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Effects of tree spacing and thinning on root reinforcement in mountain forests of the European Southern Alps

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ABSTRACT

Root reinforcement is a mechanism through which forests contribute to the prevention and mitigation of shallow instabilities in soils, one of the main hazards in mountain areas. This study aims to assess how spatial tree distribution and whether thinning operations affect root reinforcement in the most common forest types of the European Southern Alps. We measured size and position of the trees of 119 stands, belonging to sweet chestnut, European beech, Norway spruce, and spruce-beech-silver fir forest types. We developed, calibrated and validated a model for estimating root reinforcement at the stand level, using the spatial distribution of tree diameter as the input variable. Finally, we simulated a thinning of 18% stand basal area, selecting removal trees from smaller diameter classes (low thinning) or from random clusters (random cluster thinning), and assessed its effect on root reinforcement. Root reinforcement statistically differed among forest types and the lowest values were found in the sweet chestnut forest type. Irrespective of the forest type, low thinning did not significantly modify root reinforcement, while random cluster thinning reduced it five-fold.

1. Introduction

In mountain areas, forests play a significant role in protecting people, settlements and resources from natural hazards like floods, landslides, snow avalanches and rockfalls. The acknowledgement of their regulation and maintenance service is documented in the surviving literature of several ancient civilizations (Hamilton, 1992). Human use of protection forests is currently restricted by several countries to preserve soil and water resources (Dorren et al., 2004; Lingua et al., 2017). Where natural hazards or potentially adverse climate may cause damage to people and assets, forests with the potentiality to reduce this risk, provide a direct protection (Brang et al., 2001). For their importance, direct protection forests request a particular attention in terms of monitoring, planning of the human activities and financial support. In particular, trees with their canopy and root systems are effective in preventing and mitigating the triggering mechanisms of shallow landslides, common landform-shaping processes that frequently evolve in debris flows and soil slips and can cause huge sediment transport or accumulation of woody debris (Cislaghi and Bischetti, 2019; Gasser et al., 2019; Montgomery and Dietrich, 1994; Zimmermann et al., 2020). Such stabilizing effects are due to both hydrological and mechanical processes. Canopy interception, suction, and transpiration contribute to reduce soil moisture into the explored soil layers and to delay the onset of soil saturation at the soil depth where landslides are triggered (Forbes and Broadhead, 2011). At the same time, mechanical soil stabilization occurs through root reinforcement, anchorage, buttressing and arching, surcharge and soil aggregation (Sidle and Ochiai, 2006). Among these processes, root reinforcement is undoubtedly the most studied since the pioneering works of Endo and Tsuruta (1969), Gray (1969), O'Loughlin (1974) and Swanston (1974). These earliest studies showed a strong correlation between the slope failures and the timber harvesting over steep slopes, suggesting further research on changes in tree root reinforcement, which occurs after changes in stand density. Since then, the role of roots in reinforcing soil has been the subject of experimentations, field campaigns and modelling for several decades.

The scientific literature provided a large amount of site-specific data emphasising a wide spatial and temporal variability; on the other hand, modelling root reinforcement has been continuing to evolve, from the

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pioneering approach at the end of the Seventies (Burroughs and Thomas, 1977; Waldron, 1977; Wu et al., 1979) to the most refined methods (Cohen et al., 2011; Pollen and Simon, 2005; Schwarz et al., 2013). Most models combine the biomechanical properties of roots with their density and spatial distribution, whose development through time is simulated based on pipe model theory (Shinozaki et al., 1964a, 1964b) and the static fractal branching model at single-tree scale (Tobin et al., 2007). Another widespread approach is to empirically relate root diameter and its biomechanical properties (Wu et al., 1979). Furthermore, some of these models upscale the root reinforcement distribution at stand scale assuming that the root distribution decreases with increasing distance from the stem base.

Despite these advances, few works have assessed how stand structure, and its changes due to human disturbances, like silvicultural treatments, influences the protective function of the forests. In fact, silviculture can change the stand structure and composition (Sitzia et al., 2012), affecting the spatial distribution of roots in the soil and hence root reinforcement at the stand scale (Moos et al., 2016; Roering et al., 2003; Ziemer and Swanston, 1977). Thus, there is an increasing need to collect quantitative data and develop reliable models to assess the effects of silvicultural treatment on slope stability.

The present study aims to investigate the effects of tree spatial distribution on root reinforcement in four common forest types of the European Southern Alps: sweet chestnut, European beech, Norway spruce, and spruce-beech-silver fir (hereafter "mixed"). The steps of this work are as follows: (i) modelling average values and probability distribution functions of root reinforcement in the four forest types, starting from measurements of tree size and position collected by field surveys; (ii) generating virtual forests from frequency distribution of diameter at breast height (*DBH*), and use them as input variables in a root reinforcement model; (iii) comparing the root reinforcement values obtained by the virtual forests and by the field measurements; and (iv) assessing the effect on root reinforcement of running the model through simulated thinning.

2. Materials and methods

2.1. Study area

We collected stand data from 119 sampling plots in the European Southern Alps, belonging to three Italian regions (Fig. 1). The sampling plots ranged from 487 to 1,542 m a.s.l. in elevation, and from 20° to 40° in slope. The dominant canopy species were sweet chestnut (*Castanea sativa* Mill.) (35 plots), European beech (*Fagus sylvatica* L.) (16 plots), and Norway spruce (*Picea abies* L.) (30 plots). In addition, the canopy of 38 plots were composed by almost equal share of Norway spruce, European beech, and silver fir (*Abies alba* Mill.). In each sampling plot (circular with 20-m radius), we measured diameter at breast height (*DBH*), total height and position of all living trees with $DBH \geq 7.5$ cm. We measured the coordinates of all trees. In case of coppice stand, positions of shoots belonging to the same coppice stump were averaged.

2.2. Modelling root reinforcement

We developed the MATLAB package rootFORCE, which estimates root reinforcement on soil surrounding a tree as a function of its species identity, DBH and the distance from its stem base (d). Applying rootFORCE to all trees present in the survey plots, we also obtained plot-level estimates of the root reinforcement. Statistical differences of plot-level root reinforcement among forest types were assessed through

