

New Zealand Journal of Forestry Science

Minimum representative root distribution sampling for calculating slope stability in *Pinus radiata* D. Don plantations in New Zealand

Filippo Giadrossich^{1*}, Massimiliano Schwarz², Michael Marden³, Roberto Marrosu¹, Chris Phillips³

¹University of Sassari, Viale Italia 39, 07100 Sassari, Italy

²Bern University of Applied Sciences, Laenggasse 85, 3052 Zollikofen, Switzerland

³Manaaki Whenua Landcare Research, P.O. Box 69040, Lincoln 7640, New Zealand

*Corresponding author: fgiadrossich@uniss.it

(Received for publication 24 September 2019; accepted in revised form 20 July 2020)

Abstract

Background: Rainfall-triggered shallow landslides on steep slopes cause significant soil loss and can be hazards for property and people in many parts of the world. In New Zealand's hill country, they are the dominant erosion process and are responsible for soil loss and subsequent impacts on regional water quality. Use of wide-spaced trees and afforestation with fast growing conifers are the primary land management tools in New Zealand to help control erosion and improve water quality. To decide where to implement erosion controls in the landscape requires determining the most susceptible places to these processes and models that incorporate how trees reinforce soils to understand if, and when, such treatments become effective.

Methods: This paper characterises the mechanical properties of *Pinus radiata* D. Don roots (the common tree species used for afforestation in New Zealand) by means of field pullout tests and by measuring the root distribution at 360 degrees around trees. The Root Bundle Model (RBM) was used to calculate the root reinforcement. Statistical analysis was carried out to assess the statistical reduction coefficients of root reinforcement that depend on the number of measurements, used in geotechnical analysis to reduce the mean value of a parameter to a so-called characteristic value.

Results: We show that to reach an effective level of root reinforcement, trees of 0.5 m DBH require a density of about 300 trees per hectare. Trees of this size are about 30 years of age across many sites and have generally reached the recommended conditions for clear-fell harvesting. The analysis of variance shows that 4 trees are the minimum number to be excavated to obtain sufficient root information to obtain less than 5% of error with a 95% of probability on the estimation of a design value of root reinforcement in accord with geotechnical standards.

Conclusions: We found that the variability of lateral and basal root reinforcement does not limit the implementation of vegetation in slope stability models for *Pinus radiata*. We adopt for the first time the concept of a minimum sampling requirement and characteristic value, similarly to what is assumed for the value of effective soil cohesion in geotechnical guidelines for slope stability calculations.

Keywords: root reinforcement; Root Bundle Model; slope stability; shallow landslide

Introduction

Shallow landslides on steep slopes occur mostly as a result of intense rainfall and are one of the main erosion processes of concern in many countries (Crozier 2005; Goetz et al. 2015; Marden & Rowan 2015; Fan et al. 2017;

Vergani et al. 2017; Peruccacci et al. 2017; Palladino et al. 2018). In the hilly areas of North Island, New Zealand, such landslides have resulted in significant soil loss from extensively grazed, steep, erosion-prone pastoral hill country and have been most widespread in regions

where the geology consists of young, late Tertiary-aged sedimentary bedrock (e.g., Gisborne-East Coast region) (Page et al. 2000; Phillips & Marden 2005; Marden 2012).

Forests and trees, through the combined effect of their canopies (water regulation – Sidle & Bogaard, 2016) and root systems (mechanical root reinforcement of the soil – Stokes et al. 2009; Stokes et al. 2014; Vergani et al. 2016; Moos et al. 2016), are frequently used by land managers to enhance slope stability and help control erosion in such places (Phillips & Marden 2005). To mitigate shallow landslides through best forest management practice does however present a challenge. Determining the contribution of trees to slope stability through root reinforcement requires data on tensile stress-related behaviour of roots and the distribution of roots at the hillslope scale – data that are generally difficult to obtain (Schwarz et al. 2010; Giadrossich et al. 2017). To aid forest planning and management, models are required to help understand the susceptibility of the landscape to landslides and to quantify the mechanical properties of root systems (Dazio et al. 2018, Gehring et al. 2019). Models such as SOSlope (Cohen & Schwarz 2017), which are physically based, need information on the root distribution and root tensile strength of trees to define their bio-engineering characteristics. These parameters are necessary to determine the effectiveness of species in reducing the incidence of storm-initiated shallow landslides.

This work aimed to measure the root distribution of *Pinus radiata* D. Don, the most commonly planted forest species in New Zealand (e.g., Burdon 2008; Marden et al. 2016; Nixon et al. 2017), to characterise its root tensile strength, to upscale root reinforcement at the hillslope scale, and finally to quantify the minimum representative sampling size for the reliability of engineering applications for slope stability calculations.

Methods

Study site

The study site is located in the Pukeakura Forest, Waimata Valley, Gisborne region of New Zealand (Fig. 1a). Following Cyclone Bola in 1988, land was retired from farming and planting began in 1991 with *Pinus radiata* (1250 plants ha⁻¹, which after thinning, reduces to about 350–400 stems per hectare before harvesting). Trees surveyed and sampled in this study were about 25 years old and were all from within the same compartment.

The forest consists of deeply dissected hill country underlain by sedimentary bedrock comprising alternating sandstone and mudstone of late Tertiary age (Mazengarb & Speden 2000). Locally, cover bed deposits consisting of volcanic ash and colluvium are deep (>1 m) and well preserved, but on the predominantly steeper slopes the soils are shallow (<0.5 m) and skeletal (Ekanayake et al. 1997; 1999). Shallow translational landslides (Varnes 1978), with a measured mean depth of failure of 0.96 m, occur predominantly on the steeper slopes (Marden et al. 1991). Soils are a stony colluvium, varying from Orthic Recent Soils and their intergrades to Brown Soils (on well-drained sites) and Gley Soils (on poorly drained sites).



