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RESEARCH ARTICLE

Slow recovery from soil disturbance increases susceptibility of high elevation forests to landslides

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Abstract

Natural hazards such as shallow landslides are common phenomena that disturb soil and damage forests. Quantifying the recovery of forest vegetation after a hazard is important for determining the window of susceptibility to new disturbance events, especially at high elevations, where extreme weather events are frequent and the growing season is short. Plant roots can reduce the size of this window on unstable hillslopes, by adding mechanical reinforcement (c_r) to soil and changing its hydrological reinforcement (c_h); data that are used in landslide models to calculate the Factor of Safety (FoS) of a hillslope. We calculated temporal variations in c_r and c_h in naturally regenerated mixed, montane forests in the French Alps. In this closed-canopy forest, open-canopy gaps were present, with understory vegetation comprising herbs, forbs and shrubs. At three altitudes (1400, 1700 and 2000 m), we dug small trenches as proxies for shallow landslide events and calculated c_r before soil disturbance in both open gaps and closed forest. Then, using monthly tree root initiation and mortality data measured in rhizotrons, we calculated monthly c_r for four years after the disturbance. Temporal FoS was then calculated using an infinite slope stability model.

Results showed that short-lived, ephemeral roots contributed little to soil reinforcement compared to thicker, long-lived roots. After disturbance, mean c_r (over the entire soil profile) never fully recovered to the initial value at any site, although >90% recovery was observed in open gaps at 1400 m. Mean c_r was slow to recover in closed forests, especially at 2000 m, where only 19% recovery occurred after 41 months. The c_h in closed forests was considerable during the summer months, but marked increases in soil water moisture resulted in lower FoS, especially during December to April, when soil was near saturation. As c_r changed little throughout the year, it was a more reliable contributor to slope stability. Our results show therefore, that particular attention should be paid to high elevation forests after a disturbance. Also, during the process of recovery, the highly variable soil water dynamics in closed forest can result in seasonal hotspots of vulnerability. Therefore, when tree transpiration is low, our results highlight a need for careful monitoring on steep or unstable slopes, especially in closed-canopy forests.

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Running title: Tree root recovery after disturbance

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DATABASE LINK

Tree root demography data can be freely accessed at: doi.org/10.15454/C3QY4B

Initial root density along intact soil profile data can be freely accessed at: https://doi.org/10.15454/RYMVUS

Forest inventory data can be freely accessed at: https://doi.org/10.15454/JTO5DD

Key words: Fine roots; mechanical reinforcement; hydrological reinforcement; slope stability; forest gap

1 INTRODUCTION

Landslides are recognized as one of the most dangerous natural hazards that endanger human life and infrastructure in mountainous regions (IPCC, 2012, Petley, 2012). In Europe, the frequency and intensity of shallow landslides triggered by heavy rainfall are predicted to increase (Tichavský et al., 2019). Eco-engineering methods are considered appropriate for improving soil reinforcement and slope stability, through the choice and management of suitable vegetation (Schwarz et al., 2010, Mao et al., 2012, Stokes et al., 2014). Increasing evidence from landslide inventories, experimental and modelling approaches, has shown that reduced forest cover, due largely to disturbances such as tree felling, creates zones that are prone to slope failure (Roering et al., 2003, Mao et al., 2014a, Schwarz et al., 2010, Vergani et al., 2016). High elevation forests are especially susceptible to disturbance and because of the short growing season, take longer to recover than forests at lower elevations (Zhao et al., 2016), but the consequences for soil loss and slope stability are poorly understood. Therefore, forest managers in mountainous regions need more accurate data about the effects of tree removal on slope stability in forests growing at different elevations, as well as the time taken for a slope to recover stability after such disturbance.

Vegetation stabilizes soil mechanically through the binding action of thin and fine roots that cross the multiple potential shear (rupture) surfaces along a slope. These roots anchor plants to deeper soil layers (beneath the shear surface) and need to be strong when held under tension. Thicker roots act like soil nails, preventing soil collapse due to their mass, bending strength and stiffness (Greenway, 1987, Stokes et al., 2009). The majority of studies focusing on the contribution of vegetation to slope stability have estimated the number and cross-sectional area (CSA) of roots (<10 mm in diameter) in soil, as well as their tensile strength (see Mao et al., 2012, for a compilation of data). The resulting value is termed the additional cohesion from roots, also known as mechanical cohesion or mechanical reinforcement, and can be used in geotechnical models to calculate a slope's Factor of Safety (FoS, Norris et al., 2008, Greenwood 2006, Thomas and Pollen-Bankhead, 2010, Ji et al., 2012, Mao et al., 2014a). Mechanical reinforcement varies significantly in forests, depending on tree species and size, as well as stand density (Roering et al., 2003, Sakals and Sidle, 2004, Genet et al., 2008, Schwarz et al., 2010, Vergani et al., 2016). Mao et al. (2013) showed that in temperate, montane forests with a closed canopy, mechanical reinforcement was significantly greater than in open-canopy gaps that occurred either through individual tree felling or mortality. This spatial heterogeneity in mechanical reinforcement will therefore impact a slope's overall FoS. Modelling of FoS for forested slopes allows managers to calculate when a slope's mechanical integrity is compromised, and whether practical interventions are necessary. As the FoS is strongly impacted by the number and dimensions of roots crossing the potential shear surface in soil, it is important to determine how forest structure and patchiness affects root growth, but such data are scarce (Mao et al., 2014a, Rossi et al., 2017, Wang et al., 2018).

Not only does spatial heterogeneity exist in a forest, but also temporal heterogeneity, as fine roots initiate and then die, usually within several months (Leigh et al., 2002, Wang et al., 2018). Forest age also induces temporal heterogeneity in mechanical reinforcement, as both tree age and species composition (due to successional phase), alter the number, dimensions, and strength of roots present throughout the soil profile (Sakals and Sidle 2004, Genet et al., 2008, 2010, Vergani et al., 2016). However, these studies have used a synchronic approach, where measurements have been made in stands of different ages, and so do not reflect intra-annual temporal variability. A long-term (>4 years) study estimating mechanical reinforcement in forests has never been performed using a continuous or diachronic approach. The only study examining the short-term (1.5 years) impact of root initiation and growth on mechanical reinforcement (Mao et al., 2013), showed that in temperate, montane forest, once roots had been disturbed through soil excavation, root initiation and growth occurred much faster in open gaps compared to closed forest (Mao et al., 2013). Nevertheless, this study did not take into account variations in precipitation and the intra-annual dynamics of soil water content, that strongly influence the triggering of shallow landslides.

Shallow landslides usually occur when soil is saturated or near saturation (Sidle and Bogaard, 2016). On forested slopes, soil water is removed through plant transpiration and evapotranspiration, increasing soil matric suction (or soil water potential), and improving soil strength (Fredlund and Rahardjo, 1993, Terwilliger, 1990). This increase in soil strength improves slope stability, and as an analogy to mechanical cohesion or reinforcement, has been termed ‘hydrological’ or ‘hydric’ cohesion or reinforcement (Greenway, 1987, Fredlund and Rahardjo, 1993, Simon and Collison, 2002, Pollen-Bankhead and Simon, 2010, Veylon et al., 2015, Kim et al., 2017). Hydrological reinforcement has been increasingly investigated under different vegetation covers, either alone (e.g., Hayati et al., 2018a, b) or with mechanical reinforcement (e.g., Simon and Collison 2002, Pollen-Bankhead and Simon 2010, Kim et al., 2017), and was highly seasonal and strongly linked to climatic events. For example, during the growing season, hydrological reinforcement due to plant transpiration is high and is the main contributor to a slope's FoS (Simon and Collison, 2002, Kim et al., 2017). However, during the winter months or the rainy season, soil is wet and plant transpiration is minimal. Therefore, hydrological reinforcement is low, and a slope's FoS can be reduced to dangerous levels (Kim et al., 2017). Usually, changes in hydrological reinforcement with soil depth are considered using estimated values (Pollen-Bankhead and Simon, 2010), and rarely do studies combine temporal estimations of hydrological reinforcement with seasonal root growth data and their interaction throughout the soil profile (but see Kim et al. 2017). Not only are tree roots initiated throughout the year (with one or two main flushes of growth), but most fine roots die after only a few days, weeks or months (Mao et al., 2013, Wang et al., 2018). To our knowledge, the effect of this root mortality on slope stability throughout the year has never been quantified, but could contribute to seasonal hotspots of vulnerability.

Here, we aim at investigating the intra- and inter-annual variability in reinforcement of slopes recovering from disturbances in open gaps and closed forest at different elevations. Using field data, hydrological reinforcement was estimated and compared with mechanical reinforcement over time. To do this, we integrated existing data from several studies into one geotechnical model that calculated the FoS. These data comprised: (i) root intersection quantity before disturbance (Mao et al., 2012, 2015b) and monthly root initiation and mortality over 4 years (Wang et al., 2018), from which we calculated temporal mechanical reinforcement, (ii) soil mechanical properties and soil water potential (Kim et al., 2017), from which we estimated hydrological reinforcement and (iii) forest inventory data, from which we determined forest structure (Mao et al., 2012, 2015a, 2015b). We hypothesize that the recovery of mechanical reinforcement is affected by forest structure (open-canopy gaps versus closed-canopy forest), altitudes and soil depths and ask: do mechanical and hydrological reinforcement co-vary depending on forest structure and how much does each type of cohesion contribute to the recovery of the slope's FoS?

