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QUANTIFYING ROOT REINFORCEMENT IN PROTECTION FORESTS: IMPLICATIONS FOR SLOPE STABILITY AND FOREST MANAGEMENT

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ABSTRACT

The mechanical effect of roots on slope stabilization is widely recognized and is considered an important element in protection forests. However, the quantification of root reinforcement represents a challenge due to the complexity of root-soil frictional mechanisms and heterogeneous root distribution. In this work we review the state of the art on approaches for the spatial characterization of root reinforcement, and we present a novel method for the implementation of quantitative approaches in the management of protection forests. Tree root distribution of three species was characterized in a study area for the calibration of a root distribution model (RootMap). The calibrated RootMap and back analysis approaches for slope stability calculations were applied in order to quantitatively define the minimal profiles of protection forests. The results indicate that soil type and slope gradient are important factors that should be considered to define the minimal protection forests profiles. The presented results will be applied to the optimization of protection forest management strategies in steep slopes.

Keywords / Mots-clés / Parole chiave: root reinforcement, shallow landslides, management of protection forests

INTRODUCTION

The mechanical contribution of roots to the stability of steep slopes is a key factor that influences many different processes in alpine regions (e.g. shallow landslides, erosion, and sediment balance). Especially in protection forests, root reinforcement is considered as an important criteria for the definition of forest "minimal profiles" (Frehner et al., 2005). However, root reinforcement is in most cases only qualitatively considered, and the knowledge about this topic is based only on approximate scientific studies. In particular, most of the results of scientific works done during the last three decades are based only on the approach of Wu (Wu et al., 1979), and on few datasets of tree root distributions in vertical soil profiles (without considering the horizontal variability).

The limitations of the Wu approach were listed in recent studies, empathizing the importance of the progressive nature of root bundles failure and the spatial heterogeneity of root reinforcement (reviewed in Schwarz et al. (2010b)). These studies show that the Wu approach strongly overestimates root reinforcement (up to 300%, depending on the root distribution), and does not give information about the nature of root failures (stress-strain behaviors). Recent studies on root-soil interaction highlighted these aspects and proposed advanced quantitative approaches for the upscaling of root reinforcement from single root to stand scale, implementing new parameters that allow a better understanding of the root reinforcement mechanisms during the triggering of shallow landslides. The main innovative aspects of the new approaches reviewed in this work include: a) quantification of root spatial distribution and architecture (diameter and length), b) three-dimensional calculation of

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slope stability considering the lateral contribution of root reinforcement, and c) introduction of a strain-dependent quantification of root reinforcement.

The results of the above listed new approaches build up the basis for the understanding of the stabilizing mechanisms of root networks in vegetated slopes, thus allowing a better quantitative analysis of the most important factors related to forest management (such as forest structure and species composition).

The objective of this work is to review the state of the art of approaches used for the spatial characterization of root reinforcement, and to present a novel implementation of these quantitative approaches in a simple tool for the management of protection forests. In particular, this work aims to enhance the transfer of knowledge from scientific platforms to practical applications, reducing the big amount of time and efforts needed for the scientific results into simple quantitative tools for the practice.

MATERIAL AND METHODS

In the first phase of the presented study, the models for the quantification of root reinforcement are calibrated and validated with field data. Secondly, the calibrated models are used to calculate the values of root reinforcement for different type of forests. Finally, a novel method for the quick estimation of slope stability and root reinforcement distribution is applied for the planning of silvicultural interventions in forests with protective functions. The following paragraphs give the details about the collection of root distribution in the field and about the modeling approaches used to calculate root reinforcement and slope stability.

Study area

The study area (Fig. 1) is located in a catchment near the village of Schangnau in the canton of Bern (Switzerland), where a number of shallow landslides have occurred (coordinates: 629.560/185.040 CH1903). The area was chosen as representative for situations where slopes are susceptible to shallow landslides and were forest management needs to take into account the protection function as important criteria. The area is situated in a young geological formation (tertiary) dominated by continental molasse. The altitudes of the study area is about 1000 m.a.s.l. and the slope is north exposed. The soil thickness is in mean deeper than 2 m and slope inclination is about 25°. The pedogenesis is strongly influenced by the morphology, thus in general there are drained alfisols (aqualfs) with a clay enriched horizons (USDA soil taxonomy) on elevated zones, whereas more wet, reduced, and hydric soils forms in depressions and near streams. Soil texture was classified as a sandy clay (SC) with the field method (Brady and Weil, 2007). The dry and saturated soil bulk density was estimated using the USGS soil classification tables. The mechanical properties of soil material where estimated based on the soil classification as well.

