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### ► To cite this version:

Hongxi Liu, Zhun Mao, Yan Wang, John Kim, Franck Bourrier, et al.. Slow recovery from soil disturbance increases susceptibility of high elevation forests to landslides. *Forest Ecology and Management*, 2021, 485, pp.118891. 10.1016/j.foreco.2020.118891 . hal-03146559

**HAL Id: hal-03146559**

**<https://hal.inrae.fr/hal-03146559>**

Submitted on 13 Feb 2023

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1 RESEARCH ARTICLE

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

4

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17

18 **Abstract**

19 Natural hazards such as shallow landslides are common phenomena that disturb soil and  
20 damage forests. Quantifying the recovery of forest vegetation after a hazard is important for  
21 determining the window of susceptibility to new disturbance events, especially at high  
22 elevations, where extreme weather events are frequent and the growing season is short. Plant  
23 roots can reduce the size of this window on unstable hillslopes, by adding mechanical  
24 reinforcement ( $c_r$ ) to soil and changing its hydrological reinforcement ( $c_h$ ); data that are used  
25 in landslide models to calculate the Factor of Safety (FoS) of a hillslope. We calculated  
26 temporal variations in  $c_r$  and  $c_h$  in naturally regenerated mixed, montane forests in the French  
27 Alps. In this closed-canopy forest, open-canopy gaps were present, with understory vegetation  
28 comprising herbs, forbs and shrubs. At three altitudes (1400, 1700 and 2000 m), we dug small  
29 trenches as proxies for shallow landslide events and calculated  $c_r$  before soil disturbance in

30 both open gaps and closed forest. Then, using monthly tree root initiation and mortality data  
31 measured in rhizotrons, we calculated monthly  $c_r$  for four years after the disturbance.  
32 Temporal FoS was then calculated using an infinite slope stability model.

33

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

47

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49

50 **Running title:** Tree root recovery after disturbance

51

52 **ACKNOWLEDGEMENTS**

53 We are grateful to the the National Key Research and Development Program of China  
54 (2019YFC1510600), Mairie de Chamrousse for access to field sites. Funding was provided by  
55 the French and Mexican governments (ECOPICS project, ANR–16-CE03-0009 and  
56 CONACYT–2 73659). Thanks are due to B. Marin-Castro (Autonomous National University  
57 of Mexico) for descriptions of soil profiles.

58

59 **DATABASE LINK**

60 Tree root demography data can be freely accessed at: [doi.org/10.15454/C3QY4B](https://doi.org/10.15454/C3QY4B)

61

62 Initial root density along intact soil profile data can be freely accessed at:

63 <https://doi.org/10.15454/RYMVUS>

64

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

66

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

69

70

71 1 INTRODUCTION

72 Landslides are recognized as one of the most dangerous natural hazards that endanger human  
73 life and infrastructure in mountainous regions (IPCC, 2012, Petley, 2012). In Europe, the  
74 frequency and intensity of shallow landslides triggered by heavy rainfall are predicted to  
75 increase (Tichavský et al., 2019). Eco-engineering methods are considered appropriate for  
76 improving soil reinforcement and slope stability, through the choice and management of  
77 suitable vegetation (Schwarz et al., 2010, Mao et al., 2012, Stokes et al., 2014). Increasing  
78 evidence from landslide inventories, experimental and modelling approaches, has shown that  
79 reduced forest cover, due largely to disturbances such as tree felling, creates zones that are  
80 prone to slope failure (Roering et al., 2003, Mao et al., 2014a, Schwarz et al., 2010, Vergani  
81 et al., 2016). High elevation forests are especially susceptible to disturbance and because of  
82 the short growing season, take longer to recover than forests at lower elevations (Zhao et al.,  
83 2016), but the consequences for soil loss and slope stability are poorly understood. Therefore,  
84 forest managers in mountainous regions need more accurate data about the effects of tree  
85 removal on slope stability in forests growing at different elevations, as well as the time taken  
86 for a slope to recover stability after such disturbance.

