Root Tensile Force and Resistance of Several Tree and Shrub Species of Hyrcanian Forest, Iran

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Abstract

*Shallow landslides are a frequently recurring problem in some parts of Iran, including the Hyrcanian forest. In addition to traditional civil engineering measures, a potential solution for this problem is the application of soil bioengineering techniques. The mechanical reinforcement effect of plant roots is one of the major contributions of vegetation to the mitigation of shallow landslides. Given the lack of information on the mechanical properties of common Hyrcanian forest species, the present study assessed the root strength of 10 common species of this forest. Eight tree species occurring in natural regeneration sites (*Carpinus betulus, Fagus orientalis, Parrotia persica *and* Quercus castaneifolia*) and plantations (*Acer velutinum, Alnus glutinosa, Fraxinus excelsior *and* Picea abies*) and two shrub species (*Crataegus microphylla *and* Mespilus germanica*) were selected. Fresh roots were collected and mechanical tests were carried out on 487 root samples. The ranges of root diameter, tensile force, and root resistance were 0.29–5.90 mm, 3.80–487.20 N, and 2.41–224.35 MPa, respectively. Two different algorithms, including the nonlinear least square method and log-transformation, were used to obtain power regressions for diameter-force and diameter-resistance relationships. The results of the two algorithms were compared statistically to choose the optimal approach for soil bioengineering applications. The nonlinear least square method resulted in lower Akaike information criteria and higher adjusted *R^2* values for all species, which means that this model can more efficiently predict tensile force and resistance based on root diameter. Log-transformation regressions generally underestimate tensile force and resistance. Significant differences were found among mean root tensile force (*ANCOVA; F=37.36, p<0.001*) and resistance (*ANCOVA; F=34.87, p<0.001*) of different species. Also, root diameter was significant as a covariate factor in tensile force (*F=1453.77, p<0. 001*) and resistance (*F=274.26, p<0.001*). Shrub species and trees in natural regeneration sites had higher tensile force and resistance values, while trees from plantation stands had lower values. The results of this study contribute to the knowledge on the root force and resistance characteristics of several shrub and tree species of the Hyrcanian forest and can be used in evaluating the efficiency of different species for bioengineering purposes.*

Keywords: landslides, log-transformation, nonlinear least square, power regression, soil bioengineering, stability

1. Introduction

Shallow landslides are a frequently recurring problem in some parts of Iran, including the Hyrcanian forest. In Iran, the total estimated losses as a result of landslides are about $ 50 million per year (Ebrahimi et al. 2015). Landslides are defined as processes that result in the downward and outward movement of slope-forming materials, with gravity and water as the primary triggers (Stokes et al. 2014). In the Hyrcanian forest, landslides pose a severe threat to access infrastructure, including forest roads, resulting in severe economical consequences. Among the different landslide triggering mechanisms in this forest environment, rainfall-induced (Abedi et al. 2010) and human-induced (Savadkoohi and Hosseini 2013) landslides are the most frequently reported. Human-induced landslides usually occur after disturbances such as road construction, modifying the shape of the slope, removing vegetation cover, and decreasing both the density and resistance of roots (Vergani et al. 2016); such processes might also contribute to the concentration of flow and increase pore-water pressure, resulting in local instabilities (Schwarz et al. 2010b). In contrast, rainfall-induced landslides are generally triggered by high-intensity rainfall, which causes a sudden increase in soil moisture content and a decrease in soil suction, leading to soil strength reduction and possible failure (Cislaghi et al. 2017, Hayati et al. 2017). In general, high soil moisture contents (or low suction) lead to weaker apparent soil cohesion and higher landslide risks (Stokes et al. 2014).

Traditional civil engineering measures (i.e. grey solutions) with high initial costs and increasing maintenance needs over time are unsuitable in the long term (Morgan and Rickson 1995), especially in natural resources with extensive areas. Potential solutions for this problem are soil bioengineering measures or green solutions, which are characterized by the use of any form of vegetation (grass, shrubs, or trees) as materials to perform engineering functions (Morgan and Rickson 1995) such as soil reinforcement, erosion control, and the prevention of shallow instability. In recent years, using plants for soil bioengineering measures has been recognized as an eco-friendly and low CO_2 emission solution for soil stabilization, as compared to the existing traditional grey or »hard« engineering solutions (Boldrin et al. 2017). Plants are self-regenerating and respond dynamically to changes of site conditions without losing their engineering properties (Morgan and Rickson 1995); in addition, they can improve the stability of hillslopes and the ecological conditions (Bischetti et al. 2010).

Vegetation can increase slope stability by protecting and holding soil particles together, mechanically reinforcing the soil and increasing soil matric suction (Capilleri et al. 2016) through both interception of rainfall and depletion of soil water content via transpiration (Hayati et al. 2017). This is particularly the case for forest environments, where mechanical and hydrological modifications by trees enhance the stability of hillslopes (Moos et al. 2016). The mechanical effect of root systems has been recognized as one of the major contributions of vegetation to the mitigation of shallow landslides (Vergani et al. 2016). Some researchers have reported a negative correlation between the magnitude of root reinforcement and landslide susceptibility (Hubble et al. 2013, Roering et al. 2003, Schmidt et al. 2001, Moos et al. 2016), and it is now clear that plants positively influence the triggering mechanisms via root strength, hydrological regulation, and root anchorage (Cislaghi et al. 2017). Thick roots act like soil nails on slopes, reinforcing soil in the same way that steel reinforces concrete. Thin and fine roots act in tension during failure on slopes; if they cross the slip surface, they reinforce the soil by adding additional cohesion to the soil cohesion (Stokes et al. 2014). The efficiency of roots in reinforcing soil depends on root strength resistance, root distribution, and morphology. The greater the strength and the wider the distribution, the better the plants will reinforce the soil (Stokes 2002). With increasing root strength, larger masses of soil are needed to overcome resisting forces and, therefore, the critical landslide area increases (Moos et al. 2016). It is worth mentioning that the effectiveness of root reinforcement is limited to shallow landslides with a volume of less than about 1000 m^3 (Giadrossich et al. 2017), which includes most of the shallow landslides in the Hyrcanian forest.

Regarding the important role of plant roots in soil bioengineering, many studies have assessed root tensile resistance, which varies widely from thousands to millions of Pascal, depending on the species and the environment (Nilaweera and Nutalaya 1999, Abernethy and Rutherfurd 2001, Schmidt et al. 2001, Tosi 2007, Genet et al. 2008, Schwarz et al. 2010a, Vergani et al. 2012, Giadrossich et al. 2016). Tensile resistance depends on a variety of factors such as plant species (Stokes 2002), root diameter (Watson et al. 1999, Bischetti et al. 2005), soil environment (Goodman and Ennos 1999), time of year (Abernethy and Rutherfurd 2000), management type (Coppin and Richards 1990), test speed, sample length and diameter, root moisture and storage (De Baets et al. 2009, Hales and Miniat 2016), chemical composition (Genet et al. 2005), orientation along the slope (Abdi et al. 2010), plant age and altitude (Vergani et al. 2014), and the mechanical role of the root (Stokes 2002). Although some researchers have reported that variations in root tensile resistance are dependent on the species (e.g. Bischetti et al. 2009, Abdi et al. 2010, Vergani et al. 2012), many previous studies have focused on one or a few species (e.g. Watson et al. 1999, Tosi 2007, Genet et al. 2008, Abdi et al. 2009, Abdi et al. 2010). However, assessing and comparing the mechanical properties of several species provide valuable data for ranking species in terms of their potential role in bioengineering applications (Watson and Marden 2004).