FIGURE 1: Pukeakura Forest near Gisborne, East Coast, North Island, New Zealand

The climate of the East Coast region is warm temperate maritime, with moist summers and cool wet winters. Mean annual rainfall varies from about 700 mm at the coast to 2500 mm at higher elevations (New Zealand Meteorological Service 1973). The area is also prone to extreme rainfalls from ex-tropical storms and more localised events e.g. “Cyclone Bola” in 1988 (Marden & Rowan 1993), or more recently “Cyclone Cook” in 2017.

Data collection

The general framework used to upscale the root reinforcement is carried out according to Schwarz et al. (2010) applying the following steps: 1) Field pull-out tests to characterise the mechanical properties of roots (see Giadrossich et al. 2017 for reference); 2) Measure root distribution as a function of distance from stem and soil depth; 3) Calculate root reinforcement using the Root Bundle Model Weibull (RBMw) (Schwarz et al. 2013). The details of these methods are presented in the following sections

Root mechanical tests

A field root pull-out machine, in which both tensile force and displacement were measured was used to characterise the mechanical properties of roots under tension. Roots with diameters ranging from 5 to 57 mm were pulled out from vertical trenches via a hand winch following the method of Giadrossich et al. (2017). A total of 35 pull-out tests were completed (Urru 2016). The test speed was about 30 mm min⁻¹.

A more complete dataset for *Pinus radiata* roots was obtained by combining our field pull-out tests with data from previous pull-out tests (Hiltebrand, 18 field pull-out tests, unpublished report) and from the literature (Watson et al. 1999). These latter data were however, obtained by laboratory tensile tests on a small range of root diameters, ranging from 1 to 4 mm. In total, the dataset included 48 field pull-out test and 110 root tensile strength tests.

Root distribution

Lateral root distribution was determined from 18 trees of varying DBH (Table 1) with a range of different trench widths and trench numbers. In the dataset, we distinguish those trees that have a 360° soil profile

(circular trench) (RDTa) from those trees which had 2 to 8 trenches each (RDTb) (Urru 2016; Collu 2019).

For dataset RDTa, the trenches were dug at 1 and 2 m distance from the trunk. Each trench width was a 45° arc sector (0.78 radians) (Fig. 2). Then, using a 16-cm squared grid in order to divide the soil profile into horizontal layers, we measured the diameters of all roots protruding from the innermost trench face. Root diameters were recorded at depth intervals 0–16, 16–32, 32–48 cm that coincided with changes in the soil profile. In total, five trees were trenched at 360°. We used the RDTa dataset for the statistical analysis of the spatial variability of root reinforcement around single trees in a mature radiata pine plantation.

For the dataset RDTb trenches were dug at distances ranging from 0.5 to 2.5 metres from the stem (Table 1). We combined the two datasets to analyse the statistical variation of root reinforcement as a function of DBH and distance from stems.

Root diameter measurement was determined using a digital calliper and the number and frequency of roots was calculated in 1-mm root diameter classes (e.g., 0.5–1.5; 1.5–2.5; 2.5–3.5; mm).

TABLE 1: Summary of the sample trees (tree number) ranked in order of increasing diameter at breast high (DBH) and number of trenches for each tree. Trees 1, 2, 3, 4, and 5 are those included in the dataset RDTa (used for detailed spatial variability analysis of root reinforcement around single trees).

Tree number	DBH (m)	n° of trenches
9	0.15	3
10	0.15	3
12	0.16	3
16	0.18	3
17	0.18	3
6	0.35	2
7	0.35	2
8	0.37	3
1	0.47	8+4
2	0.48	8+4
11	0.50	2
3	0.52	8+4
13	0.52	8
14	0.53	8
15	0.53	2
4	0.53	8+4
5	0.61	8+4
18	0.71	2
Total n° of trenches:		104

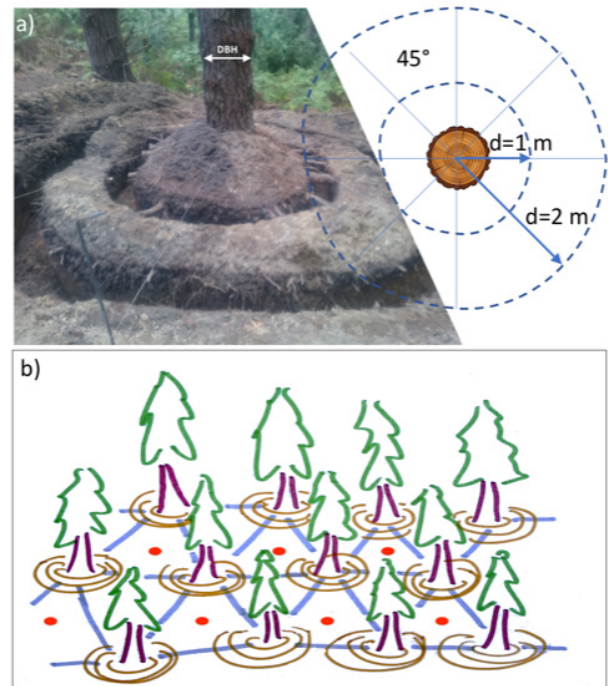


FIGURE 2: a) 360-degree trench excavation on a *Pinus radiata* tree at 1 and 2 metres of radius, and plan view where dotted lines indicate distance of trenches d at 1 and 2 metres from the trunk; b) circles represent lateral root reinforcement, red points represent the minimal value of lateral root reinforcement, blue lines connecting trees highlight the triangular lattice of the plantation.