2 MATERIALS AND METHODS

2.1 Study sites

We used data from study sites located near Chamrousse, Isère, in the French Alps (45° 07'N, 5° 52'E). All sites have been studied characterized previously and detailed information can be found in Mao et al., (2015b) and Wang et al., (2018). Sites comprised mixed, mature, naturally regenerated forests growing at altitudes of 1400 m (Prémol forest), 1700 m (Bachat-Bouloud forest) and 2000 m (near Achard Lake, at the treeline). *Abies alba* Mill., *Picea abies* (L.) Karst and *Fagus sylvatica* L. were dominant at 1400 m; *P. abies* and *A. alba* were dominant at 1700 m and *Pinus uncinata* L. was dominant at 2000 m (Mao et al., 2015b). The stand basal area (cross-sectional area of trees at 1.3 m) at 1400 m was in the range of 41-56 m^2 ha^{-1}; 27-33 m^2 ha^{-1} at 1700 m; and 9-19 m^2 ha^{-1} at 2000 m. Mean tree diameter at breast height was 19 cm at 1400 m, 18 cm at 1700 m and 14 cm at 2000 m. With different tree densities, biomass ranges from 29 – 146 t ha^{-1} at different altitudes (Figure S1). Slope angles at the three sites were generally between 10° and 25°, but sometimes could reach 35°.

Climatic data for the three sites were estimated over 2004-2014 using the AURELHY model of Météo-France (Benichou and Le Breton, 1987; Piedallu and Gegout, 2007, 2008, Stokes et al., 2020). The mean monthly air temperature is the lowest in January or February (-2.3 °C at 1400 m; -3.6°C at 1700 m and -5.2 at 2000 m) and highest in July (13.7 °C at 1400 m; 12.0°C at 1700 m; 10.2 °C at 2000 m). Mean annual precipitation is approximately 1500 mm at 1400 m, 1700 mm at 1700 m and 1900 mm at 2000 m. Precipitation amount is highly seasonal, with the lowest amount in summer and highest amount in winter (in the form of snow).

2.2 Soil physical and chemical features

In a separate study, soil features were characterised using profiles and monoliths (0.25 m × 0.25 m) in a nearby transect spanning the same elevational gradient (Table 1, Stokes et al., 2020). Infiltration tests were carried out next to each sampling plot using a constant head single ring infiltrometer and saturated hydraulic conductivity was calculated. Bulk density was determined by taking undisturbed soil cores at different depths within the soil profile. Soil was sieved at 2 mm after air drying and the soil fraction <2 mm was used to assess properties. Soil pH was measured in water as 1:2.5 extract. Soil organic matter (SOM) content was determined via loss-on-ignition at 500 °C (Dean, 1974). Soil texture was determined by laser-diffraction analysis (McCave et al., 1986). The soil sample was previously digested in hydrogen peroxide solution to destroy the organic matter and sodium hexametaphospate to release the bound clay particles.

Soils were acidic at all sites, ranging from (a) "Cambisols (Hyperdystric)" overlying green schist and with an abundant water supply at 1400 m (Joud, 2006), to (b) "Cambisols (Humic, Hyperdystric)" overlying the crystalline formation at 1700 m (Joud, 2006), and to (c) "Epileptic Umbrisols (Hyperdystric)" overlying the crystalline formation at 2000 m (IUSS Working Group WRB, 2007). Soil analyses showed that total carbon content was significantly greater in closed forests than in gaps at both 1700 m and 2000 m, and that SOM was significantly greater in closed forest compared to gaps at 1700 m. Apart from some slight differences in soil texture at 1700 m and 2000 m, no other differences in soil physicochemical properties were found (Merino-Martín et al., 2020). A seasonal water table existed in open gaps at 1400 m and 1700 m during the winter months. The average maximum rooting depth of soil was approximately 1.0 m at 1400 and 1700 m, but only 0.5 m at 2000 m (Mao et al., 2015b).

2.3 Root demography

We used data describing fine root distribution, the dynamics of root initiation and mortality in paired plots located in open gaps and closed forests at altitudes of 1400, 1700 and 2000 m. These data came from Mao et al., 2013, 2015b and Wang et al., 2018. The three studies used data from the same rhizotrons, but covered different time periods. Mao et al. (2013) started the experiment and installed rhizotrons in the summer of 2009 at 1400 and 1700 m, and 12 months later at 2000 m, and data covered a 1.5 year period. Wang et al. (2018) continued the observations of root growth and mortality until November 2013.

To measure root demography, four trenches were dug at each altitude, two in open gaps and two in closed forest. Rhizotrons were installed by inserting plexiglass sheets against one wall of the trench. Roots were cut during the process, to leave a smooth wall against which to position the plexiglass (Figure S2). Trenches were then covered with wooden boards and corrugated iron. More details on rhizotron installation can be found in Mao et al. (2013). As the installation of rhizotrons disturbed roots and soil in a way similar to that caused during a shallow landslide (e.g., soil crack and detachment and root damage during scarp formation and mass movement), it was considered as a proxy for a landslide event that damages roots around the scarp (Roering et al., 2003), with root growth considered as a recovery process after the disturbance. Initiation and mortality of each root (< 5 mm in diameter) in the rhizotrons was measured monthly, even during the winter months, for a period of 4 years.

Three root diameter classes (]0, 1] mm,]1, 2] mm and]2, 5] mm; according to the international standard ISO 31–11,]x, y] denotes a left half-open interval from x (excluded) to y (included)) were differentiated during measurements. Then, root initiation quantity ($I_{i,j}$, in roots m^{-2}), and mortality quantity ($M_{i,j}$, in roots m^{-2}) of diameter class *i* for *j*th measurement ($j \in [1, J]$, where *J* refers to the maximum sequential number of measurement, which differed with altitudes ($J = 49$ for 1400 m; $J = 47$ for 1700 m and $J = 33$ for 2000 m) were counted as a function of soil depth. Net root intersection production of diameter class *i* for *j*th measurement (R_{ij}, in roots m^{-2}) and its cumulative form ($C_{i,j}$, in roots m^{-2}) were calculated:

$$C_{ij} = \sum_{j=1}^{J} R_{i,j} = \sum_{j=1}^{J} (I_{i,j} - M_{i,j}) \qquad \text{(Eq. 1)}$$

C_{ij} was used to calculate additional cohesion (or mechanical reinforcement) due to roots after the disturbance event.

We used root distribution data from 2009 (Mao et al., 2012, 2015b), that were collected prior to the installation of rhizotrons (the proxy for a soil disturbance event), to estimate the number and diameter of roots in the soil above the bedrock (1.0 m deep at 1400 and 1700 m and 0.5 m deep at 2000 m). Roots were classed into four diameter classes (]0, 1] mm,]1, 2]mm,]2, 5]mm,]5, 10]mm). These data enabled us to calculate reference root intersection density, defined as number of roots of diameter class *i* per unit soil surface at intact soil condition (R_i, in roots m^{-2}). These data were then used as the initial value before disturbance, against which we measured root recovery.

2.4 Hydrological data

Soil hydrological data are from Kim et al. (2017), who performed measurements in our plots. In 2012, four extra trenches were dug (one trench in one open gap, and one in closed forest at each altitude), to measure soil water potential (ψ, kPa) using WaterMark© Granular Matrix sensors, (Irrometer Co., USA). These electrical-resistance type sensors are robust and easy to use. Devices at 2000 m were frequently stolen or damaged, therefore monitoring could not be performed, and due to flooding, periods of data were missing at 1700 m from August 2012 to November 2013, therefore, we only calculated c_h at 1400 m. Each trench was close (< 2.0 m) to a rhizotron to ensure that ψ data could be matched with root demography data. Sensors were installed at different depths (at 0.05, 0.1, 0.2, 0.4, 0.7 m), along a vertical soil profile and data were logged every 30 min from July 2012 to November 2013 (data are from Kim et al., 2017, Fig. S3). Despites some high values of ψ (i.e., >200 kPa, but still within the maximum range of WaterMark sensors), most of the measured values at either of the vegetation types was <150 kPa during our monitoring period (Fig. S3). Merino-Martín et al. (2020) manually measured mean monthly air (0.1 m above soil surface) and soil temperatures (at depths of 0.1 m and 0.4 m) in soil trenches where the rhizotrons were installed, from September 28th, 2010 to March 3rd, 2014 (Figure S4), using a portable thermistor thermometer (HI-93510N Hanna Instruments, USA). Results showed that gaps were slightly warmer than closed forest at all elevations, but significant differences between the two were found only at 1700 m. Temperature at topsoil was more fluctuant than at deep layers, especially at high altitudes of 1700 and 2000 m.

