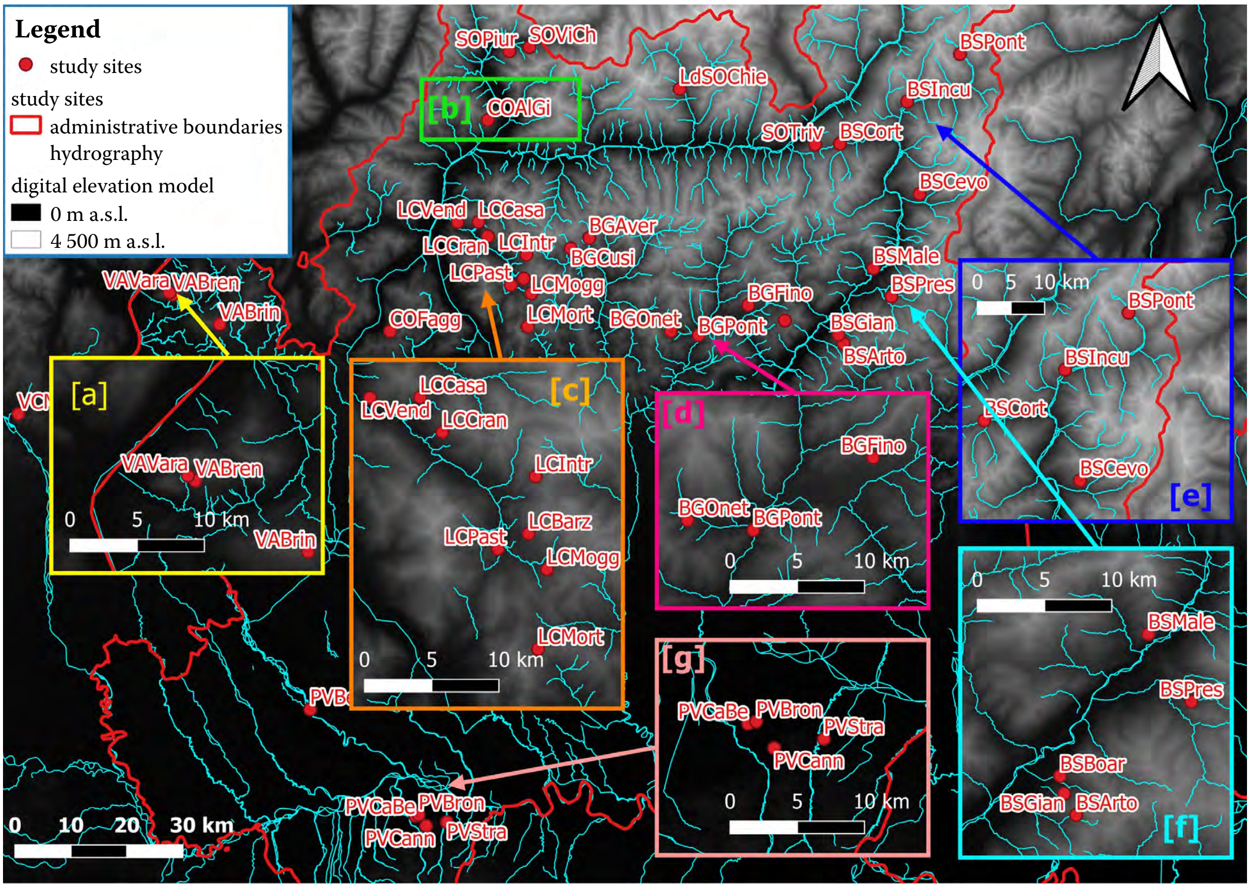

Figure 4. Subdivision of study sites in function of geographical area: (a) Valcuvia, (b) Alpe Gigiai, (c) Valsassina, (d) Valseriana, (e) Upper Valcamonica, (f) Lower Valcamonica, and (g) Oltrepò Pavese

that the most common shape (~75%) describing the stress-strain curve is hyperbolic (Figure 3A). In fact, only 24.59% ± 8.21% of roots displayed a sigmoid behaviour. This percentage varied from 13% for Qp and Qr (Table 1) to 44% for Ca, without clear evidence in function of tree species (Figure 5). Roots with sigmoid behaviour were on average finer than the others (Figure 6; MWU: $P < 0.001$), underlining greater flexibility, elasticity and tortuosity than the larger ones.

Furthermore, E_{form} and E_{mat} were calculated according to the procedure described above. The values of E_{form} ranged between 0.001 MPa (~2 mm) and 30 GPa (~1 mm), showing a high variability for each diameter class (Figure 7). The values of E_{mat} clearly decreased from 10 GPa for fine roots (~1 mm) to 10 MPa for large roots (> 7 mm). On average, E_{mat} was 4.27 ± 2.34 times larger than E_{form}. Moreover, both elastic moduli revealed a relationship with the root diameters described by a power function (E_{mat}, $E_{\text{form}} = E_0 \times \phi^{\beta}$). All E_{mat} vs. root diameter regressions are consistent rejecting the null hypothesis of the FT (i.e., the overall model is insignificant) with P-values always < 0.006. The statistical parameters of such regressions are $R^2 > 0.21$ and SE < 0.94 (Table S2 in Electronic Supplementary Material (ESM)). The regression parameters E_0 and β assumed values ranging from 64.3 to 435.0 MPa and from −1.945 to −0.376, respectively (Figure 8). Conversely, the regressions of E_{form} vs. root diameter are consistent (FT: $P < 0.004$) only in 22 cases in 56 series ($R^2 > 0.34$ and SE < 1.88), whereas the remaining cases revealed a statistical inconsistence.

Variability within tree species. No significant differences were detected for three tree species: Ar, Pa and Rp (Table 1), the three regressions were parallel ($F_{2,77} = 0.351$ and $P = 0.705$) and they were not significantly different ($F_{2,77} = 0.773$ and $P = 0.465$). For Pa, seven series were parallel ($F_{6,304} = 2.088$ and $P = 0.054$) and not statistically different ($F_{6,304} = 1.332$ and $P = 0.242$). For Rp, three series were parallel ($F_{2,105} = 1.534$ and $P = 0.220$) and not significantly different ($F_{2,107} = 0.590$ and $P = 0.556$). On the contrary, differences were found for Aa, Ap, Fe and Oc where the series were parallel ($P > 0.020$), but significantly different ($P < 0.001$). In particular, post-hoc Tukey's test showed that only one series was statistically different for Aa, Oc and Fe, whereas two of three for Ap. For Fs, nine series were not parallel ($F_{8,347} = 8.046$ and $P < 0.001$) and significantly different ($F_{8,347} = 12.875$ and $P < 0.001$). For Cs and Ld, their series were not homogeneous (Levene's test: $P < 0.001$). Thus, it was not possible to compare their series using ANCOVA. However, Figure 9 clearly shows that most of the series seem not to be

