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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 the main contribution of forests in preventing and mitigating shallow soil instabilities, one of the main hazards in mountain areas. Quantifying such factor remains complex because of a wide variability and uncertainty. This study aims to assess how spatial tree distribution affects root reinforcement, and whether the thinning operations can significantly reduce the contribution to the soil stabilization. We measured tree size and position in 103 sampling plots, located in pure and mixed forests with sweet chestnut, Norway spruce, European beech and silver fir in the Southern Alps. We developed, calibrated and validated a model for estimating root reinforcement at the stand scale, using the spatial distribution of tree diameter as input variable. Finally, we simulated how different silvicultural treatments (thinning 18% of the basal area, either randomly or in groups), affects root reinforcement. The average values of root reinforcement were 6.06, 7.97, 8.31 and 8.53 kN/m in chestnut, mixed, spruce, and beech forests respectively. Probability density functions of root reinforcement significantly differ among forest types. Randomly spaced thinning did not significantly modify root reinforcement, while group thinning reduced it five-fold. Such obtained values are consistent with previous works and can be used for assessing slope stability over forested hillslope with a poor availability of forestry data.
Keywords

Protection forest, Root reinforcement, Tree roots, Shallow landslides, Natural hazards, Disaster Risk Reduction.

1 Introduction

In mountain areas, forests play a significant role in protecting people, settlements and resources from natural hazards as floods, landslides, snow avalanches and rockfalls. Their protective function has been recognised and documented first and foremost by surviving works of ancient Greek, Hebrew and Roman literature (Hamilton, 1992). Nowadays, the term “protection forests” is found in the laws of every country establishing a specific land management that is clearly directed to preserve soil, water and all the natural resources. Where natural hazards or potentially adverse climate may cause damage, where people or assets may be damaged and where forests has the potentiality to mitigate the consequences, forests provide a “direct” protection (Brang et al., 2001) that requests a particular attention in terms of monitoring, planning of the activities (from the tourism to the forestry) 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 (e.g., 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 actions, root reinforcement is undoubtedly the most studied since the pioneering works of Endo and Tsuruta (1969), Gray (1969) and O’Loughlin (1974). 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 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 (e.g., Tobin et al., 2007). Another widespread approach is to empirically relate root diameter and its biomechanical properties (e.g., Schwarz et al., 2010). Although some of these models assume that root reinforcement decreases with increasing distance from the stem base, few works have assessed how the spatial pattern of trees, and especially its changes due to human management, influences 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).

The present study aims to investigate the variability of tree spatial distribution and its effects on root reinforcement in four common forest cover types (Norway spruce, sweet chestnut, European beech and mixed forests) in the Southern Alps. The specific steps of his work can be synthetized 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) running the model with different spatial configurations of trees (e.g., as a result of forest thinning) and assess which is the effect on root reinforcement.

2 Materials and methods

2.1 Study area

We sampled 103 plots collected in the Southern Central-Eastern Alps, belonging to three different administrative Italian regions (Piedmont, Lombardy and Veneto). The samples ranged from 487 to 1542 m asl in elevation, and from 20° to 40° in slope. The dominant tree species were Norway spruce (Picea abies L.) (30 plots), European beech (Fagus sylvatica L.) (16 plots) and sweet chestnut (Castanea sativa Mill.) (20 plots). In addition, several areas were covered by mixed forests (37 plots) with equal share of Norway spruce, silver fir (Abies alba Mill.) and European beech (Figure 1). Supplementary material 1 summarises the main characteristics of the study sites (geographical, geological, lithological, meteorological, and silvicultural features). The survey plots were selected in function of several criteria: (i) location inside a protective forest; (ii) proximity to a village or an infrastructure; (iii) hillslope inclination higher than 20°; and (iv) inclusion in publicly-owned forests. In each plot (circular with 20-m radius), we measured diameter at breast height (DBH), total height and position of all living trees with DBH ≥ 0.075 m. Average x and y coordinates were derived in case of multi-stemmed individuals.
2.2 Spatial pattern quantification
Using tree coordinates as input, in each plot we computed the Clark-Evans index (Clark and Evans, 1954; Pommerening and Grabarnik, 2019), using the Kaplan-Meier type edge correction (Kaplan and Meier, 1958) to avoid edge bias. The value of Clark-Evans index equals one when the population is randomly distributed, <1 for a clumped pattern and >1 for a regular (over-dispersed) pattern.