The Root Bundle Model

Root reinforcement was calculated using the Root Bundle Model Weibull (RBMw) (Schwarz et al. 2013; Gehring et al. 2019). The model requires (1) a dataset of field-based root pull-out tests that measures force as a function of displacement, and (2) the lateral root distribution along vertical cross sections, taken at three (or at least two) distances from the tree. The general equation to calculate root reinforcement as force (F) per linear width of the trench, in $[Nm^{-1}]$, of a bundle of roots as a function of displacement $[m]$, is

$$F_{tot}(\Delta x) = n_{\Phi} \sum_{\Phi=1}^{\Phi_{max}} F(\phi_{\Phi}, \Delta x) S(\Delta x_{\phi}^*) \quad (1)$$

where n is the number of roots, Φ is the root diameter class, ϕ is mean root diameter of each root diameter class, Φ_{max} : maximum root diameter class under consideration, Δx_{ϕ}^* : normalised displacement of each root diameter class. The parameters of the RBM that need to be calibrated are the constant and the exponent of the power law regression between force and diameter (F_0, α), and the parameters of the Weibull survival function (ω and λ) (for details and formulae see Schwarz et al. 2013, Giadrossich et al. 2016, Dazio et al. 2018).

The RBMw assumes no interaction between neighbouring roots or crossing roots (Giadrossich et

al. 2013). The RBMw has been calibrated on the basis of root pull-out and root distribution data, then root reinforcement has been calculated on the basis of root distribution (Dazio et al. 2018).

Root reinforcement upscaling

The spatial distribution of lateral root reinforcement is calculated as function of distance from the tree and its DBH, following the approach introduced by Schwarz et al. (2010). The values of the parameters used in Equation 2 are calibrated fitting the equation with the minimum sum of squared error using the maximum values of calculated lateral root reinforcement using the RBMw for each trench where root distribution has been measured.

$$RR_{lat}(DBH, d) = \begin{cases} a DBH \Gamma\left(\frac{d}{DBH18.5}, b, c\right), & \text{for } d < DBH18.5 \\ 0, & \text{for } d \geq DBH18.5 \end{cases} \quad (2)$$

Where $RR_{lat}[Nm^{-1}]$ is the maximum lateral root reinforcement, $DBH[m]$ is the tree diameter at breast height, $d[m]$ is the distance from the tree stem (Fig. 2), Γ is the gamma density function with the shape parameter b and the rate parameter c , and $a[Nm^{-1}]$ is a scaling factor. Lateral root reinforcement at the stand scale is calculated assuming a regular plantation of trees in a triangular lattice. The minimal value of lateral root reinforcement considered representative at the stand scale is calculated at the centre of the triangles formed between the trees, assuming that the contribution of each tree system to root reinforcement is cumulative. The vertical distribution of root reinforcement, $RR_{basal}[Pa]$, is calculated using the equation:

$$RR_{basal}(z) = RR_{lat}\Gamma(z, z_{\alpha}, z_{\beta}) \quad (3)$$

Where z_{α} and z_{β} are the shape and the rate parameters of the gamma density function, and z is the soil depth [m]. The upscaling of the basal root reinforcement at the stand scale is calculated integrating Equation 3 within the surface of each hexagon in which trees are centred.

Estimation of the characteristic root reinforcement value and minimum representative sampling size

In practical applications in which slope stability is analysed, the reliability of the analysis is dependent on the probabilistic analysis of contributing parameters and the characterisation of their uncertainty in the estimations. The implementation of root reinforcement in such calculations is particularly difficult due to the unpredictability in the spatial distribution of roots around a tree, and the difficulty of estimating this parameter.

Statistical reduction coefficients that depend on the number of measurements, are used in geotechnical analysis to reduce the mean value of a parameter to a so-called characteristic value that usually should be

derived such that the calculated probability of a worse value governing the occurrence of the limit state under consideration is not greater than 5%.

The characteristic value is further reduced using a partial factor to define the so-called “design value”, that should be used for the calculations of slope stability.

$$x_d = \frac{x_k}{\gamma_m} \quad (4)$$

Where γ_m is called partial factor and is defined by the Eurocode. The partial factor used for cohesion in geotechnical assessments is assumed to be 1.25 or 1.15 for persistent and transient situations respectively (Katzenbach et al. 2011). The determination of a reduction coefficient has the practical advantage by avoiding expensive measurements of geotechnical parameters for each single project.

In this work we use the large dataset on root reinforcement distribution of radiata pine in order to define: 1) the characteristic value for *Pinus radiata* at different distances from the tree and 2) quantify how the error in the estimation of the characteristic value changes as a function of the cumulative trench length used to calculate the mean root reinforcement. Due to the distribution of the calculated root reinforcement being not normally distributed, we used the Weibull distribution for the fitting of the cumulative distribution function (CDF) and the calculation of the lower 5th percentile value. The best fitting coefficients are obtained using the “nls” function within the R software package (R Core Team 2017; Baty et al. 2015).

The percentage variation of error for the estimation of the characteristic values as a function of measured trench length is calculated by randomly sampling 100 times the measured trench sectors (using the function “sample” in the software R, with the option to avoid the sampling of the same measurements twice), and increasing the number of sectors considered.

Results

Force as a function of root diameter

Figure 3 shows the tensile force of roots fitted by a power law regression as a function of root diameter (Dazio et al. 2018). The power law coefficient is $F_0 = 1.263 \times 10^6$, and the exponent $\alpha = 1.634$, while the Weibull coefficients are $\omega = 2.87$ (shape-) and $\lambda = 1.12$ (scale-factor). Table 2 compares the coefficients of the power law regression curves obtained from the two datasets. The Watson et al. (1999) data shows a particularly high coefficient leading to an overestimation of root tensile force for diameters greater than 4 millimetres. When all the data are considered (i.e. Watson et al. 1999 and field pullout tests), we found no significant differences in the trend of the power law curve.

