Environmental Engineering and Management Journal March 2021 Vol.20, No. 3, 419-433
http://www.eemj.icpm.tuiasi.ro/; http://www.eemj.eu

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INFLUENCE OF ROOT SYSTEMS OF DECIDUOUS TREES ON SOIL REINFORCEMENT – A CASE STUDY FROM THE CARPATHIANS, POLAND

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Abstract

Forests play an significant role in the protection of slopes against shallow landslides, and the presence of the tree roots in the soil is considered the most relevant factor increasing its shear strength. Most research on root reinforcement carried out in the European mountains refer to coniferous tree species but there is still not enough information about the root systems of decidous trees and their role in enhancing the slope stability. The aim of this study was to determine root reinforcement of four typical tree species (European hornbeam, common birch, black locust and small-leaved linden) growing in the forests of the Polish Carpathians. The measurements of root systems were performed using the trench wall method and the root reinforcement values were calculated using two fiber-bundle models - RBMw and RBMe, which represented different approaches to tensile force distribution within the root bundle. Studies have shown that the hornbeam roots have the highest, and the black locust roots – the lowest values of the tensile strength. Calculations showed that the values of root reinforcement obtained using the RBMw model are 17% higher than the ones calculated using the RBMe model. Root reinforcement values for common birch, black locust and small-leaved linden did not exceed 10 kPa, and in case of hornbeam they were about 20 kPa max. As part of the work, the parameters of the Root Distribution Model were estimated, which after integration with the bundle models allowed to determine the relation between the root reinforcement, the distance from the tree and its diameter.

Keywords: fiber bundle model, root area ratio, root reinforcement, root distribution model

Received: June, 2020; Revised final: December, 2020; Accepted: January, 2021; Published in final edited form: March, 2021

1. Introduction

Landslides are common phenomena that occur in different sites around the world and cause significant damage to technical infrastructure or even contribute to loss of humans' lives. According to data of the World Health Organization from between 1998-2017, landslides caused more than 18 000 deaths worldwide. The United States Geological Survey reports that an average of 25-50 people are killed by landslides each year in the United States. As Wood et al. (2015) report, despite extensive scientific research on landslides in the European Alps, data access is limited. Data are often dispersed, some of them origin from journals, different types of media, and they are mainly given at the regional level. Studies by Wood et al. (2015) show that in institutional databases of France and Switzerland, over 7 thousand cases of mass movements were descripted, in which over 5 thousand were classified as landslides. In Poland, the problem of landslides is particularly significant in the Carpathians, where the number of landslides is estimated at over 100000 (Wójcik and Wojciechowski, 2016) and some of them are classified as active ones. Considering the area of this region (19.6 thousand of km^2), the average landslide density is about 5 landslides/km^2. They occur both in forested areas, in areas used for agricultural purposes, and also

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in the vicinity of technical infrastructure.

Forests have a significant protective function for soil against erosion and mass movements (Cislaghi et al., 2017; Swanston and Dyrness, 1973; Wu, 1984; Ziemer, 1981). Trees affect soil in the mechanical and hydrological way. Plant canopies reduce the amount and the intensity of precipitation which reach the soil surface, leaves transpire water into atmosphere during the process of photosynthesis. Roots absorb water from the soil, change the soil structure and increase its infiltration capacity. As a consequence, vegetation decreases moisture content of soil (Coppin and Richards, 1990; Simon and Collison, 2002; Stokes et al., 2008; Wu, 1984). Mechanical interaction between soil and plants is related to root systems, which reinforce the soil and provide resistance of plants against wind. The increase of the soil shear strength or root fixation in the soil depends on root system morphology, strength of roots and their distribution within soil profile (Reubens et al., 2007; Stokes at al., 2008; Waldron, 1977; Wu et al., 1979). The number of roots produced by plants is related to, among other things, species features, plant size, distance from the aboveground part and habitat conditions (Abe and Ziemer, 1990; Coutts, 1983; Schmid and Kazda, 2002; Schenk and Jackson, 2005; Wu et al., 1988). Relatively large tensile strength of roots, other parts of plants (Ciuca et al., 2018) and man-made fibers (Lange et al., 1996) are commonly known and applied to improve properties of soil and other materials. Despite the fact that tree root systems in the mountain areas of Europe have been studied for many years (Bischetti et al., 2004, 2007, 2009, 2016; Chiaradia et al., 2012, 2016; Cislaghi et al., 2017; Di Iorio et al. 2013; Mao et al., 2012; Moresi et al., 2019; Schwarz et al., 2010a, 2010b, 2012a, 2012b, 2013; Tron et a. 2014; Vergani et al., 2012, 2014a, 2014b, 2016, 2017), due to their great biodiversity, there are still many species whose influence on soil reinforcement has not been recognized yet.

Over the last dozen years, a number of methods for estimation of soil reinforcement by the tree root systems have been developed, which differ in means of assessment of tensile force distribution within the root bundle and assessment of the root bundle displacement during the soil shearing. Currently, a commonly used model for calculating root reinforcement is the RBMw model created and developed by Schwarz (2013). The model assumes that the amount of force transmitted by roots depends on their deformation and is also described by Weibull survival function which takes into account strength variability of roots. There is also a model (originally called RBMs-W) proposed by Ji et al. (2019), which assumed that the amount of load carried by roots is based on the theory of energy. The Authors of the model assume that the force transmitted by the root is a function of work done while the soil is sheared. Comparison of direct shear tests and calculation results using different bundle models showed that this model provides fairly conservative predictions of root reinforcement.

The aims of this study were as follows:

- determination of root distribution and root area ratio of four tree species growing in the mountain forest of the Polish Carpathians, considering both effect of stem diameter, and distance from a stem;
- estimation of root tensile strength and its variability for the analyzed plant species;
- estimation of root reinforcement for all analyzed species by two dynamic fiber bundle models considering two different approaches to force distribution within root bundle.

2. Material and methods

2.1. Study site

The fieldwork was carried out in a forested area located in Winiary near Gdów (latitude N 49°54'05; longitude E 20°07'55) in Małopolska Voivodeship in Poland (Fig. 1). In May and June 2010, there were numerous landslides in the area, which were activated by long-term and intense rainfalls. The monthly sum of precipitation in May of 2010 measured at the nearby meteorological station in Gaik-Brzezowa (geographic coordinate 49° 52'N, 20°04'E) was equal to 475 mm. In June, the sum of rainfall was equal to 274 mm, but more than its half (146 mm) occurred in the period between the 1st and 6th day of the month. According to a report presented by the Ministry of Environment of the Republic of Poland, over 1300 landslides were activated in the Polish Carpathians in period of May and June of 2010, which damaged over 2200 buildings with 560 of them completely destroyed.

Geologically, the area is located in the Western Outer Carpathians, in the Northern part of the Silesian unit. According to the Detailed Geological Map of Poland (Burtan, 1954) the area is covered by quaternary loess clays, and below them there are some Cretaceous formations – conglomerates and shales of the Istebna and Lgota beds, variegated shales as well as sandstones and gaizes. Slope fall direction is to the southern , whereas the direction of the rock layers dip is southwestern, and their inclination range from 22 to 70°. The dominant trees in the area include deciduous species - European hornbeam (*Carpinus betulus*) and the secondary species were common birch (*Betula pendula*), black locust (*Robinia pseudoacacia*), small-leaved linden (*Tilia cordata*), common oak (*Quercus robur*) and wild cherry (*Prunus avium).*

2.2. Field measurements

The root area ratio (RAR) of the European hornbeam, common birch, black locust and small-leaved linden was determined during fieldwork using the trench wall method (Böhm, 1979). The trenches were at least 1.0 m wide and they reached the depth of 1.0 m or the depth of the bedrock. Schiechtl (1980, after Bischetti et al., 2009) indicates that in the Alpine environment such depth can be considered a good reference for rooted soils. Moreover, the results of Brożek and Zwydak (2003) obtained in the Polish

Carpathian forests revealed that below the depth of 1.0 m the roots are scarce. The tests were carried out both below and above the trunk at a distance of about 1.0, 2.5 or 4.0 m from it. After the trench was made, on one of the walls (the one closer to the tree trunk) the soil was loosened with a knife to a depth of about 2-5 cm and then removed to expose the roots. Then, 10 cm high layers were defined on the wall and the number of roots and their diameters were measured within each layer. Roots with diameters larger than 1 mm were taken into account during the measurements, while the calculations of root reinforcement were based on roots with diameters from 1 to 10 mm, which are characterized by relatively high flexibility and meet the assumptions of the bundle models (Bischetti et al., 2009).

The value of RAR was calculated as a ratio of the sum of cross-sectional area of roots intersecting the vertical surface of the trench wall and the vertical surface of the trench wall. The values of RAR were compared with the data provided in the literature.

For the purposes of the analysis, the number of roots was related to the surface of the layer (or the whole trench) and in the further part of the work it was replaced by the term root system density. Measurements of root systems were done in 18 trenches (Table 1).

Only the measurements carried out at a distance of about 1 m from the stems were taken into account in a statistical analysis. Values of root system density and RAR for each species were averaged within each layer. The normality of both parameters was tested using the Shapiro-Wilk test at the significance level of α=1%, then the correlation between these parameters and depth was determined. To obtain normal distribution of both analyzed parameters, the values of the number of roots were logarithmized, and the RAR values were transformed by the square root. In order to compare the test results between tree species, a covariance analysis was performed, where the dependent variable was the root density (as a derivative of their number) and RAR, the qualitative factor was the species, and the depth was the covariate.