87 Vegetation stabilizes soil mechanically through the binding action of thin and fine roots that  
88 cross the multiple potential shear (rupture) surfaces along a slope. These roots anchor plants  
89 to deeper soil layers (beneath the shear surface) and need to be strong when held under  
90 tension. Thicker roots act like soil nails, preventing soil collapse due to their mass, bending  
91 strength and stiffness (Greenway, 1987, Stokes et al., 2009). The majority of studies focusing

92 on the contribution of vegetation to slope stability have estimated the number and cross-  
93 sectional area (CSA) of roots (<10 mm in diameter) in soil, as well as their tensile strength  
94 (see Mao et al., 2012, for a compilation of data). The resulting value is termed the additional  
95 cohesion from roots, also known as mechanical cohesion or mechanical reinforcement, and  
96 can be used in geotechnical models to calculate a slope's Factor of Safety (FoS, Norris et al.,  
97 2008, Greenwood 2006, Thomas and Pollen-Bankhead, 2010, Ji et al., 2012, Mao et al.,  
98 2014a). Mechanical reinforcement varies significantly in forests, depending on tree species  
99 and size, as well as stand density (Roering et al., 2003, Sakals and Sidle, 2004, Genet et al.,  
100 2008, Schwarz et al., 2010, Vergani et al., 2016). Mao et al. (2013) showed that in temperate,  
101 montane forests with a closed canopy, mechanical reinforcement was significantly greater  
102 than in open-canopy gaps that occurred either through individual tree felling or mortality.  
103 This spatial heterogeneity in mechanical reinforcement will therefore impact a slope's overall  
104 FoS. Modelling of FoS for forested slopes allows managers to calculate when a slope's  
105 mechanical integrity is compromised, and whether practical interventions are necessary. As  
106 the FoS is strongly impacted by the number and dimensions of roots crossing the potential  
107 shear surface in soil, it is important to determine how forest structure and patchiness affects  
108 root growth, but such data are scarce (Mao et al., 2014a, Rossi et al., 2017, Wang et al., 2018).

109 Not only does spatial heterogeneity exist in a forest, but also temporal heterogeneity, as fine  
110 roots initiate and then die, usually within several months (Leigh et al., 2002, Wang et al.,  
111 2018). Forest age also induces temporal heterogeneity in mechanical reinforcement, as both  
112 tree age and species composition (due to successional phase), alter the number, dimensions,

113 and strength of roots present throughout the soil profile (Sakals and Sidle 2004, Genet et al.,  
114 2008, 2010, Vergani et al., 2016). However, these studies have used a synchronic approach,  
115 where measurements have been made in stands of different ages, and so do not reflect intra-  
116 annual temporal variability. A long-term (>4 years) study estimating mechanical  
117 reinforcement in forests has never been performed using a continuous or diachronic approach.  
118 The only study examining the short-term (1.5 years) impact of root initiation and growth on  
119 mechanical reinforcement (Mao et al., 2013), showed that in temperate, montane forest, once  
120 roots had been disturbed through soil excavation, root initiation and growth occurred much  
121 faster in open gaps compared to closed forest (Mao et al., 2013). Nevertheless, this study did  
122 not take into account variations in precipitation and the intra-annual dynamics of soil water  
123 content, that strongly influence the triggering of shallow landslides.

124 Shallow landslides usually occur when soil is saturated or near saturation (Sidle and Bogaard,  
125 2016). On forested slopes, soil water is removed through plant transpiration and  
126 evapotranspiration, increasing soil matric suction (or soil water potential), and improving soil  
127 strength (Fredlund and Rahardjo, 1993, Terwilliger, 1990). This increase in soil strength  
128 improves slope stability, and as an analogy to mechanical cohesion or reinforcement, has been  
129 termed 'hydrological' or 'hydraulic' cohesion or reinforcement (Greenway, 1987, Fredlund and  
130 Rahardjo, 1993, Simon and Collison, 2002, Pollen-Bankhead and Simon, 2010, Veylon et al.,  
131 2015, Kim et al., 2017). Hydrological reinforcement has been increasingly investigated under  
132 different vegetation covers, either alone (e.g., Hayati et al., 2018a, b) or with mechanical  
133 reinforcement (e.g., Simon and Collison 2002, Pollen-Bankhead and Simon 2010, Kim et al.,