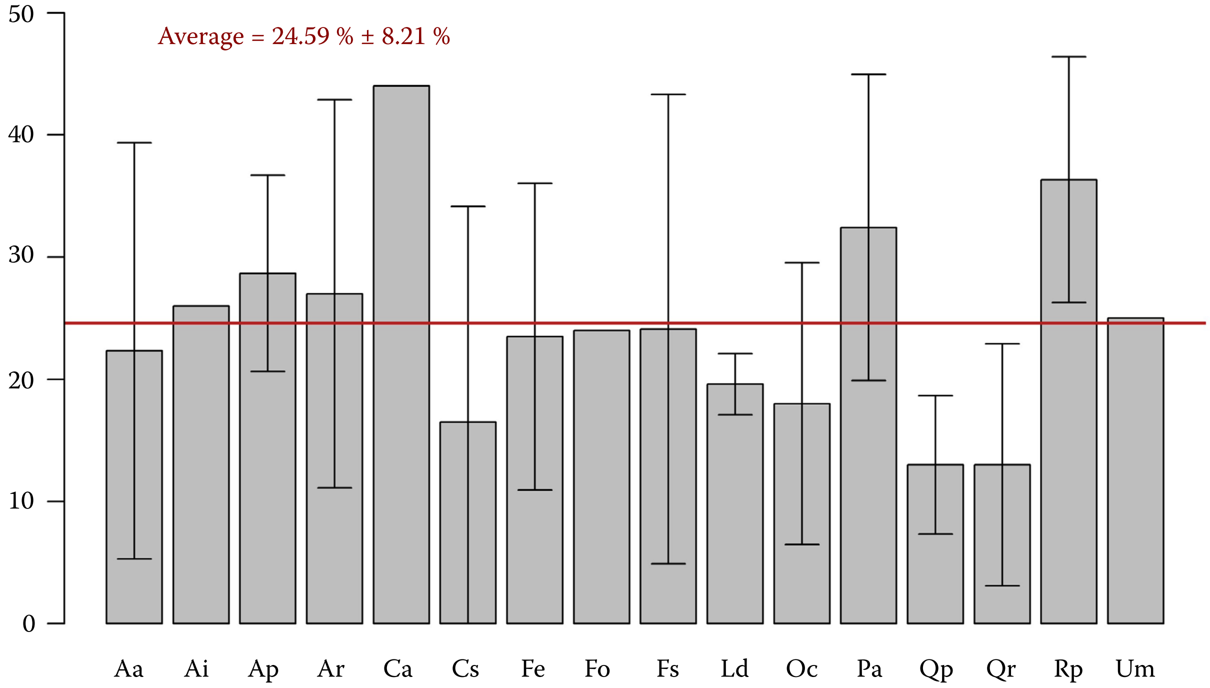

Figure 5. Percentage of sigmoid behaviour in function of tree species (see Table 1)

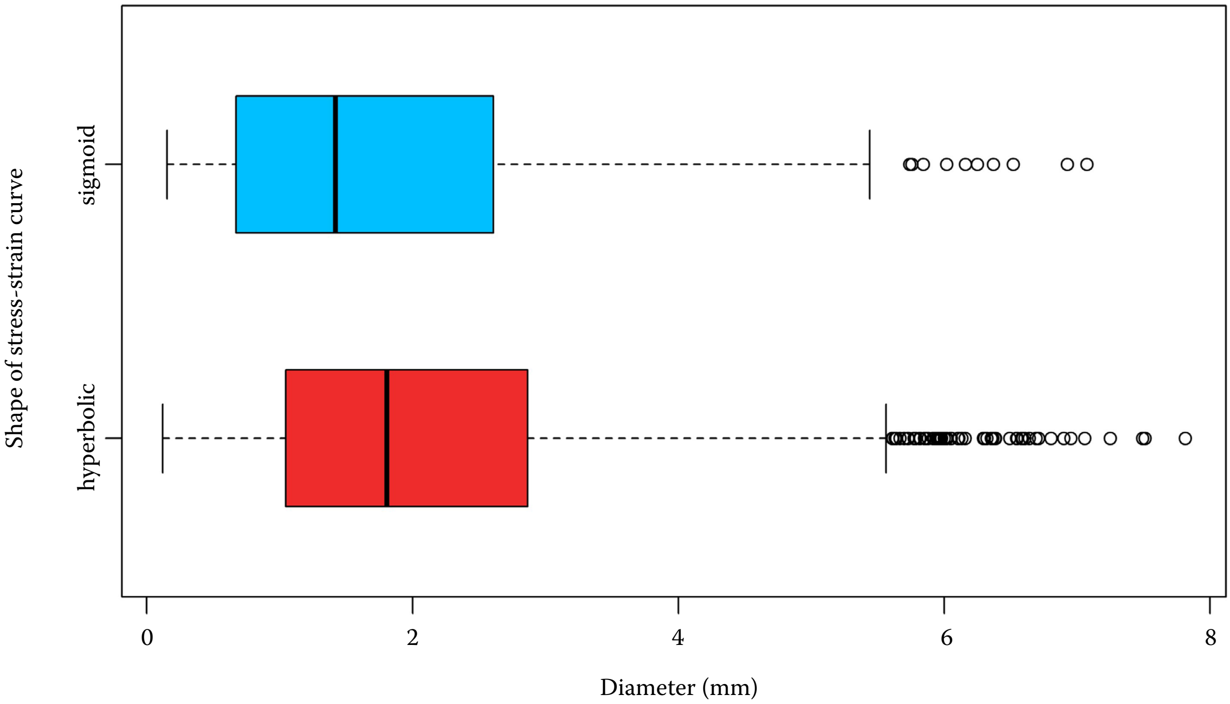

Figure 6. Root diameters in function of the shape of stress-strain curve

parallel and different for either of the tree species. Table 2 summarizes coefficients and statistical parameters of E_{mat} vs. root diameter power regression.

Variability within geographical areas. No significant differences were found for six of the seven geographical areas (Valcuvia, Alpe Gigiai, Valsassina, Valseriana, Lower Valcamonica and Oltrepo' Pavese), except for the Uppen Valcamonica. For Valcuvia, the samples CaVAVara, CsVABren and FeVAVara were parallel ($F_{2,104}$ = 0.017 and P = 0.984) and not significantly different ($F_{2,106}$ = 2.988 and P = 0.055) (Figure 10A). For Alpe Gigiai, there were three available series (FsCOAlGi, LdCOAlGi and PaCOAlGi): parallel ($F_{2,112}$ = 2.133 and P = 0.123) that were not significantly different ($F_{2,114}$ = 4.560 and P = 0.012) (Figure 10B). Although ten series belong to the geographical area of Valsassina, three of them (CsLCCasa, FsLCIntr and FsLCMogg) were removed to satisfy the ANCOVA's assumptions. The remaining series (ApLCIntr, CsLCCran, FeLCPast, FsLCBarz, FsLCMort, OcLCPast, QpLCVend) were parallel ($F_{6,231}$ = 1.013 and P = 0.418) and not significantly different ($F_{6,237}$ = 2.048 and P = 0.060) (Figure 10C). For Valseriana, four series were found, but PaBGFino was excluded to satisfy the ANCOVA's assumptions. The three series (ApBGOnet, FeBGOnet and RpBGPont) were parallel ($F_{2,136}$ = 5.363 and P = 0.006; THSD: P > 0.068) and not significantly different ($F_{2,138}$ = 2.432 and P = 0.092) (Figure 10D). For Upper Valcamonica, five series were detected: however, LT underlined non-homogeneity in variance within two series (LdBSCevo and LdBSPont), thus they were excluded. Nevertheless, the three remaining series (AiBSCort, CsBSCevo and PaBSIncu) were not parallel ($F_{2,165}$ = 18.255 and P < 1e—5) and significantly different ($F_{2,167}$ = 8.940 and P = 0.0002) (Figure 10E). In particular, THSD revealed that CsBSCevo was highly statistically different from the others. For Lower Valcamonica, seven series were parallel ($F_{6,299}$ = 3.723 and P = 0.001; THSD: P > 0.092) and not significantly different ($F_{6,305}$ = 1.779 and P = 0.103) (Figure 10F). For Oltrepò Pavese, the selected series were ArPVCann, ArPVBron, ArPVStra, RpPVCaBe and UmPVBron: they were parallel ($F_{4,139}$ = 0.733 and P = 0.571) and not significantly different ($F_{4,143}$ = 3.550 and P = 0.009; THSD: P > 0.020). All previously described results are shown in Table 3.