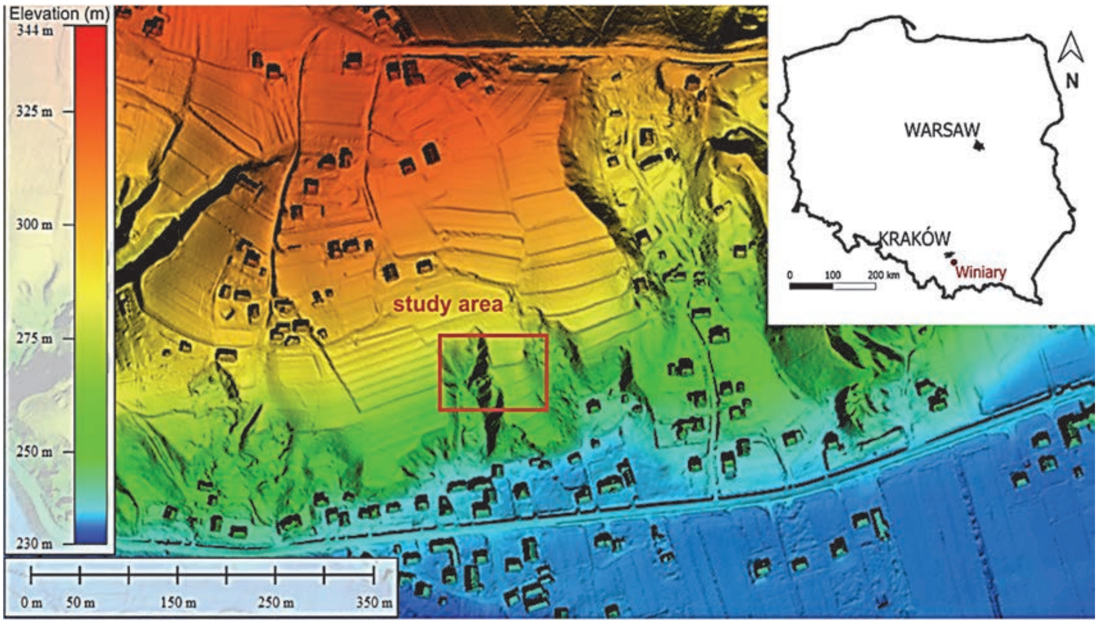

Fig. 1. Location of the study area (own elaboration based on data obtained from CODGiK*)
*- Geodesic and Cartographic Documentation Center of Poland

Table 1. Data on the tested trees

Parameters	***Species***			
	European Hornbean (Carpinus betulus)	***Common birch (Betula pendula)***	***Black locust (Robinia pseudoacacia)***	***Small-leaved linden (Tilia cordata)***
Number of trenches	7	2	4	5
Distance tree-trench, m	0.8-4.0	0.8-1.0	1.0-2.5	1.0-4.0
Depth of trench, m	0.8-1.0	0.6-1.0	1.0	1.0
Diameter at breast height, m	0.18-0.35	0.18-0.23	0.16-0.17	0.24
Diameter at root collar, m	0.30-0.34	0.31-0.34	0.21-0.31	0.28
Other woody species	Ca, Bp, Or	Cb	Cb, Bp	Or

Explanation: Ca - European hazel, Or - common oak, Bp – common birch, Cb – European hornbeam

2.3. Laboratory tests

Laboratory tests included determining basic geotechnical parameters of the soils underlying the landslide, i.e. their grain size composition, consistency limits, shear strength and tensile strength of roots collected during fieldwork. Geotechnical parameters of soils were determined using standard methods in accordance with current standards (PN-EN ISO 17892-4:2017-01; PN-EN ISO 17892-12: 2018-08; PN-EN ISO 17892-9: 2018-05; PN-EN ISO 14688-2: 2006).

Root tensile strength tests were carried out on samples that were 10 cm long and at deformation velocity of 10 $mm \cdot min^{-1}$. Before the test, the samples were placed in water for at least 24 hours to saturate them. After that, the diameter of each sample was measured in 3 places and tensile test was conducted. The analysis omitted the results of samples which were breaked in the jaws of the apparatus.

Modulus of elasticity (*E*) of each sample was determined using values of tensile force (*F*) and displacement (Δx) at its rupture. In order to compare the results of *F* and *E*, a covariance analysis (ANCOVA) was performed, where the dependent variable was the tensile force (*F*), the qualitative factor was the tree species, and the covariate – the root diameter.

The results of the tensile force (*F*) test and the number and diameter of roots were used to calculate the root cohesion.

2.4. Calculations

2.4.1. Root distribution

The number and diameter of roots were measured at different distances from the tree stems and these results were used to determine the parameters of the Root Distribution Model (RDM) developed by Schwarz et al. (2010a, 2012a). This model assumes that the radial range of the tree root system (D_{max}) is related to its above-ground part size and equals (Eq. 1):

$$D_{\max} = \psi \cdot DBH \tag{1}$$

where: ψ - proportionality coefficient; *DBH* – diameter of tree at breast height (m).

Whereas the number of roots (N_i) in a given diameter class size (d_i) equals (Schwarz et al., 2012a; Giadrossich et al., 2016) as follows (Eq. 2):

$$N_i(D, DBH) = D_{fr} \cdot \frac{\ln(1+d_{\max}) - \ln(1+d_i)}{\ln(1+d_{\max})} \cdot \left(\frac{d_i}{d_0}\right)^{\lambda} \tag{2}$$

where: *D* – distance from the tree trunk (m); D_{fr} – density of fine roots (smaller than 0.001 m); d_{max} – maximum diameter of root (m); d_i – mean root diameter in class size „i" (m); d_0 – reference diameter (equal to 0.001 m); λ - constant exponent (-).

The distance of the trench from the tree was taken into account to calculate the density of fine roots using the following equations (Schwarz et al., 2012a) (Eqs. 6-7):

$$D_{fr}(D) = \frac{\mu \cdot DBH \cdot \left(0{,}7 + 0{,}06 \cdot \frac{D}{DBH}\right)}{10 \cdot \pi \cdot DBH \cdot D_{\max}} \quad if \quad D < 5 \cdot DBH \tag{3}$$

or

$$D_{fr}(D) = \frac{\mu \cdot DBH}{2 \cdot \pi \cdot D \cdot D_{\max}} \quad if \ D \geq 5 \cdot DBH \tag{4}$$

and regardless of the distance from the tree (Giadrossich et al., 2016) (Eq. 5):

$$D_{fr}(D) = \frac{\mu \cdot DBH^2}{8 \cdot D \cdot D_{\max}} \cdot \frac{D_{\max} - D}{D_{\max}} \tag{5}$$

where: μ - pipe-theory coefficient.

The maximum root diameter depends on the distance from the stem and was calculated from the (Giadrossich et al., 2016) (Eq. 6):

$$d_{\max} = \frac{D_{\max} - D}{\eta} \tag{6}$$

where: η - scaling coefficient.

In the RDM model, the ψ, λ, μ and η parameters are unknown, and the remaining parameters are obtained based on the measurements. The estimation of the unknown parameters in the model was carried out in several stages. The value of the ψ parameter was taken from Schwarz et al. (2010a) whereas the value of the η parameter was estimated by comparing measured and theoretical values of d_{max} calculated from the (Eq. 6). Then, the remaining model parameters (λ, μ) were estimated in the Statistica v.12 program. The density of fine roots, necessary to estimate μ parameter, was determined in two ways. In the first case, the calculation method depended on the ratio of the distance from the trench to the stem and its DBH (Eqs. 3-4). In the second case only one equation was used (Eq. 5).

The results obtained from the calculations were compared with the results of field tests and evaluated based on the value of the Nash-Sutcliffe effectiveness coefficient (NSE) (Eq. 7) and the root mean square error (RMSE) (Eq. 8):

$$NSE = \frac{\sum(N_m - N_{am})^2 - \sum(N_m - N_p)^2}{\sum(N_m - N_{am})^2} \tag{7}$$

$$RMSE = \sqrt{\frac{\sum(N_p - N_m)^2}{n}} \tag{8}$$

where: N_m – measured number of roots in a given diameter class; N_{am} – average measured number of roots; N_p – estimated number of roots in a given diameter class; n – the number of observations.

The range of diameters in each root class was equal to 1 mm. The first class included roots of diameters from 1 mm to 2 mm, and the last included diameters up to 20 mm. The average measured number of roots (N_{am}) was estimated as a mean number of roots considering all diameter classes.

2.4.2. Root reinforcement

Research on the influence of plant root systems on soil reinforcement began in the second half of the last century, and the theoretical basis for describing this interaction was proposed by Waldron (1977) and Wu et al. (1979). It is assumed that during the displacement (shearing) of the soil, tensile forces in the roots are mobilized. Roots, which – as compared to the soil – are characterized by high tensile strength, provide the soil with additional shear strength (so-called root cohesion), which increases the shear strength of the soil and, as proposed by Wu et al. (1979) and Waldron (1977) (and called Wu-Waldron model), can be described as (Eq.9):

$$c_r = k \cdot \sum \left(RAR_i \cdot T_{ri} \right) \tag{9}$$

where: k – factor depending on the angle of internal friction of soil and the angle of root orientation in regard to shear plane; usually assumed as equal to 1.0 - 1.2 (Chiariadia et al., 2016); RAR_i – root area ratio of the root; T_{ri} – tensile strength of the root.