134 2017), and was highly seasonal and strongly linked to climatic events. For example, during  
135 the growing season, hydrological reinforcement due to plant transpiration is high and is the  
136 main contributor to a slope's FoS (Simon and Collison, 2002, Kim et al., 2017). However,  
137 during the winter months or the rainy season, soil is wet and plant transpiration is minimal.  
138 Therefore, hydrological reinforcement is low, and a slope's FoS can be reduced to dangerous  
139 levels (Kim et al., 2017). Usually, changes in hydrological reinforcement with soil depth are  
140 considered using estimated values (Pollen-Bankhead and Simon, 2010), and rarely do studies  
141 combine temporal estimations of hydrological reinforcement with seasonal root growth data  
142 and their interaction throughout the soil profile (but see Kim et al. 2017). Not only are tree  
143 roots initiated throughout the year (with one or two main flushes of growth), but most fine  
144 roots die after only a few days, weeks or months (Mao et al., 2013, Wang et al., 2018). To our  
145 knowledge, the effect of this root mortality on slope stability throughout the year has never  
146 been quantified, but could contribute to seasonal hotspots of vulnerability.

147 Here, we aim at investigating the intra- and inter-annual variability in reinforcement of slopes  
148 recovering from disturbances in open gaps and closed forest at different elevations. Using  
149 field data, hydrological reinforcement was estimated and compared with mechanical  
150 reinforcement over time. To do this, we integrated existing data from several studies into one  
151 geotechnical model that calculated the FoS. These data comprised: (i) root intersection  
152 quantity before disturbance (Mao et al., 2012, 2015b) and monthly root initiation and  
153 mortality over 4 years (Wang et al., 2018), from which we calculated temporal mechanical  
154 reinforcement, (ii) soil mechanical properties and soil water potential (Kim et al., 2017), from



155 which we estimated hydrological reinforcement and (iii) forest inventory data, from which we  
156 determined forest structure (Mao et al., 2012, 2015a, 2015b). We hypothesize that the  
157 recovery of mechanical reinforcement is affected by forest structure (open-canopy gaps versus  
158 closed-canopy forest), altitudes and soil depths and ask: do mechanical and hydrological  
159 reinforcement co-vary depending on forest structure and how much does each type of  
160 cohesion contribute to the recovery of the slope's FoS?

161

## 162 2 MATERIALS AND METHODS

### 163 *2.1 Study sites*

164 We used data from study sites located near Chamrousse, Isère, in the French Alps (45° 07'N,  
165 5° 52'E). All sites have been studied characterized previously and detailed information can  
166 be found in Mao et al., (2015b) and Wang et al., (2018). Sites comprised mixed, mature,  
167 naturally regenerated forests growing at altitudes of 1400 m (Prémol forest), 1700 m (Bachat-  
168 Bouloud forest) and 2000 m (near Achard Lake, at the treeline). *Abies alba* Mill., *Picea abies*  
169 (L.) Karst and *Fagus sylvatica* L. were dominant at 1400 m; *P. abies* and *A. alba* were  
170 dominant at 1700 m and *Pinus uncinata* L. was dominant at 2000 m (Mao et al., 2015b). The  
171 stand basal area (cross-sectional area of trees at 1.3 m) at 1400 m was in the range of 41-56  
172 m<sup>2</sup> ha<sup>-1</sup>; 27-33 m<sup>2</sup> ha<sup>-1</sup> at 1700 m; and 9-19 m<sup>2</sup> ha<sup>-1</sup> at 2000 m. Mean tree diameter at breast  
173 height was 19 cm at 1400 m, 18 cm at 1700 m and 14 cm at 2000 m. With different tree  
174 densities, biomass ranges from 29 – 146 t ha<sup>-1</sup> at different altitudes (Figure S1). Slope angles  
175 at the three sites were generally between 10° and 25°, but sometimes could reach 35°.

176 Climatic data for the three sites were estimated over 2004-2014 using the AURELHY model  
177 of Météo-France (Benichou and Le Breton, 1987; Piedallu and Gegout, 2007, 2008, Stokes et  
178 al., 2020). The mean monthly air temperature is the lowest in January or February (-2.3 °C at  
179 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  
180 at 1700 m; 10.2 °C at 2000 m). Mean annual precipitation is approximately 1500 mm at 1400

181 m, 1700 mm at 1700 m and 1900 mm at 2000 m. Precipitation amount is highly seasonal,  
182 with the lowest amount in summer and highest amount in winter (in the form of snow).