Differences within the elastic moduli. The stress-strain curve is a fundamental indicator of the biomechanical properties of roots, and it is the result of tensile tests conducted in the field and in a laboratory. It clearly shows the natural elastic-plastic behaviour of a root under the tension process (Chen et al. 2014). In the present study, the analysis of around 3 000

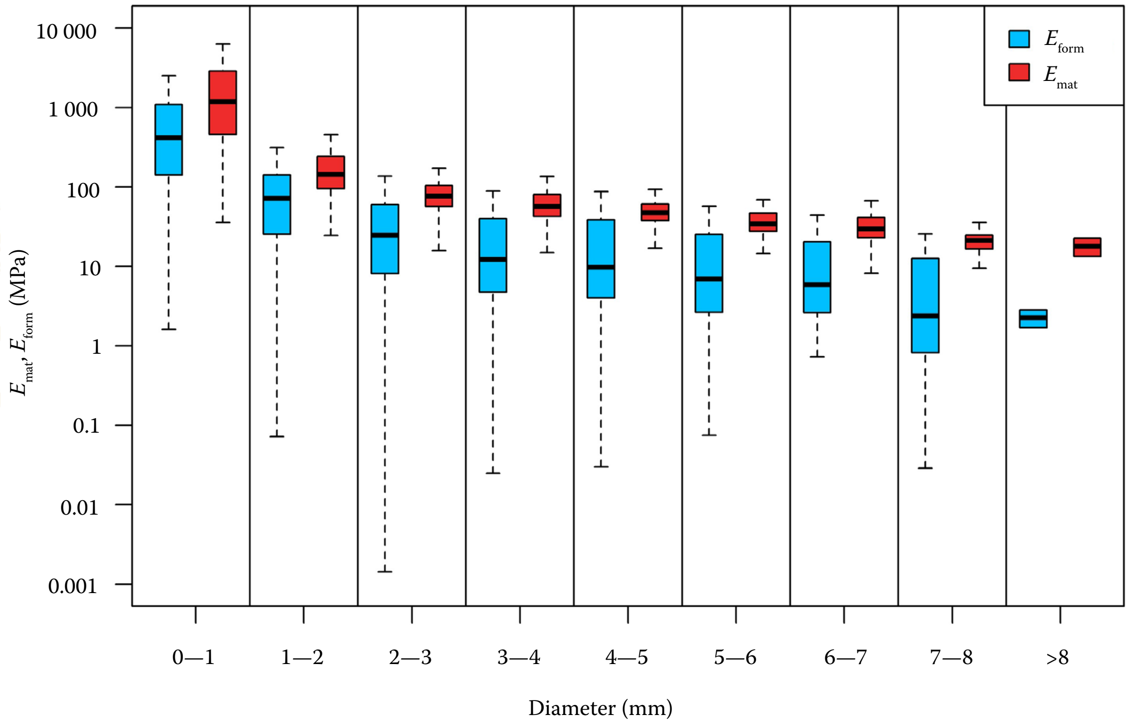

Figure 7. Distribution of the "material" elastic modulus (E_{mat}) and the "form" elastic modulus (E_{form})

stress-strain curves belonging to 56 tensile test series showed the tensile behaviour of a root as described by Commandeur and Pyles (1991) (Figure 3). In detail, two different shapes of stress-strain curve were detected: the hyperbolic and the sigmoid type. The hyperbolic shape is the most common one, while it occurred in 75% of the cases. This shape is characterized by the initial near-linear portion of stress-strain curve, whose slope corresponds to the "material" elastic modulus (E_{mat}). Conversely, the sigmoid type

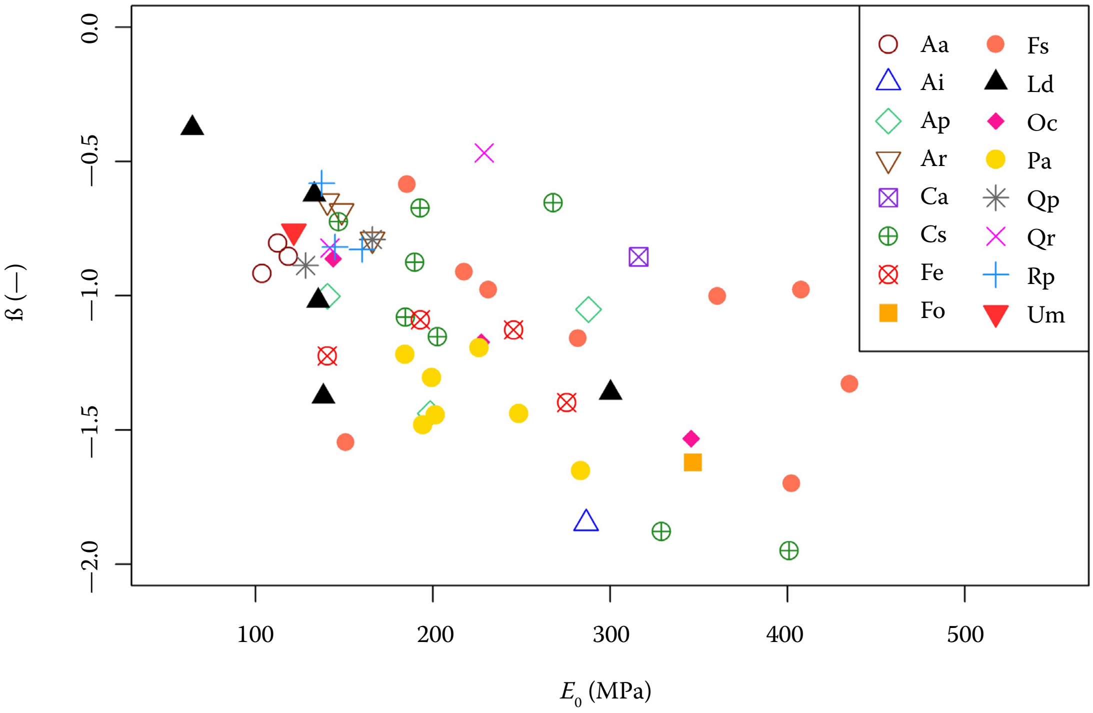

Figure 8. Regression parameters of E_{mat} vs. root diameter relationships in function of tree species (Table 1)