The model assumes that the value of force transmitted by the root system is the sum of force transmitted by single roots and the maximum tensile strength is mobilized in all roots at the same time. This assumption does not coincide with the results of tests on tree root systems (among others, Ji et al., 2019; Thomas and Pollen-Bankhead, 2010), which indicate that the failure of the root system is a more complex process, where the roots are progressively broken off from the weakest to the strongest.

Therefore, a number of bundle models (FBM, RBM) describing the interaction between roots and soil have been developed (Ji et al., 2019; Mao et al., 2012; Pollen and Simon, 2005; Schwarz et al., 2012b, 2013; Thomas and Pollen-Bankhead, 2010). In general, the bundle models, unlike the Wu-Waldron model, assume that the failure of the root bundle is progressive, and the size of forces mobilized in roots depends on how the tensile forces are distributed to individual roots, their tensile strength, and - in some models (RBM) - on their elasticity and length of individual roots.

The root reinforcement was determined using two strain step loading fiber bundle models (RBM). In the RBMw model, proposed by Schwarz et al. (2013), geometrical properties of the root are described by the following correlated formulas (Eqs. 10-12):

$$L(d) = L_0 \cdot \left(\frac{d}{d_0} \right)^A \tag{10}$$

$$E(d) = E_0 \cdot \left(\frac{d}{d_0} \right)^B \cdot r \tag{11}$$

$$F_{\max}(d) = F_0 \cdot \left(\frac{d}{d_0} \right)^C \tag{12}$$

where: L – root length; L_0 – empirical characteristic root length with d_0 diameter; E – elasticity modulus (Young's modulus); E_0 – empirical characteristic elasticity modulus of the root with d_0 diameter; F_{max} – as equation (2); F_0 – empirical characteristic tensile force of the root; r – coefficient which considers the effects of root tortuosity on the tensile behavior of a root; A, B, C – empirical exponents; d_0 – the reference diameter of the root, to simplify Eqs. (10-12) 1.0 mm can be used (Schwarz et al., 2012b).

By integrating the above equations, the value of force transmitted (mobilized) by a single root at Δx deformation was determined using the Eq. (13):

$$F(d, \Delta x) = \frac{r \cdot \pi \cdot E_0 \cdot \Delta x}{4 \cdot L_0} \cdot d^{2+B-A} \tag{13}$$

and considering high variability of mechanical parameters of roots, the value of force transmitted by a root bundle (F_{tot}), as proposed by Schwarz et al. (2013), can be described as follows (Eq. 14):

$$F_{tot}(\Delta x) = \sum F(d_i, \Delta x) \cdot S(\Delta x_i *) \tag{14}$$

where: $S(\Delta x_i*)$ – two-parameter Weibull survival function (Eq. 15):

$$S(\Delta x_i *) = \exp\left[-\left(\frac{\Delta x_i *}{\chi *} \right)^{\omega} \right] \tag{15}$$

where: Δx_i*- normalized displacement of a root; ratio of displacement and maximum displacement of a root (Δx_{max}); χ* - the scaling parameter; ω - shape factor of the survival function.

The values of χ* and ω parameters are determined based on the results of tensile strength tests, creating a survival function. This function considers the relationship between the root deformation at the moment of rupture and the theoretical maximum displacement (Δx_{max}) resulting from Eqs. (10-12).

In the RBMw model, the calculations of root reinforcement are divided into a few steps, in which deformation (Δx) of each root within the bundle is the same. If deformation of the root is lower than its maximum (Δx_{max}), force is calculated from the (Eq. 13); if not, from the (Eq. 12). In both cases the value of force is multiplied by the value of Weibull survival function (Eq. 15), and the value of force mobilized by the bundle is a sum of forces mobilized by each root (Eq. 14).

On the other hand, Ji et al. (2019) propose a different approach to determine the value of root cohesion. In the proposed model (RBMe), in the original FBMs-W (Ji et al., 2019), they assume that the amount of root displacement and the strength mobilized by the roots is a derivative of the work they have done (Eq. 16):

$$F_{tot} = \sum F\left(d_i, W\right) \tag{16}$$

where: W – the work done by the root that equals (Eq. 17):

$$W\left(d_i\right) = F\left(d_i\right) \cdot \Delta x\left(d_i\right) \tag{17}$$

There are three means by which work can be distributed to individual roots - proportionally to the number of roots, their cross-sectional area and their diameters. In the presented study it was assumed that the same value of work is transmitted to all roots. This model assumed the work done by the bundle, so the deformation of individual roots varies at each step of calculation. The calculations can be divided into two main stages (Fig. 2). In the first stage, it is checked whether individual roots are able to perform the assumed amount of work. In the second stage the value of the force transmitted through the roots and the corresponding deformation are determined using an iterative method, in accordance with the Eqs. (10-12).

The parameters of Weibull survival function (Eqs. 15) were estimated in the Statistica v. 12 program. The parameters in Eq. (10) were adopted based on the results of studies by Schwarz et al. (2010a, 2012b). The root reinforcement value was calculated as the maximum force transmitted by the root bundle divided by the surface of the trench wall.

The computations were made using Visual Basic for Application library in Microsoft Excel. Figures were prepared using Microsoft Excel and a Python data visualization libraries Matplotlib (Hunter, 2007) and Seaborn (Waskom et al., 2020).

The paper compares the results of root reinforcement calculations carried out using RBMw and RBMe models, thus showing the differences and consequences of the adopted calculation assumptions. The results between the tree species were also compared and relations between the stem diameter (DBH), the distance from the stem and the amount of root reinforcement were developed by integrating calculations using the RDM and RBMw models.

3. Results and discussion

3.1. Geotechnical parameters of soil

The results of field and laboratory tests have shown that the soil in the analyzed landslide area consists mainly of silty formations (coarse silt, sandy coarse silt, clayey coarse silt, silty clay). Based on the obtained liquid limits (w_L = 21.3-52.6% - mean 32.6%,) plastic limits (w_p = 13.0-21.3% - mean 17.6%) and the plasticity indexes (I_p = 6.8-31.22% - mean 15.0%) the tested cohesive soils were classified as soils with low and medium plasticity. Colloidal activity of the tested soils ranged from 0.6 to 2.3, so they can be classified as inactive or moderately active soils. The shear strength parameters obtained from triaxial compression test with consolidation without drainage indicate that these soils are characterized by high values of the angle of internal friction (32.7-35.8°) and low cohesion (3.2-7.2 kPa).

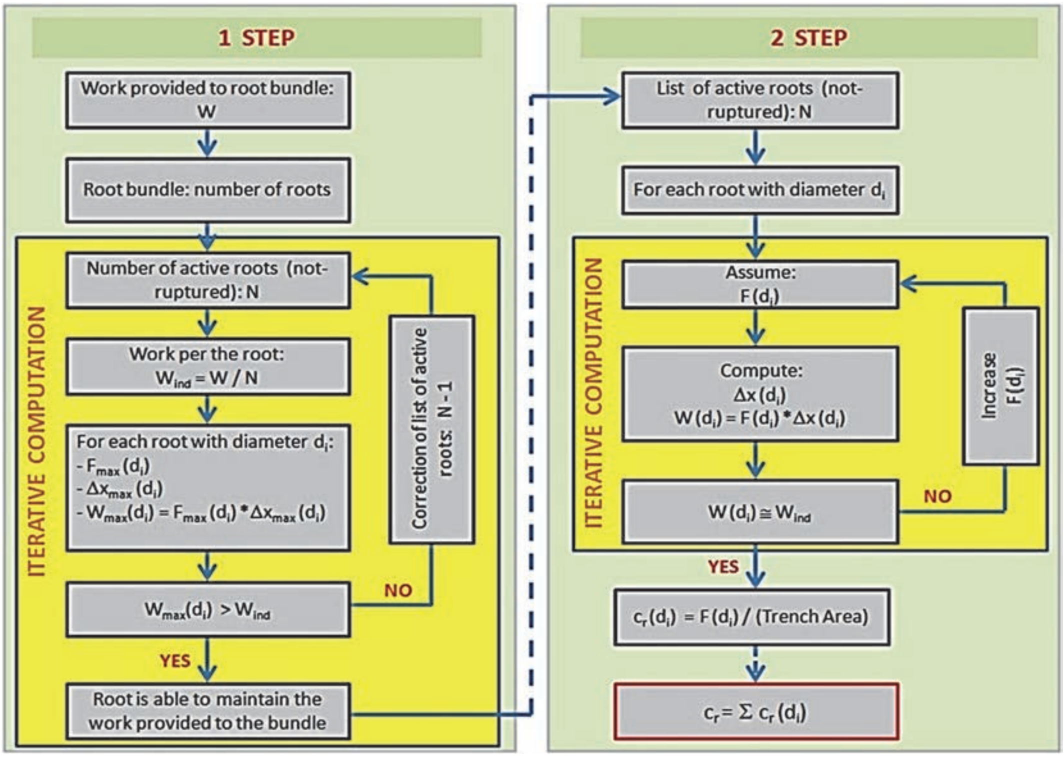

Fig. 2. Computation algorithm of RBMe model (work-driven Root Bundle Model)

3.2. RAR and density of roots

The root system density of the tested tree species (Fig. 4a, 5a) and the root area ratio (RAR) (Fig. 3b, 4b) were characterized by high variability, which is consistent with results obtained by other authors (Abdi and Deljouei, 2019; Bischetti et al., 2007, 2009; Mao et al., 2012). Both root density and root area ratio significantly decreased with depth, and 60-100% (mean 81%) of roots occured up to the depth of 0.5 m. In 7 of 15 trenches no roots were observed at the depth of 1.0 m. The maximum RAR values were generally located in the surficial layers, between 0.0 and 0.3 m.