2.3 Modelling root reinforcement
We developed the MATLAB package rootFORCE, which estimates root reinforcement provided by a single tree as a function of species, DBH and distance from the stem base (d). rootFORCE combines two separate models: a Root Distribution Model (RDM) and the Root Bundle Model Weibull (RBMw), which are described below.
2.3.1 Root Distribution Model (RDM)

RDM (Schwarz et al. 2010) estimates the density of roots belonging to different size classes, based on the static fractal branching model and the pipe theory (e.g., Ammer and Wagner, 2005). This model requests, 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:

$$FRs(DBH, d < m \sum_i DBH_i) = \Theta \frac{\pi}{4} \left[ \frac{d}{m \sum_i DBH_i} \right]^2$$

$$FRs(DBH, d \geq m \sum_i DBH_i) = \Theta \frac{\pi}{4} \left( \sum_i DBH_i \right)^2$$

Where $\Theta$ is the pipe theory coefficient (roots/m$^2$), $\alpha$ and $m$ are empirical dimensionless parameters, and $\sum_i DBH_i$ is the sum of $DBH$ of the trees belonging to the same stump.

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

$$CRs(\phi_i, DBH, d) = FRs(DBH, d) \frac{1 - \exp \left[ -\exp \left( \frac{\phi_i - \alpha}{b} \right) \right]}{1 - \exp \left[ -\exp \left( \frac{\phi_0 - \alpha}{b} \right) \right]}$$

Where $\phi_i$ is the diameter of $CRs$, $\alpha$ and $b$ are the two Gumbel parameters.

The coefficients $\alpha$, $m$, $a$ 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:

$$MPE = \frac{100\%}{M} \sum_j \frac{1}{n} \sum_i \left( \frac{y_{i,k} - x_{i,k}}{x_{i,k}} \right)$$

$$RMSE = \frac{1}{M} \sum_j \sqrt{\frac{1}{n} \sum_i (y_{i,k} - x_{i,k})^2}$$

where $M$ is the number of plots, $n$ is the number of observed trench profiles, $x_{i,k}$ and $y_{i,k}$ are the observed and predicted root density in the $i$-th trench profile at the $k$-th study site.

2.3.2 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 mechanical 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:
\[ F_{\text{max}}(\phi_i) = F_0 \left( \frac{\phi_i}{\phi_0} \right)^\xi \]  
(6)

\[ E(\phi_i) = r E_0 \left( \frac{\phi_i}{\phi_0} \right)^\beta \]  
(7)

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

where \( F_0, E_0 \) and \( L_0 \) are multiplicative coefficients, \( \xi, \beta \) and \( \gamma \) are exponential coefficients, and \( r \) represents the effect of root tortuosity on Young's modulus.

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

\[ F_{\text{tot}}(\Delta x) = \sum_i F(\phi_i, \Delta x) \cdot S(\Delta x^*) \]  
(9)

Where \( F \) is the tensile force of a single root and \( S \) is a function of the normalized displacement \( \Delta x^* \), as described by the following equations:

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

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

where \( \lambda \) is the Weibull scale parameter and \( \omega \) is the Weibull shape parameter (dimensionless).

### 2.3.3 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 pull-out 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 sample plots located in Norway spruce (18 trench profiles in 3 plots), silver fir (12 trench profiles in 2 plots), European beech (12 trench profiles in 2 plots) and sweet chestnut (24 trench profiles in 4 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 (Böhlm, 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. 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).

2.4 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 values from measurements commonly found in forest management plans, i.e., DBH frequency, tree density, and minimum distance between trees. Here, we implement the VRF workflow using field measurements collected in the 103 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 stem diameters obtained by field measurements;

2. Estimating the minimum distance between trees \(d_{\text{min}}\) as a function of average tree diameter \(DBH_m\):

\[
d_{\text{min}} = D_0 \ DBH_m^\delta
\]  

(12)

where \(D_0\) and \(\delta\) are fitted parameters;

3. Generating a set of virtual forests through a sequentially constrained Monte Carlo simulation (1,000 iterations) that produces random locations of trees 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 similarity between the root reinforcement probability distributions and maps produced by VRF and those resulting from estimation by rootFORCE from field-measured tree patterns and was examined through the Lin’s concordance correlation coefficient \(\rho_c\) (Lin, 1989):

\[
\rho_c = \frac{2\sigma_{12}}{\sigma_1^2 + \sigma_2^2 + (\mu_1 - \mu_2)^2}
\]  