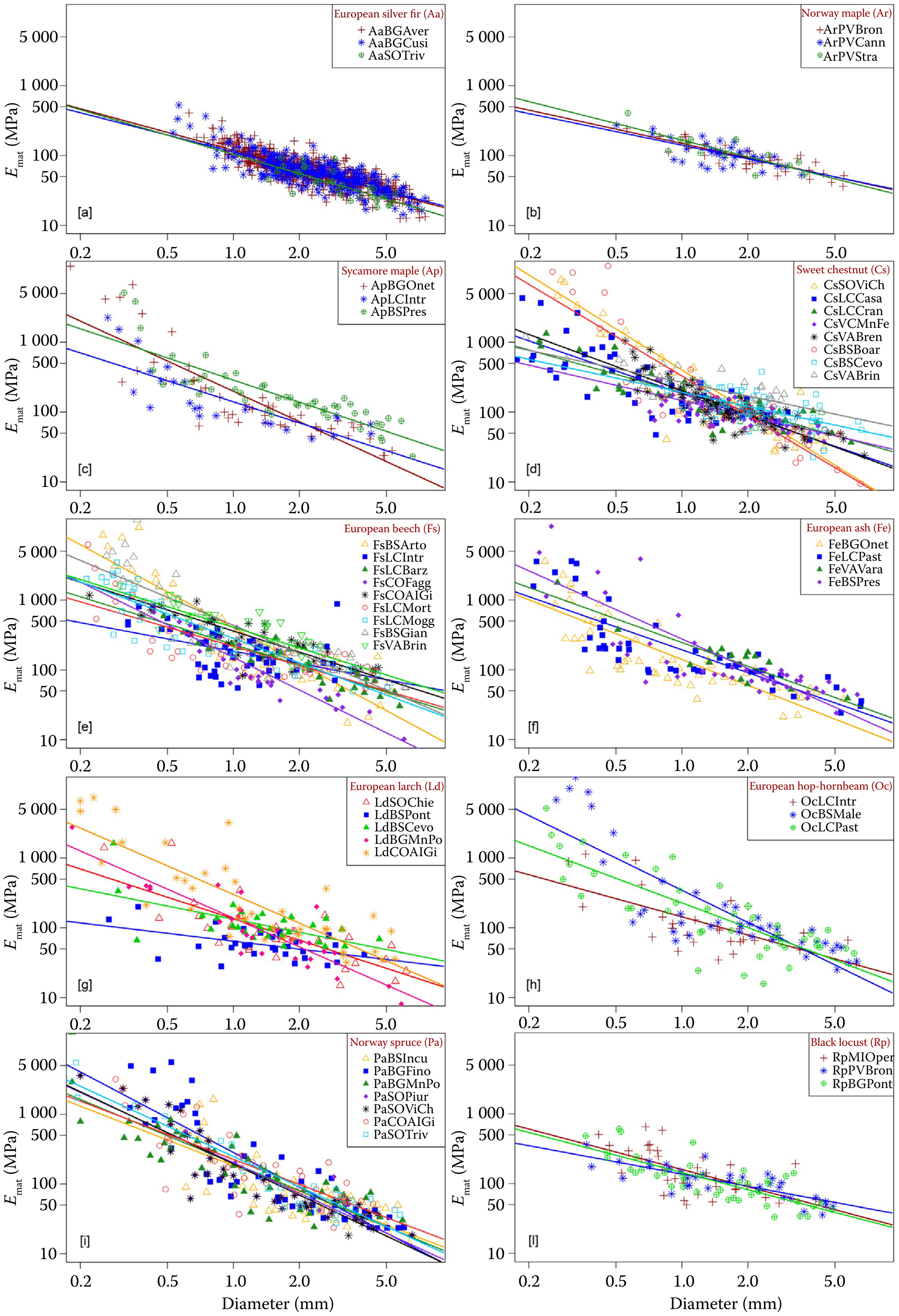

Figure 9. Regression lines of E_{mat} vs. root diameter plotted in log-log chart in function of tree species (Table 1)

Table 2. Coefficients and statistical parameters of power regression E_{mat} vs. root diameter in function of tree species (Table 1)

Species	N	SWp	LTp	ANp	A.slope	A.int	E_0	β	R^2	SE
Aa	3	0.118	0.323	0.044	0.397	0.001	116.224	−0.843	0.681	0.298
Ar	3	0.045	0.433	0.035	0.705	0.465	148.226	−0.692	0.653	0.273
Ap	3	0.015	0.326	0.026	0.022	< 0.001	211.165	−1.113	0.637	0.738
Cs	8	0.079	< 0.001*	–	–	–	231.963	−1.212	0.641	0.692
Fs	9	0.024	0.024	0.066	< 0.001	< 0.001	279.362	−1.181	0.647	0.737
Fe	4	0.134	0.527	0.043	0.323	0.001	191.878	−1.161	0.657	0.791
Ld	5	0.019	< 0.001*	–	–	–	154.009	−1.150	0.562	0.808
Oc	3	0.244	0.164	0.731	0.020	0.008	233.827	−1.241	0.615	0.869
Pa	7	0.137	0.181	0.045	0.054	0.242	214.586	−1.388	0.776	0.660
Rp	3	0.011	0.057	0.117	0.220	0.556	148.536	−0.744	0.547	0.470

N – the number of series; SWp – P-value of Shapiro Wilk test; LTp – P-value of Levene's test; ANp – P-value of the ANOVA; A.slope – P-value of ANCOVA testing the non-parallelism; A.int – P-value of ANCOVA testing the intercept; E_0 and β – coefficients of power law; R^2 – coefficient of determination; SE – the standard error; *non-homogeneity of variance within the series

(around 25% of the cases) revealed two evident near-linear gradients along the stress-strain curve (E_{form} and E_{mat}): the one is due to the root tortuosity, whereas the other is completely due to the materials composing the root. The calculation of the elastic moduli performed according to the proposed methodology (in the section "Evaluating the elastic moduli") showed that E_{mat} is 4.27 ± 2.34 times higher than E_{form}. Moreover, E_{form} displays a wider variability in magnitude than E_{mat} (Figure 7). The lower percentage of the sigmoid shape, higher uncertainties related to the natural root tortuosity and to the phase of prestressing that especially affect the finer roots, and the lower magnitude of the E_{form} suggest to consider only E_{mat} as the more representative elastic modulus of a root.

Elastic modulus vs. root diameter. In root reinforcement modelling, the elastic modulus vs. root diameter relationship is one of the most important input parameters both in the standard single root and in the fibre bundle methods (Waldron 1977; Cislaghi et al. 2017). The elastic modulus vs. root diameter relationship can be expressed through a power law regression as reported in the scientific literature (e.g., Operstein, Frydman 2000; Fan, Su 2008). The power fitting was a common non-linear regression used to correlate biomechanical properties or chemical composition (i.e. cellulose content, alpha-cellulose, and lignin) with the root size (i.e., root diameter) (Genet et al. 2005; De Baets et al. 2008; Zhang et al. 2014; Abdi, Deljouei 2019; Zavala-González et al. 2019). Comparing the results obtained in terms of E_{form} and E_{mat}, all E_{mat} vs. root diameter relationships showed a statistical significance (FT: $P < 0.006$) with $R^2 > 0.30$ in 53 out of 56 cases. This threshold (i.e., $R^2 > 0.30$) is often used in the literature when the number of observations is < 30 (Finér et al. 2011). Conversely, the E_{form} vs. root diameter relationships revealed a statistical significance only in 22 out of 56 cases (FT: $P < 0.004$ and $R^2 > 0.30$) based on small samples (4–12 values). These findings suggest focusing only on the values of E_{mat} and on the E_{mat} vs. root diameter relationships in the statistical analysis.

Considering all measured values of E_{mat}, the range varied from 10–40 MPa for larger roots (≈ 7–8 mm) to 10 GPa for thin roots (< 0.5 mm) (Figure 10). Similarities were found comparing the average values of elastic modulus with those obtained by Chen et al. (2014) for the Chinese red pine (*Pinus tabuliformis* Carr.) and Dahurian larch (*Larix gmelinii* Rupr.), whereas an underestimation emerged compared to the other two examined species, Japanese white birch (*Betula platyphylla* Sukaczev) and Mongolian oak (*Quercus mongolica* Fisch.).

The E_{mat} vs. root diameter relationships in the present study are consistent with those published for tree species by Waldron and Dakessian (1981) and by Thomas and Pollen-Bankhead (2010). Relevant differences were found comparing these results with the elastic properties of several plants classified as herbs and shrubs (Operstein, Frydman 2000). An interesting comparison could be made for Norway spruce (*Picea abies* L.): Schwarz et al. (2010) estimated a value of the multiplicative coefficient E_0 than that obtained by this study; however they suggested using a multiplicative coefficient