Statistical analysis (ANCOVA) of measurement results showed that both values – root system density (expressed as the number of roots per trench surface) and their root area ratio (RAR) – differed significantly between species (respectively F (3.35) = 5.54, p = 0.003 and F (3.35) = 5.72, p = 0.003). These differences, however, related primarily to the root systems of hornbeam and black locust, as these trees differed in DBH (Table 1). Due to the fact that DBH affects the size of the root system and is included in the RDM model, all the measured data were considered in the calculations of model parameters. The results of root density calculations based on the estimated parameters of the RDM model (Table 2) were compared with the results of field measurements (Fig. 5). The obtained relations indicate that there is a relatively good convergence of the estimated and measured number of roots, although the results of calculations using the equation (5) were better matched to the measured data. It can be stated, that the results of calculations using the RDM model were better matched to the results of measurements taken 1.0 m from the trees, especially in the case of Giadrossich et al. (2016) method. It was also observed that both models underestimate the number of roots.

3.3. Tensile strength and the elastic modulus of roots

The results of root tensile strength tests are summarized in Table 3 and Fig. 6. Statistical analysis (ANCOVA) showed that both the tensile force and modulus of elasticity are correlated with the root diameter. The calculations showed that the tensile strength of European hornbeam roots was much higher than of small-leaved linden and black locust (F (2.138) = 18,098, p = 0.0). On the other hand, the covariance analysis (ANCOVA) showed that the modulus of elasticity did not differ significantly between the analyzed tree species (F (2.138)) = 0.473, p = 0.62).

The relationship between the tensile force and the root diameter (Fig. 6a) was characterized by a high correlation, which is common in this type of tests (Vergani et al., 2012). On the other hand, the relationship between the elastic modulus and root diameter (Fig. 6b) was much weaker than indicated by the values of tensile strength. Our studies also showed that the relation between the modulus of elasticity and the root diameter is often not statistically significant. .

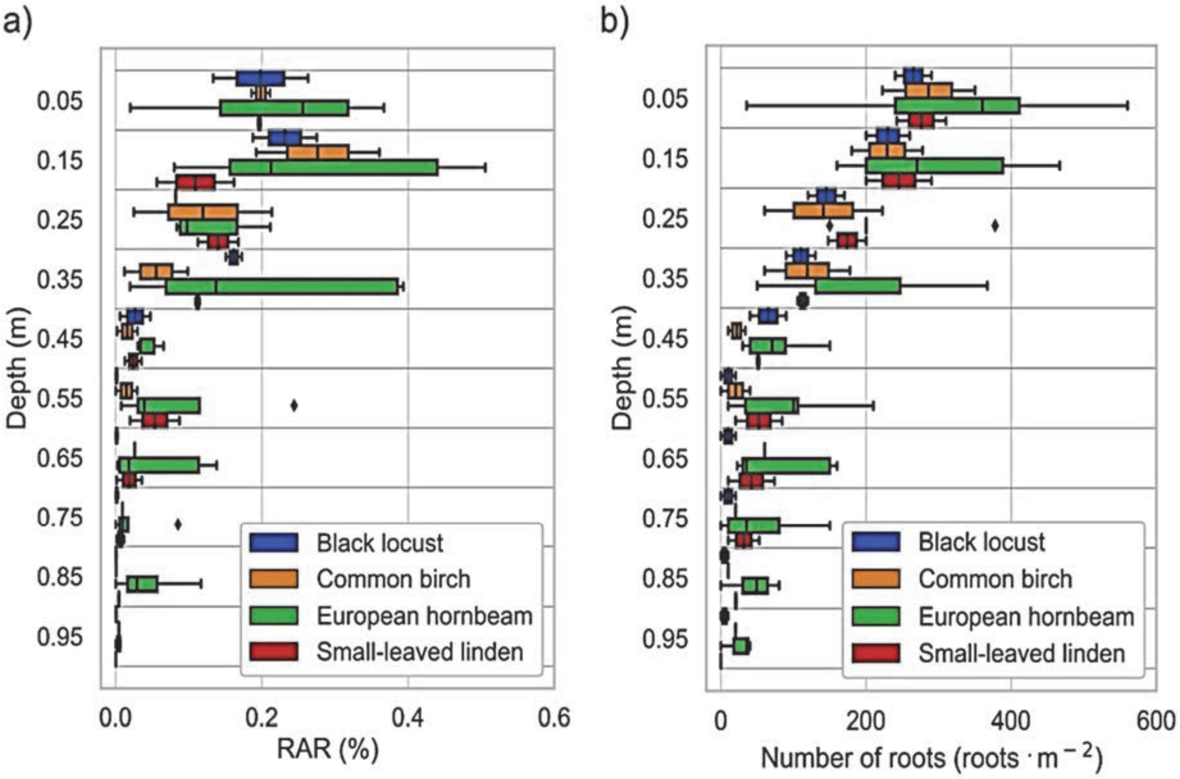

Fig. 3. Results of root density (a) and RAR (b) as function of depth at distance approximately 1 m from the tree trunks

Table 2. Values of Root Distribution Model

Calculation method of density of roots	ψ ***(-)***	η ***(-)***	λ ***(-)***	μ ***(roots·m^{-2})***	***NSE***	***RMSE***
Schwarz et al. (2012a) (Eqs. 3-4)	18.5	125	-1.67* -1.90**	4 000* 16 500**	0.60	8.16
Giadrossich et al. (2016) (Eq. 5)			-1.78	90 000	0.68	7.30

*Explanation : *for D <5 DBH, ** for D ≥5 DBH*

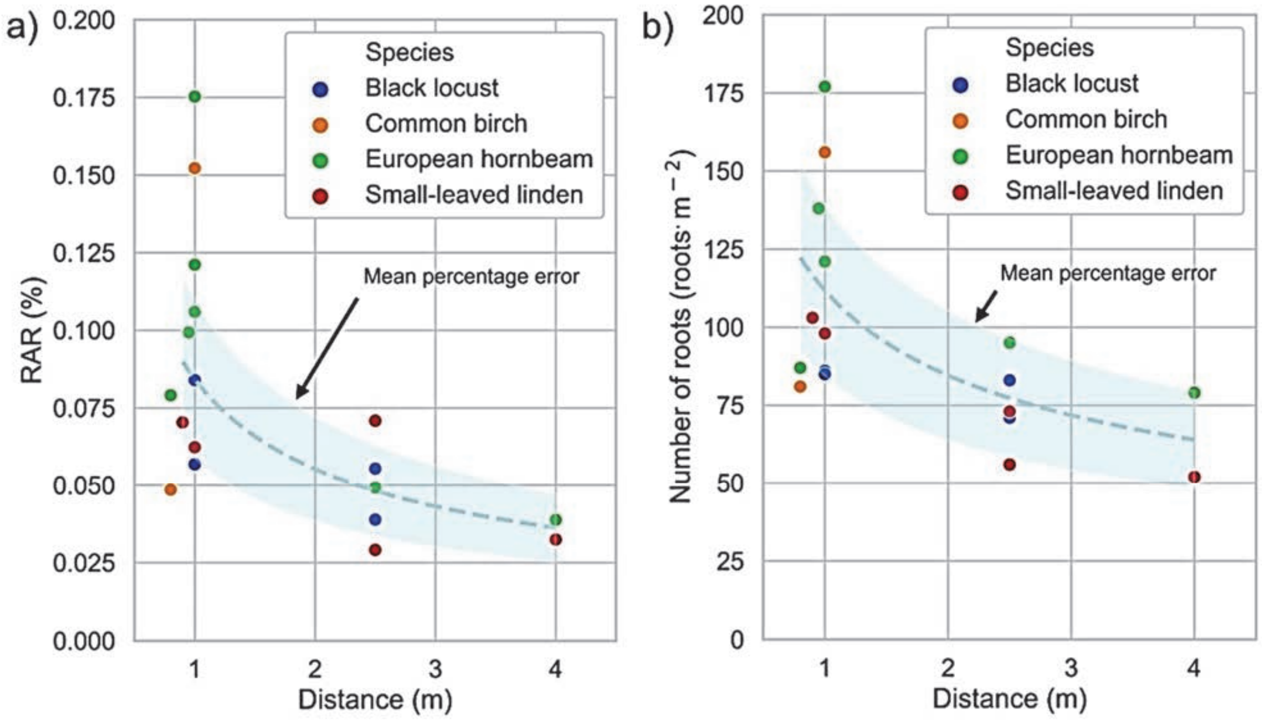

Fig. 4. Depth-averaged values of root number (a) and RAR (b) as a function of species and distance from stem of the trees