2.5 Cohesion and slope stability

2.5.1 Mechanical reinforcement from roots (c_r)

Before slope stability modelling could be performed, it was necessary to calculate mechanical (c_r) and hydrological reinforcement (c_h) from the root intersection production data. c_r was estimated using Wu and Waldron's model (WWM, Wu et al., 1979; Waldron, 1977), which assumes that all roots are mobilized and broken simultaneously, and c_r is provided by the total tensile strength of all roots per soil unit area:

$$c_{ri,j} = 1000 R_f \frac{\bar{T}_{ri} \pi \bar{d}_{ri}^2 C_{i,j}}{4 A_S} \qquad \text{Eq. (2)}$$

where 1000 is the convertor from MPa to kPa, R_f is the root orientation factor, $\bar{T}_{ri}$ is tensile strength of roots of diameter class $\bar{d}_{ri}$, $C_{i,j}$ is cumulative root intersection production as defined in Eq.(1). A_S is the soil area where roots are counted (m^2). $\bar{d}_{ri} \in \{0.5, 1.5, 3.5, d_n\}$ corresponding to diameter classes]0, 1] mm,]1, 2] mm,]2, 5] mm and]5, 10] mm. When root diameter >5 mm, we used the actual measured diameter. Roots of >10 mm in diameter were not included in the calculations of soil reinforcement, as the mechanism by which these large diameter roots stabilize slopes is not considered in the cohesion model (Wu et al., 1988).

The choice of WWM was made because it is simple and uses a limited number of parameters. WWM has been widely applied over the last 40 years, so our results can be compared easily with previous studies. It has been shown that WWM overestimates the additional cohesion from roots (Abernethy and Rutherfurd, 2001, Pollen and Simon, 2010). Therefore, we took a corrected coefficient R_f of 0.48 (Preti, 2006), instead of the 1.2 proposed by Wu et al., (1979). Ji et al. (2012) and Mao et al. (2014b) also found that this corrected WWM (Preti, 2006) gave the most conservative c_r, that is comparable to that calculated using Fibre Bundle Models (FBMs), based on force-induced root breakage (Thomas and Pollen-Bankhead, 2010), or displacement-triggered root breakage (Schwarz et al., 2010). Models such as the Root Bundle Model (RBM) (Schwarz et al., 2010) or energy based Fibre Bundle Model (FBM) (Ji et al., 2020) might yield more accurate and realistic c_r, but they require extra data, such as the modulus of elasticity of roots or root rupture energy, that we did not measure in our study.

A power relationship usually exists between root tensile strength (T_{ri}) and root diameter, i.e., $T_{ri} = \alpha \cdot d_i^{\beta}$. Mao et al. (2012) reviewed literature data relating to changes in T_r with root diameter and found that plant functional group had a limited effect on c_r estimation. Therefore, we took a justified generic equation for T_r:

$$T_{ri} = 28.97 \cdot d_i^{-0.52}. \qquad \text{Eq. (3)}$$

In order to identify forest patch type (open gaps versus closed forest) and site effects on c_r and how the recovery process possibly changes these effects, we introduced three ratios (R_{1400}, R_{1700}, R_{2000}), which indicated c_r in open gaps divided by c_r in closed forest at altitudes of 1400, 1700 and 2000 m, respectively:

$$R_{1400} = \frac{c_{r,open\,gap,1400m}}{c_{r,closed\,forest,1400m}}$$

$$R_{1700} = \frac{c_{r,open\ \ gap,1700m}}{c_{r,closed\,forest,1700m}} \qquad \text{Eq. (4)}$$

$$R_{2000} = \frac{c_{r,open\,gap,2000m}}{c_{r,closed\,forest,2000m}}$$

When a root tip appeared behind a rhizotron, it started to grow downwards along the plexiglass pane. When the root had branches, whether or not these lateral roots initiated from the main root was uncertain. Therefore, to estimate the range of bias in c_r due to this uncertainty, we performed the following two scenarios in the calculation of c_r. In Scenario A), we included both main and lateral roots; in Scenario B), we excluded lateral roots growing from main roots (Figure S5).

2.5.2 Pore-water pressures: hydrological reinforcement (c_h) and hydrostatic-uplifting force (U_z)

Hydrological reinforcement c_h and hydrostatic-uplifting force U_z were the effects of pore-water pressures on slope stability. When soil is not saturated, negative pore-water pressures produced matric suction and greater shearing resistance, defined as c_h. When soil is saturated, positive pore-water pressures produced hydrostatic-uplifting force, defined as U_z.

We used two different methods proposed by Fredlund et al. (1978) and by Kim et al. (2017), respectively, to calculate c_{h_z} (c_h at zth layer), and chose the more conservative one in data analysis and FoS calculation. First, we used the inverse power-law model between gravimetric soil moisture at zth layer (θ_{g_z}) and c_{h_z}, fitted by Kim et al. (2017). Soil samples were collected from the same study site and were then subject toshear strength test under different moisture levels to derive soil moisture-shear strength relationships under unsaturated soil condition ($\psi \neq 0$):

$$c_{h_z} = \begin{cases} c_m {\theta_{g_z}}^{-B} - c' & \psi \neq 0 \\ 0 & \psi = 0 \end{cases} \qquad \text{Eq. (5)}$$

where, c_m is the apparent maximum soil cohesion at dry condition, B is a fitted reduction coefficient derived, *c'* is the effective cohesion term subtracted from the unsaturated shear strength term (Kim et al., 2017).

Alternatively, we used the linear equation between c_{h_z} and ψ_z for the soil layer z under unsaturated soil condition (Fredlund et al., 1978, Simon and Collison, 2002):

$$c_{h_z} = \begin{cases} \psi_z tan\phi_b & \psi \neq 0 \\ 0 & \psi = 0 \end{cases} \qquad \text{Eq. (6)}$$

where, the angle ϕ_b (in °) represents the conversion rate between tensiometer measured water potential and the hydrological reinforcement. ϕ_b reportedly varied within a narrow range from 10° to 20° (Simon and Collison, 2002). In this study, we took different ϕ_b (5°, 10°, 15°, 20°) to compare c_{h_z} calculated by two methods.

The total c_h of the soil profile was calculated as:

$$c_h = \sum_{k=1}^{K} \frac{c_{h_z} \cdot A_z}{A_S} \qquad \text{Eq. (7)}$$

where A_z is the cross-section area of each layer (m^2), A_S is the cross-section area of the profile (m^2).

U_z is calculated as:

$$U_z = \begin{cases} \rho_w g(z_s - z_{sat})\cos^2(\beta)/1000 & \psi = 0 \\ 0 & \psi \neq 0 \end{cases} \qquad \text{Eq. (8)}$$

where ρ_w is the water density (kg m^{-3}), g is the gravitational acceleration (N kg^{-1}), z_s is the depth of the soil profile (m), z_{sat} is the depth at which soil saturation starts to occur (m), 1000 is to convert Pa to kPa.

2.5.3 Slope stability modelling

Following Kim et al. (2017), we defined the factor of safety (FoS) for each soil layer for a slope with an angle of β (in degree (°)). FoS for the z^{th} soil layer ($z \in Z$; Z is total number of layers), noted as FoS_z (dimensionless) was calculated as the ratio between the stabilizing and destabilizing forces:

$$FoS_z = \frac{c'_z + c_{r_z} + c_{h_z} + \tan\phi_z(\sum_{z=1}^{z} W_z \cos\beta - U_z)}{\sum_{z=1}^{z} W_z \sin\beta} \qquad \text{Eq. (9)}$$

where FoS_z determines if the slope at the z^{th} soil layer is safe (FoS ≥1.3), stable but needing monitoring (1.3 >FoS ≥1.0) or not (FoS <1.0); the numerator term is the derived equation of Fredlund et al. (1978), in which both root and hydrological reinforcement were incorporated in the framework of the classical Mohr–Coulomb failure criterion; c'_z, c_{r_z} and c_{h_z} are soil effective cohesion, additional cohesion from roots and hydrological reinforcement of the z^{th} soil layer, respectively (in kPa). $c_{h_z} = 0$ if soil is saturated (defined as $\psi = 0$). ϕ_z is internal friction angle of (degrees) of the z^{th} layer. W_z is surcharge of soil, water, and biomass of the z^{th} layer per area and accordingly $\sum_{z=1}^{z} W_z$ is the cumulative charge down to the z^{th} layer (kPa). U_z is the hydrostatic-uplifting force, considering that there is a water flow, on the saturated portion of the failure surface (kPa). $U_z = 0$ if soil is not saturated (defined as $\psi \neq 0$).

As suggested in Kim et al., (2017), we used an infinite slope length as a condition for FoS computation, because very long slopes (>500 m) at Chamrousse can commonly be found, therefore W_z was only calculated per unit slope area:

$$W_z = z\gamma_z\left(1+\theta_g\right) + B_z = z\gamma_z\left(1+\frac{\theta_v}{\gamma_z}\right) + B_z \qquad \text{Eq. (10)}$$

Where, z = soil layer thickness; γ_z = dry bulk soil density (in kN m^3); $\theta_g$and θ_v= gravimetric and volumetric soil water content (dimensionless); B_z= fresh biomass in unit slope area (i.e., tree surcharge, in kPa).

We defined a global *FoS* of the whole slope land as the minimum of *FoS*$_z$ among all the soil layers

$$FoS = \min(FoS_z) \qquad \text{Eq. (11)}$$

Differentiating *FoS* and *FoS*$_z$ enabled us to assess both slope stability and to identify the effect of the vertical distribution of roots and water on slope stability.