### 183 *2.2 Soil physical and chemical features*

184 In a separate study, soil features were characterised using profiles and monoliths (0.25 m ×  
185 0.25 m) in a nearby transect spanning the same elevational gradient (Table 1, Stokes et al.,  
186 2020). Infiltration tests were carried out next to each sampling plot using a constant head  
187 single ring infiltrometer and saturated hydraulic conductivity was calculated. Bulk density  
188 was determined by taking undisturbed soil cores at different depths within the soil profile.  
189 Soil was sieved at 2 mm after air drying and the soil fraction <2 mm was used to assess  
190 properties. Soil pH was measured in water as 1:2.5 extract. Soil organic matter (SOM) content  
191 was determined via loss-on-ignition at 500 °C (Dean, 1974). Soil texture was determined by  
192 laser-diffraction analysis (McCave et al., 1986). The soil sample was previously digested in  
193 hydrogen peroxide solution to destroy the organic matter and sodium hexametaphosphate to  
194 release the bound clay particles.

195 Soils were acidic at all sites, ranging from (a) “Cambisols (Hyperdystric)” overlying green  
196 schist and with an abundant water supply at 1400 m (Joud, 2006), to (b) “Cambisols (Humic,  
197 Hyperdystric)” overlying the crystalline formation at 1700 m (Joud, 2006), and to (c)  
198 “Epileptic Umbrisols (Hyperdystric)” overlying the crystalline formation at 2000 m (IUSS  
199 Working Group WRB, 2007). Soil analyses showed that total carbon content was significantly  
200 greater in closed forests than in gaps at both 1700 m and 2000 m, and that SOM was

201 significantly greater in closed forest compared to gaps at 1700 m. Apart from some slight  
202 differences in soil texture at 1700 m and 2000 m, no other differences in soil physicochemical  
203 properties were found (Merino-Martín et al., 2020). A seasonal water table existed in open  
204 gaps at 1400 m and 1700 m during the winter months. The average maximum rooting depth of  
205 soil was approximately 1.0 m at 1400 and 1700 m, but only 0.5 m at 2000 m (Mao et al.,  
206 2015b).

### 207 ***2.3 Root demography***

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

215 To measure root demography, four trenches were dug at each altitude, two in open gaps and  
216 two in closed forest. Rhizotrons were installed by inserting plexiglass sheets against one wall  
217 of the trench. Roots were cut during the process, to leave a smooth wall against which to  
218 position the plexiglass (Figure S2). Trenches were then covered with wooden boards and  
219 corrugated iron. More details on rhizotron installation can be found in Mao et al. (2013). As  
220 the installation of rhizotrons disturbed roots and soil in a way similar to that caused during a

221 shallow landslide (e.g., soil crack and detachment and root damage during scarp formation  
222 and mass movement), it was considered as a proxy for a landslide event that damages roots  
223 around the scarp (Roering et al., 2003), with root growth considered as a recovery process  
224 after the disturbance. Initiation and mortality of each root (< 5 mm in diameter) in the  
225 rhizotrons was measured monthly, even during the winter months, for a period of 4 years.

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

$$234 \quad C_{i,j} = \sum_{j=1}^J R_{i,j} = \sum_{j=1}^J (I_{i,j} - M_{i,j}) \quad (\text{Eq. 1})$$

235  $C_{i,j}$  was used to calculate additional cohesion (or mechanical reinforcement) due to roots after  
236 the disturbance event.

237 We used root distribution data from 2009 (Mao et al., 2012, 2015b), that were collected prior  
238 to the installation of rhizotrons (the proxy for a soil disturbance event), to estimate the number  
239 and diameter of roots in the soil above the bedrock (1.0 m deep at 1400 and 1700 m and 0.5 m  
240 deep at 2000 m). Roots were classed into four diameter classes ([0, 1] mm, ]1, 2]mm, ]2,  
241 5]mm, ]5, 10]mm). These data enabled us to calculate reference root intersection density,

242 defined as number of roots of diameter class  $i$  per unit soil surface at intact soil condition ( $R_i$ ,  
243 in roots  $m^{-2}$ ). These data were then used as the initial value before disturbance, against which  
244 we measured root recovery.