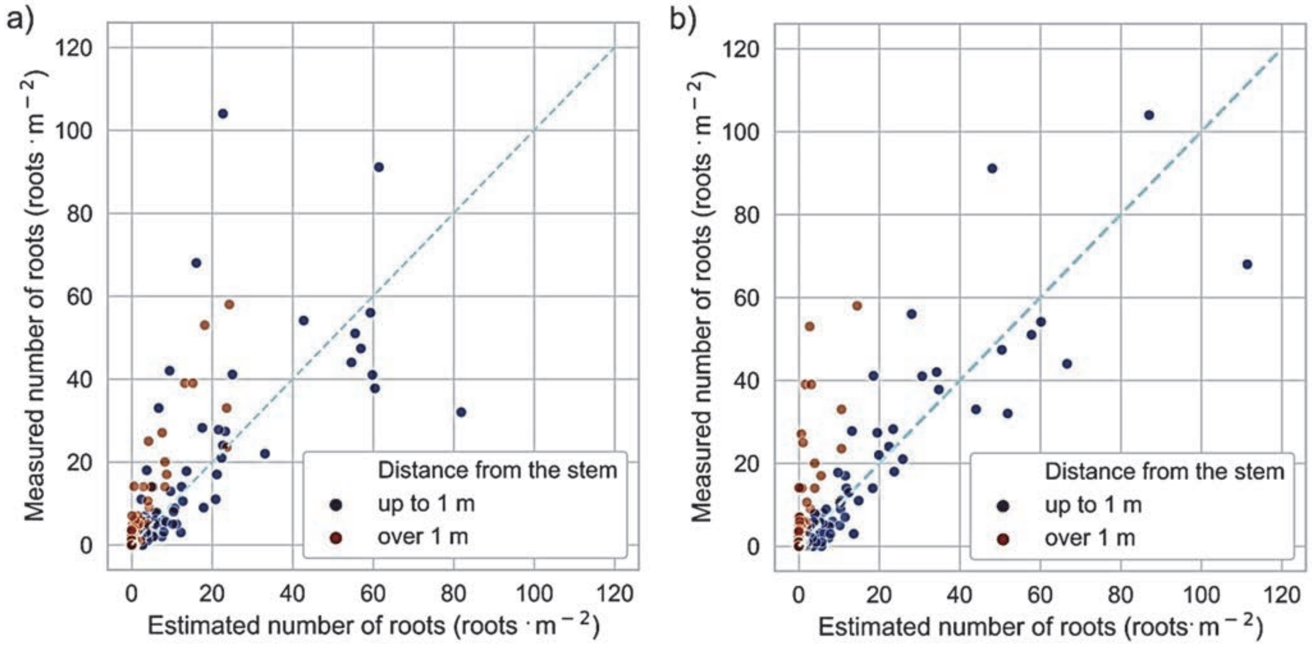

Fig. 5. Comparison of the root system density calculations using Schwarz et al. (2012a) (a) and Giadrossich et al. (2016) method (b) with the results of field measurements

3.4. Root reinforcement

Root reinforcement calculations were performed using two bundle models (RBMw and RBMe). The calculation results indicate (Fig. 7a) that the values of root reinforcement obtained using the RBMw model are about 16% higher than the ones from the RBMe model. It should be noted that the difference in the results from both models was different for each tree species. In the case of small-leaved linden, the influence of the calculation method on root cohesion was low and could be related to the fact that for the roots of this species, the Weibull function shape factor was the lowest. Schwarz et al. (2013) indicate that low values of this parameter decrease the value of root reinforcement. On the other hand, the greatest differences between the results from the RBMw and RBMe models (on average 20% relatively) were obtained for the European hornbeam roots, which had the highest tensile strength among the tested species.

In general, the values of root reinforcement, similarly to the results of RAR, decrease with the distance from the tree stem. For instance, soil shear strength increment provided by the presence of European hornbeam roots at the distance of 1.0 m from the stem was over 10 kPa, but decreased to 5.4 kPa at 4 m from the stem. It was also stated that values of root reinforcement were significantly correlated with the values of root area ratio (Fig. 7b).

In order to generalize the root reinforcement of the analyzed tree species, we integrated root distribution (RBM) and Root Bundle Model (RBMw) and performed calculations for the European hornbeam and small-leaved linden root systems. As a result of these calculations the relation between root cohesion values, DBH and distance from the stem was determined (Fig. 8). The obtained results indicate that there is a significant difference between the values of root cohesion of European hornbeam and small-leaved linden.

The maximum root reinforcement values obtained for the hornbeam are over 100 kPa for trees with DBH greater than 0.8 m at a distance of 0.5 m. However, generally for trees of this species with DBH equal 0.3 m, soil reinforcement above 20 kPa occurs only at a distance of less than 1 m from the stem. On the other hand, for small-leaved linden trees with the same value of DBH and distance from the trunk, the soil reinforcement does not exceed 5 kPa.

Table 3. Tensile, elasticity parameters of roots and parameters of Weibull survival function

Tree species	***Tensile force of roots***				***Modulus of elasticity of roots***				***Weibull function parameters***	
	F_0 (N)	**C (-)**	**R^2**	**p**	**E_0 (MPa)**	**B (-)**	**R^2**	**p**	**ω**	**χ***
Common birch*	19.7	1.69	0.80	< 0.01	206.9	-0.04	-	-	3.25	1.0
Black locust	31.3	1.16	0.51	< 0.01	155.1	-0.43	0.27	< 0.01	3.50	1.13
European hornbeam	32.1	1.61	0.82	< 0.01	214.2	-0.11	0.03	< 0.01	2.73	1.2
Small-leaved linden	22.4	1.46	0.77	< 0.01	439.0	-1.25	0.61	< 0.01	1.66	1.58

*Explanation: *data from (Zydroń, 2019)*

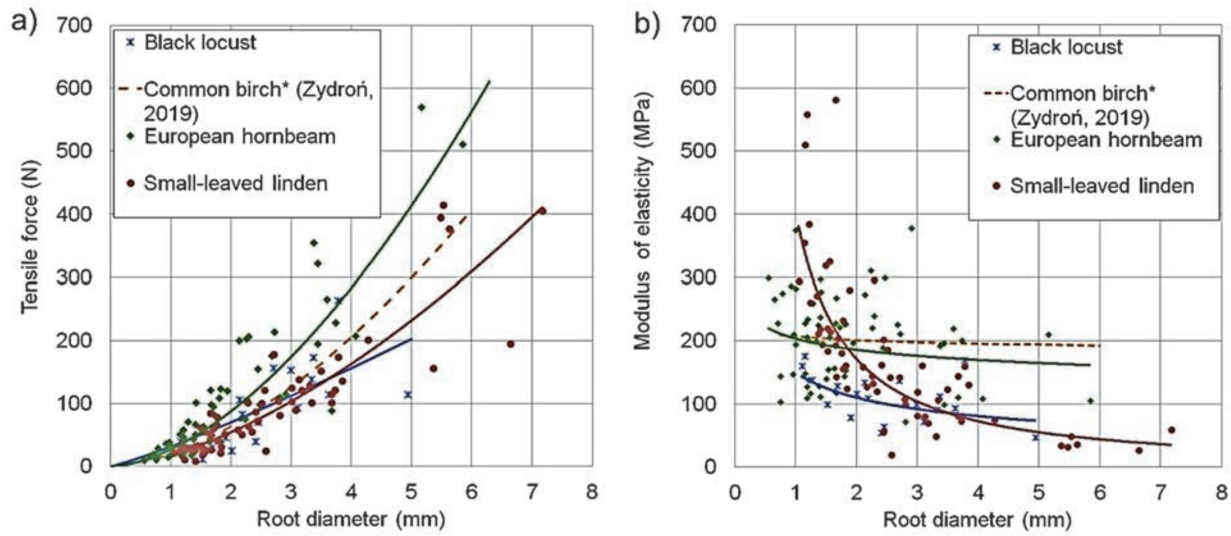

Fig. 6. Tensile force (a) and elastic modulus (b) vs. root diameter

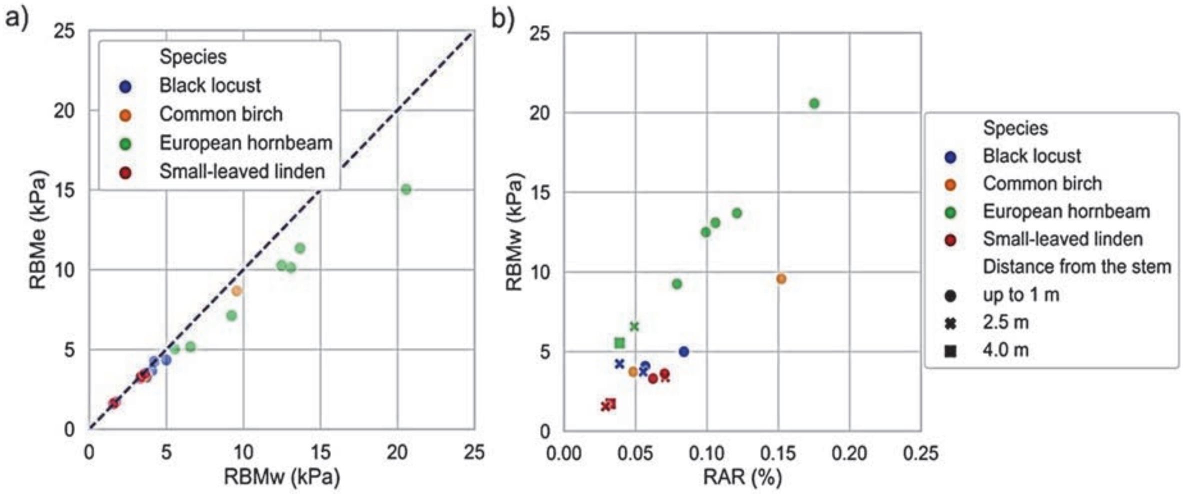

Fig. 7. Root reinforcement for the tested tree species calculated using RBMw and RBMe models (a) and relationship between root reinforcement and RAR (b)