To better facilitate cross-site comparison between mechanical and hydrological reinforcement, the following conditions were set and respected in the modelling of slope stability:

(1) $\beta = 35°$, slope angle was hypothetically fixed to 35° (Kim et al., 2017)

(2) c_z' and ϕ_z of soil at 1400 m was estimated with a shear testing device by Kim et al. (2017). They were fixed as 10 kPa and 40°to soils of different depths and altitudes, respectively.

(3) W_z, c_{r_z}, $c_{h_z}$and U_z were calculated for each soil depth. c_{r_z} was calculated for each altitude (1400, 1700, 2000 m); c_{h_z} was calculated for 1400 m based on the available data.

(4) B_Z was estimated based on aboveground biomass investigation within forest inventory plots (see Mao et al., 2012, 2015a, 2015b), in which each tree's size and position were measured (see supplementary material for more details).

2.6 Statistical analyses

One-way analysis of covariance (ANCOVA) was used to test the significance of differences in c_r calculated by two scenarios and c_r between the reference (before disturbance) and the final recovered state (the final measurement in November 2013). Tukey's honestly significant difference (HSD) test was performed when one-way ANCOVA tested for significant differences with $p < 0.05$. Analysis of variance (ANOVA) was used to calculate contribution of factors (altitude, forest patch type, soil depth, root diameter and monthly interval) to the variability of root production, mortality, living root numbers, and the c_r recovery after disturbance. Data were transformed to meet a normal distribution when necessary. All statistical analyses were performed with R version 3.4.3 ((http://www.r-project.org/).

3 RESULTS

3.1 Root initiation and mortality

Initiation and mortality of roots were highly seasonal (Figure S6-S8) and were significantly and positively correlated in all plots (Figure 1, Table S1), especially in the]0, 1] mm diameter class. Roots in the]1, 2] mm and]2, 5] mm diameter classes had very high rates of initiation compared to rates of mortality. Root diameter and soil depth best explained the variation in root initiation quantity, I_{ij}, with contributions of 11% and 10%, respectively (Table 2). Root diameter also explained 20 % and 19% of the variability in root mortality quantity, M_{ij}, and cumulative net root intersection C_{ij}, respectively, whereas soil depth only explained 5% and 7%, respectively (Table 2). Altitude and patch type (open gaps versus closed forest) were both significant and explained more variation in I_{ij} (3.1% and 4.5%, respectively) than M_{ij} (1.5% and 2.5%, respectively) and C_{ij} (2.2% and 2.5%, respectively). Although temporal effects were significant, time since disturbance explained poorly the variation in I_{ij}, M_{ij} and C_{ij} (Table 2), suggesting that much of the variation may be seasonally driven.

3.2 Recovery of mechanical reinforcement (c_r) after the disturbance event

Before the disturbance, mean c_r (over the whole soil profile) in open gaps was lower than that under closed forest at 1400 m (R_{1400_before} = 0.55) and 1700 m (R_{1700_before} = 0.54), but at 2000 m, mean c_r in open gaps was similar to that in closed forest (R_{2000_before} = 1.10; Table 4). After the disturbance, mean c_r in open gaps was almost twice that in closed forest at 1400 m (R_{1400_after} = 1.94), whereas differences between open gaps and closed forest decreased after the disturbance event at 1700 m (ratio increased from 0.54 to 0.90, Table 4).

When c_r was calculated using the two different scenarios (A: all roots included and B: branched roots excluded), results were similar at all altitudes, soil depths and in each forest patch type (Figure 4), therefore, the scenario used had little effect on the results.

Mean c_r had not fully recovered to its initial value before disturbance, at any of the sites or altitudes, by the end of the study period (Figure 2). Four years after disturbance, c_r had recovered by over 90% (in open gaps) and 26% (in closed forests) at 1400 m, and by 46% (in open gaps) and 28% (in closed forest) at 1700 m (Table 3). However, at 2000m, c_r had only recovered by 23% (in open gaps) and 19% (in closed forest) after 41 months (Table 3).

Mean c_r recovery was more dependent on root diameter than spatial or time factors (Table 2). Before disturbance, roots in the]>2 mm] contributed >50% to c_r at all altitudes (in both open gaps and closed forests). However, after the disturbance event, roots in the]> 5] mm class diameter never appeared. Roots in the]2, 5] mm were not the primary contributor to c_r at most sites and in some cases, (i.e. in open gaps at 1700 m and closed forests at 1400 m), contributed equally or slightly more than]1, 2] mm roots. Instead, roots in the]1, 2] mm class diameter became the major contributor to c_r.

3.3 Vertical distribution of mechanical reinforcement (c_r) before and after the disturbance event

At all sites, before the disturbance event, c_r was highest in the top 0.2 m and then decreased with increasing soil depth. At all sites and altitudes, there were significant differences in c_r before and after the disturbance event, with c_r decreasing significantly in the topsoil (0.0 – 0.2

m) after the disturbance (Figure 4). After disturbance, c_r in the top 0.2 m layer never recovered more than 40% at any site, but deeper in the soil, c_r recovered to >50% of the initial value at all sites and altitudes (except at 2000 m) (Figures 3, S9, S10). The fastest recovery in c_r occurred at a depth of 0.8 – 1.0 m in open gaps at 1400 m, and after only 12 months, c_r was four times greater than the value before the disturbance event (Table 3).

3.4 Seasonal variability in mechanical reinforcement (c_r) and hydrological reinforcement (c_h)

After the disturbance event, mean c_r (over the whole soil profile) increased linearly, then flattened out over time. Except for open gaps at 1400 m, the first winter caused a decreased increment in mean c_r, or delayed the appearance of root initiation in periods with snow cover, compared to those without (Figure 2). No obvious seasonal variability was observed in c_r.

Mean hydrological reinforcement (c_h) calculated using the method in Fredlund et al. (1978), was much higher than that calculated using the method from Kim et al. (2017), where ϕ_b fell in the range 10° – 20° (Simon and Collison, 2002). However, when $\phi_b = 5°$, c_h calculated using Fredlund et al. (1978) was close to that calculated using Kim et al. (2017) (Figure S11). Because Kim et al. (2017) derived soil moisture-shear strength relationships based on soil samples from our study sites, we used c_h from Kim et al. (2017) for analyses and FoS calculation. c_h varied significantly through the year (Figure 2), regardless of site or depth in the soil (Figure 3). Hydrological reinforcement was lowest in winter and spring (i.e., from December to April), but was close to, or was higher, than mean c_r in summer (i.e., from May to November, Figures 2, 3).

3.5 Slope stability

At 1400 m, 3 months after the disturbance event, the rapid increase in mean c_r in open gaps started to significantly improve slope stability, increasing FoS by over 25% (Figure 5a). However, although mean c_r in closed forest was lower than in open gaps, due to the seasonal changes in mean c_h, FoS was similar between closed forest and open gaps during the summer months (Figure 5a, b). Mean c_h contributed to the FoS more than mean c_r in closed forest, although it was highly seasonal and could even be absent (Figure 5b). Soil was occasionally close to saturation or was saturated, usually during the periods of snow cover, and so the hydrostatic-uplifting force slightly decreased FoS (Figure 5). Affected by mean c_h, FoS showed strong seasonal patterns with lower values during the winter. The FoS was less influenced by the c_r and c_h values that were estimated at depths of 0.6 – 1.0 m in the soil (Figure S12). Greater contributions of mean c_r to FoS in open gaps compared to closed forest were also observed at 1700 m and 2000 m (Figures S13, S14).

4 DISCUSSION

4.1 Recovery of mechanical reinforcement (c_r): effects of elevation, patch and depth in soil

Consistent with our hypothesis, once the soil disturbance event had occurred, the recovery of mean c_r to its initial value was more rapid in open gaps than closed forest (Table 3). At 1400 m, over 90% of c_r had recovered after 4 years in open gaps, but only 26% had recovered in the closed forest. However, this difference lessened with increasing altitude: at 1700 m, c_r

recovered by almost 50% in the open gaps but less than 30% in the closed forest. At the highest elevation (2000 m), in both open gaps and closed forest, the lack of production of thicker roots meant that c_r recovered by less than 25%, even after 41 months. As the growing season at this altitude is usually only 5 – 8 months (Wang et al., 2018), presumably it would take several years before thicker root production could match those found at lower altitudes, where the growing season is 7 – 10 months (Wang et al., 2018).

Several reasons exist to explain the faster recovery of root production in open gaps at lower elevations. Closed forests at 1400 m were significantly denser with larger trees than at the higher altitudes (Figure S1). Therefore, root systems are probably extensive and extend further into open gaps than at higher elevations. Morphological differences exist between open gaps and closed forests, resulting in a greater quantity of solar irradiance and water that reach the understory and soil in open gaps, positively impacting root growth (Coates and Burton 1997, Brett and Klinka 1998). At the same field sites as in our study, Merino-Martín et al. (2020) showed that at elevations of 1400 m and 1700 m, mean negative soil water potential was greater (soil was drier) under closed forest compared to open gaps, but that soil physical and chemical properties were similar (apart from soil carbon that was greater under closed forest at higher elevations). Therefore, microclimate may be influencing root elongation but not soil properties. It is now well documented that soil temperature is a major driver of root growth in temperate forests (Mao et al., 2013, Germon et al., 2016, Mohamed et al., 2017, Wang et al., 2018). The slightly warmer soil in open gaps compared to closed forests may have accelerated c_r recovery in open gaps compared to closed forests. But if this was the case, this phenomenon should be more obvious at 1700 m, where open gaps were significantly warmer than closed forest. It seems more likely that as coarse roots present in open gaps are distal to the tree, they will be thinner and have a greater potential for recovery after wounding (Stokes et al., 2009). Compared to proximal roots, distal roots also have greater quantities of non-structural carbohydrate (NSC, Wang et al., 2018). NSC is produced during photosynthesis and typically comprises mobile soluble sugars and large, non-mobile, granular starch, that can be mobilized for fast growth after wounding (Hoch et al., 2003). Therefore, distal roots have a better recovery rate than proximal roots.