Spatial variability of root reinforcement within a single tree's root system

The variance of root reinforcement within a single

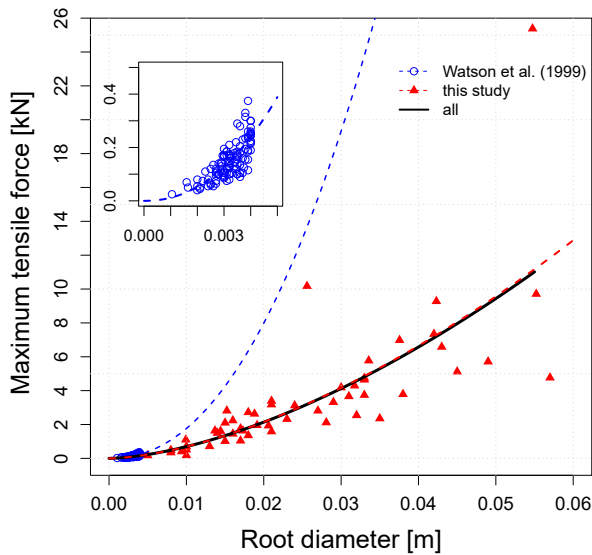


FIGURE 3: Tensile strength of roots as a function of root diameter for *Pinus radiata*. Lines indicate the power law regression for different authors and in combination (parameters in Table 2). Number of samples from this study=48, number of samples in Watson et al. (1999)=110.

root system at 1-metre distance from the stem is not significantly different between the five sampled trees (RDTa dataset). The variance of root reinforcement at 2 m (Fligner-Killeen test, $p=0.1367$ and $p=0.6809$, respectively, 4 degrees of freedom) also shows no significant difference. Analysis also shows that residuals are normally distributed.

Spatial variability of root reinforcement between trees with same age

Analysis of variance and Tukey honest significant difference tests showed that there is no significant difference (at 95% of probability) of the root reinforcement among the five sample trees. The mean calculated root reinforcement is 11.41 kNm^{-1} at 1 metre distance ($F=0.77$, $p=0.553$) from the stem, and 2.21 kNm^{-1} at 2 m distance ($F=1.12$, $p=0.367$). Figure 4 illustrates these results as boxplots for both distances from the stem.

Comparison of the lateral root reinforcement at 1 and 2 metres from the stem

The Student’s *t* test showed that mean values of root reinforcement are highly significantly different ($p<0.001$,

TABLE 2: Descriptive statistics of root reinforcement as a function of root diameter. *F* is the root tensile force, F_0 and α are the constant and the exponent of power law function $F = F_0 d^\alpha$.

	Watson et al. (1999)	This study	All data
F_0	40.35×10^6	1.26×10^6	1.21×10^6
α	2.18	1.63	1.62

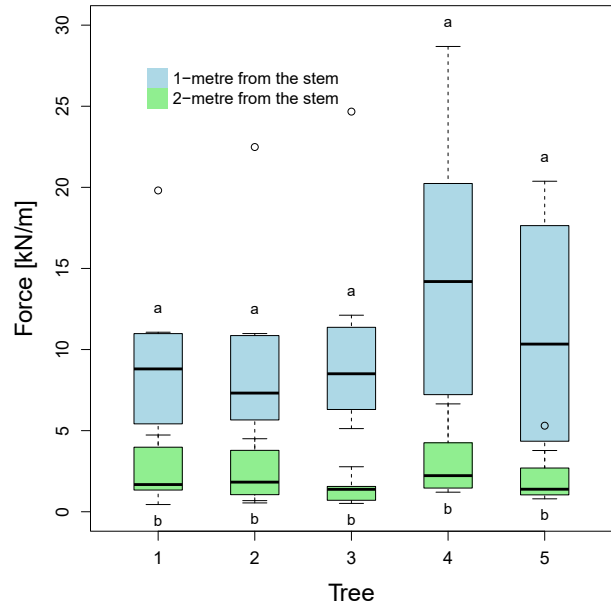


FIGURE 4: Root reinforcement calculated by the RBMw for 5 sample trees. Each boxplot shows the median, the 1st and 3rd quartile, maximum and minimum root reinforcement. Boxplots with same letters are not statistically different at 95% (Tukey Honest Significant difference analysis, $p<0.001$).

$F=30.28$, degrees of freedom 39) at 1 and 2 m distance from the stem. Tables 3 and 4 summarise the descriptive statistics. However, the coefficient of variation of the root reinforcement is similar (0.73 and 0.78 respectively). The standard error is higher at 1 metre distance, making the accuracy of the root reinforcement assessment lower (Fig. 4). Presumably this is due to the presence of big roots near the trunk, present only in some sectors. On the other hand, at 2 metres, the root reinforcement is more equally distributed around the tree, even if on average, values are one-fifth, i.e. about 2 kPa, in comparison to the 1 m distance.

Figure 5 shows the probability distribution of root reinforcement at the two considered distances from the stem. The value of lateral root reinforcement corresponding to the lower 5th percentile is 1,887

TABLE 3. Descriptive statistics of root reinforcement calculated at 1 metre from the stem.

Tree no.	n° of sectors 45° width	Mean (kNm ⁻¹)	Std. dev.	Std. error	Coefficient of variation
1	8	9.12	5.22	1.84	0.57
2	8	8.86	6.41	2.27	0.72
3	8	10.27	6.28	2.22	0.61
4	8	14.46	8.60	3.04	0.59
5	8	14.34	14.87	5.26	1.04
All	40	11.41	8.87	1.40	0.78

TABLE 4. Descriptive statistics of root reinforcement calculated at 2 metres from the stem.