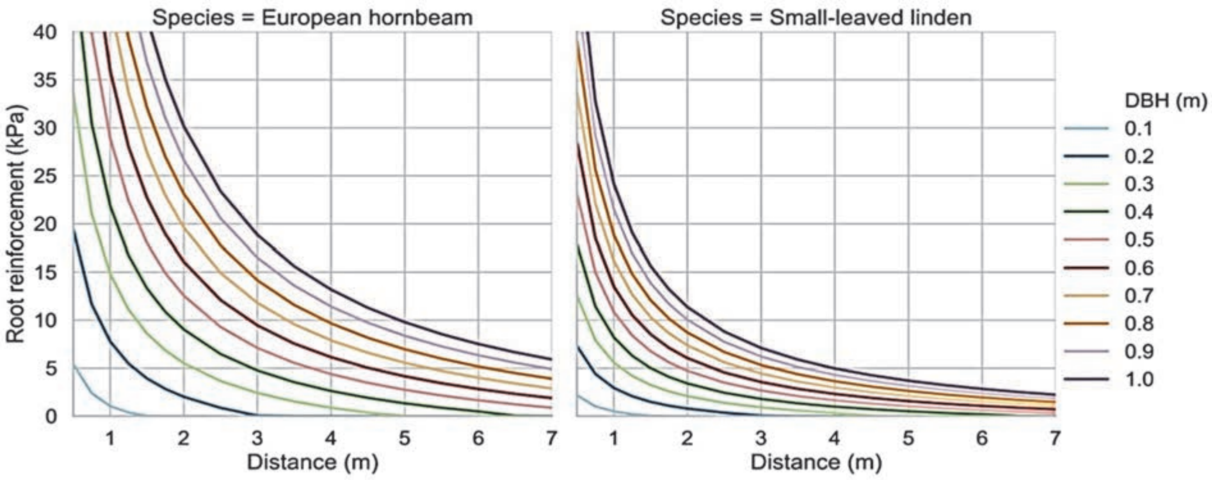

Fig. 8. Root cohesion in relation to the distance from the stem and its DBH

4. Discussion

4.1. RAR and density of roots

The test results confirmed that density of roots and RAR decrease with depth and distance from the tree stem (Abernethy and Rutherfurd, 2001; Bischetti at al. 2009; Danjon et al., 2008). The RAR values (averaged within the soil profile) ranged from 0.03 to 0.18%, which was within the range of values given in the literature (Bischetti et al., 2007, 2009; Chiaradia et al., 2012; Di Iorio et al., 2013; Mao et al., 2012; Moresi et al., 2019; Tron et al., 2014; Vergani et al., 2014a, 2014b). Generally, it can be stated that the majority of measurements of tree roots in the mountain regions are done on coniferous species and they differ significantly in methodology. Some of the most valuable information about RAR of tree species in the Alps is provided by research of Bischetti et al. (2009), in which exploration of the soil was deeper than 1.0 m. The average values of RAR given in this publication for Norway spruce, European beech, European larch, sweet chestnut and European hop-hornbeam ranged from 0.07 to 0.36%, however only in two cases the values were higher than 0.15%. It should be mentioned that the majority of these measurements were conducted in sites where soil was sand-gravel mixture. In cases where the soil was clayey the depth-averaged RAR values exceeded 0.1% only for one species. Measurements of Norway spruce roots in the Alps (Vergani et al., 2014a) revealed that the total RAR values ranged from 0.06% to 0.32% and from 0.00006% to 0.13% for Italian and Swiss areas, respectively. The results of tests by Ji et al. (2019) carried out for 26-year-old black locust trees growing in northwest China showed that the RAR values are in the range of 0.02-0.08%. In these studies, the soil was sandy loam, and its grain-size distribution seemed to be the most similar to ones which were located in our study area. Tron et al. (2014) also present the results of root area ratio measurements of black locust in a few sites in the Tuscany region, but they report the results in non-standard unit (cm^2) which makes it impossible to compare them with our studies. The RAR values for the European hornbeam trees in hilly area of northern Iran given by Abdi et al. (2009)

ranged from 0.004 to 6.431%, although these authors included in their measurements roots which were larger than 10 mm. Using the same measurement methodology in this study, the obtained RAR values for the hornbeam trees were up to 2.25%.

In the present study, we used a Root Distribution Model considering two approaches for estimating the density of fine roots, proposed by Schwarz at al. (2012a) and Giadrossich et al. (2016). The comparison of measured and calculated root number values revealed that they provide very similar results, but the second approach seems more convenient to compute. The model usually underestimates the number of fine roots which usually makes modeling results more conservative. Opposite results were provided in research by Vergani et al. (2017), carried out on Scots pine roots. They stated that the RDM model overestimates the average number of roots at a distance of 1.5 m from the trunk. On the other hand, at longer distances (2.5 and 4.0 m) the model underestimates the number of roots. These authors stated that the model performance was better at a distance of 1.5 and 2.5 than at 4.0 m from the stem. They also stated that in order to obtain a better fit of the model it is important to perform measurements on isolated trees.

4.2. Tensile strength and the elastic modulus of roots

The tensile force values obtained for the European hornbeam were similar to the results obtained by Abdi (2018) and similar or higher to the results obtained by Deljouei et al. (2020). It should be emphasized that the cited tests have been carried out in different region (Iran) than in our studies. On the other hand, the results for the black locust were similar to the results of Ji et al. (2019) and clearly smaller than the ones presented by Ji et al. (2012) and Zydroń et al. (2019). The differences in tensile strength within the same species can result from different environmental conditions (Vergani et al., 2012), different age of trees (Sonnenberg et al., 2010), their size (Deljouei et al., 2020), or might be a consequence of the adopted test methods (preparation of test samples, methodology of measuring the root diameter, deformation rate).

The values of the elastic modulus were in a wide range that is similar to the values given in the literature for different plant species (Boldrin, 2017; Ji et al., 2012, 2019). The values of elasticity modulus obtained in this study for the black locust were smaller than the ones presented by Ji et al. (2012, 2019) and Zydroń (2019), which may result from the adopted test methodology and sampling conditions. Ji et al. (2012, 2019) performed tests directly on samples taken from the field. However, the tests presented in this paper and by Zydroń (2019) were carried out on samples that were submerged in water for at least 24 hours before the tensile test. Boldrin et al. (2018) indicate that as the moisture content increases, root elasticity increases while at the same time the modulus of elasticity decreases. Results of the tests carried out for the roots of several species of trees and shrubs (Boldrin et al., 2017) indicate that the values of elasticity modulus are usually smaller than 600 MPa, on average from 150 to 320 MPa depending on the species.

4.3. Root reinforcement

Our results revealed that the RBMe model provides more conservative data on the influence of tree root systems on soil reinforcement than the RBMw model does. In the RBMe model it is assumed that at any moment of the root bundle deformation, each of its elements does the same work – multiplication of the mobilized tensile force and associated deformation. This assumption makes the deformation of the root bundle during tension heterogeneous, i.e. at the same amount of work fine roots undergo greater deformation than the coarse ones. On the other hand, the RBMw model assumes that the deformation of all roots in the bundle is identical at any time of the analysis. Using these relations in the RBMe model, caused that fine roots are ruptured "faster" than in the RBMw model. The RBMe model is a new approach to describe the interaction between soil and root systems, which was verified with in-situ testing (Ji et al., 2019). Compared to the other bundle models used by Mao et al. (2012), this model gives the values of root cohesion which are the least overestimated compared to the results of in-situ direct shear tests.

The calculation results indicate that the root reinforcement values obtained using the RBMe model are more conservative than the ones obtained using the RBMw model. The application of the RBMe model was presented in the paper by Ji et al. (2019), whereas the application of the second model has been presented in a greater number of publications, so far (Cislaghi et al., 2017; Giadrossich et al. 2016; Schwarz, 2013; Vergani et al., 2014, 2016, 2017).