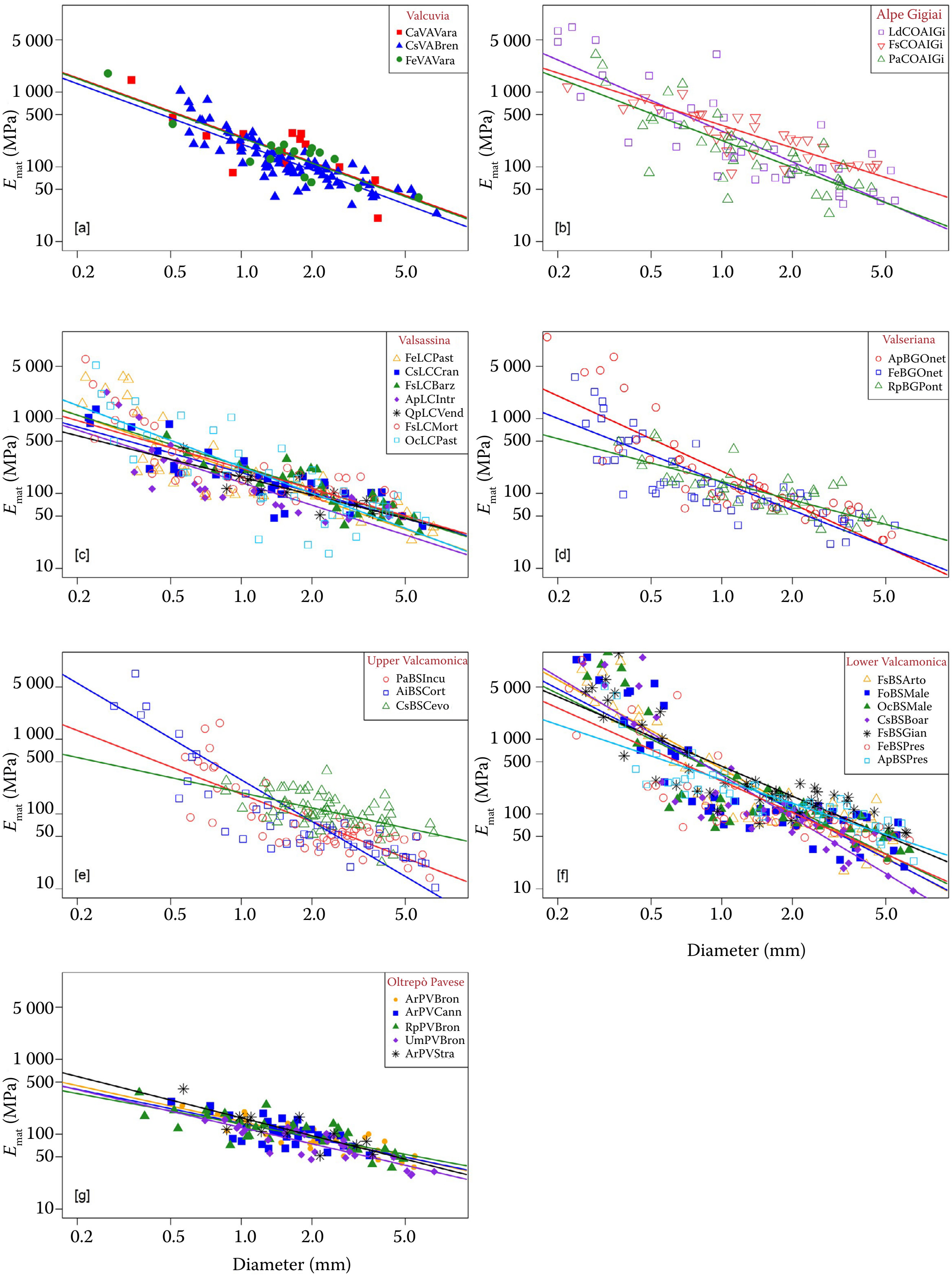

Figure 10. Regression lines of E_{mat} vs. root diameter plotted in log-log chart in function of geographic area (Figure 4)

Table 3. Coefficients and statistical parameters of power regression E_{mat} vs. root diameter in function of geographic area (Figure 4 and Table 1)

Area	*N* (*ns*)	SWp	LTp	ANp	A.slope	A.int	E_0	β	R^2	SE
(a) Valcuvia	3 (3)	0.134	0.798	0.661	0.983	0.055	215.508	–1.153	0.723	0.429.
(b) Alpe Gigiai	3 (3)	0.173	0.100	0.970	0.123	0.012	286.575	–1.203	0.707	0.738
(c) Valsassina	7 (6)	0.178	0.012	0.039	0.418	0.060	199.156	–0.985	0.663	0.632
(d) Valseriana	3 (3)	0.011	0.060	0.027	0.006*	0.092	163.452	–1.194	0.678	0.707
(e) Upper Valcamonica	3 (3)	0.137	0.043	0.012	< 0.001	< 0.001	270.032	–1.433	0.646	0.782
(f) Lower Valcamonica	7 (5)	0.015	0.250	0.783	0.001*	0.103	347.912	–1.512	0.730	0.832
(g) Oltrepò Pavese	5 (3)	0.045	0.435	0.075	0.571	0.008*	139.972	–0.676	0.665	0.292

N – number of series; *ns* – number of tree species inside the geographical area; SWp – *P*-value of Shapiro Wilk test; LTp – *P*-value of Levene's test; ANp – *P*-value of the ANOVA; A.slope – *P*-value of ANCOVA testing the non-parallelism; A.int – *P*-value of ANCOVA testing the intercept; E_0 and β – coefficients; R^2 – coefficient of determination; SE – standard error; **P*-values of Tukey's honest significant difference > 0.01

of 0.3 to take into account the effects of the root tortuosity. In such a way, the results of this study are relatively similar. Moreover, for the black locust (*Robinia pseudoacacia* L.), these results are in agreement with those obtained by Ji et al. (2012). The variability of these parameters could be affected by the methods for measuring the biomechanical properties of roots (Giadrossich et al. 2017). In fact, the exponent coefficient β in this study is always negative (from –1.949 to –0.376) and it is in perfect agreement with many studies that investigated the biomechanical properties of roots by conducting tensile tests in laboratory (Ji et al. 2012) and field direct shear tests (Mickovski et al. 2009), whereas it is in disagreement with data provided by bending tests (Meijer et al. 2018a). Moreover, the multiplier coefficient E_0, which ranged between 64.3 and 435.0 MPa, revealed a large overestimation (3–30 times higher) compared to those provided by the analysis of pullout tests (Schwarz et al. 2013). A summary of the results published in the scientific literature is reported in Table 4.

Variability of elastic modulus. Biomechanical properties of roots represent a fundamental trait for assessing the root reinforcement and consequently the contribution of vegetation to reducing the slope instabilities. Such features are characterized by natural wide variability and relevant uncertainties due to measurement methods (Giadrossich et al. 2017). The scientific community invested some efforts in investigating what factor affects the tensile resistance and, especially, the tensile strength vs. root diameter relationships. Among these factors, there are plant/tree species (Abdi, Deljouei 2019), root age (Loades et al. 2013), tree age (Genet et al. 2008), root length (Zhang et al. 2012), trunk diameter (Deljouei et al. 2018), cellulose content (Abdi et al. 2014), root moisture content (Yang et al. 2016), root dehydration (Boldrin et al. 2018), testing season (Makarova et al. 1998), living or decaying roots (Schmidt et al. 2001), lignin content (Hathaway, Penny 1975), microfibril angle (Kerstens et al. 2001), altitude (Genet et al. 2011), convergent/divergent topography (Hales et al. 2009), soil moisture content (Hales, Miniat 2017), slope gradient (Sun et al. 2008) and uphill/downhill position (Abdi et al. 2010). Conversely, nobody attempted to explain the variability of elastic modulus, despite the importance of this biomechanical feature as an input parameter in root reinforcement modelling. In the present study, the statistical analysis showed absence or presence of significant interspecific and intraspecific differences in elastic modulus vs. root diameter relationships. First, this study investigated the high variability among the intraspecific elastic modulus vs. diameter relationships. The results showed statistical differences in chestnut, beech and larch forests located in different geographical areas. Meanwhile, moderate discrepancies were identified in elastic properties of roots of silver fir, sycamore maple, ash and hop-hornbeam. No statistical differences were found in three species only: Norway maple (in three different study sites), Norway spruce (in seven different study sites) and black locust (in three different study sites) (Figure 9). The second results revealed geography-specific correlations between root di-

https://doi.org/10.17221/4/2021-JFS

Table 4. Coefficients and statistical parameters of elastic modulus vs. root diameter relationships published in scientific literature