The magnitude of soil reinforcement due to the presence of roots (*Cr*) can be modeled using different methods, e.g. the Wu method (Wu et al. 1979), the fiber bundle model or FBM (Pollen and Simon 2005), the root bundle model or RBM (Schwarz et al. 2010a), and the root bundle model Weibull or RBMw (Schwarz et al. 2013). Apart from the model type, all models consider *Cr* as a function of root tensile resistance (in Wu and FBM models) or tensile force (in RBM and RBMw models) and of root distribution within the soil.

Concerning the engineering applications, the quantification of the tensile force and the resistance of roots are key parameters for several fields of application, including slope stability (Vergani et al. 2012); root reinforcement estimation (Vergani et al. 2014); erosion control measures (Giadrossich et al. 2016), and soil bioengineering technique design (Bischetti et al. 2010). For example, in soil bioengineering applications in forest engineering, such as brush layering for the stabilization of road cuts and fill-slopes (Bischetti et al. 2010), wattle fences for stabilizing uphill cut-slopes, and brush wattles for roadside slope stabilization (Schiechtl 1980), plant roots play an important engineering role, and root tensile force and resistance values are needed to estimate the magnitude of the bioengineering effectiveness (Bischetti et al. 2010).

In the current study, root tensile force and resistance of 10 typical species (two shrub and eight tree species) of the Hyrcanian forest were investigated to expand our knowledge of the values typical of this environment and to compare and assess the variability among species. Although some studies have reported the tensile resistance of Hyrcanian forest species (e.g., Abdi et al. 2009, Abdi et al. 2010), so far, no study has assessed different species, especially trees with different stand origin (i.e. natural or artificial regeneration) and shrubs. Also, most of the previous studies have used log-transformation regression as one of the most common patterns in biology (Xiao et al. 2011), which was introduced approximately a century ago (Packard 2012) to express the relation between root tensile force and tensile resistance as a function of root diameter (e.g. Bischetti et al. 2005, Bischetti et al. 2009, Vergani et al. 2012, Vergani et al. 2014). However, Schwarz et al. (2013) and Giadrossich et al. (2017) reported that different regression methods (log-transformation and nonlinear least square) for fitting of the root diameter–force and resistance curve lead to quite different coefficients of the equation, and these changes lead to variations in the estimated reinforcement effect of vegetation. Also, in several biological studies, the use of log-transformation power regression has been criticized, suggesting that the analysis on logarithmic scales is flawed and that instead, analyses should be carried out on the original measurement scale, using nonlinear regression (e.g. Fattorini 2007, Packard 2009, Packard 2011, Packard and Birchard 2008, Packard et al. 2011). Therefore, we used two power regression methods, the Akaike information criteria (AIC) and adjusted R^2, as statistical criteria for selecting the optimal model (Zuur et al. 2007, Xiao et al. 2011, Lai et al. 2013).

In this context, the objectives of this study were as follows: i) to investigate to which extent root tensile force and resistance depend upon the species and ii) to investigate the effects of different regression methods (nonlinear least square and log-transformation) on the power regression coefficients for the relationship between root tensile force and tensile resistance as a function of root diameter.

2. Material and Methods

2.1 Characteristics of the study site

The Hyrcanian vegetation zone, also called the »Caspian forest«, is a green belt stretching across the northern slopes of the Alborz Mountain Ranges and covering about 1.9 million hectares. The area is rich in hardwood species, with about 50 tree and 80 shrub species. Broadleaved species are dominant, and some small stands of softwoods have been artificially introduced to this forest about 40 years ago. The main tree species are *Fagus orientalis, Carpinus betulus, Parrotia persica, Acer cappadocicum, Acer velutinum, Alnus glutinosa, Ulmus glabra* and *Quercus castaneifolia*.

The study was conducted in the educational and experimental forest of the University of Tehran (Kheyrud Forest), with a total area of about 7000 ha. The first district, named Patom (Fig. 1), covers an area of 900 ha and was chosen as the study area because of the high occurrence of instabilities compared to other districts. Elevation ranges from 40 to 930 m above sea level, while the gradient ranges from 0 to 70 degrees. The parent rock is composed of hard calcareous layers with a large number of cracks. According to the Unified Soil Classification System (USCS), the most frequent soil types are CH (clay with high plasticity), CL (clay with low plasticity), and ML (silt with low plasticity). Average annual precipitation at the site is about 1200 mm, with average summer and winter temperatures of 22.5 and 10 °C, respectively. The management system is the »selection system«, which is followed to ensure sustainable management and yields. The future of the forest highly depends on natural regeneration; in some areas, trees are planted in gaps.

Shallow landslides occur in some parts of this forest (Fig. 2) and are more frequent in areas where vegetation has been cleared for the construction of roads. These slides involve the shallow layers of the slopes,