With regard to different soil depths, c_r recovery in the topsoil (0.0 – 0.2 m) was poor and reached only 40% of the initial value before the disturbance event (at all sites). However, deeper in the soil, c_r recovered by over 50% at 1400 and 1700 m. In the open gaps at 1400 m, c_r at a depth of 0.8 – 1.0 m reached over six times the initial value. Reasons for this disparity in c_r recovery with soil depth may be found in the way that roots respond to the local soil climate. Root elongation is usually slower in topsoil than deeper in the soil because it is less buffered against abrupt changes in air temperature and precipitation (Mohamed et al., 2020). In general, topsoil is colder and more humid in the winter and warmer and drier in the summer compared to the deeper layers, where temperature and soil moisture are less variable (Waisel et al., 2002). We also found that this was true at our study site (Figure S4). Snowmelt may also increase the formation of frost in topsoil, hindering root growth and causing mortality (Tierney et al., 2001). However, although root elongation in topsoil was less than in the deeper layers, in terms of resistance to landslides, where mechanical reinforcement is required deeper in the soil, there will be little effect of surface roots on a slope's factor of safety.

4.2 Recovery of mechanical reinforcement (c_r): effect of root diameter

Mean c_r recovery (over the whole soil profile), was dependent on root diameter, and roots in the 1 – 2 mm and 2 – 5 mm diameter classes were the main contributors to c_r after disturbance. We suggest that c_r recovery follows the "maximum efficiency" rule of root production, i.e., more resources are required to construct thicker roots than fine roots (Kitajima et al., 2010; Valenzuela-Estrada et al., 2008). This rule also states that under suboptimal growth conditions, plants initially build 'low-cost' fine roots (0 – 2 mm) to create a transport pathway for resource provision, in order to then reach "maximum efficiency," in terms of growth and functioning. We observed that the finest roots (0 – 1 mm diameter) were the first to be initiated after the disturbance, followed by those in the 1 – 2 m diameter class, and finally by those in the 2 – 5 mm diameter class (Figure 1). Similar results were also found in the grass species, *Zea mays,* during the winter (Barlow and Rathfelder, 1985), but data for woody species are rare. However, these very fine 'low-cost' roots also had a high turnover, and therefore were of an ephemeral nature. The function of these very fine roots would be to quickly explore soil and forage for resources in the short growing season, before being 'shed' by the tree (Wang et al., 2018). Due to this high turnover, very fine roots therefore contribute little to c_r after disturbance. As these very fine ephemeral roots were rapidly initiated after disturbance, but contributed little to c_r, we estimated that at 1400 m and 1700 m, it took 1.3 – 1.6 years before longer-lived and thicker roots were produced. However, at 2000 m, c_r never returned to the original value during the 3.5 years of monitoring, underlining the fragility of these subalpine forests when exposed to disturbance.

Including branched roots or not, into the calculation of c_r did not change results significantly (Figure 4). Therefore, although rhizotrons may induce artefacts because they force roots to grow against the plexiglass window (Joslin and Wolfe, 1999), they did not impact the calculation of mean c_r.

4.3 Which type of reinforcement contributes more to slope stability?

Although root initiation and mortality were strongly affected by season, mean cumulative c_r (i.e., regardless of soil depth), increased continuously until a stable state was reached. However, distinct fluctuations in hydrological reinforcement (c_h), controlled by pore-water pressure (Terwilliger, 1990), were noted in all open gaps and closed forest, as well as soil depths, as also observed by others (Pollen-Bankhead and Simon, 2010, Kim et al., 2017, Hayati et al., 2018a). During the winter months, soil moisture is high and can be saturated from precipitation and snow, and water uptake by dominant plants is minimal. Low c_h in both open gaps and closed forests also supported the findings of previous studies that the effects of vegetation on soil hydrologic conditions could be neglected during dormant season (Pollen-Bankhead and Simon, 2010, Hayati et al., 2018a). During the spring, despite the physiological activities of vegetation that increase evapotranspiration, snowmelt leads to high soil moisture and even saturation (Hayati et al., 2018a). Reduced c_h, and extra uplifting force during soil saturation increases the likelihood of shallow landslides. However, during the summer (June –

August), plant transpiration increases, drying the soil and making negative pore-water pressure lower and c_h higher, often to levels similar to or greater than c_r (Figure 3). As for differences in c_h between closed forest and open gaps, higher c_h in forest stands compared to areas lacking a canopy, has already been observed, largely because of rainfall interception by the canopy, or root water uptake (Simon and Collison, 2002, Hayati et al., 2018a). Although c_h is high in the summer, mechanical reinforcement from roots is more stable throughout the year, and is therefore a more reliable contribution to slope stability.

Our results were slightly different from a previous study at the same site, that showed a smaller impact of c_r on FoS (Kim et al., 2017). This difference in results was because Kim et al. (2017), used data commencing 2.5 years after rhizotron installation to calculate c_r. Therefore, root growth had already recovered significantly after the disturbance. Our results also demonstrate a net disparity in the calculation of c_h depending on the method used (Eq. (6) from Fredlund et al., (1978) versus Kim et al. (2017)'s empirical model). We esteem that Kim et al. (2017)'s model using c_h and soil moisture was more reliable, as the model used experimental data from all plots. Also, c_h calculated using the method from Kim et al. (2017) provided more conservative values than c_h using Eq. (6) where an arbitrary choice of the ϕ_b can cause major variations in c_h. Such a comparison highlights the utmost importance of properly choosing ϕ_b values for c_h estimation when Fredlund et al., (1978)'s method is used.

4.4 How does disturbance and recovery of roots affect slope stability?

Compared to the summer months, slope stability decreases in the winter, due not only to the low contribution of c_h, but also because of the rising water table in deeper soil layers. Once soil is saturated because of a high water table, the decrease in FoS could be exacerbated due to the water uplifting force (Simon and Collison, 2002). In our study, a seasonal water table was only observed in gaps at 1400 m and 1700 m, not in closed forest. Therefore, gaps could become vulnerable in winter due to such a hydrological process, highlighting the importance of the mechanical role of tree roots on slope stability.

The rapid recovery of root production and growth is important for reducing the window of landslide susceptibility after a disturbance. We showed that this recovery was fastest in open gaps growing at the lowest elevation (1400 m). In closed forests, there were more roots initially, as well as the presence of coarse root systems, binding and nailing soil in place. However, c_r recovery was poor, particularly deeper in the soil. To reinforce a slope, it is important that the contribution from c_r is high deeper in the soil where the potential shear zone is likely to be located (Stokes et al., 2009). As a result, after soil disturbance, slopes under closed forests at 1400 m and 1700 m had a lower FoS than in open gaps, except during the summer, when c_h was high, but this is the time of year when precipitation-induced landslides are minimal in this region. Our results show therefore that very dense closed forests have higher resistance, but lower resilience than open gaps, when subjected to disturbances that can cause root mortality. The presence of very dense, closed forest around small gaps (<625 m^2), also hastens root recovery in gaps, especially at lower elevations where temperatures are warmer. Therefore, high elevation forests, with small, sparsely distributed trees, have a lower resilience to soil disturbance, increasing the window of susceptibility to landslides and natural hazards.

Including our study, most modelling work on the effects of vegetation and/or water on FoS have been based on the paradigm of Mohr–Coulomb failure criterion, in which the contributions of vegetation and water to shear resistance are considered as cohesion terms (c_r and c_h) juxtaposed with the soil's effective cohesion (c') (Simon and Collison, 2002, Pollen-Bankhead and Simon, 2010, Kim et al., 2017). Such a simplification greatly enhances the model's applicability, as c_r and c_h, along with c', can be measured or modelled separately prior to their incorporation to the Mohr–Coulomb failure criterion. However, to what extent such a paradigm reflects real soil-root biophysical processes is uncertain, especially as the impact of large roots on slope stability are not considered. Although we show that slope stability can be temporarily compromised in closed forests once a disturbance event has occurred, we did not include the effect of large roots in our model, even though they were always present and will significantly improve slope stability (Nakamura et al., 2007, Giadrossich et al., 2019). Therefore, although our results provide useful information on the recovery of root growth after a disturbance event, and the impact for cohesion over time, a simple comparison of safety factors between open gaps and closed forest must be performed with care. Similarly, comparisons of different types of vegetation on slope stability, based on results from models using only data on fine roots should be assessed with caution. The development of a robust slope stability model that integrates all root size classes with soil and water, as well as their interactions, is now a priority.