(13)

where \(\mu_1\) and \(\sigma_1^2\) represent the mean and the variance for the root reinforcement values provided by the VRF procedure, \(\mu_2\) and \(\sigma_2^2\) represent the mean and the variance for the root reinforcement values provided by the application of rootFORCE using the surveyed plots and the \(\sigma_{12}\) is the covariance of the two outputs. This index denotes an almost perfect concordance when \(\rho_c\) > 0.99, substantial when 0.95-0.99, moderate when 0.90-0.95, and poor when <0.90 (McBride, 2005).
2.5 Thinning simulation

Thinning influences the growth and survival of the trees remaining in the stand, hence affecting the spatial distribution of root reinforcement and possibly slope stability (e.g., Cislaghi et al., 2019; Sakals and Sidle, 2004). In the present study, we simulated two thinning scenarios aimed at removing suppressed and sub-dominant trees, in order to funnel the resources for the growth of the remaining trees (Kerr and Haufe, 2011).

In the first scenario, trees were randomly removed from the plot, whereas in the second they were removed in small groups from local hot-spots with high tree density. In both scenarios, thinning removed 18% of the total basal area of the plot as suggested by Del Favero (2004) for the Italian Alpine area. Furthermore, we operated under the following assumptions: (i) roots of removed 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 the applying thinning scenarios to the study plots, rootFORCE was applied again to estimate the change in the probability distribution of root reinforcement.
3 Results

3.1 Stand structure

The range of DBH was 0.18-0.53 m in mixed forest plots, 0.13-0.73 m in sweet chestnut plots, 0.15-0.25 m in European beech plots and 0.28-0.50 m in Norway spruce plots. Tree height ranged between 14 and 31 m in mixed forest plots, 12-25 m in sweet chestnut plots, 15-20 m in European beech plots and 15-32 in Norway spruce plots (Fig. 3). The degree of tree spatial aggregation varied among forest types. Mean Clark-Evans index was 1.07 in European beech and Norway spruce plots, 1.29 in sweet chestnut plots (indicating a tendency towards a regular point pattern), and 0.94 in mixed forests and it was 0.94, suggesting a clumped tree pattern (Fig.3).

The relationship between the minimum distance between trees and $DBH_m$ (Eq.12) was significant for all the forest types. Sweet chestnut and European beech releveled a moderate goodness-of-fit ($R^2=0.23$ and $R^2=0.36$), whereas Norway spruce and mixed forest exhibited a strong fitting ($R^2=0.53$ and $R^2=0.68$) (Fig.4).

Figure 3. Dendrometric features observed in the surveyed plots in function of the forest types (Mx = mixed forest; Cs = sweet chestnut; Fs = European beech; Pa = Norway spruce).
Figure 4. Relationship between average minimum distance among trees and DBH in function of forest types: markers are the observations, red lines are the fitted relationships (Eq.12) and the yellow areas are the 95th confidence intervals.

3.2 Calibration of rootFORCE package

The calibration of the RDM coefficients aimed to minimize the differences between observed and simulated root density. In silver fir MPE was 3.73% (±1.74%) and RMSE was 26.47 root m$^{-2}$ (±14.56), 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), and in Norway spruce MPE was 1.22% (±1.42%) and RMSE was 15.29 root m$^{-2}$ (±10.44). In the optimal set of RDM coefficients (Table 1), m and α can be approximated to values of 4.00 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.

Table 1. Results of calibration of Root Distribution Model (RDM).

<table>
<thead>
<tr>
<th>Species</th>
<th>Θ (root/m$^2$)</th>
<th>m (-)</th>
<th>α (-)</th>
<th>a (-)</th>
<th>b (-)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silver fir</td>
<td>19712</td>
<td>3.967</td>
<td>0.500</td>
<td>1.587</td>
<td>0.797</td>
</tr>
<tr>
<td>Sweet chestnut</td>
<td>25044</td>
<td>3.996</td>
<td>0.495</td>
<td>1.472</td>
<td>0.534</td>
</tr>
<tr>
<td>European beech</td>
<td>56000</td>
<td>4.001</td>
<td>0.496</td>
<td>1.420</td>
<td>0.389</td>
</tr>
<tr>
<td>Norway spruce</td>
<td>31500</td>
<td>4.000</td>
<td>0.489</td>
<td>1.557</td>
<td>0.689</td>
</tr>
</tbody>
</table>
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. 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 2).