Tree no.	n° of sectors 45° width	Mean (kNm ⁻¹)	Std. dev.	Std. error	Coefficient of variation
1	8	2.40	1.6	0.57	0.67
2	8	2.30	1.6	0.55	0.70
3	8	1.32	0.7	0.25	0.54
4	8	2.97	2.2	0.76	0.73
5	8	2.04	1.6	0.57	0.80
All	40	2.21	1.6	0.25	0.73

and 316 Nm⁻¹ at 1 and 2 m distance respectively. The coefficient values of the fitted cumulative Weibull distribution function are shape factor = 1.66 and scale factor = 11,280 for the 1 m distance, and a shape factor = 1.55 and scale factor = 2,161 for the 2 m distance. The residual standard errors of the fitting are 0.04 and 0.06, respectively on 38 degrees of freedom. In comparison to the value predicted with Equation 2, these values of the lower 5th percentile correspond to a factor of 0.16 and 0.14 for the two distances respectively. The values of lateral root reinforcement calculated with Equation 2

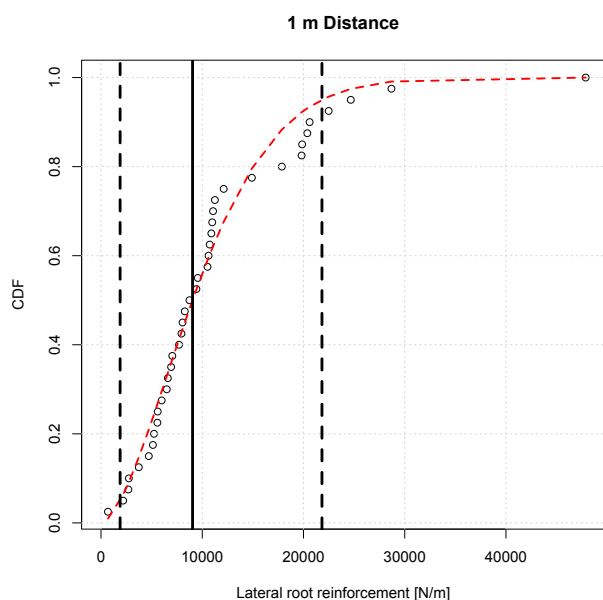


FIGURE 5. The fitting of the cumulative probability curve for root reinforcement has been carried out by the Weibull function for 1-metre and 2-metre distance from the stem (shape =1.66, scale =11280, shape =1.55, scale = 2161, respectively). The dotted lines indicate the lower and the upper 5th percentile of the cumulative density function (CDF), and the continuous line the 50th percentile for the CDF.

considering a mean DBH of 0.52 m, are 9,432 and 1,874 Nm⁻¹ at 1 and 2 m distance respectively. The calibrated values of the parameter of Equation 2 are a=5976 [Nm⁻¹], b=0.966 [-], and c=15.39[-].

Figure 6 shows the calculated lateral root reinforcement for each analysed trench as a function of tree DBH and distance from tree stem (1 m and 2 m). The line shows the fitted values of Equation 2. The root mean squared error of the model is 5,525 Nm⁻¹ and the correlation coefficient is 0.64. The residuals of the model are normally distributed and tend to decrease with increasing distance from the stem and decreasing DBH.

Minimum representative trench length for the estimation of the lateral root reinforcement characteristic value

Depending on the cumulative length of trenches analysed at a defined distance from tree stems with the same DBH, it is possible to estimate the probability of error expected in the calculation of the characteristic value of lateral root reinforcement. Figure 7 shows the boxplot of percentage errors as a function of the cumulative length of trenches. Each boxplot is the sampling distribution of the sample mean repeated 10 times. The values of cumulative trench length correspond to the sum of trench length of sectors considered. The results show that at least 36 sectors are needed to keep the error of root reinforcement characteristic value calculation within the 5% with a probability 95% (whiskers of boxplot), both for 1 and 2 m distance from the tree. Considering that each sector is 45 degree wide, it corresponds to 4.5 root systems where roots are exposed in trenches encircling 360 degree around a tree. The cumulative trench length is 28 and 56 metres for 1 and 2 m distance from the tree, respectively. Summarising, the whiskers of the boxplots

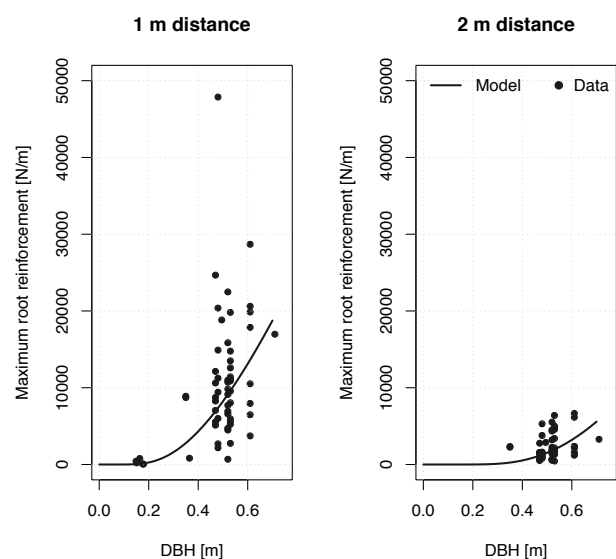


FIGURE 6. Lateral root reinforcement as a function of the diameter at breast height (DBH). Estimated values of parameters for Eq. 2 are a= 5976 (Nm⁻¹), b= 0.966 [-], and c= 15.39[-].