5 Conclusions

We show that after a soil disturbance event, distinct differences occurred in the recovery of root initiation and growth in open gaps and closed forests at different elevations. Mean mechanical reinforcement (over the whole soil profile) never fully recovered to the value before the disturbance. However, in open gaps, mechanical reinforcement at depths of 0.8 – 1.0 m recovered after 12 months at elevations of 1400 m and 24 months at 1700 m. In closed forests, recovery took 48 months at the same depth. In forests at 2000 m, root initiation and growth were minimal after the disturbance and only recovered by 25% of the initial value, even after 41 months. Therefore, these high elevation forests are particularly vulnerable to disturbance. Although mechanical reinforcement under closed forests was higher than that in gaps before disturbance, the recovery after disturbance was slow, compromising slope stability for at least 4 years. Such distinct effects of elevation and forest patchiness should be considered by managers working in landslide prone areas. Regarding the type of cohesion, we demonstrate that hydrological reinforcement due to transpiration and drying of soils was high during the summer, particularly in the closed forests. However, during the winter months, when soil was saturated and transpiration was minimal, hydrological reinforcement was negligible. The mechanical effects of roots on soil cohesion was much more stable throughout the year, and increased over the years following disturbance. Therefore, hydrological reinforcement contributed little to long-term slope stability, and mechanical reinforcement from roots was a much more reliable contributor to slope stability.

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TABLES

Table 1 Physical and chemical soil properties at different altitudes at the study site (from Stokes et al., 2020).

Altitude (m)	Soil depth (cm)	Clay-silt-sand (%)	Organic carbon content (%)	Bulk density (g cm^{-3})	Mean saturated hydraulic conductivity (cm h^{-1})	FAO soil type
2000	0-30	29-44-27	5.1	1.5	12.73	Histic Hyperskeletic Cambisol (Turbic)
	30-50	13-40-47	1.9	1.3		
1700	0-20	36-41-23	15.1	1.4	19.04	Histic Orthoskeletic Cambisol (Loamic, Turbic)
	20-40	26-45-29	7.4	1.6		
	40-80	18-44-37	6.5	1.6		
	80-100	15-48-37	6.8	1.8		
1400	0-20	28-49-23	13.5	1.5	10.09	Someric Histic Umbrisol (Turbic)
	20-40	13-48-39	2.7	1.1		
	40-60	8-42-50	1.3	1.2		
	60-80	11-44-45	1.9	1.2		
	80-100	9-44-47	2.4	1.2		

In the dataset from Stokes et al., (2020), soil samples were taken from a nearby transect along the slope, at depths of 0-7 cm, 7-25 cm, 25-40 cm, 40-65 cm, 65-77 cm, 77-92 cm at 1400 m; at depths of 0-14 cm, 14-45 cm, 45-76 cm, 76-97 cm at 1600 m; and at depths of 0-30 cm, 30-54 cm at 2000 m. We used the soil properties measured at 1600 m to represent those at 1700 m in this study.

Table 2 Results of two-way ANCOVA test on the effects of spatial (altitude, patch, soil depth), biological (root diameter) and temporal factors on the recovery process of root initiation quantity (I_{ij}, m^{-2}), root mortality quantity (M_{ij}, m^{-2}), cumulative net root intersection production (C_{ij}, m^{-2}) and mechanical reinforcement (c_r, kPa). Asterisks indicate significant correlations (where, ***, $p < 0.001$). Numbers in bold indicate the highest contributions (%).

Factor	**Root initiation quantity (I_{ij}, in m^{-2}),**		**Root mortality quantity (M_{ij}, in m^{-2}),**		**Cumulative net root intersection (C_{ij}, in m^{-2})**		**Mechanical reinforcement (c_r in kPa)**	
	F	Contribution (%)	F	Contribution (%)	F	Contribution (%)	F	Contribution (%)
Altitude	146.08***	3.10	70.98***	1.52	104.05***	2.18	8.47***	0.18
Patch (open gap/closed forest)	426.29***	4.52	231.65***	2.47	236.75***	2.48	159.04***	1.73
Soil depth	247.22***	**10.48**	124.63***	5.32	162.30***	6.80	202.54***	8.81
Root diameter	517.40***	**10.97**	912.81***	**19.50**	892.90***	**18.71**	771.07***	**16.76**
Time (month)	5.35***	0.62	3.02***	0.36	2.87***	0.33	3.51***	0.42
Residuals	NA	70.31	NA	70.84	NA	69.49	NA	72.10

Table 3. Ratio between mechanical reinforcement (c_r) before and after the soil disturbance event. The table was filled with different background colours depending on the ratio: red in the range]0, 0.25], orange in the range]0.25, 0.5], blue in the range]0.5, 1.0], green in the range]>1.0].]0, 12],]12, 24],]24, 36],]36, 48]and]48, 53] represent the five periods of recovery since disturbance.

Altitude	**Depth (cm)**	**Open gap**					**Closed forest**				
		]0, 12]	]12, 24]	]24, 36]	]36, 48]	]48, 53]	]0, 12]	]12, 24]	]24, 36]	]36, 48]	]48, 53]
2000	0-20	0.09	0.28	0.37	0.39$^{\#}$	-	0.09	0.23	0.27	0.29$^{\#}$	-
	20-40	0.21	0.51	0.56	0.58$^{\#}$	-	0.43	0.44	0.47	0.49$^{\#}$	-
	40-50	0	0.01	0.01	0.01$^{\#}$	-	0.00	0	0	0$^{\#}$	-
	Average	**0.07**	**0.20**	**0.22**	**0.23**$^{\#}$	-	**0.06**	**0.16**	**0.17**	**0.19**$^{\#}$	-
1700	0-20	0.03	0.20	0.24	0.27	0.28	0.06	0.07	0.09	0.11	0.12
	20-40	0.15	0.55	0.65	0.73	0.75	0.15	0.29	0.32	0.37	0.40
	40-60	0.20	0.62	0.75	1.03	1.06	0.12	0.39	0.73	1.06	1.19
	60-80	0.15	0.64	0.68	0.79	0.81	0.09	0.40	0.94	1.82	2.12
	80-100##	0.35	1.10	1.48	1.48	1.48	-	-	-	-	
	Average	**0.09**	**0.33**	**0.39**	**0.44**	**0.46**	**0.08**	**0.14**	**0.18**	**0.25**	**0.29**
1400	0-20	0.13	0.14	0.14	0.15	0.16	0.02	0.05	0.07	0.10	0.12
	20-40	0.97	1.09	1.14	1.16	1.18	0.10	0.20	0.26	0.31	0.33
	40-60	1.99	2.32	2.49	2.51	2.51	0.07	0.18	0.24	0.43	0.48
	60-80	1.86	2.75	3.03	3.08	3.08	0.03	0.10	0.16	0.44	0.56
	80-100	4.21	5.40	6.40	6.59	6.65	0.08	0.35	0.47	1.06	1.12
	Average	**0.71**	**0.82**	**0.88**	**0.90**	**0.91**	**0.05**	**0.11**	**0.15**	**0.22**	**0.26**

[#] Rhizotrons at 2000m were installed 12 months later than 1400 and 1700 m, therefore the observation time at 2000 m lasted 41 months, not 48 months.

[##] No roots were observed at 0.8 – 1.0 m in the closed forest at 1700 m, so there were no corresponding data (-).

Table 4 Effects of patch (open gaps and closed forest) at different altitudes (1400, 1700 and 2000 m) on mechanical reinforcement (c_r) before and after the disturbance. R_{1400}, R_{1700} and R_{2000} indicate the ratios of c_r between open gaps and closed forests at 1400, 1700 and 2000 m, respectively (see Eq. (4))

Soil depth (m)	R_{1400}		R_{1700}		R_{2000}	
	Before	After	Before	After	Before	After
0.0 – 0.2	0.58	0.79	0.47	1.11	1.27	1.37
0.2 – 0.4	0.54	1.91	0.60	1.08	1.00	1.16
0.4 – 0.6	0.48	2.42	0.94	0.82	0.92	-
0.6 – 0.8	0.57	3.08	0.82	0.32	-	-
0.8 – 1.0	0.45	2.59	-	1.41	-	-
Total	0.55	1.94	0.54	0.90	1.10	1.16

FIGURE CAPTIONS

Figure 1 Root initiation quantity and mortality quantity in open gaps and closed forests from different root diameter classes at (a,b) 2000 m, (c,d) 1700 m, (e,f) 1400 m. Root diameter classes are indicated in subscript in the legend and represented by: (a,c,e) squares ($R_{0\text{-}1}$ for roots]0,1] mm), (b,d,f) triangles ($R_{1\text{-}2}$ for roots]1,2] mm) and circles ($R_{2\text{-}5}$ for roots of]2,5] mm). When root initiation quantity and mortality quantity were significantly correlated ($p < 0.01$), regression lines were plotted (see Table S1 for equations) for data from open gaps (dashed lines, filled symbols) and closed forests (solid lines, empty symbols).

Figure 2 Mechanical reinforcement (c_r) due to roots of different diameter classes before and after disturbance in (a, c, e) open gaps and (b, d, f) closed forests, at different altitudes (1400, 1700 and 2000 m) from 2009 to 2014. Triangles indicate hydrological reinforcement monitored from July 2012 to November 2013. The horizontal line corresponds to the initial c_r prior to the disturbance; the arrow indicates the time when the disturbance occurred. The grey background indicates the time when the soil surface was covered by snow.