The site has a dominant vegetation cover composed of spruce (*Picea abies*) and fir (*Abies alba*), with the presence of beech (*Fagus silvatica*) and maple (*Acer pseudoplatanus*). The mean stem diameter is about 0.3 m (DBH). The Forest has a one layer structure with a cover ratio of 80%. The cover is homogeneous, interrupted by small gaps (max 5 m width). Cover height is between 20 and 25 m. Forest regeneration is dominated by fir (*Abies alba*) and maple (*Acer pseudoplatanus*) species. Forest regeneration cover range between 20 and 60%. The stand is classified as a fir-beech forest (*Abieti-Fagetum*).

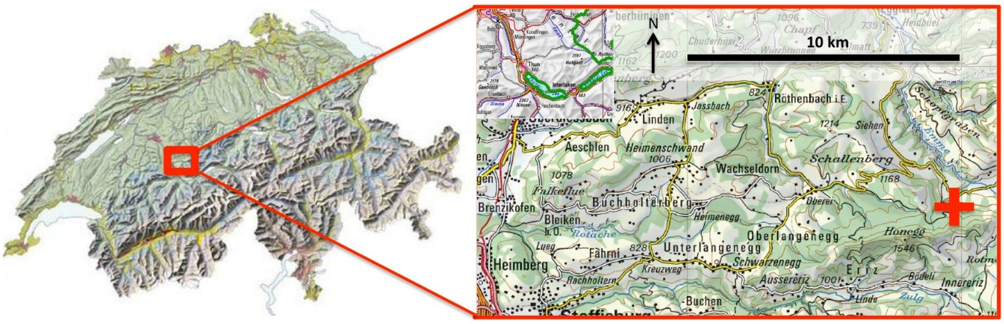


Fig. 1 Localization of the study area (red cross).

Root distribution measurements

Root distribution is characterized in term of lateral-horizontal distribution. Vertical distribution of roots is considered less important for shallow landslides in deep soils because few roots usually cross the shear plane of the landslides, thus their contribution to stability may be neglected (Schwarz et al., 2010a). The root distribution is described as number of roots for each root diameter classes. The trees for the collection of the data are chosen based on their diameter (DBH), social position within the stand, and aspect. Near each tree, three soil profiles are excavated at three distances from stem (0.5, 1.5, and 2.5 m), as shown in figure 2. The soil profiles are 0.5 m width and 0.5 m deep. The direction where the soil profiles are excavated is chosen minimizing the possible concurrence effects of neighbor trees. Death roots could be distinguished from the live roots on the base of the consistence of the root phloem/xylem and the cortex. Moreover, the species of the roots was determinate based on the bark color/morphology, as well as on root topology. For each soil profile, the diameter (with root cortex) of each root was measured and noted as root frequency vs. root diameter classes. Roots were defined as fine roots with diameter lower or equal than 1.5 mm, and as coarse roots with diameter larger than 1.5 mm. Coarse roots were classified in 1 mm diameter classes.

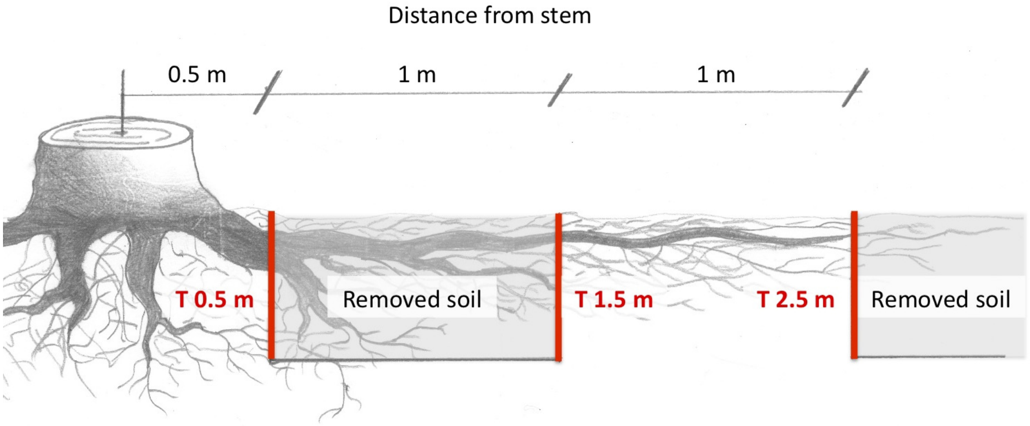


Fig. 2 Schema of the soil profiles positions where root distributions were collected for each selected tree.

Root distribution modeling

The model used for the simulation of root distribution is based on four parameters (Schwarz et al., 2010b) (pipe coefficient, maximal lateral rooting distance, scaling factor, and an exponent used to calculate the density of coarse roots). Schwarz et al. (2010b) show how these parameters may be obtained from the literature or from field measurements, and how this approach allows a realistic estimation of root distribution for spruce trees (*Picea abies*). The up-scaling of root distribution at the stand scale is done considering a simple superposition of single root systems.