### Table 2. Results of calibration of Root Bundle Model weibull (RBMw).

<table>
<thead>
<tr>
<th>Eq.</th>
<th>Species</th>
<th>Silver fir</th>
<th>Sweet chestnut</th>
<th>European beech</th>
<th>Norway spruce</th>
</tr>
</thead>
<tbody>
<tr>
<td>(6)</td>
<td>$F_0$ (N)</td>
<td>7.733</td>
<td>13.498</td>
<td>27.478</td>
<td>13.928</td>
</tr>
<tr>
<td></td>
<td>$\xi$ (-)</td>
<td>1.745</td>
<td>1.514</td>
<td>1.491</td>
<td>1.568</td>
</tr>
<tr>
<td></td>
<td>$R^2$</td>
<td>0.759</td>
<td>0.749</td>
<td>0.777</td>
<td>0.664</td>
</tr>
<tr>
<td>(7)</td>
<td>$E_0$ (MPa)</td>
<td>116.319</td>
<td>230.197</td>
<td>288.155</td>
<td>211.886</td>
</tr>
<tr>
<td></td>
<td>$\beta$ (-)</td>
<td>-0.836</td>
<td>-1.189</td>
<td>-1.193</td>
<td>-1.385</td>
</tr>
<tr>
<td></td>
<td>$R^2$</td>
<td>0.683</td>
<td>0.642</td>
<td>0.646</td>
<td>0.763</td>
</tr>
<tr>
<td>(8)</td>
<td>$L_0$ (mm)</td>
<td>0.062</td>
<td>0.065</td>
<td>0.069</td>
<td>0.068</td>
</tr>
<tr>
<td></td>
<td>$\gamma$ (-)</td>
<td>0.129</td>
<td>0.067</td>
<td>0.114</td>
<td>0.134</td>
</tr>
<tr>
<td></td>
<td>$R^2$</td>
<td>0.381</td>
<td>0.228</td>
<td>0.518</td>
<td>0.441</td>
</tr>
<tr>
<td>(11)</td>
<td>$\lambda$ (-)</td>
<td>1.072</td>
<td>1.079</td>
<td>1.090</td>
<td>1.116</td>
</tr>
<tr>
<td></td>
<td>$\omega$ (-)</td>
<td>2.970</td>
<td>3.319</td>
<td>3.242</td>
<td>2.359</td>
</tr>
<tr>
<td></td>
<td>$R^2$</td>
<td>0.985</td>
<td>0.946</td>
<td>0.944</td>
<td>0.977</td>
</tr>
</tbody>
</table>

### 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, 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. 5). The average plot-scale root reinforcement for each forest type was 7.97 ± 2.10, 8.31 ± 1.70, 8.53 ± 2.32, and 6.06 ± 2.69 kN/m in mixed forest, Norway spruce, European beech and sweet chestnut stands, respectively. The probability distribution of root reinforcement significantly differed among forest types (Fig. 6). This was underlined also by the difference in average maximum root reinforcement in all sample plots: 34.75 ± 7.38 kN/m for European beech, 28.60 ± 8.71 kN/m for mixed forests, 20.85 ± 3.24 kN/m for Norway spruce, and 15.04 ± 4.04 kN/m for sweet chestnut stands.
Figure 5. 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 (silver fir, sweet chestnut, European beech and Norway spruce).

Figure 6. 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 the four forest types (mixed forest, sweet chestnut, European beech and Norway spruce).
3.4 Virtual random forest

We generated 1,000 virtual forests for each DBH frequency of the survey plots, and hence 1,000 distribution maps of root reinforcement values (Fig.7). 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 ($\rho^c=0.99\pm0.01$) in Norway spruce, suggesting a perfect concordance. A substantial concordance was obtained for chestnut and beech stands ($\rho^c=0.95\pm0.05$ and $\rho^c=0.99\pm0.02$ respectively). The lowest value of $\rho^c$ was obtained in mixed forest ($0.92\pm0.13$), probably due to an exacerbated bimodal DBH frequency distribution and a grouped tree spatial distribution inside the observed plots.

Figure 7. Root reinforcement probability distribution obtained by VRF methodology compared to those obtained directly using the observed forest configurations as input parameter.