The results of our research indicate that, in general, soil reinforcement by the root systems of the trees, independly of the used computing model, usually did not exceed 10 kPa; 20 kPa at most. This is consistent with the results of tests on root systems presented in the literature (Table 4). The results of back-analysis given by Cislaghi et al. (2017) showed that almost 40% values of root reinforcement were in the range of 5-10 kPa, 23% - between 10-15kPa and less than 20% between 1-5kPa. Schwarz et al (2010) inverse analysis considering soil failure at unsaturated conditions revealed that the mean lateral reinforcement was equal to 14 kPa and this value was consistent with the results of theoretical computing using the RBM model.

The range of root reinforcement values estimated using fiber bundle model given by Chiaradia et al. (2016) for European beech indicates that they can be over 10 kPa, but the average values for sweet chestnut and Norway spruce are only 3.5 kPa and about 8 kPa for beech. Research of Vergani et al. (2017) carried out for Scots pine root system showed that root reinforcement was lower than 5 kPa.

Table 4. Values of root reinforcement of different European tree species available in the literature

Root reinforcement (kPa)	*Calculation method*	*Vegetation type*	*Location*	*References*
4-9	back-analysis	European beech (*Fagus sylvatica* L.)	Italy	Bischetti et al. (2004)
6-9	W-W model, k = 0.56			
14.4-86	FBM*	European beech (*Fagus sylvatica* L.)	Italy	Bischetti et al. (2009)
13.8-35.4		Norway spruce (*Picea abies* (L.) Karst.)		
17.4-38.3		European larch (*Larix decidua* Mill.)		
15.2-15.4		Sweet chestnut (*Castanea sativa* Mill.)		
14.6		European hop-hornbeam (*Ostrya carpinifolia* Scop.)		
1.8-15.1	W-W model, k =0.7	Coniferous forest Norway spruces (*Picea excelsa* L.) and European larch (*Larix decidua* Mill.)	Italy	Chiaradia et al. (2012)
1.3-.12.1		Hydric forest		
1.3-4.2		Sweet chestnut (*Castanea sativa* Mill.)		
2.4-21.8		European beech (*Fagus sylvatica* L.)		
5.8-21.2		Disturbed forests – dominant black locust (*Robinia pseudoacacia* L.)		
0.9-3.9		Deciduos conifers		
1.6-8.6		Thermophilous forests		
1.3-8.3	FBM**	Norway spruce (*Picea abies* (L.) Karst.)	Italy	Chiaradia et al. (2016)
2.5-14.7		European beech (*Fagus sylvatica* L.)		
1.0-10.2		Sweet chestnut (*Castanea sativa* Mill.)		
0 to over 20	back-analysis	mixed forest European silver fir (*Abies alba* Mill.) and Norway spruce (*Picea abies* (L.) Karst.)	Italy	Cislaghi et al. (2017)
14	back-analysis**	Sweet chestnut (*Castanea sativa* Mill.)	Tuscany, Italy	Schwarz et al. (2010)
2-13 (mainly 5-10)	RBM	Ash (*Fraxinus Excelsior* L.)	Switzerland	Schwarz et al. (2012a)
11.2	FBM*	mixed forest European silver fir (*Abies alba* Mill.) and Norway spruce (*Picea abies* (L.) Karst.)	Italy	Vergani et al. (2014a)
0.3-15.0***	RBM	Norway spruce (*Picea abies* (L.) Karst.)	Italian and Swiss Alps	Vergani et al. (2014b)
1.7-3.7	RBM	Norway spruce (*Picea abies* (L.) Karst.)	Switzerland	Vergani et al. (2016)
approx. 0.8-5.0***	RBM	Scots pine (*Pinus sylvestris*)	Switzerland	Vergani et al. (2017)

Explanation: -root reinforcement was calculated as a sum of basal and lateral reinforcement;** - values of lateral reinforcement;*** - values were computed based on the dimensions of the trench wall and maximum force mobilized by roots;RBM – bundle model considering strain-step loading of a root bundle;FBM – bundle model not considering strain-step loading of a root bundle.*

Low values of root reinforcement obtained for the black locust, which due to its expansive root system is generally considered a species that significantly strengthens the soil, seem puzzling considering some publications (Chiaradia et al. 2012; Ji et al., 2012). On the other hand, the authors' results might be confirmed by Ji et al. (2019), who showed that black locust has the smallest impact on soil reinforcement.

The results of the presented tests indicate that the root system of hornbeam had a significant impact on soil reinforcement. Literature on such research is scarce (Zydroń, 2014). However, the results given by Abdi (2018) show that European hornbeam is characterized by high tensile strength, which might be a premise (indication) for the use of this species in soil reinforcement.

5. Conclusions

Our study allowed to determine the distribution of root systems of four typical coniferous tree species growing in the forests of the Polish Carpathians and its contribution to soil reinforcement. Implications of using two strain-step loading of the root bundle were presented. Based on the results of the tests, their analysis and discussion, it was found that:

1. The root system density and root area ratio of the studied trees was characterized by very high variability depending on the depth and distance from the tree and its size. The test confirmed that density of roots and RAR decrease with depth and distance from the tree stem.
2. Tensile strength tests revealed that European hornbeam roots were characterized by high values of

this parameter while the values for black locust roots and linden roots were much lower.

3. Root cohesion values obtained using the RBMw bundle model, which takes into account the variability of strength properties, were on average 16% higher than those obtained using the RBMe model, which takes into account non-uniform displacement of the roots in the bundle.

4. Soil reinforcement provided by root systems of the analyzed tree species generally did not exceed 10 kPa. Tests revealed that the root system of European hornbeam more efficiently enhances soil shear strength than root systems of common birch, black locust and small-leaved linden.

In conclusion, it can be stated that the architecture of root systems of the studied tree species can be relatively well described using the RDM model, which makes it possible to apply it in engineering practice for estimating the root system density. Integration of this model with the bundle models allows estimating the spatial distribution of soil reinforcement by roots, which can be used to predict slope stability in areas threatened by mass movements.

The authors' observations of landslide areas in the Polish Carpathians confirm the positive influence of root systems on slope stability. On the other hand, including this influence in a typical two-dimensional stability analysis is a complex task, mainly because of the relatively small amount of data and high species diversity in the environment. Therefore, further research will focus on a better understanding of the influence of root systems of both deciduous and coniferous tree species found in the Carpathian area on soil reinforcement.

References

Abe K., Ziemer R., (1990), *Effect of Tree Roots on Shallow-Seated Landslides*, XIX World Congress, Int. Union of Forestry Research Organizations, August 5-11, Montreal, Canada.

Abernethy B., Rutherfurd I.D., (2001), The distribution and strength of riparian tree roots in relation to riverbank reinforcement, *Hydrological Processes*, **15**, 63-79.

Abdi E., Majnounian B., Rahimi H., Zobeiri M., (2009), Distribution and tensile strength of Hornbeam (*Carpinus betulus*) roots growing on slopes of Caspian Forests, Iran, *Journal of Forestry Research*, **20**, 105-110.

Abdi E., (2018), Root tensile force and resistance of several tree and shrub species of Hyrcanian Forest, Iran, *Croatian Journal of Forest Engineering*, **39**, 255-270.

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*, **3**, 175-198.

Bischetti G.B., Bonfanti F., Geppi M., (2004), *The Role of Root Reinforcement on May 2002 Shallow Slope Failures in St. Giulio Creek Catchment (Northern Italy)*, Proc. Int. Symp. The 1st Congress INTERPRAEVENT 2004, Riva del Garda, Trient, Italy, 57-67.

Bischetti G.B., Chiaradia E.A., Simonato T., Speziali B., Vitali B., Vullo P., Zocco A., (2007), *Root Strength and Root Area Ratio of Forest Species in Lombardy (Northern Italy)*, In: *Eco-and Ground Bio-Engineering: The Use of Vegetation to Improve Slope Stability. Developments in Plant and Soil Sciences,* Stokes A., Spanos I., Norris J.E., Cammeraat E. (Eds), Springer, Dordrecht, 31-41.

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.

Bischetti G.B., Bassanelli C., Chiaradia E.A., Minotta G., Vergani C., (2016), The effect of gap openings on soil reinforcement in two conifer stands in northern Italy, *Forest Ecology and Management*, **359**, 286-299.

Boldrin D., Leung A.K., Bengough A.G., (2017), Root biomechanical properties during establishment of woody perennials, *Ecological Engineering*, **109**, 196, http://doi.org/10.1016/j.ecoleng.2017.05.002.

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.

Böhm W., (1979), *Methods of Studying Root Systems*, Springer-Verlag, Berlin Heidelberg New York.

Brożek S., Zwydak M., (2003), *Atlas of Polish Forest Soils* (in Polish), CILP, Warszawa.

Burtan J., (1954), *Detailed Geological Map of Poland in scale 1:50,000, Wieliczka Sheet* (in Polish), Polish Geological Institute-National Research Institute, Warszawa, Poland.

Chiaradia E.A., Bischetti G.B., Vergani C., (2012), Incorporating the effect of root systems of forest species into spatially distributed models of shallow landslides. *International Journal of Forest, Soil and Erosion*, **2**, 107-118.

Chiaradia E.A. Vergani C., Bischetti G.B., (2016), Evaluation of the effects of three European forest types on slope stability by field and probabilistic analyses and their implications for forest management, *Forest Ecology and Management*, **370**, 114-129.