The root distribution is characterized considering root diameter classes and frequency.

Once the model is calibrated, it can predict the dimension and the number of roots at a certain distance from a defined tree/plant. Different calibrations are needed as a function of the tree/plant species and the climatic station.

In this study, the model is calibrated with new data collected in the selected study area. In order to give a quantitative, but relative, estimation of the model's goodness of fit, we minimized the sum of squared errors (SSE) for the calibration of the model parameters, and we compared the SSE of the calibration with the SSE of the validated data. The validation of the model parameters for the estimation of root frequency in different root diameter classes was done with a weighted sum of squared errors (wSSE). The weighting factor was calculated on the base of the mechanical properties of the roots, so that the calibration takes into account the effects that root distribution has on the calculation of root reinforcement (the error of reinforcement due to the overestimation of one big root is higher then the overestimation of one small root).

Root reinforcement modeling

We estimate the spatial distribution of root reinforcement by upscaling the mechanical behavior of a single root to a large number of roots distributed in a forest stand using the model framework of Schwarz et al. (2010b). The framework combines two independent models: (1) a root distribution model for secondary lateral roots (explained above), and (2) a root bundle model for computing pullout force. For simplicity, we assume that:

- Root distribution of a single tree is symmetrical and not influenced by neighboring trees;
- The pullout force behavior of a single root is not influenced by neighboring roots;
- Lateral root reinforcement is independent of direction (isotropic).

To estimate mechanical reinforcement, we use a modified version of the root bundle model (RBM) (Schwarz et al., 2010c). The RBM is an extension of the fiber bundle model where bundles are made up of many roots, each with distinct geometrical and mechanical characteristics. These characteristics are given by three power-law equations that relate root diameter to length, apparent Young's modulus, and maximum tensile force. Root length is given by

$$L_{(\Phi)} = L_0 \left(\frac{\Phi}{\Phi_0} \right)^{\gamma} \qquad \text{[m]} \qquad (1)$$

where $L_{(\Phi)}$ is the tortuous root length, L_0 is an empirical characteristic length, Φ is root diameter, Φ_0 is the reference diameter used in equation ~1 (to make the ratio dimensionless), and γ is an empirical power-law exponent. Based on the RBM parameter study of Schwarz et al. (2010b), root length is one of the parameter that has the largest effect on bundle pullout force.

The apparent Young's modulus is computed from

$$E_{(\Phi)} = E_0 \left(\frac{\Phi}{\Phi_0} \right)^{-\beta} r \qquad \text{[Pa]} \qquad (2)$$

where $E_{(\Phi)}$is the Young's modulus, E_0 is an empirical characteristic modulus, β is an empirical power-law exponent, and r is a dimensionless coefficient introduced to consider the effects of root tortuosity on the tensile behavior of a root (see Schwarz et al., 2010c). The maximum (breaking) tensile force as a function of diameter is given by

$$F_{\max(\Phi)} = F_0 \left(\frac{\Phi}{\Phi_0} \right)^{\xi} \qquad [\mathrm{N}] \qquad (3)$$

where $F_{\max(\Phi)}$ is the maximum tensile force, F_0 is an empirical characteristic tensile force, and ξ is an empirical power-law exponent. Values of parameters in equations 1 through 3 are given in Table 1.

Tab. 1 Literature values of the mechanical parameters used for the RBM for different tree species.

Species	L_0	γ	E_0	β	F_0	ζ	Ref.
Picea abies	285	0.7	600	1	28	1.3	Schwarz et al., 2010c
Abies alba	285*	0.7*	600*	1*	28*	1.3*	-
Fagus silvatica	285*	0.7*	600*	1*	41	0.9	Bischetti et al., 2009

*In the case where no literature data where found, values of other known species where applied.

Assuming roots behave as elastic-brittle fibers and using equations 1 through 3, the RBM computes the pullout force of a root bundle as a function of displacement during displacement-controlled loading of the bundle. With increasing displacement, the force in each root increases and roots fail progressively from weakest to strongest. In this modified version of the RBM, we assume that all roots break rather than slip out of the soil matrix based on field pullout tests that indicate that most roots fail under tension (Schwarz et al., 2010c; Schwarz et al., 2011). The implementation of the root distribution model and the RBM in a spatial referential system (considering the position and the dimensions of the trees) allows the spatial characterization of root reinforcement distribution at the stand scale. This model is called RootMap.