Figure 3 Mechanical reinforcement (c_r) due to roots of different diameter classes before and after the disturbance in: (a, c, e, g, i) open gaps and (b, d, f, h, j) closed forests at different soil depths (every 0.20 m) at an altitude of 1400 m. Triangles indicate hydrological reinforcement monitored from July 2012 to November 2013. The horizontal line corresponds to the reference level; the arrow indicates the time when the disturbance occurred. The grey background indicates the time when the soil surface was covered by snow.

Figure 4 Vertical distribution of mechanical reinforcement (c_r) due to roots before and 4 years after the disturbance at 1400 and 1700 m in open gaps (a and c) and closed forests (b and d). c_{r1} and c_{r2} indicated two scenarios: including branched roots or not, respectively, into the c_r

calculation after the disturbance. There were no significant differences between altitudes and between patch types (open gaps versus closed forests). Data are means ± standard error.

Figure 5 Global factor of safety (FoS) of slopes in open gaps and closed forests at 1400 m during the monitoring period (2009 – 2014). Each component of FoS is shown where soil load, water load and biomass correspond to W_Z in Eq. (9); soil cohesion corresponds to $\frac{c_z'}{W_Z sin\beta}$ in Eq. (9), which was obtained from root free direct soil shear tests and is given as 3.0 kPa; mechanical and hydrological reinforcement correspond to $\frac{c_{r_z}}{W_Z sin\beta}$ and $\frac{c_{h_z}}{W_Z sin\beta}_{h_z}$ in Eq. (9), respectively; hydrostatic-uplifting corresponds to U_Z in Eq. (9), which gives a negative value to FoS when soil is saturated. The arrow indicates the time when the soil moisture was included. FoS > 1.3 indicates that the slope is stable; 1 < FoS < 1.3 the slope is safe but should be monitored and FoS < 1 is an unstable slope. The grey background indicates the time when the soil surface was covered by snow.

Figure 1

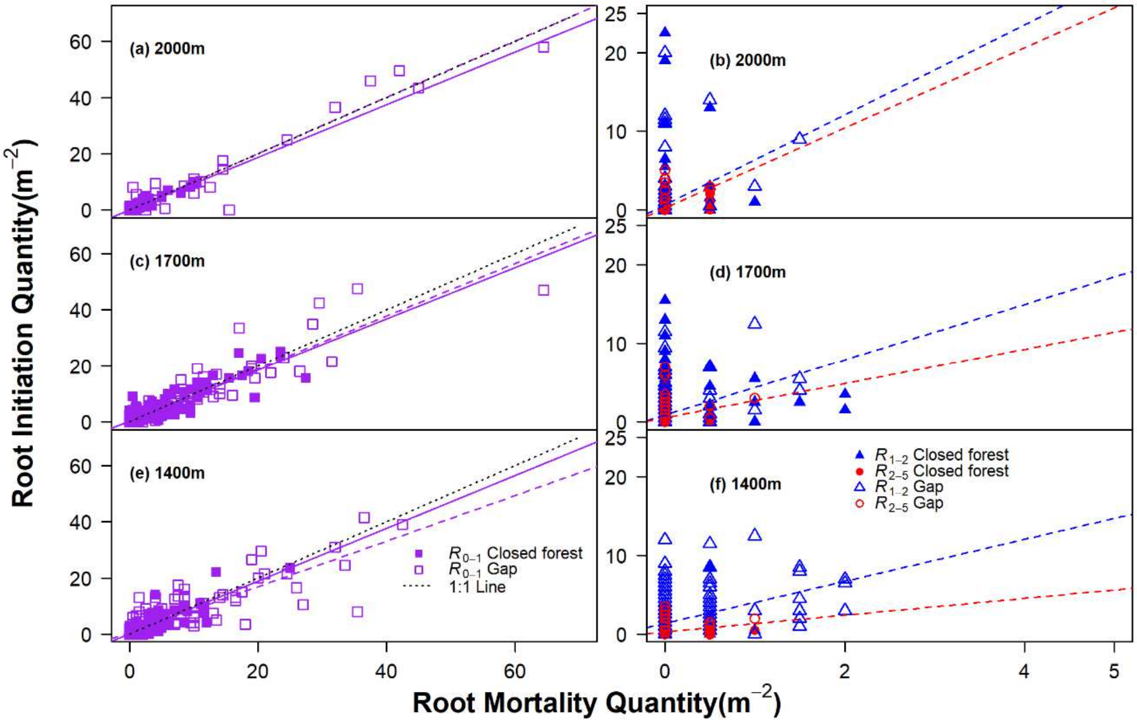

(a) 2000m
(b) 2000m
(c) 1700m
(d) 1700m
(e) 1400m
(f) 1400m
Root Initiation Quantity(m^{-2})
Root Mortality Quantity(m^{-2})
R_{0-1} Closed forest
R_{0-1} Gap
1:1 Line
R_{1-2} Closed forest
R_{2-5} Closed forest
R_{1-2} Gap
R_{2-5} Gap
0
20
40
60
0
10
20
25
0
2
4
5