3.5 Thinning effects

Despite having the same intensity (-18% of the total basal area), the two thinning scenarios produced significant different effects (Fig.8). Random thinning reduced average root reinforcement value by less than 11% relative to before treatment. A mean reduction of approximately 2% was estimated in mixed and chestnut forests, and of 4-6% in Norway spruce and European beech stands. Group thinning had a stronger impact on root reinforcement, with reductions of 25% to 28% on average. Forest types showed similar average effects but differed widely in their variability, which was much larger in chestnut forests. Norway
spruce and European beech plots were again more sensitive to thinning on average, even if maximum reductions of root reinforcement were registered in mixed and chestnut stands (-47.6% and -56.9% respectively).

![Figure 8. Root reinforcement in function of forest types (Mx = mixed forest; Cs = sweet chestnut; Fs = European beech; Pa = Norway spruce) and thinning spatial configuration (random or group).]

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 mixed forest, Norway spruce, sweet chestnut and European beech 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 stand. 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 Norway spruce, silver fir and European beech 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 paper.

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 analysis are sometimes too expensive and time-consuming (hours of specialized users and specific instruments) 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). The results of the thinning simulation confirmed what has been already showed in Cislaghi et al. (2019): a random thinning planned to remove 18% of trees causes a slight reduction of spatial root reinforcement below the 6%, on average. The canopy perimeter and the canopy cover have been investigated as proxy for estimating root lateral expansions and of root reinforcement (Choi et al., 2016; Hodgkins and Nichols, 1977). Another advantage consists in not exacerbate 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, i.e., the measured distance between a boarder tree and a landslide scarp (Bischetti et al., 2016; Mao et al., 2014; Moos et al., 2016). Conversely, this last preventive measure is not observed in case of the group thinning. The group thinning with the same intensity of the random thinning exerts more influence on the spatial distribution of root reinforcement. Opening gap causes a reduction of root reinforcement ranging between -23.85% and -29.92%, on average, with extreme case reaching almost -60%. For this reason, the group 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°. In addition, differences in terms of root reinforcement values were found among the investigated forest types. Spruce
and beech stands, often composed by trees of similar size and age, showed more susceptibility to thinning than mixed forest and sweet chestnut stands. This discrepancy was probably due to the fact that, in mixed forest and sweet chestnut stands, low thinning led to remove all small trees with DBH < 0.15 m that contribute least to the root reinforcement (Fig.5).

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 cut tree, the root expansion and the tree growth of the remaining trees and the root expansion of new seedlings. Root degradation is a natural process that includes both the deterioration of root mechanical 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):

\[ ΔC = \exp(-kt^n) \] (13)

where ΔC is the rate of root reinforcement (dimensionless with a range 0-1), k and n are two empirical coefficients, and t is the time after cutting in years.

Despite 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 3), most of the studies underlined how the minimum reinforcement was reached within 10 years after cutting.

### Table 3. Reduction rate of tensile strength and root reinforcement for different species and sites available from the literature. The estimation rate was calculated fitting a negative exponential relationship.