Species	E_0 (MPa)	β	R^2	N	Test	Reference
Prickly Sesban (*Sesbania cannabina* Merr.)	987.7	–1.030	0.577	21	Direct shear test	Fan and Su (2008)
Black locust (*Robinia pseudoacacia* L.)	198	–0.265	0.312	50	Tensile test	Ji et al. (2012)
Chinese arborvitae (*Platycladus orientalis*)	85	–0.316	0.21	50		
Basket willow (*Salix viminalis* L.)	180.2	–1.054	0.441	83	Direct shear test	Mickovski et al. (2009)
Alfalfa (*Medicago sativa* L.)	714	–1.120	–	65	Tensile test	Operstein and Frydman (2000)
Cistus (*Cistus spp.* L.)	1 090	–1.110	–	16		
Mastic (*Pistacia lentiscus* L.)	362	–1.160	–	16		
Rosemary (*Rosmarinus officinalis* L.)	649	–0.826	–	24		
Norway spruce (*Picea abies* L.)	696	–1.000	0.515	–	Tensile test	Schwarz et al. (2010)
Norway spruce (*Picea abies* L.)	24.8	–0.300	–	–	Pullout test	Schwarz et al. (2013)
Oregon ash (*Fraxinus latifolia* Benth.)	162	–0.819	–	–	Tensile test	Thomas and Pollen-Bankhead (2010)
Eastern sycamore (*Platanus occidentalis* L.)	259	–1.208	–	–		
Alamo Switchgrass (*Panacum virgatum* L.)	101	–1.780	–	–		
Western yellow pine (*Pinus ponderosa*)	141.2	–0.389	0.257	44	Direct shear test	Waldron and Dakessian (1981)
Barley (*Hordeum vulgare* L.)	13.2	–1.210	0.536	56		
Hawthorn (*Crataegus monogyna* Jacq.)	248.6	–0.300	0.195	49	Tensile test	Boldrin et al. (2017)
European spindle tree (*Euonymus europaeus* L.)	232.1	–0.490	0.221	61		
Grapevine rootstock SO4 (*Vitis berlandieri* x *Vitis riparia*)	99.4	–0.894	0.551	34	Tensile test	Cislaghi et al. (2017)
Sweet acacia (*Acacia farnesiana* (L.) Willd.)	337.0	–1.667	0.833	30	Tensile test	Zavala-González et al. (2019)
Guajillo acacia (*Acacia berlandieri* (Benth.) Seigler, Ebinger)	299.9	–1.609	0.622	30		
Black brush acacia (*Acacia rigidula* Benth)	313.1	–1.877	0.790	30		
Mexican olive (*Cordia boissieri* A. DC.)	1 347.5	–3.463	0.903	30		
Powder-puff (*Havardia pallens* Britton, Rose)	208.8	–2.132	0.886	30		
Loquat leaf oak (*Quercus rysophylla* Weath.)	196.1	–0.469	0.449	30		
Smooth-bark Mexican pine (*Pinus pseudostrobus* Lindl.)	1 266.8	–2.773	0.940	30		
Mexican red oak (*Quercus canbyi* Trel.)	643.3	–2.091	0.724	30		
Netleaf white oak (*Quercus polymorpha* Schltdl., Cham)	18.9	–0.320	0.217	30		
Texas madrone (Arbutus xalapensis Kunth)	1 612.7	–3.078	0.927	30		

Table 4 to be continued

Species	E_0 (MPa)	β	R^2	N	Test	Reference
Taiwan cotton rose (*Hibiscus taiwanensis* S.Y.Hu)	51.2	–0.819	0.678	29	Tensile test	Lee et al. (2020)
Parasol leaf tree (*Macaranga tanarius* (L.) Müll.Arg.)	166.6	–0.543	0.612	28		
Turn-in-the-wind (*Mallotus paniculatus* (Lam.) Muell.Arg.)	171.4	–0.488	0.694	32		
Black currant (*Ribes nigrum* L.)	125.8	–0.046	0.030	48	3-point bending test	Meijer et al. (2018a)
Black currant (*Ribes nigrum* L.)	60.2	0.084	0.040	60	Tensile test	
Sitka spruce (*Picea sitchensis* (Bong.) Carr.)	122	0.245	0.200	62	3-point bending test	Meijer et al. (2018a, b)
Sitka spruce (*Picea sitchensis* (Bong.) Carr.)	107.8	0.060	0.026	76	Tensile test	
Sitka spruce (*Picea sitchensis* (Bong.) Carr.)	201	0.310	0.110	32	Tensile test	Meijer et al. (2019)
Pedunculate oak (*Quercus robur* L.)	230	0.114	0.038	53	3-point bending test	Meijer et al. (2018b)
Pedunculate oak (*Quercus robur* L.)	399	0.188	0.090	53	Tensile test	
Tufted hairgrass (*Deschampsia cespitosa* (L.) P.Beauv.)	58.0	–1.063	0.726	30	Tensile test	Cislaghi et al. (2019b)
Coltsfoot (*Tussilago farfara* L.)	48.1	–1.459	0.749	25		
Buckler sorrel (*Rumex scutatus* L.)	143.9	–1.065	0.447	25		
Masterwort (*Peucedanum ostruthium* (L.) W. D. J. Koch)	66.6	–0.850	0.740	35		
Matgrass (*Nardus stricta* L.)	56.4	–0.686	0.486	30		
Thyme (*Thymus alpestris* L.)	80.1	–0.478	0.157	22		
Stinging nettle (*Urtica dioica* L.)	66.2	–0.862	0.596	30		

N – number of tested roots; E_0 and β – coefficients of power law; *R2* – coefficient of determination; test – method to measure the stress-strain curve ameter and elastic modulus. In most cases, these relationships within a given species that are not significantly different tend to belong to the same study site. In addition, no evident differences were detected in interspecific relationships obtained in roots collected in the same geographical area (Figure 10). The only exception is the Upper Valcamonica, where the interspecific differences were marked probably due to the non-homogeneity of the environmental conditions (e.g., the altitude of the study sites varies from 1 000 to 1 700 m a.s.l.). Another exception was evident in two series of tensile tests conducted on roots of larch that showed the most significant variability in elastic properties (Figure 9G). Nevertheless, these findings indicate that the same geographical position describes similar environmental situation and uniform growth conditions. It could be a useful criterion to explain the variability in root elasticity and a promising approach to studies on root reinforcement, especially for assessing the input parameter in root reinforcement modelling. Such results are further supported by previous studies of Genet et al. (2011) and Vergani et al. (2012), who investigated the interspecific and intraspecific tensile strength vs. root diameter relationships.

CONCLUSION

This study investigated one of the most important biomechanical properties of roots, i.e. the root elasticity. In particular, the elastic modulus is a fundamental parameter in root reinforcement modelling. The present study analysed 56 series of tensile tests (a total of almost 3 000 measurements) conducted on roots belonging to 16 European Southern Alpine tree species collected in 36 different study sites. First, the stress-strain curves clearly displayed the tensile elastic-plastic behaviour of roots. As expected, the elastic modulus, like other biomechanical properties of roots, is strongly related to the root diameter. Then, elastic modulus vs. root diameter relationships were fitted as a power regression ($R^2 > 0.21$). These relationships were not statistically different when roots of the same species, but also of different species, were collected in the same geographical area characterized by similar environmental conditions. Finally, the outcomes of this study could be summarized by the following bullet points:

– the development of a standard approach to calculate the elastic properties of a root using the stress-strain curve as input data;

– the detection and the quantification of two elastic moduli: the "form" elastic modulus affected by the root tortuosity and the "material" elastic modulus, showing that the latter is 4 times greater than the former;

– the lack of correlation between the "form" elastic modulus and the root diameter;

– the estimation of elastic modulus vs. root diameter relationships for 56 different study sites covered by 16 different European Alpine tree species;

– the intraspecific difference in elastic modulus vs. root diameter relationships is evident in several tree species;

– the interspecific difference in elastic modulus vs. root diameter relationships is less evident in those tree species that grow in the same geographical area;

– the geographic area, when characterized by uniform growth conditions, could be a criterion useful to overcome the scarcity of data on biomechanical properties of roots as input parameters in root reinforcement modelling.

Acknowledgement: The author expresses his sincere thanks to Dr. Chiara Vergani, Dr. Chiara Bassanelli, Dr. Enrico Antonio Chiaradia and Prof. Gian Battista Bischetti for supporting in the field campaigns and in the laboratory measurements.

REFERENCES

Abdi E. (2014): Effect of Oriental beech root reinforcement on slope stability (Hyrcanian Forest, Iran). Journal of Forest Science, 60: 166–173.

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

Abdi E., Majnounian B., Genet M., Rahimi H. (2010): Quantifying the effects of root reinforcement of Persian Ironwood (*Parrotia persica*) on slope stability; a case study: Hillslope of Hyrcanian forests, northern Iran. Ecological Engineering, 36: 1409–1416.

Abdi E., Azhdari F., Abdulkhani A., Mariv H.S. (2014): Tensile strength and cellulose content of Persian ironwood (*Parrotia persica*) roots as bioengineering material. Journal of Forest Science, 60: 425–430.

Abe K., Ziemer R.R. (1991): Effect of tree roots on a shear zone: Modeling reinforced shear stress. Canadian Journal of Forest Research, 21: 1012–1019.

Askeland D.R., Fulay P.P., Wright W.J. (2011): The Science and Engineering of Materials. 6th Ed. Stamford, Cengage Learning: 921.