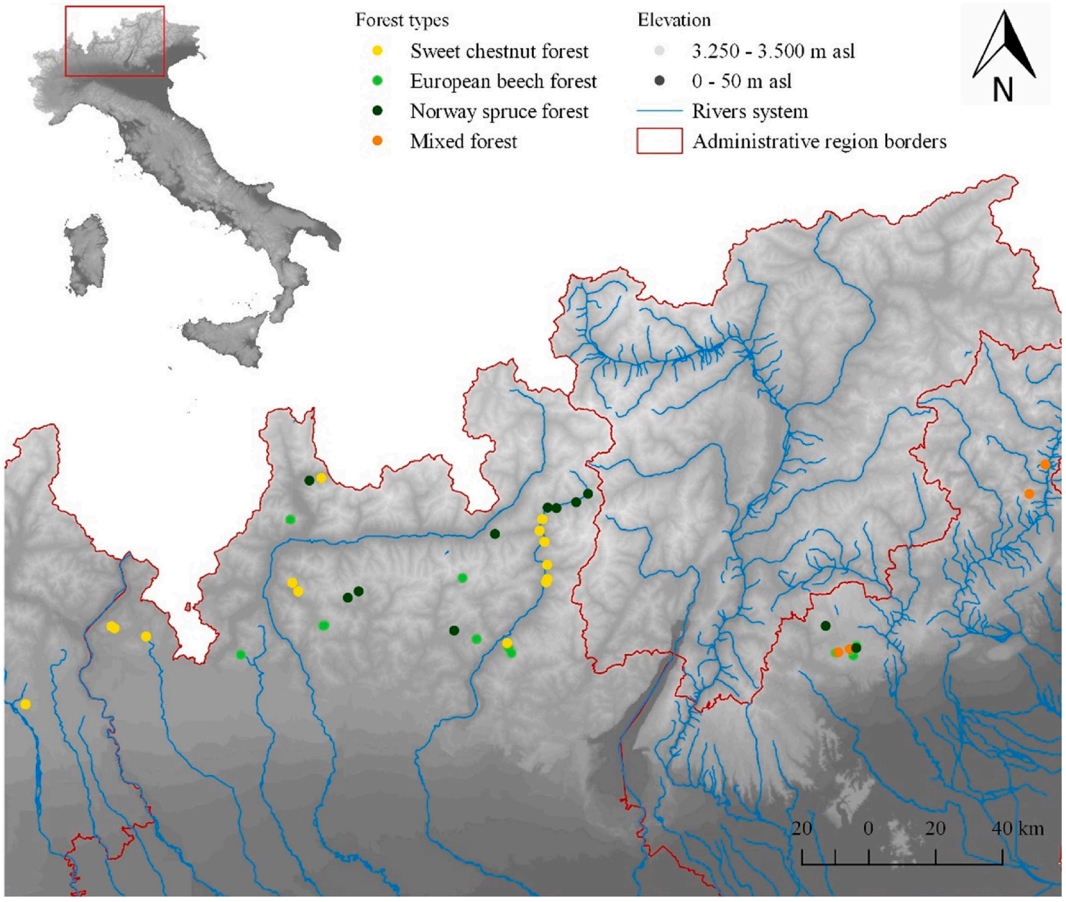


Fig. 1. Location of sampling plots surveyed in this study (several points refer to multiple sampling plots).

a non-parametric Kruskal-Wallis test followed by a post hoc Dunn's multiple comparison test (Dunn, 1961). The rootFORCE package combines two separate models: a Root Distribution Model (RDM) and the Root Bundle Model Weibull (RBMw), which are described in the following sections.

2.2.1. Root distribution Model (RDM)

RDM estimates density and distribution of roots belonging to different size classes, based on the static fractal branching model and the pipe theory (e.g., Ammer and Wagner, 2005; Schwarz et al., 2010). Based on the model developed by Schwarz et al. (2012), this model requires, as input parameters, d (m) and DBH (m). RDM estimates the density of the fine roots (i.e., with a diameter < 1.5 mm) (FRs) using the following equations:

$$FRs(DBH,d) = \begin{cases} \Theta \dfrac{\frac{\pi}{4}\left(\sum_i^n DBH_i\right)^2 \left[\alpha + (1-\alpha)\dfrac{d}{m\sum_i^n DBH_i}\right]}{2\pi m \sum_i^n DBH_i}, & d < m\sum_i^n DBH_i \\ \Theta \dfrac{\frac{\pi}{4}\left(\sum_i^n DBH_i\right)^2}{2\pi d}, & d \geq m\sum_i^n DBH_i \end{cases} \quad (1)$$

$$\Theta = \frac{\mu}{a_0 \sum_i^n DBH_i} \quad (2)$$

where Θ (roots/m^2) is the ratio between μ (roots/m) the pipe theory coefficient and $a_0 \cdot \sum_i^n DBH_i$ (m) the maximum spread of root system, α and m are empirical dimensionless parameters, and $\sum_i^n DBH_i$ is the sum of DBH of the shoots (i = 1,2,…n) belonging to the same stump. Obviously, in case of high forest system, $\sum_i^n DBH_i$ is the single tree DBH.

To estimate the density of roots > 1.5 mm (CRs), we used a two-parameter Gumbel cumulative distribution function:

$$CRs(\phi_j, DBH, d) = FRs(DBH,d)\left\{1 - \exp\left[-exp\left(-\frac{\frac{\phi_j}{\phi_0} - a}{b}\right)\right]\right\} \quad (3)$$

where $\phi_j$is the root diameter of the j-th diameter class, ϕ_0 is the reference diameter equal to the unity (to make the ratio dimensionless), a and b are the two Gumbel parameters.

The coefficients α, m, a and b are estimated via ordinary least square regression between observed and simulated root density; Mean Percentage Error (MPE, Eq. (4)) and Root Mean Square Error (RMSE, Eq. (5)) were chosen as goodness-of-fit metrics:

$$MPE = \frac{100\%}{M}\sum_k^M \frac{1}{T}\sum_t^T \left(\frac{y_{t,k} - x_{t,k}}{x_{t,k}}\right) \quad (4)$$

$$RMSE = \sqrt{\frac{1}{M}\sum_k^M \left(\sum_t^T y_{t,k} - \sum_t^T x_{t,k}\right)^2} \quad (5)$$

where $x_{t,k}$ and $y_{t,k}$ are the observed and predicted root density, t is the index of trench profile (t = 1,2,…T) and k is the index of study site (k = 1,2,…M)..

2.2.2. Root Bundle Model Weibull (RBMw)

RBMw estimates the tensile strength of a root bundle (Schwarz et al., 2013). The model is based on a strain-step loading approach and is calibrated on force–displacement curves of root bundles. RBMw includes biomechanical and geometrical properties of roots, such as modulus of elasticity (E), ultimate tensile resistance (F_{max}) and root elongation (L), which are modelled by power functions:

$$F_{max}(\phi_i) = F_0\left(\frac{\phi_i}{\phi_0}\right)^{\xi} \quad (6)$$

$$E(\phi_i) = rE_0\left(\frac{\phi_i}{\phi_0}\right)^{\beta} \quad (7)$$

$$L(\phi_i) = L_0\left(\frac{\phi_i}{\phi_0}\right)^{\gamma} \quad (8)$$

where F_0, E_0 and L_0 are multiplicative coefficients, ξ, β and γ are exponential coefficients, ϕ_0 is the reference diameter of 1 mm and r represents the effect of root tortuosity on Young's modulus. In this case, we directly measured the elasticity of root material neglecting the effects of pre-stretching and tortuosity (Commandeur and Pyles, 1991), and therefore we assumed that r is equal to 1.

In accordance with the elasticity law, the root reinforcement of a bundle of roots (F_{tot}) is calculated by summing the contribution of each root as a function of displacement (Δx):

$$F_{tot}(\Delta x) = \sum_i^N F(\phi_i, \Delta x) S(\Delta x^*) \quad (9)$$

where F is the tensile force of a single root and S is a function of the normalized displacement Δx*, as described by the following equations:

$$F(\phi_i, \Delta x) = \frac{r\pi E_0}{4L_0}\phi_i^{2+\beta-\gamma}\Delta x F(\phi_i, \Delta x) \leq F_{max}(\phi_i) \quad (10)$$

$$S(\Delta x^*) = \exp\left[-\left(\frac{\Delta x}{\lambda}\right)^{\omega}\right] \quad (11)$$

where λ is the Weibull scale parameter and ω is the Weibull shape parameter (dimensionless).

The accuracy of the non-linear regressions (Eqs. (6)–(8), (11) was assessed calculating the RMSE (Eq. (5)).

2.2.3. RDM and RBMw calibration

RDM calibration requires measures of root spatial distribution and root density collected in trench profiles at different distances from the stem base. RBMw calibration requires an evaluation of the biomechanical properties of roots (tensile properties), observed through tensile tests in the laboratory or by pullout tests in the field (Cislaghi et al., 2017a; Giadrossich et al., 2017). In the present study, RDM and RBMw parameters were calibrated using a total of 27 sampling plots placed in sweet chestnut (24 trench profiles in 4 plots), European beech (12 trench profiles in 2 plots), Norway spruce (18 trench profiles in 3 plots), and silver fir (12 trench profiles in 2 plots) stands. In each plot, we measured

root spatial distribution and root density at different distances from the stem base (approximately 1.5 m, 2.5 m and 3.5 m) using the trench wall method (Böhm, 1979). We imaged the vertical profile of each excavated trench into raw pictures that were manually rectified using a GIS software (Schmid and Kazda, 2002). On each picture, we identified all roots and measured their diameter. Roots with a diameter smaller than 0.5 mm were excluded due to high uncertainty in photointerpretation (Vergani et al., 2014). To assess root tensile properties, we collected samples of living roots from the 27 plots and preserved them into plastic tappers with 15% alcohol solution. Then, within two weeks from the collection of samples, we performed tensile tests in laboratory, using an Electromechanical Universal Testing Machine (MTS Criterion® Series 40). Tensile tests consisted in measuring the tensile resistance in function of strain using a load cell (full scale 500 N, accuracy 0.5 N).