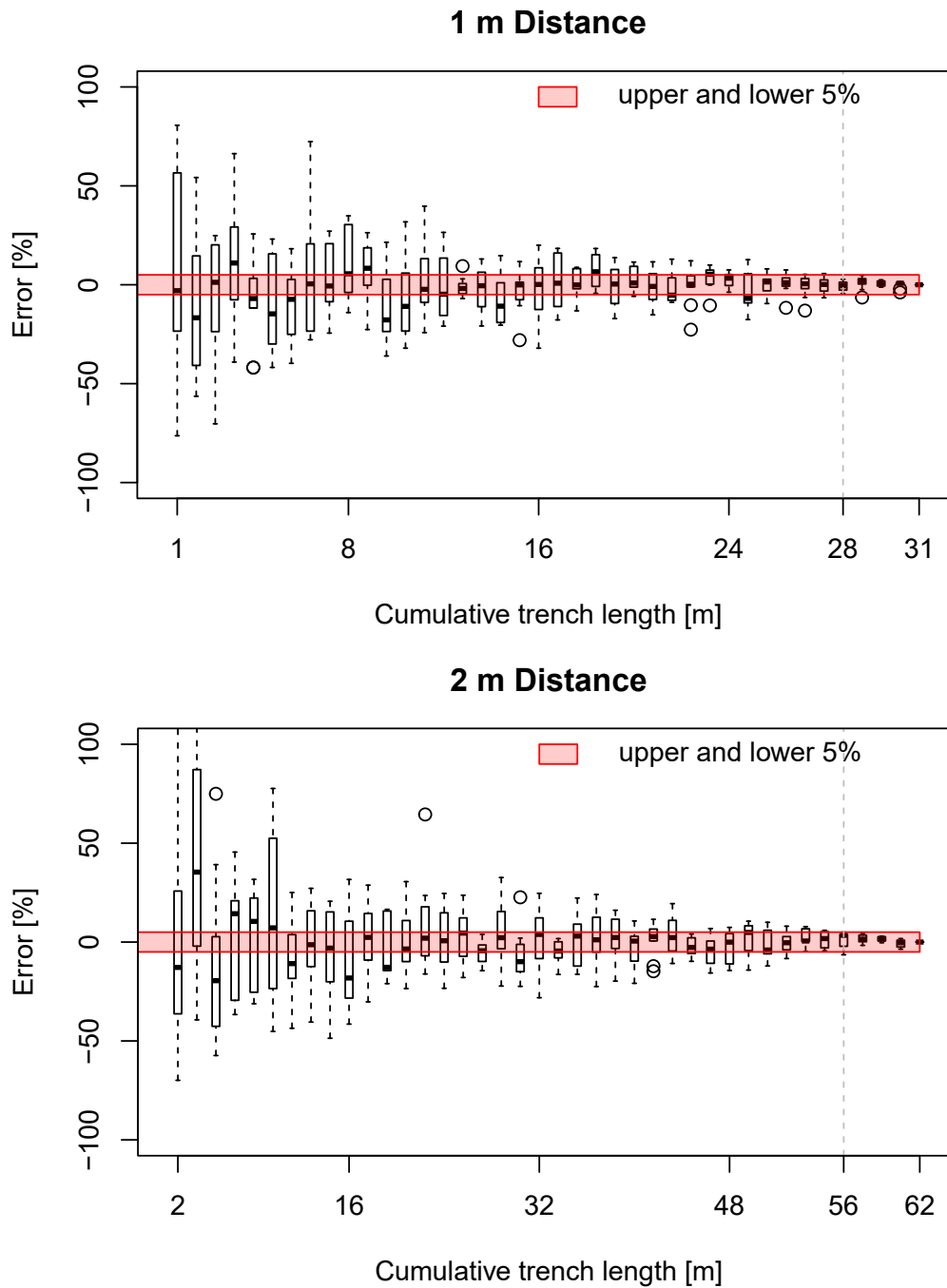


FIGURE 7: Calculated error of the estimation of the root reinforcement characteristic value depending on the cumulative trench length sampled randomly. The continuous red lines show the threshold of the 5% error. The grey dotted line represents the minimal cumulative trench length of sampling in order to obtain an error less than 5%.

(95% of the data) of the various samplings in Figure 7 do not represent the characteristic value, but they represent the sampling error of the mean.

So, for example, if the whiskers in the boxplot are 25% higher than the mean, we should reduce this value by 20%.

Vertical distribution of basal root reinforcement

The vertical distribution of basal root reinforcement is analysed as a relative value normalised to the total lateral root reinforcement calculated in each analysed

trench. (thus, considering both dataset RDTa and RDTb). Figure 8 shows the relative basal root reinforcement as a function of soil depth. The three values calculated for each trench are representative of 16 cm soil depth. The mean values of relative basal root reinforcement are 0.59, 0.25, and 0.16 at the soil depths of 8, 24, and 40 cm respectively. The value of the fitted parameters of Equation 3 are $z_{\alpha}=1.145$ and $z_{\beta}=6.722$. The minimum sum of squared errors of the model is 0.05 and the root mean squared errors is 0.24. The correlation coefficient of the model is 0.6.

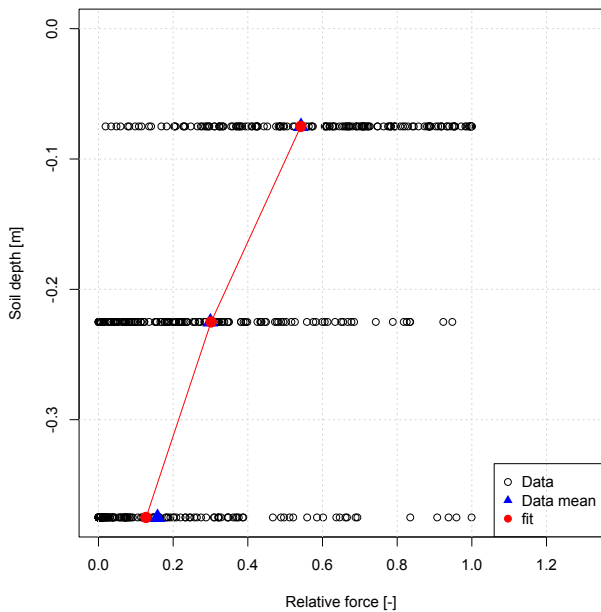


FIGURE 8: Normalised root reinforcement as a function of soil depth. Estimated values of parameters for Eq. 3 are $z_{\alpha}=1.145$ and $z_{\beta}=6.722$. The root mean squared error is 0.24, and the correlation coefficient is 0.6.