Slope stability calculations

We implement limit equilibrium assumptions for an infinite slope to compute slope stability. The failure condition was quantified using the Mohr-Coulomb criterion. The inclusion of lateral root reinforcement in slope stability calculations was achieved by considering an additional stabilizing force proportional to the scarp surface and to the mean root reinforcement.

Additionally, we computed the force balance for different landslide shapes (varying the ratio between the two principal axes) and dimensions.

The standard formulation of the limit equilibrium equation for the infinite slope is

$$SF = \frac{A \cdot \tau_{bas}}{F_{par}} \qquad [-] \qquad (4)$$

where SF is the Safety Factor, A is the landslide area (m^2), τ is the shear strength at the slip interface (kPa), and F_{par} is the destabilizing force parallel to slip interface.

The modified formulation of the limit equilibrium equation for a safety factor SF considering lateral root reinforcement is:

$$SF = \frac{A \cdot \tau_{bas} + F_{lat.veg.}}{F_{par}} \qquad [-] \qquad (5)$$

including the terms for lateral and basal forces, $F_{lat.veg}$ and τ_{bas}, and the driving force $F_{par.}$ Below the expressions for the various forces and strengths are listed:

$$F_{par.} = [(A \cdot h) \cdot \gamma \cdot g \cdot \sin\beta] + (A \cdot m_{veg.} \cdot g \cdot \sin\beta) \qquad [\text{kN}] \quad (6)$$

$$F_{lat\_veg} = \frac{lateral\_Area}{2} \cdot c_{lat} \qquad [\text{kN}] \quad (7)$$

$$\tau_{bas.} = c + \sigma^{*} \cdot \tan\phi' \qquad [\text{kPa}] \quad (8)$$

$$c = c_s + c_{bas.veg.} \qquad [\text{kPa}] \quad (9)$$

where $\sigma^{*} = \sigma - u$ [kPa] (10)

is the effective normal stress.

σ= total normal stress, considering also the mass of the vegetation [kPa]
u = pore water pressure [kPa]
ϕ'= residual friction angle [°]
A = basal area [m^2]
h = soil depth [m], perpendicular to the slope
γ = soil bulk density [t/m^3]
β = slope angle [°]
m_{veg} = weight of vegetation cover [t/m^2]
c_s = residual soil cohesion [kPa]
$c_{lat.\ veg.}$ = lateral root reinforcement [kPa]
$c_{bas.veg.}$ = basal root reinforcement [kPa]
g = gravitational acceleration [m/s^2]

The main assumption for the implementation of root reinforcement in the slope stability calculations is that roots along the scarp were subjected to similar displacement. In reality, roots on the upper part of the scarp are activated before roots located on the sides of the landslide scarp. The RBM was applied considering a series of static strain-controlled loading of a bundle of roots containing roots with different properties (e.g., Young's modulus and maximum tensile strength, which varies as a function of root diameter) to quantify the bundle stress-strain behavior.

For the back calculation of the needed lateral root reinforcement ($c_{lat.root}$) for different slope inclinations, soil types and landslide dimensions, the following formula was applied:

$$c_{lat.root} = \left(\left(SF * F_{par.}\right) - (A\,\tau)\right) / A_{lat} \qquad [\text{kPa}] \quad (11)$$

where A_{lat} [m^2] is the lateral surface on which the root reinforcement is applied. In this case is calculated as the upper half part of the lateral surface (with depth h) of an typical elliptical landslide where the length axis is double than the width axis (Graf and Rickli, 2009).

In order to simplify the estimation of the soil mechanical properties, the USGS soil types were grouped in four classes as follow:

- Soil class 1 (ϕ = 20-25° ±5°): MH, OH, OL, CH.
- Soil class 2 (ϕ = 26-30° ±5°): CL, SC-CL, GC-CL.
- Soil class 3 (ϕ = 31-35° ±5°): ML, SC, SM, GM-ML, GC.
- Soil class 4 (ϕ = 36-40° ±5°): SP, SW, GM, GP, GW.

The minimal tree densities are calculated considering the minimal distance needed between two trees in order to reach the defined minimal value of root reinforcement. For instance, if the needed reinforcement is 5 kPa, the distance at which a single tree reach the value of 2.5 kPa is extrapolated from the root reinforcement curves (see figure 5) and is multiplied time 2. This calculation assumes that root reinforcement of two overlapping root systems can be lineary added. Tree density (N° of trees/ha) is calculated dividing one ha by the squared mean distance between trees (thus assuming a squared area of occupancy for each tree). The maximal gap area is calculated considering a mean root reinforcement along the gap edges of 5 kPa and back calculating the minimal area of a shallow landslide for a factor of safety equal to 1, and considering a shape of the landslide where the main axes is 3 time the perpendicular one. Gap edges are defined in the swiss guidelines for protection forest management (NaiS), as the limits of the crown projection on the ground.