2.3. Virtual random forest

Root reinforcement is highly dependent on the spatial distribution of trees (Moos et al., 2016; Roering et al., 2003; Schmidt et al., 2001). Cislaghi et al. (2017b) developed the Virtual Random Forest (VRF) model to estimate the spatial distribution of root reinforcement from measurements commonly found in forest management plans, such as *DBH* frequency, tree density, and minimum distance between trees. Here, we implement the VRF workflow using field measurements collected in the 119 sample plots and reducing the input to only one variable (i.e., the *DBH* frequency). The algorithm (Fig. 2) includes the following steps:

1. parameterising the frequency distribution of trees or sum of stump shoots diameters obtained by field measurements;
2. estimating the minimum distance between trees or stumps (d_{min}) as a function of average diameter DBH_m:

$$d_{min} = D_0 \left(\frac{\sum_i^n DBH_i}{N} \right)^{\delta} = D_0 DBH_m{}^{\delta} \quad (12)$$

where D_0 and δ are fitted parameters, whereas N is the number of trees/stumps inside a sampling plot;

3. generating of a set of virtual forests through a sequentially constrained Monte Carlo simulation (1,000 iterations) that produces random locations of trees/stumps respecting the inter-tree distance constrained through the empirical rule (Eq. (12)) and the *DBH* frequency distribution from step 1;
4. estimating root reinforcement values and using the rootFORCE package, described in the Section 2.3;
5. generating a cumulative distribution function and spatially explicit map of root reinforcement values based on root density in each virtual forest.

The fitting between the root reinforcement probability distributions produced by VRF stand data and those produced by field stand data was examined through the Lin's concordance correlation coefficient ρ^c (Lin, 1989):

$$\rho^c = \frac{2\sigma_{1,2}}{\sigma_1^2 + \sigma_2^2 + (\mu_1 - \mu_2)^2} \quad (13)$$

where μ_1 and σ_1^2 represent the mean and the variance for the root reinforcement values provided by the VRF procedure, μ_2 and σ_2^2 represent the mean and the variance for the root reinforcement values pro-

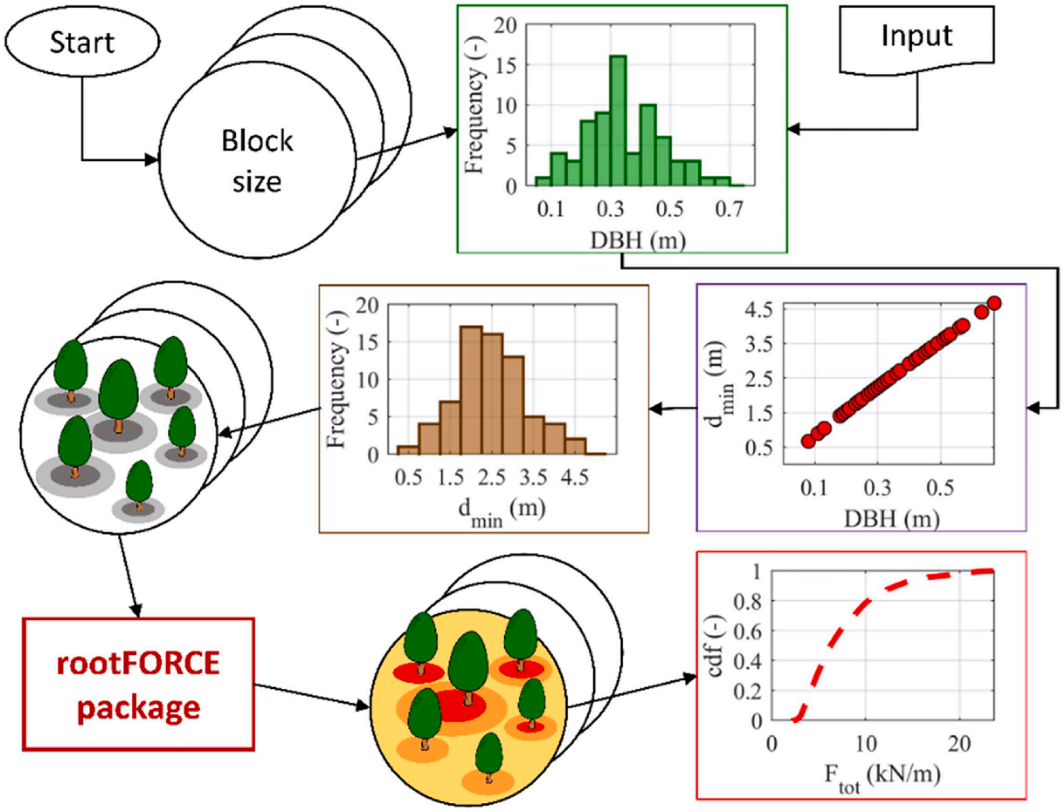


Fig. 2. Flowchart of the virtual random forest (VRF) procedure. The main steps are as follows: (i) parameterising the DBH frequency distribution; (ii) estimating the minimum distance between trees/stumps by applying empirical relationships with the average DBH inside a sampling plot; (ii) generating tree/stump positions constrained by minimum distances between trees, and sized constrained by the DBH frequency; (iv) generating root reinforcement maps using rootFORCE; and (v) calculating a cumulative distribution function for root reinforcement in each VRF plot.