Root reinforcement upscaling

Root reinforcement decreases rapidly with distance from the stem. However, the more than 2 kPa of mean root reinforcement at 2 m distance from the stem still is an important contribution to slope stability. Given a plantation with a density of about 400 trees per hectare, such as in the study area, the minimal lateral root reinforcement in the potential zone of weakness (i.e. the mid-point position between adjacent trees), can still be more than 500 Nm⁻¹ (see Figure 9). For a plantation with a density of 1,000 sph or higher, lateral root reinforcement is negligible considering that the DBHs for such densities

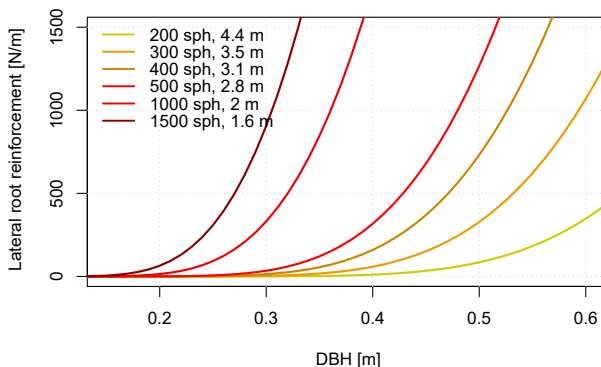


FIGURE 9: Calculated lateral root reinforcement as a function of tree diameter at breast height (DBH) and stem density per hectare (sph). The values in the legend indicate the stem density per hectare (sph) and the distance between trees and the vertices of the hexagons where trees are centred.

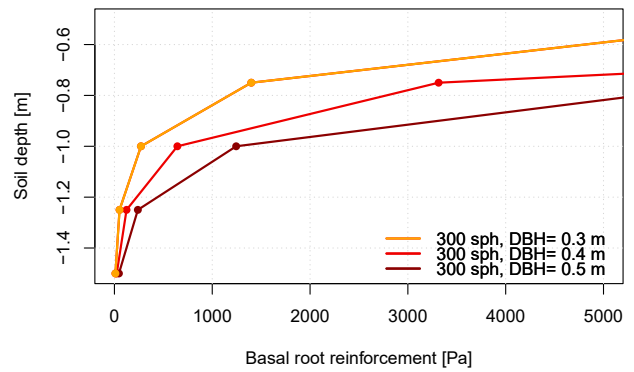


FIGURE 10: Calculated basal root reinforcement as function of soil depth, tree DBH and stem density per hectare (sph).

are lower than 0.2 m (i.e. younger dense stands).

Lateral root reinforcement is estimated to reach values between 270 and 1,200 Pa at 1 m soil depth at the end of the rotation (about 30 years). Figure 10 shows the calculated values of basal root reinforcement as a function of soil depth for a stand with a density of 300 sph and DBH between 0.3 and 0.5 m. At a soil depth of 1.5 m, lateral root reinforcement is expected to be negligible.

Discussion

Root tensile strength predicted by the regression model gives completely different results if the model only considers laboratory test data (Watson et al. 1999), or data obtained from field pull-out tests such as carried out in this study. The use of laboratory-only tests will greatly overestimate root tensile strength, as highlighted in Docker and Hubble (2008) and Giadrossich et al. (2017, 2019). However, root tensile strength for small diameter classes is similar for data obtained from the laboratory or in the field, thus when merging the two datasets, the model parameters do not change significantly from those obtained considering data only from the field pull-out tests. Thus, we considered both datasets in our study in as much as small roots don't significantly affect the prediction of root tensile strength.

The variability of lateral root reinforcement within tree systems can be high but also significantly different within 1 m lateral distance from the tree stem (Fig. 4). Growth direction is unpredictable and the variability of root reinforcement around the tree is high. This is a difficulty for upscaling of root reinforcement beyond individual trees and groups of trees to stands. Despite this, the mean root reinforcement between trees is similar, and root reinforcement decreases with similar rates as a function of distance from the stem.

The lateral and basal root reinforcement assessment must consider the growth of the tree with time, as this influences how far roots extend and thus the effectiveness of the root network to contribute to slope stability. For example, Watson and O'Loughlin (1990) showed from one forest in New Zealand how the excavated root systems of *Pinus radiata* extend as a function of DBH and tree age (8, 16, and 25-year-old

trees). They reported that by age 25 the “root networks had developed into massive systems dominated by shallow lateral roots” with strong development across and down slope. All laterals grew in the upper 1 m of the soil profile, and most were within 50 cm of the soil surface. In younger trees, the lateral roots were often asymmetrical about the stem seemingly reflecting competition from adjacent trees. Selective or systematic removal of trees in plantations (thinning) helps regulate tree growth and canopy and stem shape and promote volume growth. But, tree thinning can also be important to control root reinforcement effectiveness, by allowing the establishment of a good or “optimal” root network.

High plantation densities don't necessarily mean higher root reinforcement, because of the short extension of lateral roots at young tree ages. Currently, most *Pinus radiata* plantations are planted at around 1,000 stems per hectare in New Zealand but can range from as low as 600 to a high of 1,500 seedlings per hectare (NZFFA 2007). Usually, stands are thinned to 300–400 sph at the end of the rotation when mean DBH reaches 0.2–0.25 m. At 25 years old a typical *Pinus radiata* plantation, such as measured in this study, with 400 sph, the minimum lateral root reinforcement within the stand is about 0.75 k Nm⁻¹. This means that near the tree stems this value can be much higher, up to 30–40 k Nm⁻¹. In a space-planted “plantation” of “Veronese” poplar with a similar stand density and DBH, the calculated lateral root reinforcement is expected to be much higher (>10–15 k Nm⁻¹) (Schwarz et al. 2016). This seems to be due to the differences in both root distribution and root mechanical properties. For instance, a 10 mm root of poplar is estimated to break under tension at 913 N, whereas one of radiata pine is estimated to break at 681 N. In comparison to forest stands with other broad-leaf species in the European Alps (chestnut and beech), values of lateral root reinforcement of *Pinus radiata* are much lower (Dazio et al. 2018; Gehring et al. 2019). However, these are comparable to the lateral root reinforcement of mature stands of scots pine in the European Alps (Vergani et al. 2017).