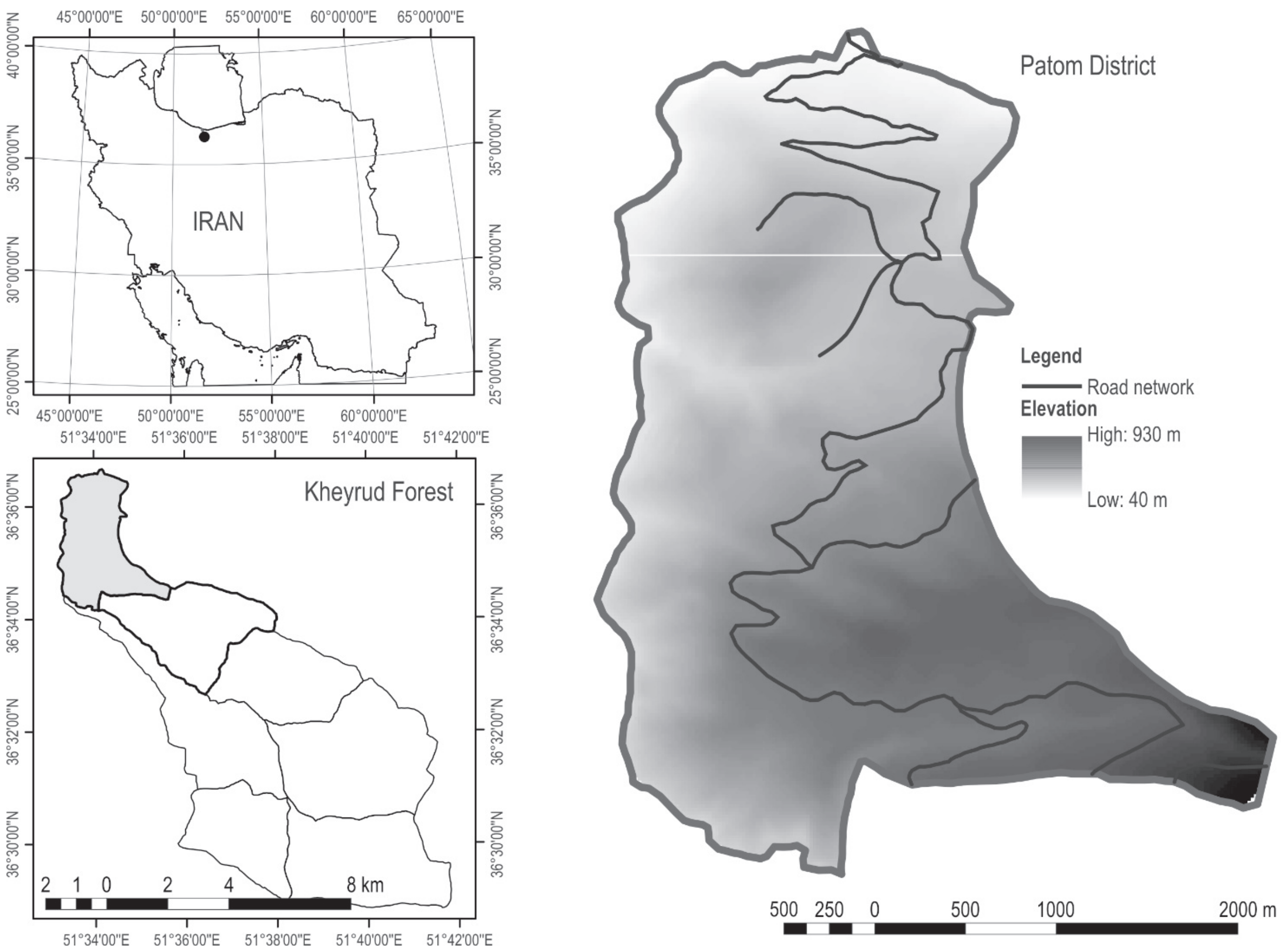

Fig. 1 Location of the study area in the Kheyrud forest, northern Iran (the black point)

where vegetation can have a beneficial effect on the stability through the reinforcing action of lateral roots and the action of coarse taproots. In 1994 and 2004, a series of landslides have occurred that caused the closure of the road network in the Patom district, resulting in costs of about $ 47 000 for the maintenance of a

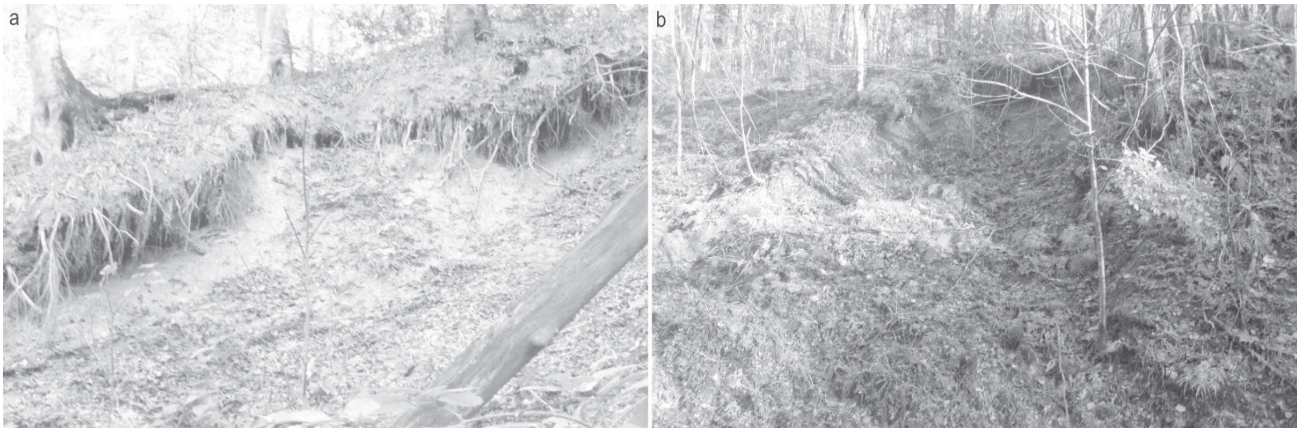

Fig. 2 A natural shallow landslide; lateral root reinforcement can be seen along the tension crack (a) and failure of forest road cut slope (b) in the study area

Fig. 3 Gully erosion formed by concentrated flow from a road side ditch

Table 1 List of studied plant species

	Tree species			Shrub species	
ID	Botanical name	English name	ID	Botanical name	English name
1	*Acer velutinum*	Persian maple	9	*Crataegus microphylla*	Hawthorn
2	*Alnus glutinosa*	Black alder	10	*Mespilus germanica*	Medlar
3	*Carpinus betulus*	Common hornbeam			
4	*Fagus orientalis*	Oriental beech			
5	*Fraxinus excelsior*	Common ash			
6	*Parrotia persica*	Persian ironwood			
7	*Picea abies*	Norway spruce			
8	*Quercus castaneifolia*	Chestnut-leaved oak			

damaged segment and the construction of gabion walls in some parts of the road network. Also, gully erosion by concentrated flow from road drainage can be seen along some parts of the road (Fig. 3).

2.2 Sampling

Eight tree and two shrub species were selected for resistance investigations due to their dominance and frequent distribution in the road edge zone (Table 1).

Six specimens were selected randomly from each species to consider intra-species variability, and live root samples were collected randomly from the soil by excavating pits beside the trees at a depth of about 30 cm below the soil surface (Cofie and Koolen 2001, Abdi et al. 2010). To prevent pre-stress effects, roots were cut with sharp scissors and placed in plastic bags. In most previous studies, the root samples were treated with a 15% alcohol solution (e.g. Bischetti et al. 2005, Bischetti et al. 2016) to preserve them from deterioration prior to the tensile tests. Therefore, their moisture content is higher than that of field-tested roots (Vergani et al. 2016), and the root is slightly swollen, resulting in a higher root diameter (Boldrin et al. 2017) and possible error sources. Hales and Miniat (2016) found that roots with 50% less moisture were more than twice as strong as fresh roots. To overcome this problem and prevent severe changes of root moisture content, we only sprayed the roots with a 15% alcohol solution instead of adding the solution to the root bags. Roots were preserved at 4 °C for a few days to avoid an impact on the measured parameters (Bischetti et al. 2005).

2.3 Resistance tests

In the laboratory, roots were carefully inspected for possible damage. Prior to the experiment, root diameter was measured at three different positions along the middle length of the root to obtain a representative value (Bischetti et al. 2005, Vergani et al. 2012, Abdi et al. 2014). Tensile tests were carried out using a Floor Model 4486 computer-controlled Instron Universal Testing Machine (UK), equipped with a 5 kN maximum-capacity reversible load cell.

The root ends were clamped and a strain rate of 10 mm/min (Bischetti et al. 2005, Mattia et al. 2005, Pollen 2007, Abdi et al. 2014) was selected, similar to the approach used in previous studies, to allow comparison. De Baets et al. (2008) reported velocities ranging between 1 and 300 mm/min for rapid landslides. As most shallow instabilities in the study area are classified as rapid and occur during and after heavy rainfalls, this test speed was considered adequate. Only samples ruptured near the middle of the root between the clamps were considered. A total of 487 root samples were tested.

The tensile force (N) at the point of rupture was taken as the peak load (F_{Max}), and the related tensile resistance (MPa) was calculated by dividing the breaking force by the cross-sectional area of each tested root (mm^2), see (Eq. 1):

$$TR = \frac{F_{\mathrm{Max}}}{\left(\frac{\pi}{4}\right) \times d^2} \tag{1}$$

here:

TR tensile resistance

F_{Max} maximum force to break the root

d root diameter.

The diameters of the root samples ranged from 0.29 to 5.90 mm. Thicker roots were difficult to test because of clamping constraints (De Baets et al. 2008).