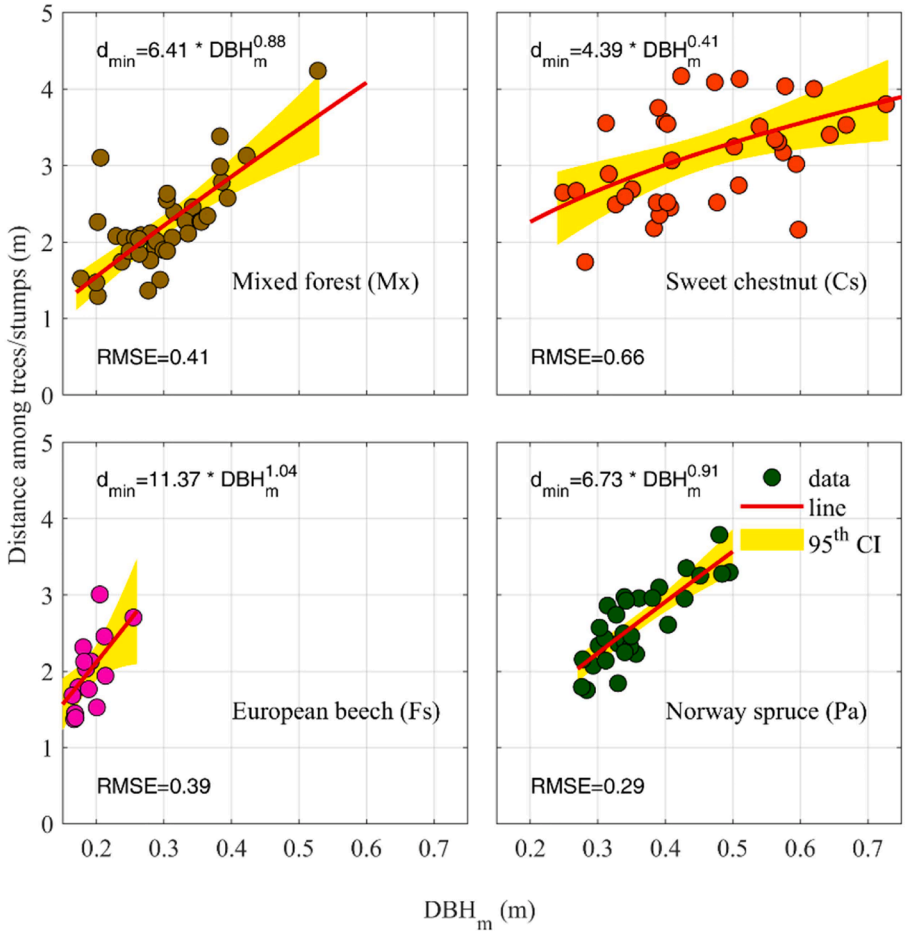


Fig. 3. Relationship between average minimum distance among trees and DBH_m under different forest types: markers are the sampling units; red lines are the fitted relationships (Eq. (12)) and the yellow areas are the 95th confidence intervals. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 1
Root density and root distribution observed in the study area in function of diameter-based classes and of tree species: avergae root density in bold and the min/max range of root density between the square brackets.

	Sweet chestnut	European beech	Norway spruce	Silver fir
Fine (ϕ = 0.5–2 mm)	**89.83**	**143.70**	**162.33**	**133.00**
	[38–130]	[93–241]	[102–261]	[85–232]
Small (ϕ = 2–5 mm)	**18.50**	**15.20**	**59.89**	**38.33**
	[7–39]	[3–26]	[36–84]	[16–96]
Medium (ϕ = 5–10 mm)	**4.33**	**3.10**	**5.67**	**1.75**
	[2–7]	[0–10]	[0–16]	[0–4]
Large (ϕ > 10 mm)	**1.67**	**2.60**	**3.00**	**0.58**
	[0–4]	[0–9]	[2–5]	[0–4]

Table 2
Results of the calibration of Root Distribution Model (RDM).

	Θ(root/m^2)	m (-)	α (-)	a (-)	b (-)
Sweet chestnut	25,044	3.996	0.495	1.472	0.534
European beech	56,000	4.001	0.496	1.420	0.389
Norway spruce	31,500	4.000	0.489	1.557	0.689
Silver fir	19,712	3.967	0.500	1.587	0.797

vided by the application of rootFORCE using the surveyed plots and the $\sigma_{1,2}$ is the covariance of the two outputs. This index denotes an almost perfect concordance when > 0.99, substantial when 0.95–0.99, moderate when 0.90–0.95, and poor when < 0.90 (McBride, 2005).

2.4. Thinning simulation

Thinning expands the available growing space of the trees that are retained in the stand, in turn affecting the spatial distribution of root reinforcement and possibly slope stability (Cislaghi et al., 2019a; Sakals

Table 3
Number and diameter range of tested roots, and results of maximum tensile force and elastic modulus.

	Sweet chestnut	European beech	Norway spruce	Silver fir
N_{tr} (#)	559	305	289	857
ϕ(mm)	0.15–6.80	0.14–6.13	0.12–6.55	0.53–7.81
F_{max} (N)	1.68–387.52	1.90–553.61	1.38–380.60	3.17–374.21
E (GPa)	0.01–87.86	0.17–48.40	0.14–14.94	0.01–2.53

Table 4
Results of the calibration of Root Bundle Model weibull (RBMw).

Eq.	Species	Sweet chestnut	European beech	Norway spruce	Silver fir
(6)	F_0 (N)	13.498	27.478	13.928	7.733
	ξ (-)	1.514	1.491	1.568	1.745
	RMSE (N)	23.193	41.482	39.019	26.846
(7)	E_0 (MPa)	230.197	288.155	211.886	116.319
	β (-)	−1.189	−1.193	−1.385	−0.836
	RMSE (MPa)	0.273	0.328	0.294	0.128
(8)	L_0 (mm)	0.065	0.069	0.068	0.062
	ϒ (-)	0.067	0.114	0.134	0.129
	RMSE (mm)	0.006	0.006	0.009	0.006
(11)	λ (-)	1.079	1.09	1.116	1.072
	ω (-)	3.319	3.242	2.359	2.97
	RMSE (-)	0.067	0.068	0.044	0.035

and Sidle, 2004). In the present study, we simulated the removal of 18% stand basal area through two different thinning methods. The first method (low thinning) removes smaller diameter trees until the threshold of basal area is exceeded. This method corresponds to a low thinning, which aims at removing suppressed and sub-dominant trees, in order to funnel the resources for the growth of the dominant trees (Kerr and Haufe, 2011). The second method (random cluster thinning) randomly selects a tree in the stand, around which the nearest neighbour trees are removed, until the same threshold of basal area is exceeded. This method corresponds to a free thinning, where trees are removed in clusters, without adhering to any particular selection criteria of competing trees. Both the silvicultural treatments were applied to all the forest types analysed in this study, despite they are typical of high forest system.

We operated under the following assumptions: (i) roots of removal trees are completely degraded after ten years from cutting (Bischetti et al., 2016; Sidle and Bogaard, 2016); (ii) the remaining trees grow according to a power *DBH*-time function (Bertogliati and Conedera, 2012); and (iii) ingrowth is negligible. After simulating thinning scenarios to the study plots, rootFORCE was applied again to estimate the change in root reinforcement. In the first method, owing to the selection criteria, just one average value per sampling plot was obtained. Conversely, in the second method, we run 1,000 random selections and virtual thinning simulations obtaining 1,000 average values of root reinforcement for each sampling plot; then, we considered the average of them. The one-way non parametric Kruskal-Wallis test was used to statistically determine the presence of main effect among both forest types and thinning methods (including no thinning) on root

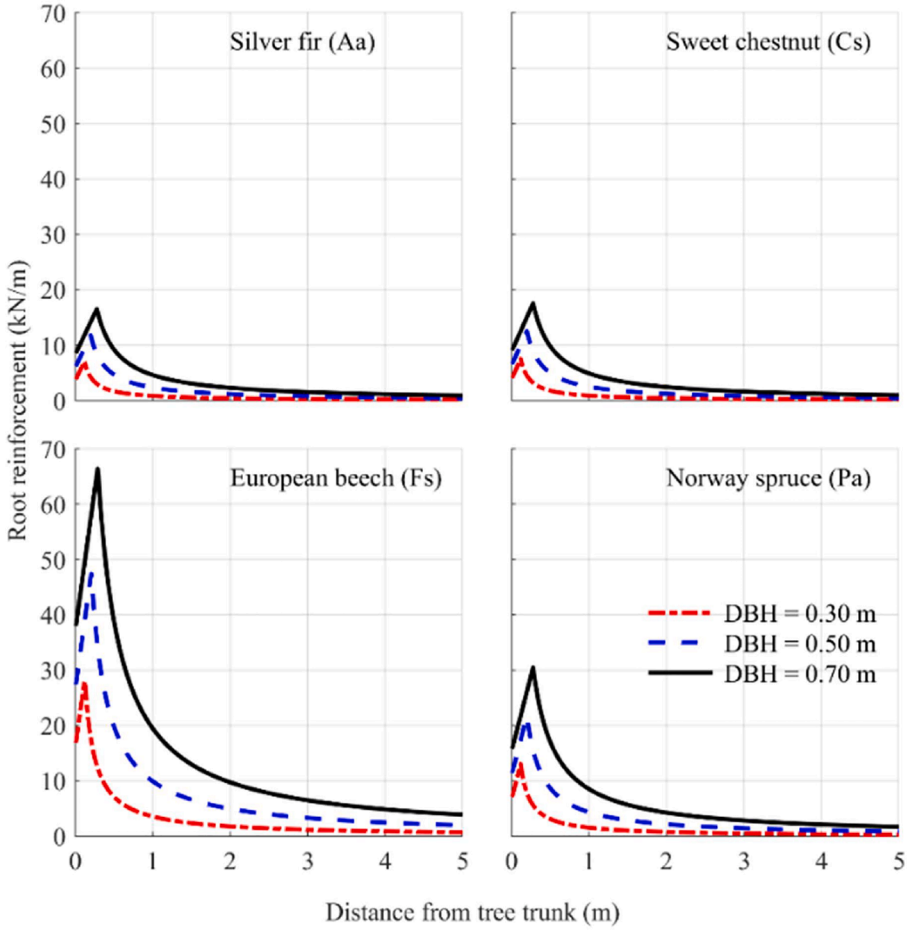


Fig. 4. Root reinforcement of a tree in relation to the distance from the stem base, the DBHs (0.30 m, 0.50 m and 0.70 m), and the tree species (sweet chestnut, European beech, Norway spruce, and silver fir).