Basal root reinforcement is expected to play a much more important role in slope stabilisation in radiata pine plantations than lateral root reinforcement. Although the investigations of this study were limited to 0.48 m soil depth, due to the structure of the root system of radiata documented by other authors (Wu & Watson 1998; Watson & O'Loughlin 1990) it is expected that sinker roots contribute more to reinforcement than previously estimated. Considering that the mean depth of failure surface of analysed shallow landslides in some regions of New Zealand range between 0.57 and 0.84 m (sd=0.18–0.33 m) (Zahner 2016), basal root reinforcement is considered to be the major contributor to slope stability in *Pinus radiata* stands with values ranging between 0.5 to 5 kPa at the end of the rotation period. Slope stability calculations presented by Gehring et al. (2019) show that for this range of soil depths, basal root reinforcement will stabilise slopes under most combinations of soil type and slope inclination. A better investigation of basal root reinforcement should include the analysis of root

distribution under the stump, but this type of analysis is both difficult and highly time and resources consuming, especially with large trees. Indirect evidence could be gained by field observations along road edge/cuts. At the moment the values provided in this work can be considered conservative.

Engineered root reinforcement criteria

Where shallow landslides are a hazard for infrastructure and people, the analysis of slope stability should be based on reliable criteria defined in typical engineering standards. This study provides a unique combination of datasets and methods that allows the analysis of these criteria for the implementation of root reinforcement in slope stability calculations. In particular, the results show that the characteristic value of root reinforcement can be calculated using a reduction coefficient of about 0.15 (the quotient between the mean value and the lower 5th percentile value). This means that for a calculated mean value of 5 kPa of basal root reinforcement (for example estimated from figure 10), a characteristic value of 0.75 kPa can be considered (= 5*0.15) for the calculation. Depending on the different conditions for which the calculation is applied (for example permanent versus transient conditions), a partial factor of 1 to 1.25 can be applied, analogous to what is assumed for the value of effective soil cohesion in geotechnical guidelines for slope stability calculations. This leads to a final design value for basal root reinforcement that ranges, in this case, between 0.6 and 0.75 kPa. Although considerably reduced, these values of basal root reinforcement still have an important influence on slope stability and can be considered representative for radiata pine's mature stands on slopes prone to shallow landslides in New Zealand.

In order to fully consider vegetation as a contributing factor in a geotechnical approach to slope stability analyses at the hillslope scale, we adopt for the first time, the concept of a minimum sampling requirement and characteristic value determination. The exceptionally large amount of root distribution data has allowed this type of analysis. The results have shown that the excavation of 4 to 5 complete root systems allows a good approximation of the mean root reinforcement of radiata pine at the hillslope scale. This result may change depending on several factors, of which tree species and site are probably the most important. Between the different possible criteria used to define the minimum representative size, we use the threshold of 5% error in the calculation of the characteristic value following the technical-normative EC7 (Eurocode 7: Geotechnical Design 2004; Bond et al. 2013).

Conclusions

We analysed *Pinus radiata* roots and their distribution to estimate the effectiveness of root reinforcement to contribute to slope stability. We found that the variability of lateral and basal root reinforcement does not limit the implementation of vegetation in slope stability models, and mature stands of *Pinus radiata* effectively stabilise steep slopes. Mature stands of about 300–400 sph

(about 0.5 m in DBH) effectively stabilise steep slopes at 2 m distance from the stem, both as lateral and basal root reinforcement. Trees of this size are around 25–30 years-old across many sites and have generally reached the recommended conditions for clear-fell harvesting (NZFFA 2007). In the case of younger dense stands (e.g. 1000 sph) lateral root reinforcement is expected to be low, whereas the effect of anchor or sinker roots (basal root reinforcement) can be effective.

In order to fully consider vegetation as a contributing factor in a geotechnical approach to slope stability analyses at the hillslope scale, we adopt for the first time, the concept of a minimum sampling requirement and characteristic value determination. For mature *Pinus radiata*, a reliable estimate of root reinforcement would require the root distribution to be measured in trenches excavated at 1 and 2 m distance from the stem, with each trench and encircling around the circumference of a minimum of between 4 to 5 trees, depending on the level of uncertainty that is acceptable for the calculations.

The dataset provided in this paper is a good starting point for the analysis of entire root systems, however to better assess the influence of *Pinus radiata* root systems on slope stability and their effectiveness in mitigating the initiation of shallow landslides in steep terrain, further investigations are needed to obtain data on factors that influence the preferential direction of root.

Competing interests

The authors declare that there are no conflicts of interest.

Authors' contributions

FG, MS and CP contributed to the project concept; FG and MS developed the methodology, undertook the analysis, data curation, manuscript preparation, visualisation and supervision; MS and CP administered the project and acquired funding; RM and MM undertook the investigation; data curation was managed by FG, MS, RM, and MM. All authors have reviewed, edited and agreed on the published version of the manuscript.

Funding

This research was supported by funding from the New Zealand Ministry of Business, Innovation and Employment (MBIE), 'Growing Confidence in Forestry's Future' research programme Contract No. CO4X1306.

Acknowledgements

We thank the interns from Bern University of Applied Sciences (Switzerland) and University of Sassari (Italy), who over several years have contributed small pieces to the story and provided useful and necessary data to enable refinements in our understanding of *Pinus radiata* root systems and their contribution to erosion control in New Zealand. These include Daniel Oertig, Fabien Hildebrand, Emanuele Dazio, Antonia Zahner, Matteo Urru, Carla Deiana, and Paolo Collu. Jagath Ekanayake is thanked for constructing the pullout test machine. We thank Juken New Zealand Ltd for permission to access their forest and undertake our data collection.

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