#### 245 ***2.4 Hydrological data***

246 Soil hydrological data are from Kim et al. (2017), who performed measurements in our plots.  
247 In 2012, four extra trenches were dug (one trench in one open gap, and one in closed forest at  
248 each altitude), to measure soil water potential ( $\psi$ , kPa) using WaterMark© Granular Matrix  
249 sensors, (Irrometer Co., USA). These electrical-resistance type sensors are robust and easy to  
250 use. Devices at 2000 m were frequently stolen or damaged, therefore monitoring could not be  
251 performed, and due to flooding, periods of data were missing at 1700 m from August 2012 to  
252 November 2013, therefore, we only calculated  $c_h$  at 1400 m. Each trench was close ( $< 2.0$  m)  
253 to a rhizotron to ensure that  $\psi$  data could be matched with root demography data. Sensors  
254 were installed at different depths (at 0.05, 0.1, 0.2, 0.4, 0.7 m), along a vertical soil profile and  
255 data were logged every 30 min from July 2012 to November 2013 (data are from Kim et al.,  
256 2017, Fig. S3). Despite some high values of  $\psi$  (i.e.,  $>200$  kPa, but still within the maximum  
257 range of WaterMark sensors), most of the measured values at either of the vegetation types  
258 was  $<150$  kPa during our monitoring period (Fig. S3). Merino-Martín et al. (2020) manually  
259 measured mean monthly air (0.1 m above soil surface) and soil temperatures (at depths of 0.1  
260 m and 0.4 m) in soil trenches where the rhizotrons were installed, from September 28<sup>th</sup>, 2010  
261 to March 3<sup>rd</sup>, 2014 (Figure S4), using a portable thermistor thermometer (HI-93510N Hanna  
262 Instruments, USA). Results showed that gaps were slightly warmer than closed forest at all

263 elevations, but significant differences between the two were found only at 1700 m.  
264 Temperature at topsoil was more fluctuant than at deep layers, especially at high altitudes of  
265 1700 and 2000 m.

## 266 **2.5 Cohesion and slope stability**

### 267 2.5.1 Mechanical reinforcement from roots ( $c_r$ )

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

$$273 \quad c_{r,i,j} = 1000R_f \frac{\bar{T}_{ri}\pi\bar{d}_{ri}^2 C_{i,j}}{4A_S} \quad \text{Eq. (2)}$$

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

281 The choice of WWM was made because it is simple and uses a limited number of parameters.  
282 WWM has been widely applied over the last 40 years, so our results can be compared easily  
283 with previous studies. It has been shown that WWM overestimates the additional cohesion  
284 from roots (Abernethy and Rutherford, 2001, Pollen and Simon, 2010). Therefore, we took a  
285 corrected coefficient  $R_f$  of 0.48 (Preti, 2006), instead of the 1.2 proposed by Wu et al., (1979).  
286 Ji et al. (2012) and Mao et al. (2014b) also found that this corrected WWM (Preti, 2006) gave  
287 the most conservative  $c_r$ , that is comparable to that calculated using Fibre Bundle Models  
288 (FBMs), based on force-induced root breakage (Thomas and Pollen-Bankhead, 2010), or  
289 displacement-triggered root breakage (Schwarz et al., 2010). Models such as the Root Bundle  
290 Model (RBM) (Schwarz et al., 2010) or energy based Fibre Bundle Model (FBM) (Ji et al.,  
291 2020) might yield more accurate and realistic  $c_r$ , but they require extra data, such as the  
292 modulus of elasticity of roots or root rupture energy, that we did not measure in our study.