Cislaghi A., Chiaradia E.A., Bischetti G.B., (2017), Including root reinforcement variability in a probabilistic 3D stability model, *Earth Surface Processes and Landforms*, **42**, 1789-1806.

Ciuca I., Stanescu M.M., Bolcu D., (2018), A study on the mechanical properties of some green-composites, *Environmental Engineering and Management Journal*, **17**, 2991-2998.

Coppin N.J., Richards I.J., (1990), *Use of Vegetation in Civil Engineering*, CIRIA, London, UK.

Coutts M.P., (1983), Root architecture and tree stability, *Plant and Soil*, **71**, 171-88.

Danjon F., Barker D.H., Drexhage M., Stokes A., (2008), Using three-dimensional plant root architecture in models of shallow-slope stability, *Annals of Botany*, **101**, 1281-1293.

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.

Di Iorio A., Montagnoli A., Terzaghi M., Scippa G.S., Chiatante D., (2013), Effect of tree density on root distribution in *Fagus sylvatica* stands: a semi-automatic digitising device approach to trench wall method, *Trees*, **27**, 150,-1513.

Giadrossich F., Cohen D., Schwarz M., Seddaiua G., Contran N., Lubino M., Andrea Valdés-Rodríguez A.O., Niedda M., (2016), Modeling bio-engineering traits of *Jatropha curcas* L., *Ecological Engineering*, **89**, 40-48.

Hunter J.D., (2007), Matplotlib: A 2D graphics environment, *Computing in Science & Engineering*, **9**, 90-95.

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.

Ji J., Mao Z., Qu W., Zhang Z., (2019), Energy-based fibre bundle model algorithms to predict soil reinforcement by roots, *Plant and Soil*, **446**, doi: 10.1007/s11104-019-04327-z.

Lange D.A., Ouyang C., Shah S.P., (1996), Behavior of cement based matrices reinforced by randomly dispersed microfibers, *Advanced Cement Based Materials*, **3**, 20-30.

Mao Z., Saint-André V., Genet M., Mined F-X., Jourdan C., Reye H., Courbaud B., Stokes A., (2012), Engineering ecological protection against landslides in diverse mountain forests: Choosing cohesion models, *Ecological Engineering*, **45**, 55-69.

Moresi F.V., Maesano M., Matteucci G., Romagnoli M., Sidle R.C., Mugnozza G.S., (2019), Root biomechanical traits in a montane Mediterranean forest watershed: variations with species diversity and soil depth, *Forests*, **10**, 341.

PN-EN ISO 17892-4:2017-01, (2017), Geotechnical investigation and testing. Laboratory testing of soil. Part 4: Determination of particle size distribution, The Polish Committee for Standardization, Warszawa, Poland.

PN-EN ISO 17892-12:2018-08, (2018), Geotechnical investigation and testing. Laboratory testing of soil. Part 12: Determination of Atterberg limits, The Polish Committee for Standardization, Warszawa, Poland.

PN-EN ISO 17892-9:2018-05, (2018), Geotechnical investigation and testing. Laboratory testing of soil. Part 9: Consolidated traxial compression test on water saturated (in Polish). The Polish Committee for Standardization, Warszawa, Poland.

PN-EN ISO 14688-2:2006, (2006), Geotechnical investigations and testing – Identification and classification of soil. Part 2: Principles for a classification (in Polish), The Polish Committee for Standardization, Warszawa, Poland.

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.

Reubens B., Poesen J., Danjon F., Geudens G., Muys B., (2007), The role of fine and coarse roots in shallow slope stability and soil erosion control with a focus on root system architecture: a review, *Trees*, **21**, 385-402.

Schenk H.J., Jackson R.B., (2005), Mapping the global distribution of deep roots in relation to climate and soil characteristics, *Geoderma*, **126**, 129-140.

Schmid I., Kazda M., (2002), Root distribution of Norway spruce in monospecific and mixed stands on different soil, *Forest Ecology and Management*, **159**, 37-47.

Schwarz M., Lehmann P., Or D., (2010a), Quantifying lateral root reinforcement in steep slopes – from a bundle of roots to tree stands, *Earth Surface. Processes and Landforms*, **35**, 354-367.

Schwarz M., Preti F., Giadrossich F., Lehmann P., Or D., (2010b), Quantifying the role of vegetation in slope stability: A case study in Tuscany (Italy), *Ecological Engineering*, **36**, 285-291.

Schwarz M., Cohen D., Or D., (2012a), Spatial characterization of root reinforcement at stand scale: Theory and case study, *Geomorphology*, **171-172**, 190-200.

Schwarz M., Thormann J.-J., Zürcher K., Feller K., (2012b), *Quantifying Root Reinforcement in Protection Forests: Implications for Slope Stability and Forest Management*, 12th Congress INTERPRAEVENT, Grenoble, France, 791-802.

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.

Simon A., Collison A.J.C., (2002), Quantifying the mechanical and hydrologic effects of riparian vegetation on streambank stability, *Earth Surface Processes and Landforms*, **27**, 527-546.

Schiechtl H.M., (1980), *Bioengineering for Land Reclamation and Conservation*, University of Alberta Press, Edmond, Canada.

Stokes A., Norris J.E., van Beek L.P.H., Bogaard T., Cammeraat E., Mickovski S.B., Jenner A., Di Iorio A., Fourcaud T., (2008), *How Vegetation Reinforces Soil on Slopes,* In: *Slope Stability and Erosion Control: Ecotechnological Solutions*, Norris J.E., Stokes A., Mickovski S.B., Cammeraat E., van Beek R., Nicoll B.C., Achim A. (Eds.), Springer, Dordrecht, The Netherlands.

Swanston D.N., Dyrness C.T., (1973), Stability of steep land, *Journal of Forestry*, **71**, 264-269.

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

Tron S., Dani A., Laio F., Preti F., Ridolfi L., (2014), Mean root depth estimation at landslide slopes, *Ecological Engineering*, **69**, 118-125.

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., Chiaradia E.A., Bassanelli C., Bischetii G.B., (2014a), Root strength and density decay after felling in a Silver Fir-Norway Spruce stand in the Italian Alps, *Plant and Soil*, **377**, 63-81.

Vergani C., Schwarz M., Cohen D., Thormann J.J., Bischetti G.B., (2014b), Effects of root tensile force and diameter distribution variability on root reinforcement in the Swiss and Italian Alps, *Canadian Journal of Forest Research*, **44**, 1426-1440.

Vergani C., Schwarz M., Soldati M., Corda A., Giadrossich F., Chiaradia E.A., Morando P., Bassanelli C., (2016), Root reinforcement dynamics in subalpine spruce forests following timber harvest: a case study in Canton Schwyz, Switzerland, *Catena*, **143**, 275-288.

Vergani C., Werlen M., Conedera M., Cohen D., Schwarz M., (2017), Investigation of root reinforcement decay after a forest fire in a Scots pine (*Pinus sylvestris*) protection forest, *Forest Ecology and Management*, **400**, 339-352.

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

Waskom M., Botvinnik O., Gelbart M., Ostblom J., Hobson P., Lukauskas S., Gemperline D.C., Augspurger T., Halchenko Y., Warmenhoven J., Cole J.B., de Ruiter J., Vanderplas J., Hoyer S., Pye C., Miles A., Swain C., Meyer K., Martin M., Bachant P., Quintero E., Kunter G., Villalba S., Clark B., Brian, Fitzgerald C., Evans C.G., Williams M.L., O'Kane D., Yarkoni T., Brunner T., (2020), *mwaskom/seaborn: v0.11.0,* Zenodo, http://doi.org/10.5281/zenodo.592845.

Wood J.L., Turkington R., Reinhardt I., (2015), Landslides and synoptic weather trends in the European Alps, *Geomorphology*, **228**, 398-408.

Wójcik A.,Wojciechowski Y., (2016), Landslides as one of the most important elements of geological hazards in Poland (in Polish), *Przegląd Geologiczny*, **64**, 701-709.

Wu T.H., (1984), Effect of vegetation on slope stability, *Transportation Research Record*, **965**, 37-46.

Wu T.H., McKinnell III W.P., Swanston D.N., (1979), Strength of tree roots and landslides on Prince of Wales Island, Alaska, *Canadian Geotechnical Journal,* **16**, 19-33.

Wu T.H., Bettadapura D.P., Beal P.E., (1988), A statistical model of root geometry, *Forest Science*, **34**, 980-997.

Ziemer R.R., (1981), *The Role of Vegetation in the Stability of Forested Slopes*, Proc. Referate Exposes of XVII Int. Union of Forest Research Organizations World Congress, Japan, 297-308, On line at: https://www.fs.fed.us/psw/publications/ziemer/ZiemerIUFRO1981.PDF

Zydroń T., (2014), The influence of hornbeam roots on shear strength of soil (in Polish), *Infrastruktura i Ekologia Terenów Wiejskich*, **I**, 21-33.

Zydroń T., (2019), *The Influence of Root Systems of Selected Tree Species on the Increase of the Soil Shear Strength,* (in Polish), Publishing House of University of Agriculture in Kraków, Kraków, Poland.

Zydroń T., Gruchot A., Kluba M., (2019), Spatial variability of reinforcement provided by juvenile root systems of black locust and black poplar, *Polish Journal of Environmental Studies*, **28**, 4027-4037.

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