2.4 Statistical analyses

The relationship between root tensile force, F (N), and tensile resistance, TR (MPa), as a function of root diameter d (mm), was interpreted through power regressions. To obtain the power regression coefficients (i.e., α and β), two different methods were used: nonlinear least square and log-transformation methods, using *R* software. The suitability of the regressions and goodness of fit (efficiency of the model) were evaluated using the Akaike information criterion (AIC) and the adjusted R^2 values as statistical criteria for model selection (Zuur et al. 2007, Xiao et al. 2011, Lai et al. 2013). To compare root tensile force and resistance values between species and to take diameter into consideration as a covariate factor, *ANCOVA* was used (Abdi et al. 2010, Vergani et al. 2014, Vergani et al. 2016). The Kolmogorov–Smirnov test was used to check the normality of the data before proceeding the *ANCOVA*; due to the non-normality of the data (force and resistance values), the values were log-transformed to ensure homogeneous residual variance and normality. Tukey´s test was used to compare mean root tensile force and resistance of different species.

3. Results

Descriptive statistics of tested roots and their corresponding force and resistance values are shown in Table 2. Regarding Table 2, the number of valid tensile tests ranged between 30 and 64, based on the species. Root diameter ranged from 0.29 to 5.90 mm, and mean root diameter for each species varied between 1.53 and 2.45 mm.

3.1 Tensile Force

As shown in Table 2, the variability of force and resistance among and even within a given species was high. The minimum force values ranged between 3.80 and 12.10 N for hardwood tree species, 4.30 N for the only softwood tree species, and between 8.90 N and 15.30 N for the two shrubs. Considering the maximum values, the ranges were 203.80 o 398.10 N for hardwood tree species, 198.70 N for the only softwood tree

Table 2 Descriptive statistics of tested roots including diameter, force, and resistance

Species	*n*	Diameter, mm				Force, N				Resistance, MPa			
		Mean	*SD*	*Max.*	*Min.*	*Mean*	*SD*	*Max.*	*Min.*	*Mean*	*SD*	*Max.*	*Min.*
Acer velutinum	56	1.72	1.26	4.45	0.29	64.15	75.11	291.30	7.11	30.77	25.03	135.87	3.97
Alnus glutinosa	59	1.71	1.25	4.68	0.38	60.25	64.84	251.80	7.20	26.12	16.79	108.43	4.52
Carpinus betulus	32	1.63	0.80	3.17	0.35	95.36	83.23	349.50	8.30	43.31	23.55	124.39	13.65
Fagus orientalis	33	1.69	0.94	4.00	0.52	74.92	61.68	237.40	8.30	30.47	12.34	66.47	12.92
Fraxinus excelsior	50	2.39	1.12	4.71	0.52	54.29	42.62	203.80	3.80	12.74	6.61	30.60	3.32
Parrotia persica	58	1.72	1.15	4.77	0.49	84.59	91.29	398.10	12.10	36.41	24.12	123.76	10.91
Picea abies	47	2.41	1.18	4.85	0.40	66.51	51.97	198.70	4.30	15.75	15.51	108.10	2.41
Quercus castaneifolia	30	1.53	0.93	4.02	0.60	83.59	69.87	249.00	9.90	42.67	21.79	104.47	15.83
Crataegus microphylla	64	2.08	1.08	5.90	0.40	135.86	100.06	441.90	8.90	44.94	29.77	224.35	11.01
Mespilus germanica	58	2.45	1.34	5.00	0.50	143.25	123.94	487.20	15.30	32.69	18.28	89.95	7.74

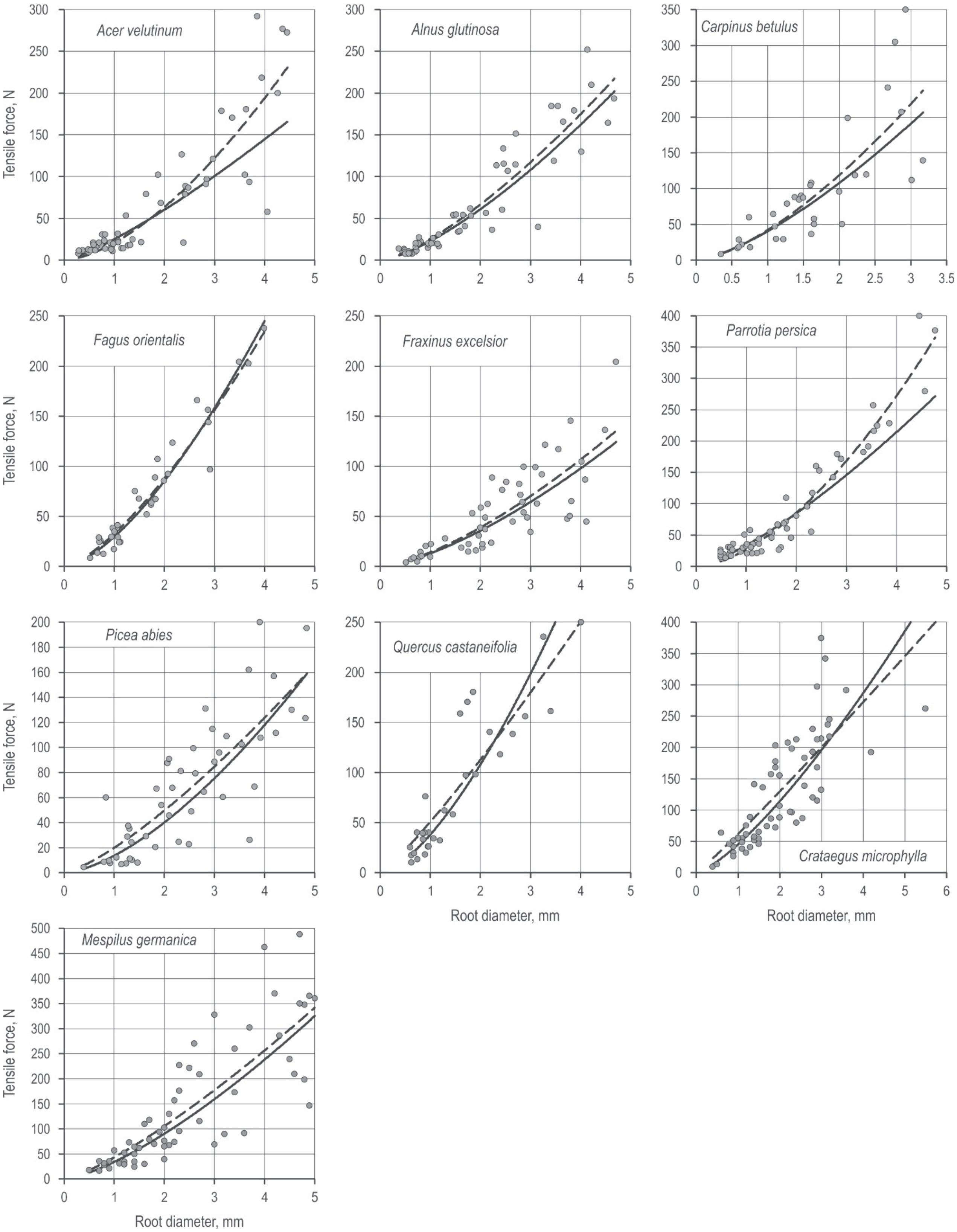

Fig. 4 Tensile force as a function of root diameter. Nonlinear least squares approximation (dashed line) and log-transformation method (continues line)