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

$$297 \quad T_{ri} = 28.97 \cdot d_i^{-0.52}. \quad \text{Eq. (3)}$$

298 In order to identify forest patch type (open gaps versus closed forest) and site effects on  $c_r$ ,  
299 and how the recovery process possibly changes these effects, we introduced three ratios ( $R_{1400}$ ,  
300  $R_{1700}$ ,  $R_{2000}$ ), which indicated  $c_r$  in open gaps divided by  $c_r$  in closed forest at altitudes of 1400,  
301 1700 and 2000 m, respectively:



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

$$R_{1700} = \frac{c_{r,open\ gap,1700m}}{c_{r,closed\ forest,1700m}}$$

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  $z^{\text{th}}$  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  $z^{\text{th}}$  layer ( $\theta_{g_z}$ ) and  $c_{h_z}$ , fitted by Kim et al. (2017). Soil samples were collected from the same study site and were then subject to shear strength test under

321 different moisture levels to derive soil moisture-shear strength relationships under unsaturated  
 322 soil condition ( $\psi \neq 0$ ):

$$323 \quad c_{h_z} = \begin{cases} c_m \theta_{g_z}^{-B} - c' & \psi \neq 0 \\ 0 & \psi = 0 \end{cases} \quad \text{Eq. (5)}$$

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

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

$$329 \quad c_{h_z} = \begin{cases} \psi_z \tan \phi_b & \psi \neq 0 \\ 0 & \psi = 0 \end{cases} \quad \text{Eq. (6)}$$

330 where, the angle  $\phi_b$  (in  $^\circ$ ) represents the conversion rate between tensiometer measured water  
 331 potential and the hydrological reinforcement.  $\phi_b$  reportedly varied within a narrow range  
 332 from  $10^\circ$  to  $20^\circ$  (Simon and Collison, 2002). In this study, we took different  $\phi_b$  ( $5^\circ$ ,  $10^\circ$ ,  $15^\circ$ ,  
 333  $20^\circ$ ) to compare  $c_{h_z}$  calculated by two methods.

334 The total  $c_h$  of the soil profile was calculated as:

$$335 \quad c_h = \sum_{k=1}^K \frac{c_{h_z} \cdot A_z}{A_s} \quad \text{Eq. (7)}$$

336 where  $A_z$  is the cross-section area of each layer ( $\text{m}^2$ ),  $A_s$  is the cross-section area of the profile  
 337 ( $\text{m}^2$ ).

338  $U_z$  is calculated as:

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

where  $\rho_w$  is the water density ( $\text{kg m}^{-3}$ ),  $g$  is the gravitational acceleration ( $\text{N kg}^{-1}$ ),  $z_s$  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  $\beta$  (in degree ( $^\circ$ )). 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:

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

where  $FoS_z$  determines if the slope at the  $z^{th}$  soil layer is safe ( $FoS \geq 1.3$ ), stable but needing monitoring ( $1.3 > Fos \geq 1.0$ ) 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  $\psi = 0$ ).  $\phi_z$  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  $\psi \neq 0$ ).

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

$$362 \quad W_z = z\gamma_z(1 + \theta_g) + B_z = z\gamma_z \left(1 + \frac{\theta_v}{\gamma_z}\right) + B_z \quad \text{Eq. (10)}$$

363 Where,  $z$  = soil layer thickness;  $\gamma_z$  = dry bulk soil density (in kN m<sup>3</sup>);  $\theta_g$  and  $\theta_v$  = gravimetric  
364 and volumetric soil water content (dimensionless);  $B_z$  = fresh biomass in unit slope area (i.e.,  
365 tree surcharge, in kPa).

366 We defined a global  $FoS$  of the whole slope land as the minimum of  $FoS_z$  among all the soil  
367 layers

$$368 \quad FoS = \min(FoS_z) \quad \text{Eq. (11)}$$

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

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

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

374 (2)  $c'_z$  and  $\phi_z$  of soil at 1400 m was estimated with a shear testing device by Kim et al.

375 (2017). They were fixed as 10 kPa and  $40^\circ$  to soils of different depths and altitudes,

376 respectively.

377 (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  
378 (1400, 1700, 2000 m);  $c_{h_z}$  was calculated for 1400 m based on the available data.