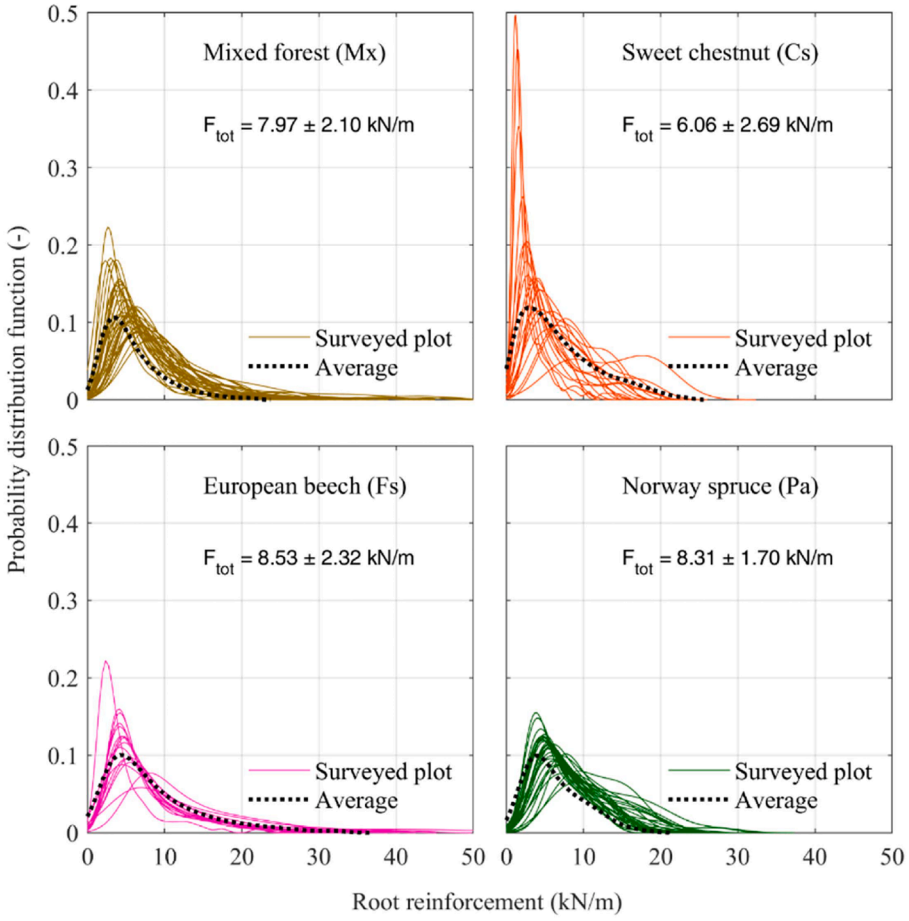


Fig. 5. Probability distribution of root reinforcement values evaluated applying the rootFORCE package. Continuous lines represent the probability distribution in each plot, whereas dashed lines represent the average probability distribution in each forest type.

reinforcement. Moreover, the two-way non parametric Skillings-Mack test (Skillings and Mack, 1981) was used to assess the presence of a statistical combined effects of forest type and thinning method.

3. Results

3.1. Stand structure description

Stand features were measured in stands that span over a range of tree densities. The highest variability was found in sweet chestnut with 2966 ± 1616 stems/ha and 851 ± 411 stumps/ha. A moderate variability was observed in European beech plots with 1034 ± 353 trees/ha, whereas a moderate variability was observed in mixed and Norway spruce samples with 566 ± 197 and 517 ± 160 trees/ha. The range of *DBH* was 0.13–0.73 m in sweet chestnut plots, 0.15–0.25 m in European beech plots, 0.28–0.50 m in Norway spruce plots, and 0.18–0.53 m in mixed forest plots. Tree height ranged between 12 and 25 m in sweet chestnut plots, 15–20 m in European beech plots, 15–32 in Norway spruce plots, and 14–31 m in mixed forest plots. The relationship between the minimum distance between trees/stumps and DBH_m (Eq. (12)) was significant for all the forest types. Sweet chestnut, European beech and mixed forest showed a moderate goodness-of-fit (RMSE = 0.66, 0.39 and 0.41, respectively), whereas Norway spruce exhibited a better fitting (RMSE = 0.29) (Fig. 3).

3.2. Calibration of rootFORCE package

The calibration of the RDM coefficients aimed to minimize the differences between observed and simulated root density (Table 1). In sweet chestnut MPE was 7.43% (±1.03%) and RMSE was 39.50 root m^{-2} (±20.82), in European beech MPE was 2.47% (±2.08%) and RMSE was 18.68 root m^{-2} (±15.49), in Norway spruce MPE was 1.22% (±1.42%) and RMSE was 15.29 root m^{-2} (±10.44), and in silver fir MPE was 3.73% (±1.74%) and RMSE was 26.47 root m^{-2} (±14.56). In the optimal set of RDM coefficients (Table 2), m and α can be approximated to values of 4.000 and 0.500, respectively. Parameters *a* and *b*, which are used to estimate the distribution of coarse roots, showed a wider range (1.420–1.587 and 0.389–0.797, respectively). Finally, the parameter Θ, which is linked to fine root density, showed the highest variability with values up to three times as high in beech as in silver fir.

The calibration of RBMw was attained by fitting the non-linear regression for the maximum tensile force (Eq. (6)), the elastic modulus (Eq. (7)), the root elongation (Eq. (8)) and the Weibull function (Eq. (9)), using the results of the tensile tests (Table 3). In terms of biomechanical properties, the roots of beech were stronger and, at the same time, more flexible than those of other species. On the other hand, the roots of Norway spruce and sweet chestnut were more rigid. The roots of silver fir are the weakest in term of tensile resistance (Table 4).