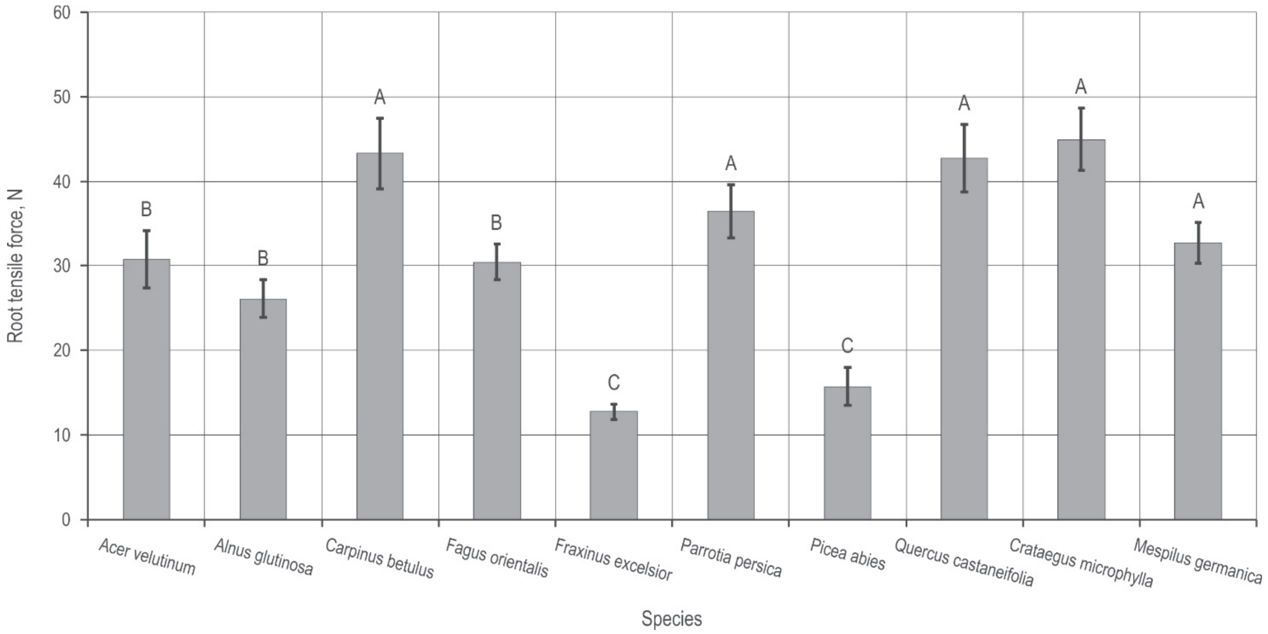

Fig. 5 Root tensile force (mean±SE). Means with different letters are statistically different ($p<0.05$)

species, and between 441.90 N and 487.20 N for the two shrubs. Mean tensile force values for hardwoods, softwood, and shrub species were 54.29–95.36, 66.51, and 135.86–143.25 N, respectively.

The relationship between root tensile force *F* (N) and root diameter *d* (mm) through power regressions (nonlinear least square and log-transformation) is presented in Fig. (4).

As shown in Fig. (4), log-transformation regressions generally underestimate the situation. Exceptions were found for *F. orientalis*, *Q. castaneifolia*, and *C. microphylla*, for which the nonlinear least square regressions were below the curves for the log-transformation. Generally, the main differences occurred at the top of the curves (thicker root diameters).

The regression coefficients (α and β), *AIC*, and adjusted R^2 for tensile force regression models are presented in Table (3).

The ranges of α and β were $13.02<\alpha<45.41$ and $1.26<\beta<1.55$ for log-transformation and $14.16<\alpha<61.83$ and $1.07<\beta<1.66$ for nonlinear least square power regressions regarding all species (Table 3).

Table 3 Regression coefficients, adjusted R^2 and AIC for tensile force of different species

		Log-transformation				Nonlinear least square		
Species	α	β	Adj. R^2	*AIC*	α	β	Adj. R^2	*AIC*
Acer velutinum	25.02	1.26	0.70	575.96	20.71	1.61	0.79	556.85
Alnus glutinosa	22.98	1.41	0.85	547.63	25.48	1.38	0.86	543.35
Carpinus betulus	40.64	1.40	0.60	346.39	42.17	1.49	0.63	344.30
Fagus orientalis	29.77	1.52	0.92	280.37	32.96	1.41	0.93	278.59
Fraxinus excelsior	13.02	1.45	0.62	470.92	14.16	1.45	0.63	468.79
Parrotia persica	33.44	1.34	0.87	573.50	26.95	1.66	0.93	527.34
Picea abies	13.62	1.55	0.64	458.97	19.90	1.32	0.66	455.64
Quercus castaneifolia	38.01	1.50	0.73	302.22	50.77	1.15	0.80	293.58
Crataegus microphylla	45.41	1.33	0.61	711.91	61.83	1.07	0.65	705.95
Mespilus germanica	34.38	1.39	0.65	663.95	43.50	1.28	0.67	661.17

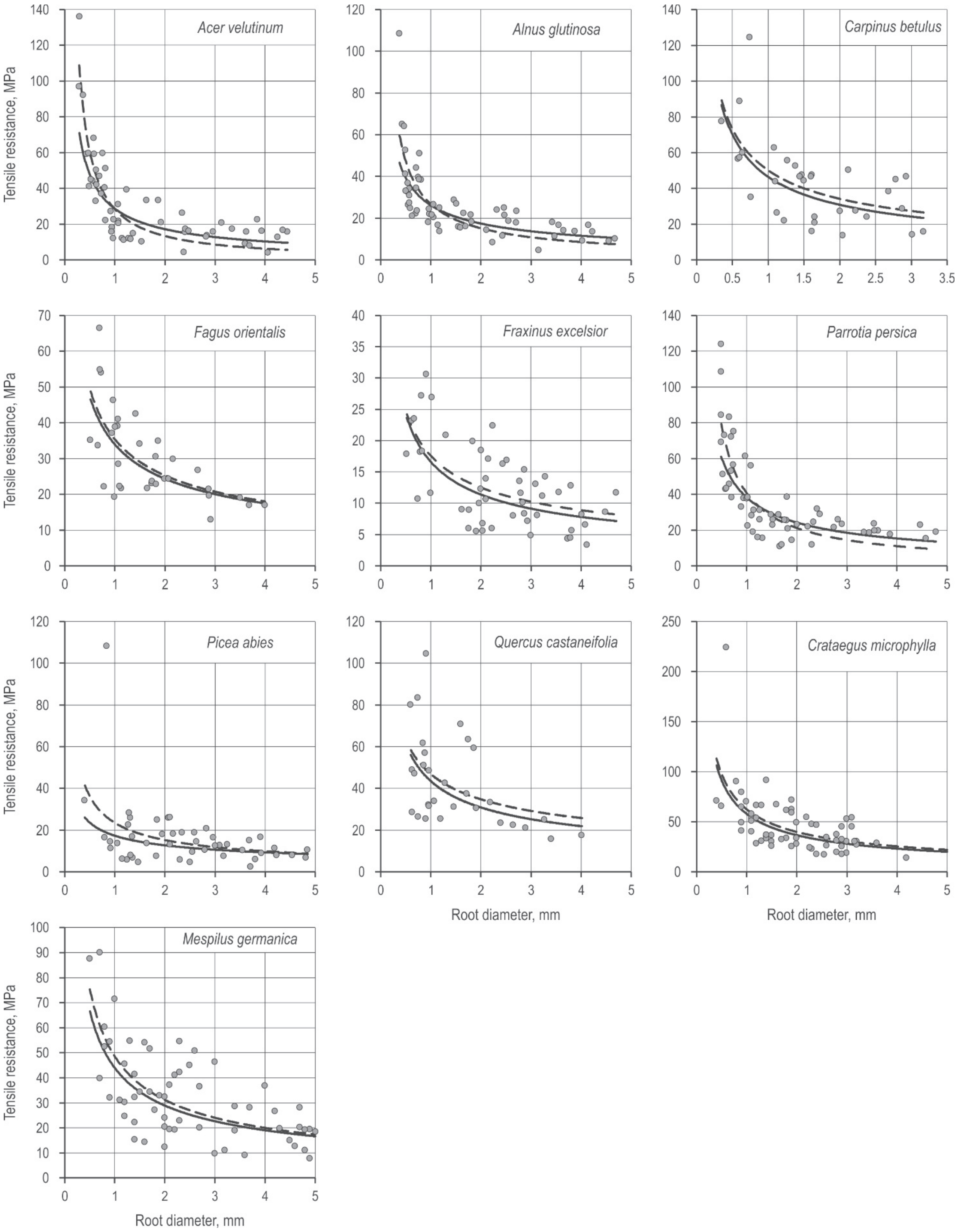

Fig. 6 Root resistance as a function of root diameter. Nonlinear least squares approximation (dashed line) and log-transformation method (continues line)