Figure 2

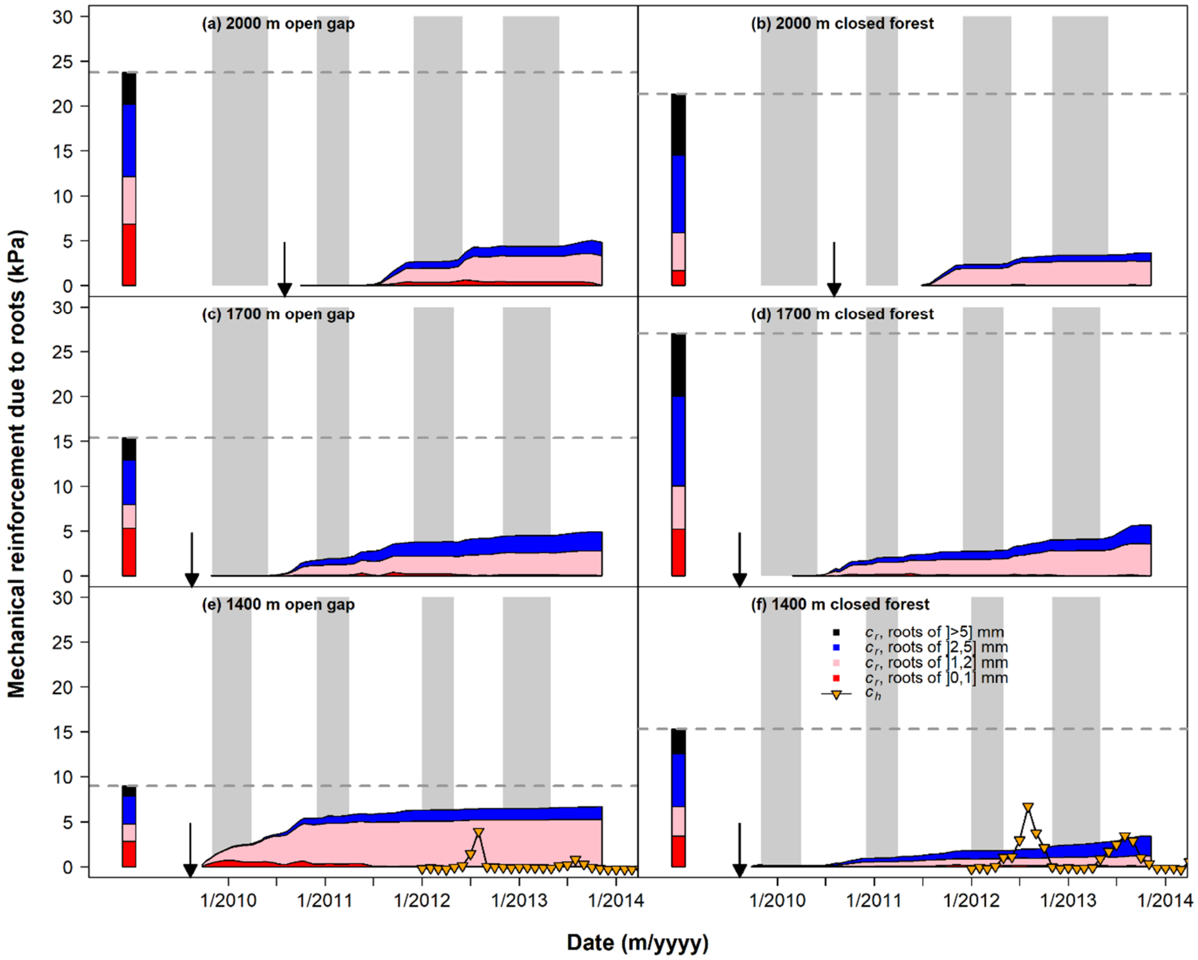
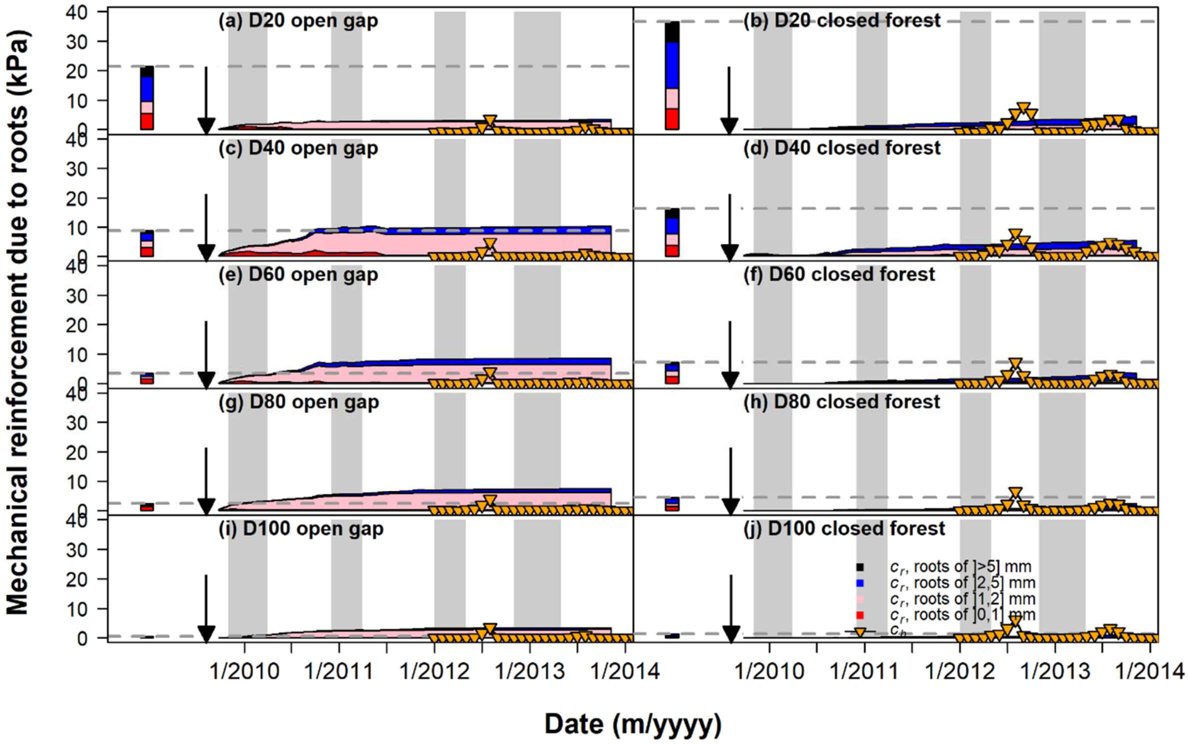
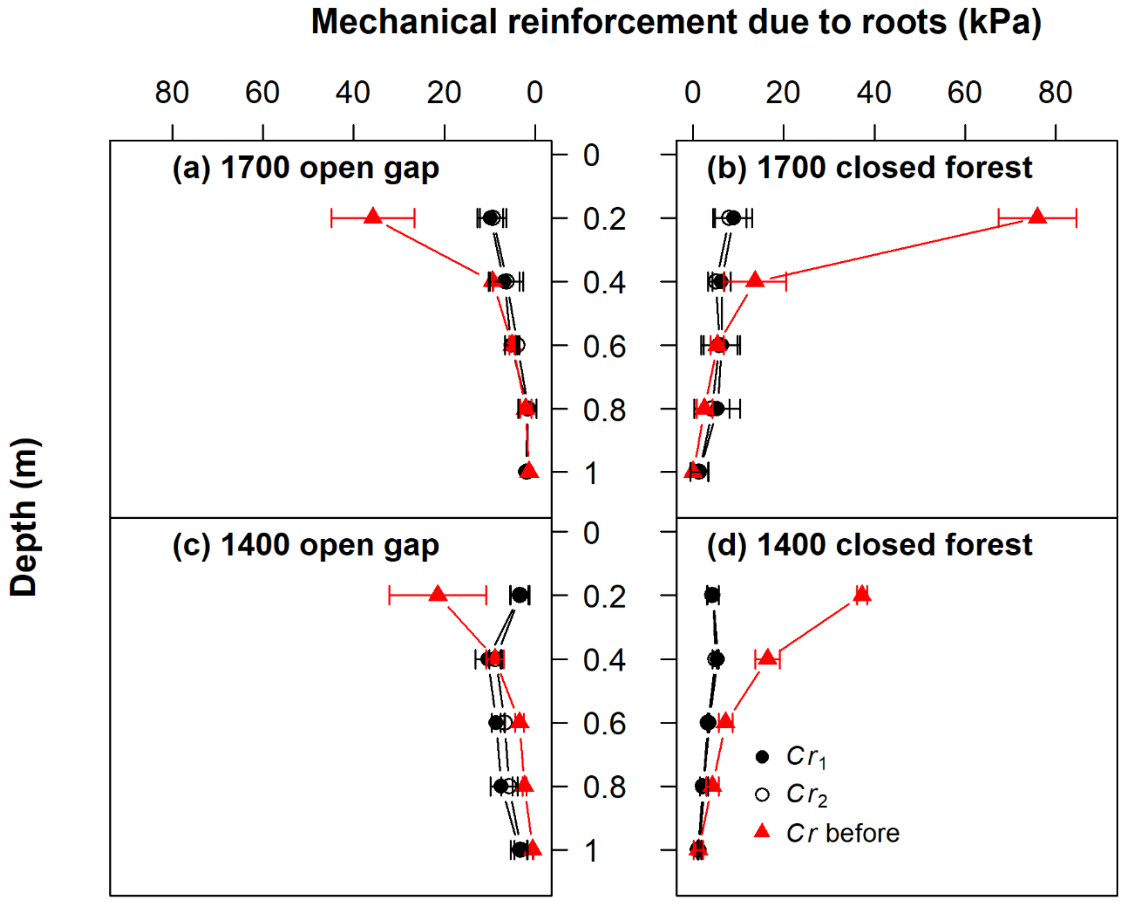

(a) 2000 m open gap
(b) 2000 m closed forest
(c) 1700 m open gap
(d) 1700 m closed forest
(e) 1400 m open gap
(f) 1400 m closed forest
■ c_r, roots of]>5] mm
■ c_r, roots of]2,5] mm
■ c_r, roots of]1,2] mm
■ c_r, roots of]0,1] mm
▽ c_h
Mechanical reinforcement due to roots (kPa)
0
5
10
15
20
25
30
1/2010
1/2011
1/2012
1/2013
1/2014
Date (m/yyyy)

Figure 3

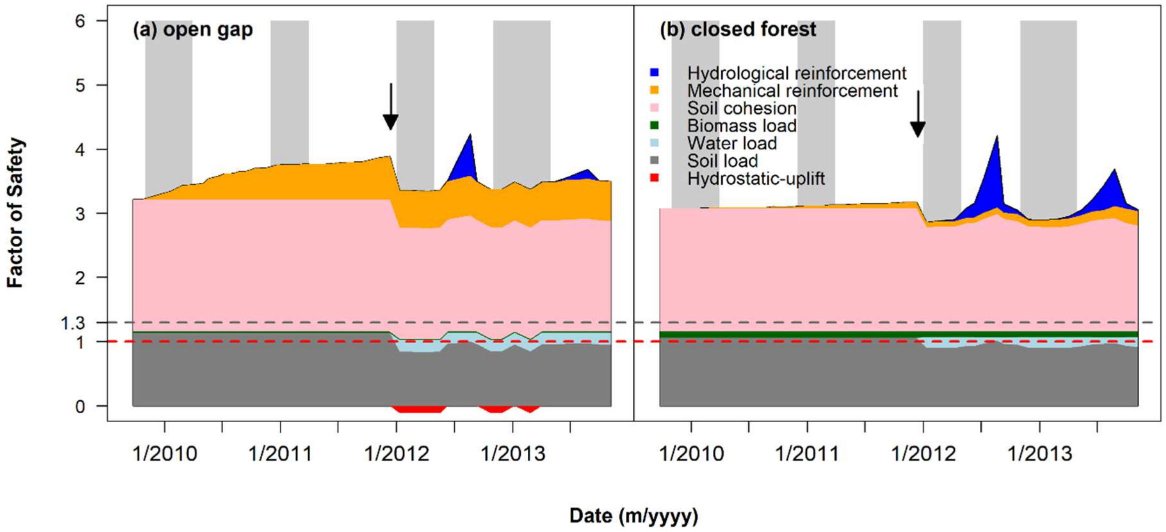

Mechanical reinforcement due to roots (kPa)
Date (m/yyyy)
(a) D20 open gap
(b) D20 closed forest
(c) D40 open gap
(d) D40 closed forest
(e) D60 open gap
(f) D60 closed forest
(g) D80 open gap
(h) D80 closed forest
(i) D100 open gap
(j) D100 closed forest
0
10
20
30
40
1/2010
1/2011
1/2012
1/2013
1/2014
■ c_r, roots of]>5] mm
■ c_r, roots of]2,5] mm
■ c_r, roots of]1,2] mm
■ c_r, roots of]0,1] mm
▼ c_h

910 Figure 4



911

Figure 5


(a) open gap
(b) closed forest
Hydrological reinforcement
Mechanical reinforcement
Soil cohesion
Biomass load
Water load
Soil load
Hydrostatic-uplift
Factor of Safety
6
5
4
3
2
1.3
1
0
1/2010
1/2011
1/2012
1/2013
Date (m/yyyy)