Bischetti G.B., Chiaradia E.A., Simonato T., Speziali B., Vitali B., Vullo P., Zocco A. (2005): Root strength and root area ratio of forest species in Lombardy (Northern Italy). Plant and Soil, 278: 11–22.

Bischetti G.B., Chiaradia E.A., Epis T., Morlotti E. (2009): Root cohesion of forest species in the Italian Alps. Plant and Soil, 324: 71–89.

Boldrin D., Leung A.K., Bengough A.G. (2017): Correlating hydrologic reinforcement of vegetated soil with plant traits during establishment of woody perennials. Plant and Soil, 416: 437–451.

Boldrin D., Leung A.K., Bengough A.G. (2018): Effects of root dehydration on biomechanical properties of woody roots of *Ulex europaeus*. Plant and Soil, 431: 347–369.

Burri K., Graf F., Böll A. (2009): Revegetation measures improve soil aggregate stability: A case study of a landslide area in Central Switzerland. Forest Snow and Landscape Research, 82: 45–60.

Burroughs E.R., Thomas B.R. (1977): Declining Root Strength in Douglas-fir After Felling as a Factor in Slope Stability. Ogden, Intermountain Forest and Range Experiment Station, Forest Service, U.S. Dept. of Agriculture: 27.

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.

Böhm W. (1979): Methods of Studying Root Systems. Berlin, Springer: 188.

Chen L., Wang P., Yang Y., He J. (2014): Constitutive model of single root system's resistance to tensile stress-taking *Pinus tabulaeformis*, *Betula platyphylla*, *Quercus mongolica* and *Larix gmelinii* as experimental objects. PLoS ONE 9: e93066.

Cislaghi A., Bischetti G.B. (2019): Source areas, connectivity, and delivery rate of sediments in mountainous-forested hillslopes: A probabilistic approach. Science of the Total Environment, 652: 1168–1186.

Cislaghi A., Bordoni M., Meisina C., Bischetti G.B. (2017): Soil reinforcement provided by the root system of grapevines: Quantification and spatial variability. Ecological Engineering, 109: 169–185.

Cislaghi A., Cohen D., Gasser E., Bischetti G.B., Schwarz M. (2019a): Field measurements of passive earth forces in steep, shallow, landslide-prone areas. Journal of Geophysical Research: Earth Surface, 124: 838–866.

Cislaghi A., Giupponi L., Tamburini A., Giorgi A., Bischetti G.B. (2019b): The effects of mountain grazing abandonment on plant community, forage value and soil properties: observations and field measurements in an alpine area. Catena, 181: 104086.

Cohen D., Lehmann P., Or D. (2009): Fiber bundle model for multiscale modeling of hydromechanical triggering of shallow landslides. Water Resources Research, 45: W10436.

Commandeur P.R., Pyles M.R. (1991): Modulus of elasticity and tensile strength of Douglas-fir roots. Canadian Journal of Forest Research, 21: 48–52.

Cutler D.F., Rudall P.J., Gasson P.E., Gale R.M.O. (1987): Root Identification Manual of Trees and Shrubs: A Guide to the Anatomy of Roots of Trees and Shrubs Hardy in Britain and Northern Europe. London, Chapman and Hall: 247.

De Baets S., Poesen J., Reubens B., Wemans K., De Baerdemaeker J., Muys B. (2008): Root tensile strength and root distribution of typical Mediterranean plant species and their contribution to soil shear strength. Plant and Soil, 305: 207–226.

Deljouei A., Abdi E., Majnonian Garagiz B., Schwarz M. (2018): Comparing roots mechanical characteristics of hornbeam trees in different diameter at breast height classes. Forest and Wood Products, 71: 199–207.

Deljouei A., Abdi E., Schwarz M., Majnounian B., Sohrabi H., Dumroese R.K. (2020): Mechanical characteristics of the fine roots of two broadleaved tree species from the temperate Caspian Hyrcanian ecoregion. Forests, 11: 345.

Dias A.S., Pirone M., Urciuoli G. (2017): Review of the methods for evaluation of root reinforcement in shallow landslides. In: WLF 2017: Advancing Culture of Living with Landslide. Workshop on World Landslide Forum. Ljubljana, Slovenia. May 29, 2017. 641-648.

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.

Ettbeb A.E., Rahman Z.A., Razi Idris W.M., Adam J., Rahim S.A., Ahmad Tarmidzi S.N., Lihan T. (2020): Root tensile resistance of selected pennisetum species and shear strength of root-permeated soil. Applied and Environmental Soil Science, 2020: 3484718.

Fan C.-C., Su C.-F. (2008): Role of roots in the shear strength of root-reinforced soils with high moisture content. Ecological Engineering, 33: 157–166.

FAO (2014): World Reference Base for Soil Resources 2014: International Soil Classification System for Naming Soils and Creating Legends for Soil Maps. Rome, FAO: 181.

Finér L., Ohashi M., Noguchi K., Hirano Y. (2011): Factors causing variation in fine root biomass in forest ecosystems. Forest Ecology and Management, 261: 265–277.

Genet M., Stokes A., Salin F., Mickovski S.B., Fourcaud T., Dumail J.-F., Van Beek R. (2005): The influence of cellulose content on tensile strength in tree roots. Plant and Soil, 278: 1–9.

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 Ecology and Management, 256: 1517–1526.

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*. Annals of Botany, 107: 311–320.

Giadrossich F., Schwarz M., Cohen D., Cislaghi A., Vergani C., Hubble T., Phillips C., Stokes A. (2017): Methods to measure the mechanical behaviour of tree roots: A review. Ecological Engineering, 109: 256–271.

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. New Zealand Journal of Forestry Science, 50: 1–12.

Giupponi L., Pentimalli D., Manzo A., Panseri S., Giorgi A. (2018): Effectiveness of fine root fingerprinting as a tool to identify plants of the Alps: Results of a preliminary study. Plant Biosystems – An International Journal Dealing with all Aspects of Plant Biology, 152: 464–473.

Gray D.H., Ohashi H. (1983): Mechanics of fiber reinforcement in sand. Journal of Geotechnical Engineering, 109: 335–353.

Gray D.H., Sotir R.B. (1996): Biotechnical and Soil Bioengineering Slope Stabilization: A Practical Guide for Erosion Control. New York, John Wiley & Sons: 400.

Hales T.C., Ford C.R., Hwang T., Vose J.M., Band L.E. (2009): Topographic and ecologic controls on root reinforcement. Journal of Geophysical Research, 114: F03013.

Hales T.C., Cole-Hawthorne C., Lovell L., Evans S.L. (2013): Assessing the accuracy of simple field based root strength measurements. Plant and Soil, 372: 553–565.

Hales T.C., Miniat C.F. (2017): Soil moisture causes dynamic adjustments to root reinforcement that reduce slope stability. Earth Surface Processes and Landforms, 42: 803–813.

Hathaway R.L., Penny D. (1975): Root strength in some *Populus* and *Salix* clones. New Zealand Journal of Botany, 13: 333–344.

Ji J., Kokutse N., Genet M., Fourcaud T., Zhang Z. (2012): Effect of spatial variation of tree root characteristics on slope stability. A case study on Black Locust (*Robinia pseudoacacia*) and Arborvitae (*Platycladus orientalis*) stands on the Loess Plateau, China. Catena, 92: 139–154.

Kerstens S., Decraemer W.F., Verbelen J.-P. (2001): Cell walls at the plant surface behave mechanically like fiber-reinforced composite materials. Plant Physiology, 127: 381–385.

Lee J.-T., Chu M.-Y., Lin Y.-S., Kung K.-N., Lin W.-C., Lee M.-J. (2020): Root traits and biomechanical properties of three tropical pioneer tree species for forest restoration in landslide areas. Forests, 11: 179.

Levene H. (1960): Robust tests for equality of variances. In: Olkin I., Ghurye S.G., Hoeffding W., Madow W.G., Mann H.B. (eds): Contributions to Probability and Statistics: Essays in Honor of Harold Hotelling. Stanford, Stanford University Press: 278–292.