Table 4 Regression coefficients, adjusted R^2, and AIC for resistance of different species

	Log-transformation				Nonlinear least square			
Species	α	β	Adj. R^2	*AIC*	α	β	Adj. R^2	*AIC*
Acer velutinum	28.59	–0.73	0.66	461.68	28.34	–1.08	0.79	434.86
Alnus glutinosa	26.27	–0.59	0.53	458.25	26.87	–0.82	0.58	450.79
Carpinus betulus	46.45	–0.59	0.37	280.30	50.05	–0.55	0.39	279.16
Fagus orientalis	34.02	–0.48	0.41	244.15	35.47	–0.48	0.42	243.52
Fraxinus excelsior	16.58	–0.54	0.35	310.97	17.56	–0.49	0.38	308.93
Parrotia persica	38.22	–0.65	0.58	484.82	40.63	–0.94	0.67	470.90
Picea abies	17.34	–0.44	0.08	389.31	23.49	–0.62	0.15	385.61
Quercus castaneifolia	43.44	–0.49	0.17	266.45	46.79	–0.43	0.20	265.49
Crataegus microphylla	57.85	–0.66	0.33	591.87	62.44	–0.65	0.35	590.32
Mespilus germanica	43.80	–0.60	0.44	470.42	48.38	–0.64	0.47	467.32

As shown in Table (3), nonlinear least square regression resulted in lower AIC and higher adjusted R^2 values in all cases; therefore, lower residuals and better goodness of fit, indicating the advantage of nonlinear least square models and their coefficients for the relationship between force and diameter.

The results of the *ANCOVA* showed that mean root tensile forces were significantly different among species (F=37.36, p<0.001) with regards to root diameter as covariate factor (F=1453.77, p<0.000). The results of Tukey's test for mean comparisons are presented in Fig. 5.

The two shrub species, along with *C. betulus, P. persica*, and *Q. castaneifolia*, are categorized as the strongest species or as the species with the highest tensile force among the studied species (group A in Fig. 5). The species *A. velutinum* and *A. glutinosa* are intermediate (group B), while *P. abies* and *F. excelsior* are the weakest species regarding tensile force (group C in Fig. 5). The exception was *F. orientalis*, which, although the samples were obtained from a natural regeneration stand, was not among the strongest species regarding tensile force.

3.2 Root resistance

As shown in Table 2, minimum root resistance ranged between 3.32 and 15.83 MPa for hardwood tree species, 2.41 MPa for the only softwood tree species, and between 7.74 and 11.01 MPa for the two hardwood shrubs. Considering the maximum values, the ranges were 30.60 to 135.87 MPa for hardwood tree species, 108.10 MPa for the only softwood tree species, and 89.95 to 224.35 MPa for the two hardwood shrubs. Mean tensile resistance values for hardwoods, softwood, and shrubs were 12.74–43.31, 15.75, and 32.69–44.94 MPa, respectively.

The relationship between root resistance (MPa) and root diameter d (mm) through power regression (nonlinear least square and log-transformation) is presented in Fig. (6).

As shown in Fig. (6), log-transformation regressions generally underestimate the situation, especially in smaller root sizes. The exceptions were *A. velutinum*, *A. glutinosa*, and *P. persica*, where nonlinear least square regressions are below the log-transformation curves in roots greater than 1 mm in diameter.

The regression coefficients (α and β), *AIC*, and adjusted R^2 for root resistance regression models are presented in Table (4).

The ranges of α and β in resistance were $16.58<\alpha<57.85$ and $-0.66<\beta<-0.44$ for log-transformation and $17.56<\alpha<62.44$ and $-1.08<\beta<-0.43$ for nonlinear least square power regression.

As shown in Table (4), nonlinear least square regression resulted in lower *AIC* and higher adjusted R^2 values for all species and, therefore, lower residuals and better goodness of fit, indicating the advantage of nonlinear least square models and their coefficients for the relationship between resistance and diameter.

The results of the *ANCOVA* revealed that mean root tensile resistance was significantly different among the tested species (F=34.87, p<0.001) with regards to root diameter as covariate (F=274.26, p<0.000). The results of Tukey's test for mean comparisons are presented in Fig. (7).

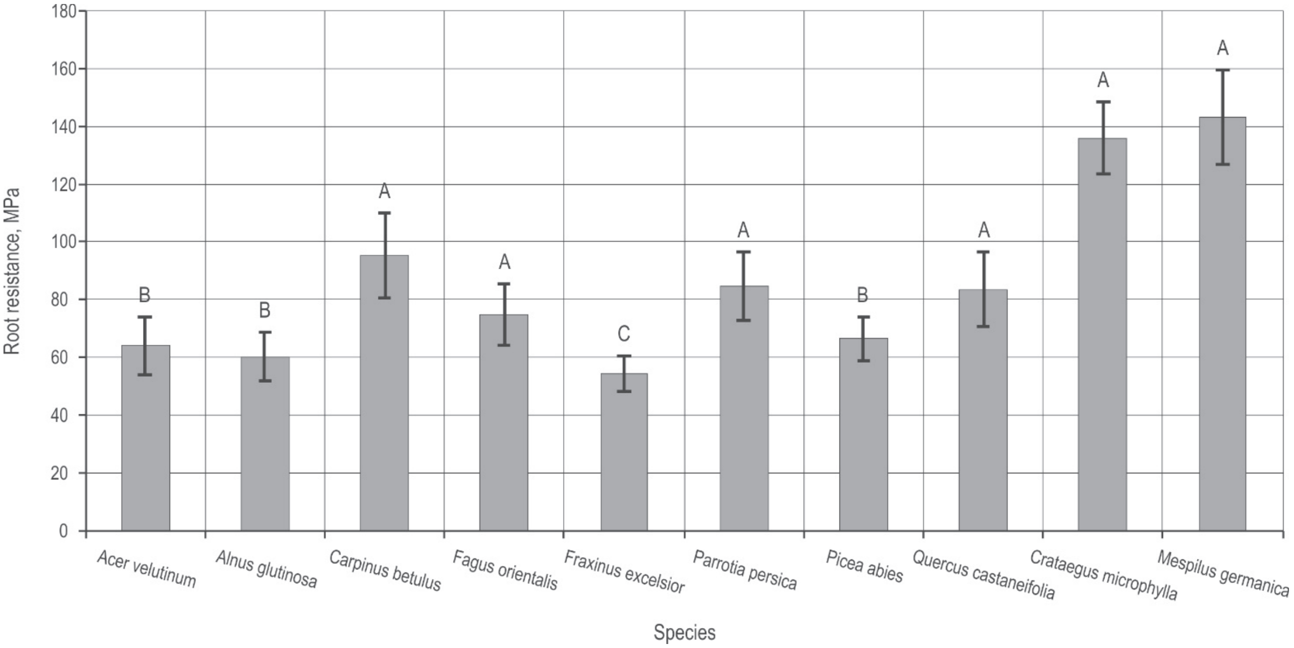

Fig. 7 Root resistance (mean±SE). Means with different letters are statistically different ($p<0.05$)

Regarding Fig. (7), the species can be classified in three groups (A, B, and C) based on root tensile resistance. The weakest species (classified as group C) was represented by *F. excelsior* in the 40-year-old plantation. Intermediate species (group B) were *A. velutinum*, *A. glutinosa*, and *P. abies* in plantation stands. Two shrub species as well as *C. betulus*, *F. orientalis*, *P. persica*, and *Q. castaneifolia* were the strongest species regarding root resistance (group A).