3.3. Root reinforcement estimation

After the calibration phase, rootFORCE provided an estimation of root reinforcement by a single tree, as a function of its species, diameter and biomechanical root properties. Silver fir had the lowest root reinforcement (7.08, 11.80, and 16.53 kN/m at a distance of 0.12, 0.20, and 0.30 m from stem base and for a *DBH* of 0.30, 0.50, and 0.70 m, respectively. The values were slightly higher in sweet chestnut (7.52, 12.54 and 17.56 kN/m), almost twice as high in Norway spruce (13.06,

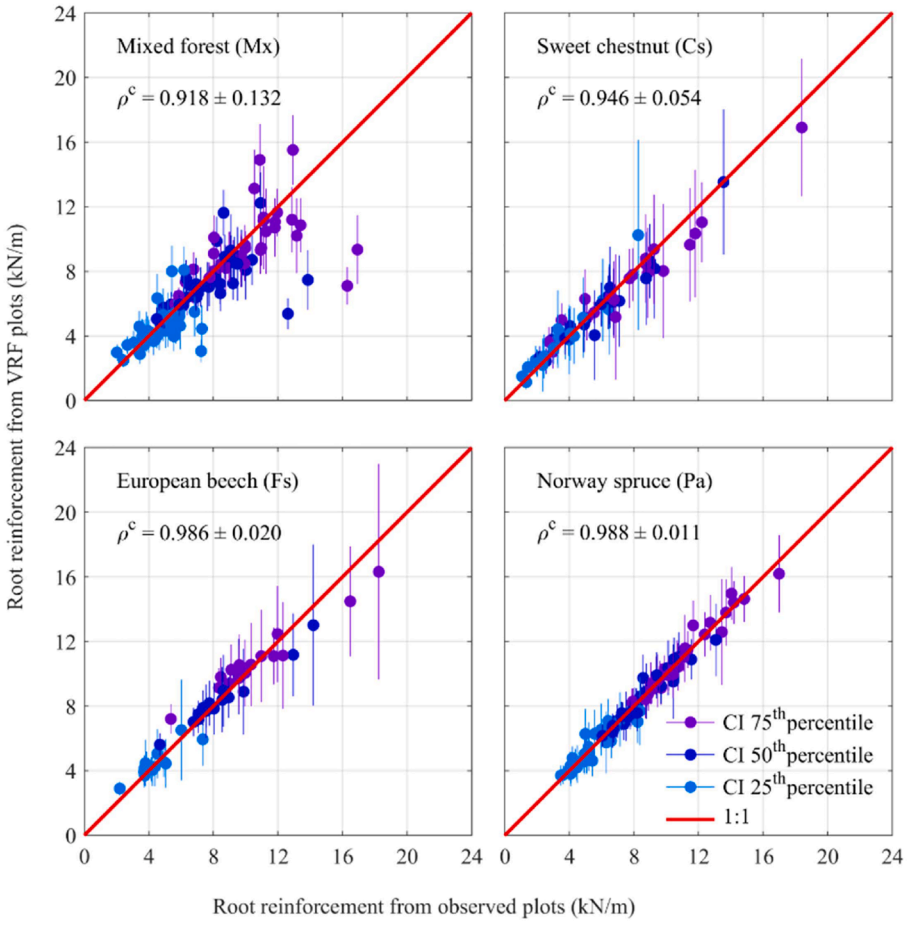


Fig. 6. Root reinforcement probability distributions obtained by VRF stand data methology compared to those obtained by field stand data.

21.76, and 30.46 kN/m) and highest European beech (28.02, 47.36, and 66.38 kN/m, i.e., almost four times higher than those of silver fir and sweet chestnut).

As expected, root reinforcement declined sharply with increasing distance. Indeed, at a distance of 3.5 m, root reinforcement was < 0.75 kN/m for single silver fir and chestnut, slightly higher than 1.25 kN/m for spruce, and as high as 2.85 kN/m for beech (Fig. 4). Plot-level estimates of root reinforcement were statistically different among forest types (Kruskal-Wallis p-value < 0.001). The Dunn's post hoc test revealed that the sweet chestnut root reinforcement was statistically different from the other forest types, showing the lowest average value (6.06 ± 2.69, 8.53 ± 2.32, 8.31 ± 1.70, and 7.97 ± 2.10 kN/m in sweet chestnut, European beech, Norway spruce, and mixed forest stands, respectively). The probability distribution of root reinforcement significantly differed among forest types (Fig. 5). This was underlined also by the difference in average maximum root reinforcement in all sample plots: 15.04 ± 4.04 kN/m for sweet chestnut, 34.75 ± 7.38 kN/m for European beech, 20.85 ± 3.24 kN/m for Norway spruce, and 28.60 ± 8.71 kN/m for mixed stands.

3.4. Virtual random forest

We generated 1,000 virtual forests for each *DBH* frequency distribution of the survey plots, and hence 1,000 distribution maps of root reinforcement values (Fig. 6). The concordance between maps of root reinforcement obtained from VRF and from field measurement plus rootFORCE estimation depended strictly on the type of *DBH* frequency distribution. The average Lin's concordance correlation coefficient was higher (ρ^c = 0.99 ± 0.01) in Norway spruce, suggesting a perfect concordance. A substantial concordance was obtained for chestnut and beech stands (ρ^c = 0.95 ± 0.05 and ρ^c = 0.99 ± 0.02 respectively). The lowest value of ρ^c was obtained in mixed forest (0.92 ± 0.13), probably due to an exacerbated bimodal *DBH* frequency distribution and a grouped tree spatial distribution inside the observed plots.

3.5. Thinning effects

The two thinning methods produced different effects. Low thinning reduced average root reinforcement by<11%. A mean reduction of approximately 2% was estimated in sweet chestnut and mixed forests, and of 4–6% in Norway spruce and European beech forests. Random cluster thinning had a stronger impact on root reinforcement, with reductions of 25% to 28%, on average. Indeed, the Kruskal-Wallis test showed statistical differences between thinning methods (p-level < 0.001). Forest types showed similar average effects, but differed widely in their variability, which was much larger in sweet chestnut forest. Although the Kruskal Wallis test also demonstrated the main effect of the forest type, no combined effect of forest type and thinning method existed, according to the Skillings-Mack test (p-level = 0.12). However, Norway spruce and European beech stands seems to be more sensitive to thinning, on average, while the maximum reductions of root reinforcement were registered in sweet chestnut and mixed forests (47.6% and 56.9%, respectively). (Fig. 7).

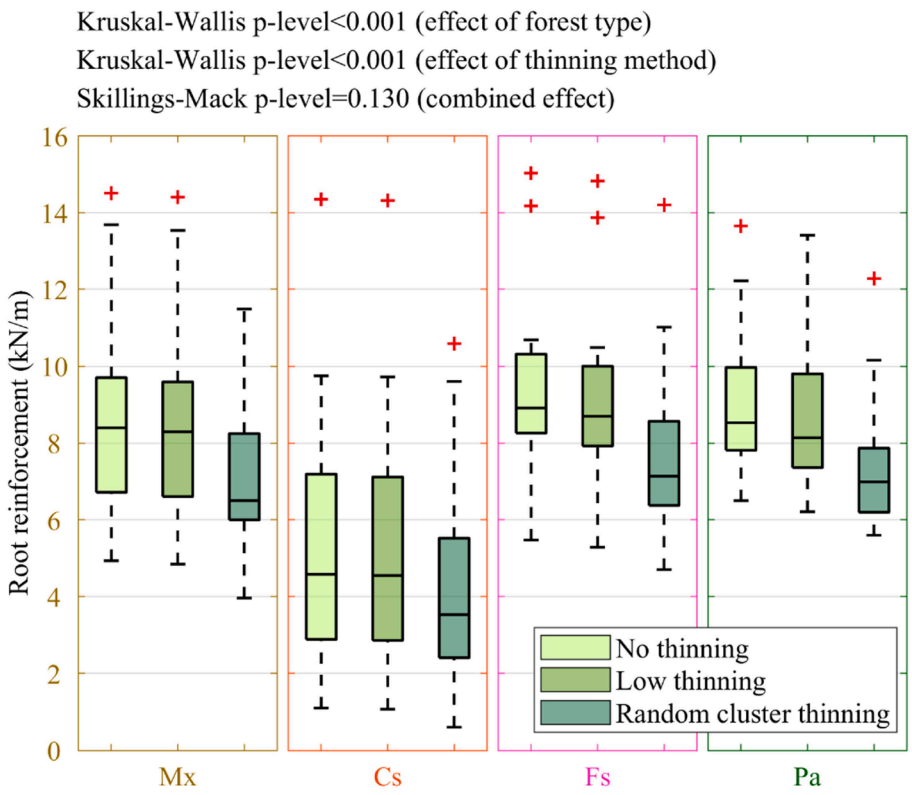


Fig. 7. Root reinforcement under different forest types (Cs = sweet chestnut, Fs = European beech, Pa = Norway spruce, and Mx = mixed forest) and thinning methods (including no thinning). The Skillings-Mack test showed that no combined effect of the two factors (forest type and thinning method) is present. However, each factor has a main effect, according to the Kruskal-Wallis test.