<table>
<thead>
<tr>
<th>Site</th>
<th>Species</th>
<th>Root reinforcement</th>
<th>ΔCr (T=2 yr)</th>
<th>ΔCr (T=5 yr)</th>
<th>ΔCr (T=10 yr)</th>
<th>ΔCr (T=20 yr)</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brembana valley (Italy)</td>
<td>Silver fir (Abies alba) and Norway spruce (Picea abies)</td>
<td>Fiber Bundle Model</td>
<td>9.47%</td>
<td>2.80%</td>
<td>0.74%</td>
<td>0.12%</td>
<td>Bischetti et al. (2016)</td>
</tr>
<tr>
<td>Idaho (United States)</td>
<td>Douglas fir (Pseudotsuga menziesii)</td>
<td>Empirical Model</td>
<td>44.88%</td>
<td>6.14%</td>
<td>0.08%</td>
<td>0.00%</td>
<td>Burroughs and Thomas (1977)</td>
</tr>
<tr>
<td>Western Oregon (United States)</td>
<td>Douglas fir (Pseudotsuga menziesii)</td>
<td>Empirical Model</td>
<td>37.65%</td>
<td>32.73%</td>
<td>29.05%</td>
<td>25.45%</td>
<td>Burroughs and Thomas (1977)</td>
</tr>
<tr>
<td>Serchio valley (Italy)</td>
<td>European beech (Fagus sylvatica)</td>
<td>Wu &amp; Waldron Model</td>
<td>74.84%</td>
<td>42.59%</td>
<td>14.48%</td>
<td>1.26%</td>
<td>Preti (2013)</td>
</tr>
<tr>
<td>North Westland (New Zealand)</td>
<td>Hard beech (Nothofagus truncata), red beech N. fusca, kamahi (Weinmannia racemosa) and rimu (Dacrydium cupressinum)</td>
<td>Wu &amp; Waldron Model</td>
<td>60.45%</td>
<td>27.52%</td>
<td>7.21%</td>
<td>0.47%</td>
<td>O’Loughlin and Zieler (1982)</td>
</tr>
<tr>
<td>Southeast Alaska (United States)</td>
<td>Yellow-cedar (Cupressus nootkatensis), Sitka spruce (Picea sitchensis), and western hemlock (Tsuga heterophylla)</td>
<td>Wu &amp; Waldron Model</td>
<td>88.23%</td>
<td>74.22%</td>
<td>56.28%</td>
<td>33.02%</td>
<td>Johnson and Wilcock (2002)</td>
</tr>
<tr>
<td>Sanko catchment (Japan)</td>
<td>Sugi (Cryptomeria japonica)</td>
<td>Empirical Model</td>
<td>61.22%</td>
<td>43.71%</td>
<td>29.27%</td>
<td>16.13%</td>
<td>Kitamura and Namba (1981)</td>
</tr>
<tr>
<td>Ashley State Forest (New Zealand)</td>
<td>Radiata pine (Pinus radiata D.Don)</td>
<td>Average Tensile Strength</td>
<td>29.77%</td>
<td>1.09%</td>
<td>0.00%</td>
<td>0.00%</td>
<td>O’Loughlin and Watson (1979)</td>
</tr>
<tr>
<td>Southeast Alaska (United States)</td>
<td>Hemlock</td>
<td>Average Tensile Strength</td>
<td>76.08%</td>
<td>70.56%</td>
<td>65.76%</td>
<td>60.42%</td>
<td>Ziemer and Swanston (1977)</td>
</tr>
<tr>
<td>Southeast Alaska (United States)</td>
<td>Sitka spruce</td>
<td>Average Tensile Strength</td>
<td>94.10%</td>
<td>76.34%</td>
<td>43.43%</td>
<td>7.61%</td>
<td>Ziemer and Swanston (1977)</td>
</tr>
<tr>
<td>British Columbia (Canada)</td>
<td>Douglas fir (Pseudotsuga menziesii)</td>
<td>Average Tensile Strength</td>
<td>65.14%</td>
<td>17.44%</td>
<td>0.64%</td>
<td>0.00%</td>
<td>O’Loughlin (1974)</td>
</tr>
</tbody>
</table>
### Table of Tensile Strength Data

<table>
<thead>
<tr>
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</tr>
</thead>
<tbody>
<tr>
<td>British Columbia (Canada)</td>
<td>Western red cedar (Thuja plicata Don)</td>
<td>76.49 %</td>
<td>76.49 %</td>
<td>47.64 %</td>
<td>47.64 %</td>
<td>Douglas fir (Pseudotsuga menziesii)</td>
<td>Empirical Model</td>
<td>Canton of Glanora (Switzerland)</td>
</tr>
</tbody>
</table>

### 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 as the unique parameter. Stand structure data were collected in 103 plots, belonging to four common Alpine forest types (Norway spruce, sweet chestnut, European beech and mixed forest with same cover of Norway spruce, silver fir and European beech). The average values of root reinforcement within forest types were 7.97 kN/m, 8.31 kN/m, 8.53 kN/m, and 6.06 kN/m in mixed forest, Norway spruce, European beech and sweet chestnut stands respectively. The shapes of the probability distribution functions were significantly different among forest types. 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, $\rho_c = 0.99 \pm 0.01$). The thinning simulation gave different reduction of root reinforcement in function of the different spatial distribution of the cuttings. The random thinning did not significantly modify the root reinforcement, causing a quite negligible reduction below the 6%. On the other hand, group thinning causes a significant decrease, approximately 25% on average. These results suggest that forest management must be mistake into account the contribution of trees to mitigate the landslide triggering, especially proximity of infrastructures or villages. The spatial modelling of root reinforcement through the here-tested rootFORCE and VRF models may help forest managers to assess the contribution of forests on reduce landslides.

### Acknowledgements

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