4. Discussion

Root tensile force and resistance are important factors that influence soil reinforcement and tree anchorage and provide essential data about using live materials for bioengineering techniques (Bischetti et al. 2010). Similar to several previous studies (e.g., Bischetti et al. 2005, Mattia et al. 2005, Schwarz et al. 2013, Vergani et al. 2014), we found a large variability in root tensile force and resistance based on species and root diameter. According to previous studies (e.g., Nilaweera and Nutalaya 1999, Bischetti et al. 2005, Abdi et al. 2010, Vergani et al. 2014), this relationship is well described, in terms of both force and resistance, by positive and negative power law regressions, respectively, confirming the strong dependence of root strength on root size. Genet et al. (2005) justified this relationship by different cellulose to lignin ratios, with smaller roots having higher ratios. Also Ye et al. (2017) attributed this relationship to the chemical composition of root tissues and showed that tensile force was significantly negatively correlated with cellulose and holocellulose and significantly positively correlated with lignin and the lignin to cellulose ratio, while for tensile resistance, opposite correlations have been reported.

In the current study, two regression methods (nonlinear least square and log-transformation) were used to obtain the coefficients of the power regressions (i.e., α and β). Based on the results, the power equation parameters were different in the two regression types (Tables 3 and 4). Regarding the *AIC* values and the adjusted R^2 values for model selection, the nonlinear least square method resulted in lower *AIC* and higher adjusted R^2 values, making it the preferred model for both force and resistance power regressions. This is consistent with Changyong et al. (2014), who reported that log-transformation may inaccurately estimate model parameters. Zuur et al. (2007) stated that the model with the lowest *AIC* and the highest adjusted R^2 values can be selected as the optimal model, which indicates the improved fit of the model to the data and, therefore, a lower residual sum of square (lack of fit). This may be due to the basis of the nonlinear least square method, which approximates the model first and then refines the parameters by successive iterations (Hesse 2006). This is consistent with the results of Schwarz et al. (2013) and Giadrossich et al. (2017), who indicated that different algorithms lead to different coefficients of the equation, although they did not report the optimal model. Previous studies (e.g., Vergani et al. 2014, Giadrossich et al. 2017) reported that small changes in the fitting curve of the root diameter–force or resistance relationship lead to changes in the output of root reinforcement models as an important factor in efficiency assessment of bioengineering measures (Bischetti et al. 2010). It has, therefore, been suggested that root resistance and force are critical factors in slope stability evaluations. Giadrossich et al. (2016) reported that using the log-transformation method results in an underestimation of force. Our results agree with the findings of Giadrossich et al. (2016) and showed that using the log-transformation method leads to an underestimation of both tensile force and resistance. Therefore, using values of the equation parameters of log-transformation will underestimate the effect of root reinforcement in stability analyses.

From a statistical point of view, Packard et al. (2011) point out that log-transformed models predict the geometric mean for the response variable, and that log-transformation inherently distorts the relationship between variables. The authors, therefore, recommend that analyses should be performed on the arithmetic scale via nonlinear regression, and this was reported as the advantage of nonlinear regression. Also, Packard (2012) showed that log-transformation of data created new distributions that actually obscured the relationships between predictor and response variables and led to bias. The author concluded that log-transformation is not a generally reliable way to estimate parameters in a simple power function on the original scale. The other advantage of nonlinear regression is that the use of nonlinear model fitting is facilitated by the availability of easy-to-use advanced statistical packages (Lai et al. 2013), which were not available at the time when log-transformation power regression appeared (Packard 2012).

Regarding the advantages of nonlinear regression and as power model coefficients are important factors in root reinforcement assessments in soil bioengineering measures, it is suggested that log-transformation models be replaced by nonlinear least square models to obtain more realistic estimates based on observations (tested root samples).

Regarding tensile force coefficients, Vergani et al. (2012) obtained the following α and β ranges for seven common European tree species: $8.31<\alpha<19.66$ and $1.49<\beta<1.85$. In the current study, α and β coefficients for the force-diameter relationship are generally out of the range for European tree species in both log-transformation and nonlinear least square methods. In this study, the ranges for eight common tree species of Hyrcanian species were $13.2<\alpha<40.64$ and $1.26<\beta<1.55$ for the log-transformation method and $14.16<\alpha<50.77$ and $1.15<\beta<1.66$ for the nonlinear least square method. The difference between the coefficients may be a result of different species and varying environmental conditions (Vergani et al. 2012, Boldrin et al. 2017).

Regarding root resistance coefficients, Nilaweera (1994) suggested the following α and β ranges for hardwood tree species roots: $29.1<\alpha<87.0$ and $-0.8<\beta<-0.4$. In this study, the ranges for eight common tree species of the Hyrcanian forest were $16.58<\alpha<46.45$ and $-0.73<\beta<-0.44$ for the log-transformation method and $17.56<\alpha<50.05$ and $-1.08<\beta<-0.43$ for the nonlinear least square method. In the current study, the α and β coefficients were generally in the range obtained for the log-transformation method (except α for *F. excelsior* and *P. abies*). However, for *F. excelsior* and *P. abies*, the α values were in the range obtained from the nonlinear least square method, while for *A. velutinum*, *A. glutinosa*, and *P. persica*, the β values were outside of this range (below -0.8). As ranges reported in Nilaweera (1994) are based on forests in Thailand, they may need to be reconsidered and modified based on more recent studies in different forest zones.

In the current study, the measured mean tensile forces for the Hyrcanian forest species (*A. velutinum* 64.15 N, *A. glutinosa* 60.25 N, *C. betulus* 93.36, *F. orientalis* 74.92 N, *F. excelsior* 54.29 N, *P. abies* 66.51 N) were similar to those obtained by Vergani et al. (2016) for some European species (*Acer pseudoplatanus* 65 N, *Ostrya carpinifolia* 56 N, *Fagus sylvatica* 84 N, *Fraxinus excelsior* 47 N, *Picea abies* 46 N). However, they were lower than those reported by Chiaradia et al. (2016) for *Fagus sylvatica* (122.46 N) and *Picea abies* (70.68 N). The differences between the values presented in this study and those in the literature may be explained by the different responses of plants to different environmental conditions (plasticity) to minimize abiotic and biotic stresses (Boldrin et al. 2017).