4. Discussion

4.1. Applicability of rootFORCE

The rootFORCE package allows to provide the probability distribution of root reinforcement in forest stands. In this study, the root reinforcement was estimated for sweet chestnut, European beech, Norway spruce, and mixed forest stands, starting from *DBH* spatial distribution. The proposed methodology is an attempt to face the wide variability and uncertainty derived from the observations of root systems in calculating root reinforcement for a specific area through not the estimation of a single value for the entire forest stand but providing a stochastic sample in function of the forest stand configuration. The obtained probability distribution of root reinforcement values in function of forest types can be included in raster-based stochastic slope stability analysis overcoming specific distributions adopted so far (e.g., uniform, normal and lognormal distributions) (Arnone et al., 2016; Hammond et al., 1992; Milledge et al., 2014; Pack et al., 1998) and improving the alternative methodology previously developed (Cislaghi et al., 2018).

In this study, the estimation of root reinforcement showed a significant variability, ranging from 0 kN/m to 50 kN/m in according to their specific main characteristics of the forest stands. Such range is more precautionary than reference values estimated by Schmidt et al. (2001) for an old Douglas fir forest, by Schwarz et al. (2012) in an Apennine chestnut forest and by Mao et al. (2012) in an Alpine conifer forest. On the other hand, these results are in perfect agreement with some recent works. Dorren and Schwarz (2016) analysed the root reinforcement for European beech, Norway spruce and silver fir in Switzerland, quantifying a range between 0 and 15 kPa. Chiaradia et al. (2016) achieved similar results investigating the same tree species; however, they neglected the role of stand structure. Dazio et al. (2018) investigated the role of coppicing on root reinforcement in chestnut stands collecting data on root distribution and biomechanical properties of roots providing results in agreement with those one showed in this study. Plot-level root reinforcement statistical differed among forest types. The lowest values were found in sweet chestnut forest. This is probably due to both biomechanical properties of sweet chestnut roots and the stand structure. Namely, the results showed that the lowest values of plot-level root reinforcement are given by coppice stands. Conversely, the highest values are given by high forests dominated by conifers or beech.

Besides the use of *DBH* spatial distribution as input parameter, the present study proposed an alternative feasible method, the VRF, aimed to quantify the root reinforcement at stand level starting from simpler stand features such as *DBH* frequency distribution. These forestry data are often available from forest management plans where can be found as average values for each forest section or can be derived from other forestry stand characteristics such as tree age, total basal area or tree density. Therefore, it is possible to characterize each forest section also in terms of root reinforcement (and consequently in terms of slope stability). VRF can be replaced when detailed field surveys and forestry inventories obtained through LiDAR applications are available (Duncanson et al., 2015; Marchi et al., 2018; Moser et al., 2017). In fact, tree-based methods used in LiDAR data analysis can give information about position and dimension of each tree belonging to the stand, even if the performance of the results depend on tree species and forest type (Eysn et al., 2015). However, such analyses are sometimes too expensive and time-consuming in particular over large territory.

4.2. Root reinforcement and thinning simulation

Thinning is a primary silvicultural practice that modifies stand structure and tree density, influencing the contribution of trees on the slope stability (Bishop and Stevens, 1964). In this study, we found statistical differences between thinning methods (Fig. 7). The low thinning caused a slight reduction, below 6%, of root reinforcement. The canopy perimeter and the canopy cover have been investigated as proxy for

Table 5
Reduction rate of tensile strength and root reinforcement under different species and sites available from the literature. The estimation rate was calculated fitting a negative exponential relationship.

Site	Species	Root reinforcement	ΔCr (T = 2 yr)	ΔCr (T = 5 yr)	ΔCr (T = 10 yr)	ΔCr (T = 20 yr)	References
Brembana valley (Italy)	Silver fir (*Abies alba*) and Norway spruce (*Picea abies*)	Fiber Bundle Model	9.47%	2.80%	0.74%	0.12%	Bischetti et al. (2016)
Idaho (United States)	Douglas fir (*Pseudotsuga menziesii*)	Empirical Model	44.88%	6.14%	0.08%	0.00%	Burroughs and Thomas (1977)
Western Oregon (United States)	Douglas fir (*Pseudotsuga menziesii*)	Empirical Model	37.65%	32.73%	29.05%	25.45%	Burroughs and Thomas (1977)
Serchio valley (Italy)	European beech (*Fagus sylvatica*)	Wu & Waldron Model	74.84%	42.59%	14.48%	1.26%	Preti (2013)
North Westland (New Zealand)	Hard beech (*Nothofagus truncata*), redbeech (*Notofagus fusca*), kamahi (*Weinmannia racemosa*) and rimu(*Dacrydium cupressinum*)	Wu & Waldron Model	60.45%	27.52%	7.21%	0.47%	O'Loughlin and Ziemer (1982)
Southest Alaska (United States)	Yellow cedar (*Cupressus nootkatensis*), Sitka spruce (*Picea sitchensis*), and western hemlock (*Tsuga heterophylla*)	Wu & Waldron Model	88.23%	74.22%	56.28%	33.02%	Johnson and Wilcock (2002)
Sanko catchment (Japan)	Sugi (*Cryptomeria japonica*)	Empirical Model	61.22%	43.71%	29.27%	16.13%	Kitamura and Namba (1981)
Ashley State Forest (New Zeland)	Radiata pine (*Pinus radiata*)	Average Tensile Strength	29.77%	1.09%	0.00%	0.00%	O'Loughlin and Watson (1979)
Southest Alaska (United States)	Hemlock	Average Tensile Strength	76.08%	70.56%	65.76%	60.42%	Ziemer and Swanston (1977)
Southest Alaska (United States)	Sitka spruce	Average Tensile Strength	94.10%	76.34%	43.43%	7.61%	Ziemer and Swanston (1977)
British Columbia (Canada)	Douglas fir (*Pseudotsuga menziesii*)	Average Tensile Strength	65.14%	17.44%	0.64%	0.00%	O'Loughlin (1974)
British Columbia (Canada)	Western red cedar (*Thuja plicata*)	Average Tensile Strength	76.49%	34.27%	4.72%	0.02%	O'Loughlin (1974)
Northern California (United States)	Shore pine (*Pinus contorta*)	Average Tensile Strength	47.64%	30.98%	19.08%	9.61%	Ziemer (1981)
North Island (New Zealand)	Kanuka (*Kunzea ericoides* var. *ericoides*)	Average Tensile Strength	54.04%	20.92%	4.21%	0.16%	Watson et al. (1997, 1999)
North Island (New Zealand)	Southern Rata (*Metrosideros umbellata*)	Average Tensile Strength	57.67%	26.70%	7.73%	0.70%	Watson et al. (1997, 1999)
British Columbia (Canada)	Douglas fir (*Pseudotsuga menziesii*)	Empirical Model	53.15%	47.30%	42.71%	38.02%	Sakals and Sidle (2004)
Canton of Glanora (Switzerland)	Norway spruce (*Picea abies*)	Average Tensile Strength	98.05%	86.37%	51.28%	4.76%	Ammann et al. (2009)
Canton of Schwyz (Switzerland)	Norway spruce (*Picea abies*)	RBMw Model	80.64%	43.12%	9.45%	0.13%	Vergani et al. (2016)