RESULTS

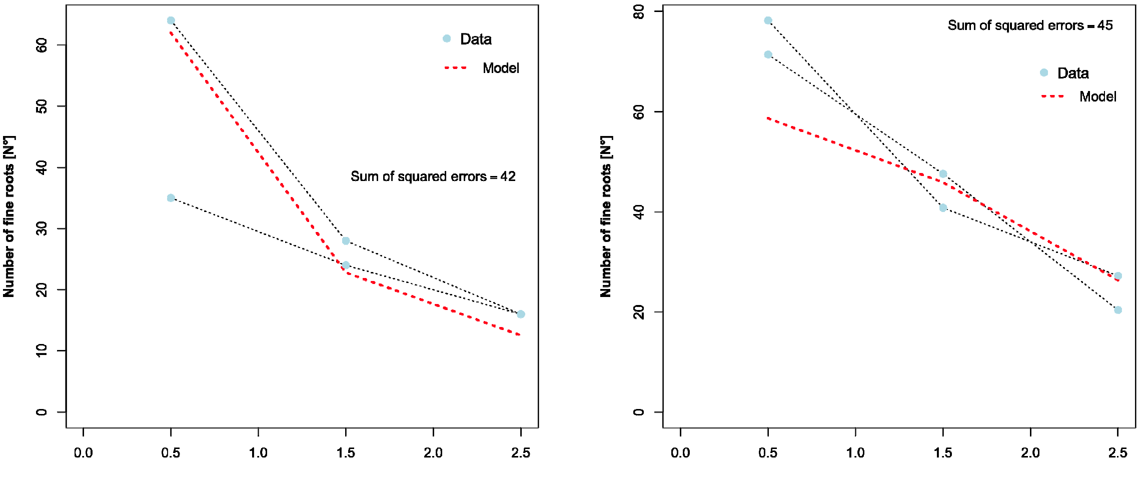
Root distribution

Root distribution data were collected for 10 trees and a total of 30 soil profiles. Table 2 gives an overview of the selected trees and their DBH. Two classes of stem diameter (DBH) could be selected (a 0.2 m class and a 0.4 m class). The data of the 0.2 m DBH class was used for calibration and the data of the 0.4 m DBH class was used for validation.

Tab. 2 Summary of the selected trees sampled for root distribution data. Species are indicated with S=spruce, F=fir, and B=beech.

Tree N°	Species	DBH [m]
1	S	0.37
2	S	0.22
3	S	0.2
4	S	0.37
5	F	0.22
6	F	0.38
7	F	0.24
8	F	-
9	F	0.24
10	B	0.36
11	B	0.35

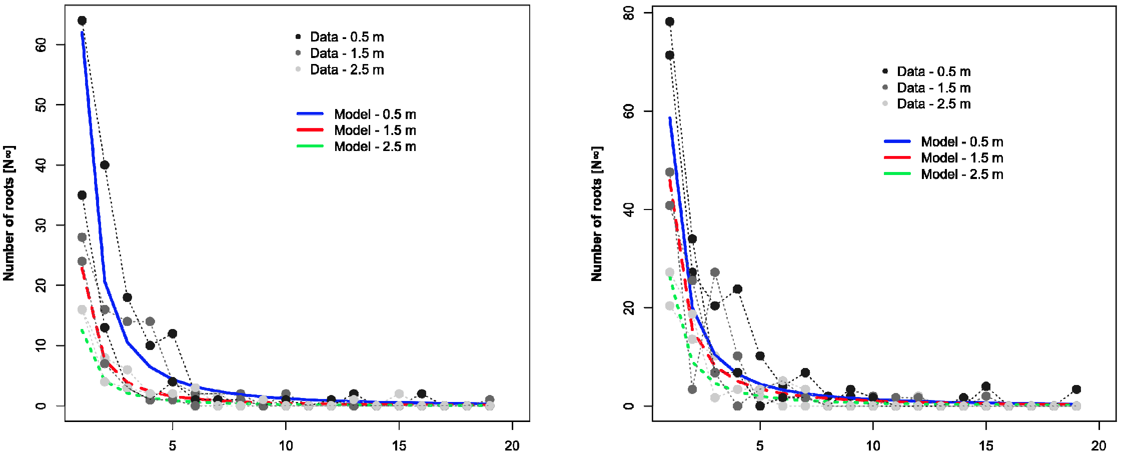
In the first phase of the study the model for the quantification of root reinforcement is calibrated and validated with the field data of root distribution. Two types of data regressions are important for the calibration: the distribution of fine root in function of the distance from tree stem, and the root frequency in different root diameter classes at different distances from tree stem. Figure 3 shows the fine root distribution data used for calibration (3a) and for validation (3b) of the model. The number of fine roots per linear circumferential meter tends to decrease with increasing distance from tree stem for all tree species. However, in the range of distance between 5-8 times the DBH, the number of fine root reaches the maximal intensity and decrease in the proximity of the tree stem. Generally, the total number of fine roots increases with increasing tree DBH. While it was possible to validate the model for spruce and fir species, the uncompleted dataset for beech species did not allowed a validation.