The measured mean tensile resistance values in the current study (*A. velutinum* 30.77 MPa, *A. glutinosa* 26.12 MPa, *C. betulus* 43.31 MPa, *F. orientalis* 30.47 MPa, *F. excelsior* 12.74 MPa, *P. persica* 36.41 MPa, *P. abies* 15.75 MPa and *Q. castanefolia* 42.67 MPa) are comparable to those reported in Stokes (2002), including *Alnus incana* (22 MPa), *Fraxinus excelsior* (26 MPa), *Acer platanoides* (27 MPa), *Picea abies* (28 MPa), *Quercus rubra* (32 MPa) and *Alnus japonica* (41 MPa). However, our values were larger than the mean resistance values reported by Boldrin et al. (2017) for re-established small trees (7.1–23.2 MPa). This may be explained by the report of Genet et al. (2006), who showed that tensile resistance was lower in the early growth stage and increased in older plants.

Comparisons of force–diameter relationships for different species (*ANCOVA*, Fig. 5) confirmed that there are statistically significant differences in root tensile force between species. In this regard, *F. excelsior* and *P. abies* can be considered as the weakest species, while *C. microphylla* and *M. germanica* (shrubs) are among the strongest ones. Broadleaved species generally have a higher tensile force than conifer species (except *F. excelsior* species), which is consistent with the results of Vergani et al. (2012). Stokes and Mattheck (1996) justified this with the different root anatomy of broadleaves and conifers, as broadleaves generally have larger cells and thinner cell walls.

We found statistically significant differences in root tensile resistance between species, with mean values ranging between 12.74 and 44.49 MPa. Several authors attributed these differences to genetic and environmental factors and the root system tissue composition (Genet et al. 2005, De Baets et al. 2008, Chiaradia et al. 2016, Ye et al. 2017).

In this regard, *F. excelsior* was the weakest species, while *C. microphylla* and *M. germanica* (shrubs) were among the strongest ones. This is in contrast with Morgan and Rickson (1995), who stated that the range of root resistance of shrub species is not significantly different from that of trees, although our results showed that they may even have higher values than some tree species. This is in agreement with Burylo et al. (2011) and Boldrin et al. (2017), who revealed that the roots of shrubs were more resistant than those of tree species. The mean resistance values of the two shrub species in our study (i.e., 44.94 and 32.69 MPa) are comparable to the results of Mattia et al. (2005) (*Pistacia lentiscus* 55.0, *Atriplex halimus* 57.2 MPa), and are higher than those found by Tosi (2007) (*Rosa canina* 22.95, *Inula viscosa* 18.72, and *Spartium junceum* 29.93 MPa) and Comino and Marengo (2010) (*Rosa canina* 42.9 *Cotoneaster dammeri* 18.7 and *Juniperus horizontalis* 14.8 MPa). Concerning the results of Boldrin et al. (2017), *Crataegus monogyna* had the highest tensile resistance (23.2 MPa) among the 10 shrubs and small trees of Europe, but in our study, the resistance of *Crataegus microphylla* (44.94 MPa) was about twice as high as that reported by Boldrin et al. (2017). This may partly be explained by the different environments and the fact that the species assessed by Boldrin et al. (2017) were in the early stage of establishment. Watson et al. (1999) reported a direct relationship between plant growth and increased reinforcement effect; similarly, Genet et al. (2006) reported increasing tensile resistance with plant growth and attributed this phenomenon to higher quantities of cellulose in older plants.

Previous studies have reported ranges for coefficients of root resistance power regressions in shrub species (e.g., Mattia et al. 2005, De Baets et al. 2008, Comino and Marengo 2010, Burylo et al. 2011). They reported the following ranges: $73.0<\alpha<91.2$ and $-0.60<\beta<-0.45$ for two shrub species (*Atriplex halimus* and *Pistacia lentiscus*) in Mattia et al. (2005); $4.41<\alpha<45.59$ and $-1.77<\beta<-0.45$ for 14 Mediterranean shrub species in De Baets et al. (2008); $14.79<\alpha<37.77$ and $-1.28<\beta<-0.83$ for three species (*Rosa canina, Cotoneaster dammeri* and *Juniperus horizontalis*) in Comino and Marengo (2010); and $4.4<\alpha<91.2$ and $-1.75<\beta<-0.52$ for two shrubby species (*Genista cinerea* and *Thymus serpyllum*) in Burylo et al. (2011). The results of the current study are consistent with those of Burylo et al. (2011), but do not fall into the range of De Baets et al. (2008) for α coefficients and De Baets et al. (2008) and Comino and Marengo (2010) for both α and β coefficients. Again, the difference between coefficients may be the result of different species and environmental conditions (Vergani et al. 2012, Boldrin et al. 2017).

The weakest species, based on resistance, were species in 40-year-old plantations (Fig. 7). This is consistent with the results of Watson and Marden (2004), who reported lower resistance values for plantations of radiate pine (17 MPa) and Douglas fir (25 MPa) compared to 11 New Zealand indigenous riparian plant species. The mean resistance values of plantation species in our study (ranging from 54–66 MPa) were significantly higher than those reported by Watson and Marden (2004) for radiate pine (17 MPa) and Douglas fir (25 MPa) in plantations and by Genet et al. (2008) for three different age stages of *Cryptomeria japonica* plantations, i.e., 22.6, 25.3, and 31.7 MPa for the juvenile, intermediate, and mature stands, respectively.

Considering that most landslides in the study area are rainfall-induced, hydrological effects of vegetation might not significantly affect soil stability in seasons with heavy rainfall (autumn and winter). In these seasons, the mechanical effects of vegetation or root reinforcement can play an important role in soil stabilization. Roots can mobilize their tensile resistance during failures along tension cracks (Vergani et al. 2017) and at the lateral surface of the landslide (Fig. 2a) and increase the resisting force against the driving force, thereby improving the stability of the slope. For this reason, species with higher root resistance (group A in Fig. 7) are preferred (Stokes 2002) in soil bioengineering systems (Bischetti et al. 2010), and the magnitude of the root resistance can influence the performance of these species. The results of our study should, therefore, be considered by forest managers when selecting suitable species for the reestablishment of vegetation on cut and fill slopes after road construction. In addition to tensile resistance, surcharge is an important criterion for soil bioengineering measures, especially on forest road cut and fill slopes that usually have higher slope angles than natural slopes. In this study, shrubs showed high root resistance, and as the negative effect of surcharge on slope stability (Chiaradia et al. 2016) is negligible for them compared to tree species (Morgan and Rickson 1995), they can be good choices for forest road stabilization. This may represent an advantage of shrubs compared to trees in soil bioengineering applications, especially on forest road cut and fill slopes.

5. Conclusions

We investigated the root mechanical behavior of eight common tree and two shrub species of the Hyrcanian forest. Two algorithms (nonlinear least square and log-transformation) were used to estimate the coefficients of the power regressions for force-diameter and resistance-diameter.

Root mechanical behavior is dependent on root diameter and can be well described by power law relationships as a function of the root diameter for both force and resistance functions. Our results showed that α and β not only depend on the species, but also on the statistical method applied. The nonlinear least square method was selected as the optimal model and can better explain the relationship between diameter-force and diameter-resistance. Also, using the log-transformation model underestimates power regressions of root force and resistance and therefore will underestimate the root reinforcement magnitude. Root tensile force and resistance differed significantly among species (*ANCOVA*) and were grouped into three strength classes; in terms of both force and resistance, shrubs constituted the strongest class. Furthermore, this study showed that trees in plantation stands had a lower resistance than trees in natural stands. Root tensile force and resistance are important inputs of root reinforcement models to estimate the quantity of increased soil cohesion and calculate slope stability, considering the presence of plant roots. These data may be used for the reestablishment of vegetation in cut and fill slopes, with the aim to reduce the risk of instabilities.

Further studies on the use of plants in bioengineering strategies should consider additional factors that might influence root mechanical behavior, such as site type, soil type, plant age, and elevation.

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