estimating root lateral expansions and of root reinforcement (Choi et al., 2016; Hodgkins and Nichols, 1977). Another advantage consists in not exacerbating the distance among trees preserving a maximum distance of 5 m. In fact, several authors investigating coniferous stands, emphasized as a distance > 6 m between two neighbouring trees could be a zone of weakness (for example, the measured distance between a boarder tree and a landslide scarp) (Bischetti et al., 2016; Mao et al., 2014; Moos et al., 2016). Conversely, the random cluster thinning caused the highest reduction of root reinforcement, ranging between 23.8% and 29.9%, on average, with extreme case reaching almost 60%. According to these results, the random cluster thinning can cause a significant reduction of root reinforcement, and therefore, an increase of landslide susceptibility, especially where the slope inclination is higher than 20°. The reason of the difference in terms of root reinforcement reduction between low thinning and random cluster thinning is probably due to the different selection criteria of the removal trees. Indeed, in the low thinning, only the smallest diameter trees were selected and removed from the whole of the plot surface. Conversely, in the random cluster thinning, the removal trees belonged to a small group formed by the nearest neighbours of a randomly selected tree. Since this thinning method was based on a merely criterion of proximity, also trees belonged to higher diameter classes may be removed. Therefore, the selection and the cut of higher diameter trees led to the relevant reduction of root reinforcement mainly found in the random cluster thinning, compared with low thinning. We found that there is no combined effect of forest type and thinning method on root reinforcement. Thus, forest types seem to show the same behaviour in response to the thinning method.

In addition to the changes in the stand structure due to tree cuttings, other aspects must be considered such as the root degradation of a felled tree, the root expansion and the tree growth of the remaining trees. Root degradation is a natural process that includes both the deterioration of root biomechanical properties and the reduction in the number of roots causing a rapid decay in terms of root reinforcement. Since the Seventies, pioneering studies investigated the root decay over the time after tree cutting, in particular after a clear-cutting, describing the rate of root reinforcement (ΔC) in function of time through negative exponential functions (Burroughs and Thomas, 1977; Sidle, 1992; Vergani et al., 2016). The results of these researches showed that the estimated rate of root reinforcement decay was extremely wide because of differences in environmental conditions, tree species, thinning intensity and methodology for quantifying root reinforcement (as reported in Table 5) (Vergani et al., 2014). Despite, most of the studies underlined how the minimum reinforcement was reached within 10 years after clear-cutting. Such available data can make more reliable conceptual models of change in relative of root reinforcement after thinning operations (Ziemer, 1981; Vergani et al., 2017) that integrate the root decay and, if possible, the regrowth of residuals or the regeneration of new roots. This procedure could be a necessary support for forest managers, where the protective role of the forests is primary (i.e., in proximity of a village or an infrastructure) in order to plan each forest management work balancing appropriately the economic benefits, the ecological requests and the safety.

4.3. Stand structure, silvicultural systems and root reinforcement

In this study, the structure of the examined stands is the result of a wide spectrum of interactions, of which the most important is certainly the forest management. Measurements and observations of many sampling plots provided a large dataset that includes different forest types and different silvicultural treatments that revealed a wide variability in stand structure. For example, the sampling plots of sweet chestnut are representative of large forests planted by mountain communities over the last century. Such forests have always been a source of food and firewood, traditionally managed as coppice system for wood production or as high forest system for picking chestnuts (Buonincontri et al., 2015). Nevertheless, the depopulation of mountain villages and the widespread use of alternative energy and food sources caused an inexorable abandonment of the forests, favouring an increase of complexity in stand structure and species composition. As in the case of sweet chestnut forests, the European beech stands have been usually managed as coppice; however, these activities gradually started to become less economically viable and have led the forest managers to convert the coppice system to even-aged high forest system, which are considered more productive (Nocentini, 2009). In mixed spruce-beech-silver fir stands, selective-cutting is usually the most common silvicultural treatment, which ensures the continuous presence of canopy cover and preserves a multi-layered high forest structure over time (Del Favero, 2004; Nascimbene et al., 2007). Concerning the Norway spruce forests, surveyed in the present study, they were planted to reduce the soil erosion due to the past over-exploitation of mountain slopes (Pâques, 2013), or were the result of forest expansion caused by the abandonment of pastoral and agricultural activities (Cislaghi et al., 2019b). These forests are even aged and are usually managed by shelterwood system or group selection system (Del Favero, 2004). In this context and in light of the results obtained by the thinning simulations, it could be interesting to infer how different silvicultural systems and stand structures above mentioned may affect the root reinforcement. In particular, the continuous canopy cover ensured by selective cutting is very useful to preserve the root reinforcement over space and time. Instead, where the silvicultural treatment temporally interrupts canopy cover by gaps, the root reinforcement can be reduced. This could occur in Norway spruce forest stands, where group selection or small clear-cutting are often employed. Concerning the coppice system, although this treatment can ensure a continuous canopy cover, the abandonment of this silvicultural practice can provoke a stand structural evolution, moving stands away from their highest degree of stability, and threatening the forest's structural ability to give protection (Motta and Haudemand, 2000). From this point of view, predicting the future implications of the sweet chestnut coppice abandonment on root reinforcement is still complex. Conversely, the conversion of beech coppice stands to high forest is a consolidated strategy to increase the stability of stand structure and to ensure a reasonable degree of root reinforcement. Further researches should be focused on permanent plots where the effect of different silvicultural systems on root reinforcement are assessed over the term, to address the best forest management practice for the direct protection forests.

5. Conclusions

In the present study we developed, calibrated and validated a model for estimating the root reinforcement at stand scale, using the spatial distribution of tree diameter, collected from 119 forest plots belonging to sweet chestnut, European beech, Norway spruce, and mixed spruce-fir-beech stands, as the unique parameter. Plot-level root reinforcement statistical differed among forest types and the lowest values were found in sweet chestnut forest. The best concordance between root reinforcement modelled from field *DBH* spatial distribution and VRF method was obtained in Norway spruce forest (Lin's concordance correlation coefficient, ρ^c=0.99 ± 0.01). The low thinning did not significantly modify the root reinforcement, causing a quite negligible reduction below the 6%. On the other hand, random cluster thinning causes a significant decrease, approximately 25% on average. In addition, forest types seem to show the same behaviour in response to the thinning method. The results suggest that the lowest contribution in terms of root reinforcement is provided by sweet chestnut forest. In the Italian Alps, sweet chestnut forests are common. However, if on one hand the presence of this species does not assure high levels of root reinforcement, any attempt to promote other species than the sweet chestnut must take into account also economic, cultural and ecological aspects. An additional outcome is provided by the thinning simulation, which gave different reduction of root reinforcement in function of the different thinning methods. Moreover, the proposed procedure allows to simulate, test and compare different thinning types and intensity to select the best management practices in terms of the reduction of root reinforcement, especially for direct protection forests. Finally, the results obtained in this study suggest that forest management strategy must be planned also in function of the contribution of trees to reduce the triggering mechanisms of shallow landslides, especially in proximity of infrastructures or villages. The spatial modelling of root reinforcement through the rootFORCE and VRF models, here tested, may help to extrapolate root reinforcement for large forested hillslopes using data on forest types and stand structure distribution. This would help forest managers to assess the contribution of forests on mitigating shallow landslide hazard.

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CRediT authorship contribution statement

Alessio Cislaghi: Conceptualization, Methodology, Writing - original draft, Formal analysis, Writing - review & editing. **Edoardo Alterio:** Conceptualization, Methodology, Writing - review & editing, Investigation. **Paolo Fogliata:** Investigation, Methodology. **Andrea Rizzi:** Investigation. **Emanuele Lingua:** Writing - review & editing. **Giorgio Vacchiano:** Writing - review & editing. **Gian Battista Bischetti:** Project administration, Methodology, Writing - review & editing, Supervision. **Tommaso Sitzia:** Conceptualization, Project administration, Methodology, Writing - review & editing, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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