a) b)

Fig. 3 Fine root frequency distribution in function of distance from tree stem. Figure 3a shows the calibration data of the tree number 2 and 3 (DBH class 0.2 m), whereas the figure 3b shows the validation data of tree number 1 and 4 (DBH class 0.4 m). The number of fine roots is referred to one linear circumferential meter.

The distribution of fine roots is an important input parameter for the calculation of the frequency of coarse roots. Figures 4a and 4b show typical relationships between the number of coarse roots and the different root diameter classes for three distances from tree stem (0.5, 1.5, and 2.5 m), for calibration data (4a) and validation data (4b). The number of roots decays exponentially with increasing class of root diameter. The total number of root decreases by increasing the distance from tree stem, and the maximal root diameter decreases with increasing distance from tree stem. The number of roots for each diameter class ad different distances from tree stem is used as an input for the calculation of root reinforcement with the RBM. The ranges of errors shown in table 3 correspond to circa 20-60% error in the estimation of the total fine root frequency and to circa 15-20% error in the root reinforcement calculation.



a) b)

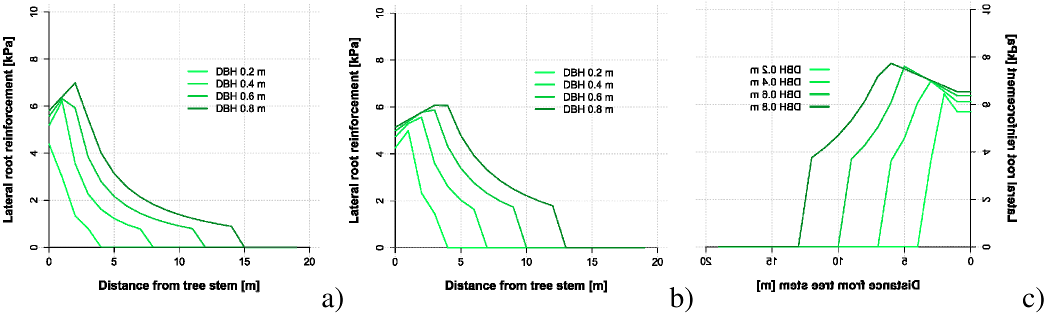
Fig. 4 Coarse root frequencies for each root diameter class at different distance from tree stem. Figure 4a shows the calibration data of the tree number 2 and 3 (DBH class 0.2 m), whereas the figure 4b shows the validation data of tree number 1 and 4 (DBH class 0.4 m). The number roots is referred to one linear circumferential meter.

Tab. 3 Summary of the goodness of fit values obtained for the calibration and validation of the model for fine root distribution. For the definitions of SSE see methods.

Tree N°	Calibration/Validation	SSE
2,3	Calibration	21
1,4	Validation	22
5,7,9	Calibration	60
6	Validation	110
10,11	Calibration	4

Root reinforcement

Using the calibrated model for the estimation of root distribution is it possible to quantify the distribution of root reinforcement. The figures 5a-b-c show the results of the calculated root reinforcement for the three species in four DBH classes. Spruce has the lowest values of reinforcement, but the root system reaches lateral distances that are about 20 times the DBH. The root system of fir trees is less spread, but even small DBH classes reach high values of root reinforcement (up to 5 kPa). The root systems of beech species result to be the most reinforcing one. However, the lateral spread of this species is limited (max. spread up to 15 times the DBH). The calculated root reinforcement is considered to be representative for the first 0.5 m of soil depth.



a) b) c)

Fig. 5 Maximal root reinforcement distribution in function of distance form tree stem, calculated for different tree species (a-spruce, b-fir, and c-beech) and DBH classes (0.2, 0.4, 0.6, 0.8 m).