Loades K.W., Bengough A.G., Bransby M.F., Hallett P.D. (2013): Biomechanics of nodal, seminal and lateral roots of barley: Effects of diameter, waterlogging and mechanical impedance. Plant and Soil, 370: 407–418.

Löbmann M.T., Geitner C., Wellstein C., Zerbe S. (2020): The influence of herbaceous vegetation on slope stability – A review. Earth-Science Reviews, 209: 103328.

Makarova O.V., Cofie P., Koolen A.J. (1998): Axial stress–strain relationships of fine roots of beech and larch in loading to failure and in cyclic loading. Soil and Tillage Research, 45: 175–187.

Mao Z., Jourdan C., Bonis M.-L., Pailler F., Rey H., Saint-André L., Stokes A. (2013): Modelling root demography in heterogeneous mountain forests and applications for slope stability analysis. Plant and Soil, 363: 357–382.

Mattia C., Bischetti G.B., Gentile F. (2005): Biotechnical characteristics of root systems of typical Mediterranean species. Plant and Soil, 278: 23–32.

Meijer G.J., Bengough A.G., Knappett J.A., Loades K.W., Nicoll B.C. (2018a): In situ measurement of root-reinforcement using the corkscrew extraction method. Canadian Geotechnical Journal, 55: 1372–1390.

Meijer G.J., Bengough G., Knappett J., Loades K, Nicoll B. (2018b): In situ root identification through blade penetrometer testing – part 2: Field testing. Géotechnique, 68: 320–331.

Meijer G.J., Bengough G.A., Knappett J., Loades K., Nicoll B. (2019): Measuring the strength of root-reinforced soil on steep natural slopes using the corkscrew extraction method. Forests, 10: 1135.

Meyer F.H., Gottsche D. (1971): Distribution of root tips and tender roots of beech. In: Ellenberg H. (ed): Integrated Experimental Ecology. Berlin, Heidelberg, Springer: 48–52.

Mickovski S.B., Hallett P.D., Bransby M.F., Davies M.C., Sonnenberg R., Bengough A.G. (2009): Mechanical reinforcement of soil by willow roots: Impacts of root properties and root failure mechanism. Soil Science Society of America Journal, 73: 1276–1285.

Naghdi R., Maleki S., Abdi E., Mousavi R., Nikooy M. (2013): Assessing the effect of *Alnus* roots on hillslope stability in order to use in soil bioengineering. Journal of Forest Science, 59: 417–423.

O'Loughlin C.L. (1974a): A study of tree root strength deterioration following clearfelling. Canadian Journal of Forest Research, 4: 107–113.

O'Loughlin C.L. (1974b): The effect of timber removal on the stability of forest soils. Journal of Hydrology (New Zealand), 13: 121–134.

Operstein V., Frydman S. (2000): The influence of vegetation on soil strength. Proceedings of the Institution of Civil Engineers-Ground Improvement, 4: 81–89.

Pollen N., Simon A. (2005): Estimating the mechanical effects of riparian vegetation on stream bank stability using a fiber bundle model. Water Resources Research, 41: W07025.

Pourmalekshah A.A.M.A., Moayeri M.H., Parsakhoo A. (2019): Effect of the root biotechnical characteristics of *Alnus subcordata*, *Paulownia fortunei* and *Populus deltoides* on the soil mechanics. Journal of Forest Science, 65: 283–290.

Rewald B., Meinen C., Trockenbrodt M., Ephrath J.E., Rachmilevitch S. (2012): Root taxa identification in plant mixtures – current techniques and future challenges. Plant and Soil, 359: 165–182.

Sanchez-Castillo L., Kubota T., Cantu-Silva I., Yañez-Diaz M., Pequeño-Ledezma M. (2017): Comparisons of the root mechanical properties of three native Mexican tree species for soil bioengineering practices. Botanical Sciences, 95: 259–269.

Schmidt K.M., Roering J.J., Stock J.D., Dietrich W.E., Montgomery D.R., Schaub T. (2001): The variability of root cohesion as an influence on shallow landslide susceptibility in the Oregon Coast Range. Canadian Geotechnical Journal, 38: 995–1024.

Schoeneberger P.J. (2002): Field Book for Describing and Sampling Soils, Version 3.0. Lincoln, National Soil Survey Center, Natural Resources Conservation Service, U.S. Dept. of Agriculture: 300.

Schwarz M., Lehmann P., Or D. (2010): Quantifying lateral root reinforcement in steep slopes – from a bundle of roots to tree stands. Earth Surface Processes and Landforms: The Journal of the British Geomorphological Research Group, 35: 354–367.

Schwarz M., Giadrossich F., Cohen D. (2013): Modeling root reinforcement using a root-failure Weibull survival function. Hydrology and Earth System Sciences, 17: 4367–4377.

Schwarz M., Rist A., Cohen D., Giadrossich F., Egorov P., Büttner D., Stolz M., Thormann J.-J. (2015): Root reinforcement of soils under compression. Journal of Geophysical Research: Earth Surface, 120: 2103–2120.

Shapiro S.S., Wilk M.B. (1965): An analysis of variance test for normality (complete samples). Biometrika, 52: 591–611.

Stokes A., Ghani M.A., Salin F., Danjon F., Jeannin H., Berthier S., Kokutse A.D., Frochot H. (2007): Root morphology and strain distribution during tree failure on mountain slopes. In: Stokes A., Spanos I., Norris J.E., Cammeraat E. (eds): Eco-and Ground Bio-Engineering: The Use of Vegetation to Improve Slope Stability. Dordrecht, Springer Netherlands: 165–173.

Sun H.-L., Li S.-C., Xiong W.-L., Yang Z.-R., Cui B.-S., Tao-Yang (2008): Influence of slope on root system anchorage of *Pinus yunnanensis*. Ecological Engineering, 32: 60–67.

Thomas R.E., Pollen-Bankhead N. (2010): Modeling root-reinforcement with a fiber-bundle model and Monte Carlo simulation. Ecological Engineering, 36: 47–61.

Vergani C., Graf F. (2016): Soil permeability, aggregate stability and root growth: A pot experiment from a soil bioengineering perspective. Ecohydrology, 9: 830–842.

Vergani C., Chiaradia E.A., Bischetti G.B. (2012): Variability in the tensile resistance of roots in Alpine forest tree species. Ecological Engineering, 46: 43–56.

Vergani C., Giadrossich F., Buckley P., Conedera M., Pividori M., Salbitano F., Rauch H.S., Lovreglio R., Schwarz M. (2017): Root reinforcement dynamics of European coppice woodlands and their effect on shallow landslides: A review. Earth-Science Reviews, 167: 88–102.

Waisel Y., Eshel A., Kafkafi, U. (1991): Plant Roots: The Hidden Half. New York, Marcel Dekker, Inc: 948.

Waldron L.J. (1977): The shear resistance of root-permeated homogeneous and stratified soil. Soil Science Society of America Journal, 41: 843–849.

Waldron L.J., Dakessian S. (1981): Soil reinforcement by roots: Calculation of increased soil shear resistance from root properties. Soil Science, 132: 427–435.

Watson A., Marden M., Rowan D. (1997): Root-wood strength deterioration in kanuka after clearfelling. New Zealand Journal of Forestry Science, 27: 205–215.

Yang Y., Chen L., Li N., Zhang Q. (2016): Effect of root moisture content and diameter on root tensile properties. PLoS ONE, 11: e0151791.

Zavala-González R., Cantú-Silva I., Sánchez-Castillo L., González-Rodríguez H., Kubota T., Hasnawir (2019): Ten native tree species for potential use in soil bioengineering in northeastern Mexico. Botanical Sciences, 97: 291–300.

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.

Zhang C.-B., Chen L.-H., Jiang J. (2014): Why fine tree roots are stronger than thicker roots: the role of cellulose and lignin in relation to slope stability. Geomorphology, 206: 196–202.

Zhou W.-H., Qi X.-H. (2019): Root cohesion estimation of riparian trees based on model uncertainty characterization. Journal of Materials in Civil Engineering, 31: 04018389.

Received: January 19, 2021
Accepted: May 3, 2021