Based on the results shown, it is possible to formulate easy-to-use table for field applications and estimations. Characterising the soil type of an area and measuring the range of slopes, it is possible to back calculate the minimal value of root reinforcement needed to stabilise sliding areas up to 400 m^2 (see methods). Table 4 shows the values of lateral root reinforcement needed to stabilise different conditions of soil and slopes for landslide with 1 m soil depth and an area of 100 m^2. The calculations were done considering a safety factor of 1.2. Values for new tables with other stability criterions can be easily calculated. The classes of root reinforcement result to be wide (large range of 20 kPa), and the effective range of values is between 0 and 30 kPa (considering that in Switzerland, most of the shallow landslides occurred on slopes between 30 and 35°)(Graf and Rickli, 2009). In order to Table 5 shows the tree densities needed in order to reach the defined root reinforcement, considering the mean DBH of the forest stand. Densities range from 2500 trees/ha for small DBH classes of spruce to 15 trees/ha for large DBH classes of beech. The results show that in any case, it is not possible to reach root reinforcement higher than 10-15 kPa (for these species, in this stand), thus forest cover results to be effective only in situations where the slope inclination is not higher than 5-10° than the residual angle of internal friction of the soil. Table 6 summarises the maximal calculated dimensions that are allowed in a forest stand without compromising the susceptibility to shallow landslides smaller than 500 m^3. Gaps dimensions between 100 and 300 m^2, and slot width between 10 and 20 m are allowed only in slopes that are not more than 5° steeper than the angle of internal friction of the soil.

Tab. 4 Table of the calculated needed lateral root reinforcement (in kPa) considering the soil type classification and the slope inclination.

Slope [°]	Soil class 1 (ϕ = 20-25°)	Soil class 2 (ϕ = 26-30°)	Soil class 3 (ϕ = 31-35°)	Soil class 4 (ϕ = 36-40°)
20	≥2	-	-	-
25	≥5	≥2	-	-
30	≥10	≥5	≥2	-
35	≥15	≥10	≥5	≥2
40	≥20	≥15	≥10	≥5
45	≥30	≥20	≥15	≥10

Tab. 5 Table for the estimation of the mean tree density (N° trees/ha) using the tree species and the mean DBH. The coloured values correspond to the Swiss Forest Inventory (LFI, 2010) classes of basal area (y 0-20 m^2/ha, b 21-40 m^2/ha, g 41-60 m^2/ha); these are the plausible measured values.

DBH [m]	Root Reinforcement 2 [kPa]			Root Reinforcement 5 [kPa]			Root Reinforcement 10 [kPa]			Root Reinforcement >10 [kPa]		
	s	f	b	s	f	b	s	f	b	s	f	b
0.2	≥ 150	≥ 150	≥ 140	≥ 2500	≥ 400	≥ 150	-	≥ 1100	≥ 400	-	-	-
0.4	≥ 100	≥ 70	≥ 60	≥ 400	≥ 120	≥ 70	≥ 625	≥ 280	≥ 100	-	-	-
0.6	≥ 40	≥ 30	≥ 25	≥ 120	≥ 70	≥ 30	≥ 280	≥ 150	≥ 45	-	-	-
0.8	≥ 25	≥ 17	≥ 15	≥ 70	≥ 30	≥ 17	≥ 150	≥ 100	≥ 25	-	-	-

Tab. 6 Maximal gap area and slot width defined based on the slope inclination and the soil classes. The area values are indicated in m^2 and the slot width in m (m^2/m).

Slope [°]	Soil class 1 (ϕ = 20-25°)	Soil class 2 (ϕ = 26-30°)	Soil class 3 (ϕ = 31-35°)	Soil class 4 (ϕ = 36-40°)
20	-	-	-	-
25	**<300/<17**	-	-	-
30	<100/<10	**<300/<17**	-	-
35	<100/<10	<100/<10	**<300/<17**	-
40	<100/<10	<100/<10	<100/<10	**<300/<17**
45	<100/<10	<100/<10	<100/<10	<100/<10

DISCUSSION

The results show that the model RootMap can successfully be applied for the characterization of lateral root distribution at the stand scale. However, the big amount of work needed for the collection of root distribution data (2-4 soil profiles per man per day) limits the number of data for a more strong validation of the model. Further research will contribute to increase the number of datasets for root distribution.

The results of root distribution indicate that the root system of spruce is likely to be wide spread and shallow, whereas fir and beech form less spread and deeper root systems. However, the comparison of our results with previous studies (Schwarz et al., 2010b) suggests that the architecture of the root systems may be strongly influenced also by the stand conditions.

The results of this study are obtained considering only homogeneous forest stands, for simplicity. In fact, forests have more complicated structure and species compositions. Therefore, the presented tables for the definition of the minimal profiles (5 and 6) are aimed to be a valid quantitative support for decisions in the field. In the case where more detail is needed, numerical modeling approaches (such as RootMap) could be applied for the creation of root reinforcement distribution maps, as shown in figure 6. Nearby the distribution or root reinforcement, a map of slope inclinations of the area can be used to define zones where specific silvicultural measures need to be applied. The sensitivity of the results (in term of needed root reinforcement) depending on the estimation of the mechanical properties of the soil is quite high, and can be estimated that to a ±5° error in the estimation of the internal friction angle corresponds to a variation of ±5 kPa needed minimal root reinforcement.
The comparison between the calculated tree densities and the data of the swiss forest inventory (LFI, 2010) shows that most of the calculated values fall in the range of plausible values measured in the swiss protection forests. However, the compared data of the LFI do not distinguish between the DBH classes and the tree species. The results of table 5 indicate that for the considered study area (soil, tree species, and stand), beech assure the best protection function. From a silvicultural point of view, it results that assisting the regeneration of fir and beech, and assure a tree density between 400 and 1000 trees/ha (depending on the DBH) would guarantee the stability of slopes up to 35-40° steep.

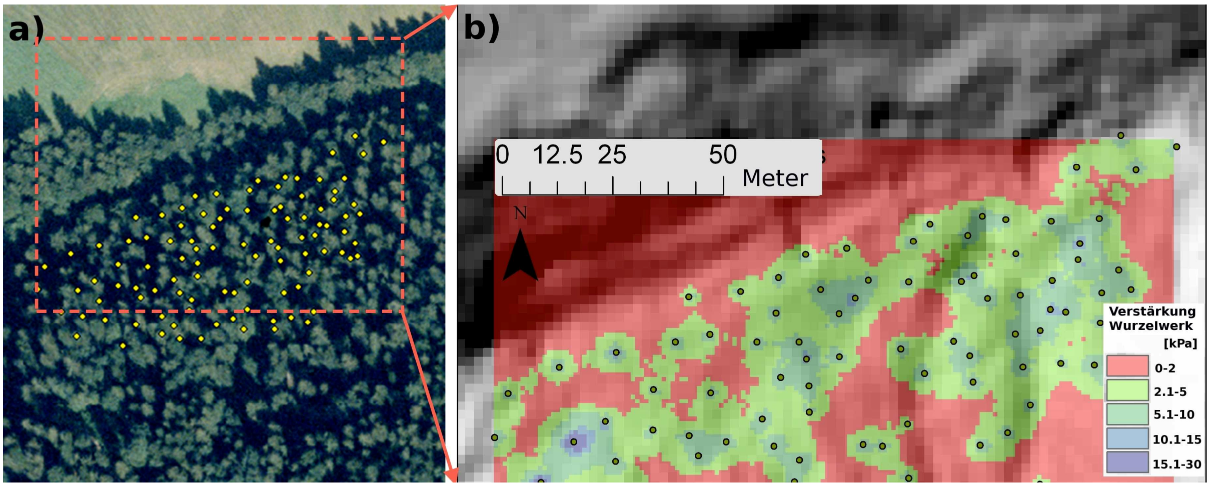


Fig. 6 Plan view of lateral root reinforcement distribution in a forest stand obtained with RootMap. a) The position (yellow points) and dimension (in this case the height) of the trees were obtained by stereo analysis (Schwarz et al., 2012). b) By the visualisation of the model results the red colours indicate low root reinforcement, whereas green-violet colours indicate high values of reinforcement (>2 kPa). The zones with increasing root reinforcement correspond to the position of the trees.

The ability to quantitatively define different zones of susceptibility to shallow landslides and to evaluate the potential stabilizing effect of the forest in those zones, allows the optimizations of forest measures. The use of table 4, 5 and 6 remarkably speed up the evaluation process and allow a quick field analysis. The proposed method also allow a better support for the planning of combined management strategies such as thinning, reforestation, or temporal technical measures. Future research studies could focus on the experimentation and discussion of such new combined management strategies of protection forests in steep slopes.

CONCLUSIONS

In this study we present a novel method for the implementation of recent consolidated research findings in practical tools for the management of protection forest. In particular, we show how detailed data on root distribution and root mechanics can be upscaled to stand scale, and how these data can be used to characterize the spatial distribution of root reinforcement in a forest stand. These calculations of root reinforcement, combined with other simple stand characteristics (such as soil type, geology, and slope angle), are condensed in simple tables for a quantitative estimation of root reinforcement and slope stability in the field. This method is used to define a specific "minimal profile" of forest stands in the contest of a sustainable management concept for protection forests (Thormann and Schwitter, 2004).

The results show the applicability of the novel method. New selected study areas are the objects of a planned monitoring program for the evaluation of the silvicultural measure effectivity in the long term. Practitioners will be asked to use this method in the chosen study areas, and the application of the method is replicated for each practitioner in different study areas allowing for cross comparison and evaluation. Further study areas will be selected for the calibration of the models.

For more detailed silvicultural plans, it will be possible to use numerical models (such as RootMap) in order to localize and quantify the distribution of root reinforcement, and relate it to the susceptibility of the slope to shallow landslides (Schwarz et al., 2009).

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