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

## 382 ***2.6 Statistical analyses***

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

392

## 393 **3 RESULTS**

### 394 ***3.1 Root initiation and mortality***

395 Initiation and mortality of roots were highly seasonal (Figure S6-S8) and were significantly  
396 and positively correlated in all plots (Figure 1, Table S1), especially in the ]0, 1] mm diameter  
397 class. Roots in the ]1, 2] mm and ]2, 5] mm diameter classes had very high rates of initiation  
398 compared to rates of mortality. Root diameter and soil depth best explained the variation in  
399 root initiation quantity,  $I_{ij}$ , with contributions of 11% and 10%, respectively (Table 2). Root  
400 diameter also explained 20 % and 19% of the variability in root mortality quantity,  $M_{ij}$ , and  
401 cumulative net root intersection  $C_{ij}$ , respectively, whereas soil depth only explained 5% and  
402 7%, respectively (Table 2). Altitude and patch type (open gaps versus closed forest) were both  
403 significant and explained more variation in  $I_{ij}$  (3.1% and 4.5%, respectively) than  $M_{ij}$  (1.5%  
404 and 2.5%, respectively) and  $C_{ij}$  (2.2% and 2.5%, respectively). Although temporal effects  
405 were significant, time since disturbance explained poorly the variation in  $I_{ij}$ ,  $M_{ij}$  and  $C_{ij}$  (Table  
406 2), suggesting that much of the variation may be seasonally driven.

### 407 ***3.2 Recovery of mechanical reinforcement ( $c_r$ ) after the disturbance event***

408 Before the disturbance, mean  $c_r$  (over the whole soil profile) in open gaps was lower than that  
409 under closed forest at 1400 m ( $R_{1400\_before} = 0.55$ ) and 1700 m ( $R_{1700\_before} = 0.54$ ), but at  
410 2000 m, mean  $c_r$  in open gaps was similar to that in closed forest ( $R_{2000\_before} = 1.10$ ; Table  
411 4). After the disturbance, mean  $c_r$  in open gaps was almost twice that in closed forest at 1400  
412 m ( $R_{1400\_after} = 1.94$ ), whereas differences between open gaps and closed forest decreased  
413 after the disturbance event at 1700 m (ratio increased from 0.54 to 0.90, Table 4).

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

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

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

### 429 *3.3 Vertical distribution of mechanical reinforcement ( $c_r$ ) before and after the* 430 *disturbance event*

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

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

### 439 **3.4 Seasonal variability in mechanical reinforcement ( $c_r$ ) and hydrological reinforcement** 440 **( $c_h$ )**

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

445 Mean hydrological reinforcement ( $c_h$ ) calculated using the method in Fredlund et al. (1978),  
446 was much higher than that calculated using the method from Kim et al. (2017), where  $\phi_b$  fell  
447 in the range  $10^\circ - 20^\circ$  (Simon and Collison, 2002). However, when  $\phi_b = 5^\circ$ ,  $c_h$  calculated  
448 using Fredlund et al. (1978) was close to that calculated using Kim et al. (2017) (Figure S11).

449 Because Kim et al. (2017) derived soil moisture-shear strength relationships based on soil  
450 samples from our study sites, we used  $c_h$  from Kim et al. (2017) for analyses and FoS  
451 calculation.  $c_h$  varied significantly through the year (Figure 2), regardless of site or depth in  
452 the soil (Figure 3). Hydrological reinforcement was lowest in winter and spring (i.e., from  
453 December to April), but was close to, or was higher, than mean  $c_r$  in summer (i.e., from May  
454 to November, Figures 2, 3).



### 455 **3.5 Slope stability**

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

## 468 **4 DISCUSSION**

### 469 **4.1 Recovery of mechanical reinforcement ( $c_r$ ): effects of elevation, patch and depth** 470 ***in soil***

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

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

481 Several reasons exist to explain the faster recovery of root production in open gaps at lower  
482 elevations. Closed forests at 1400 m were significantly denser with larger trees than at the  
483 higher altitudes (Figure S1). Therefore, root systems are probably extensive and extend  
484 further into open gaps than at higher elevations. Morphological differences exist between  
485 open gaps and closed forests, resulting in a greater quantity of solar irradiance and water that  
486 reach the understory and soil in open gaps, positively impacting root growth (Coates and  
487 Burton 1997, Brett and Klinka 1998). At the same field sites as in our study, Merino-Martín et  
488 al. (2020) showed that at elevations of 1400 m and 1700 m, mean negative soil water potential  
489 was greater (soil was drier) under closed forest compared to open gaps, but that soil physical  
490 and chemical properties were similar (apart from soil carbon that was greater under closed  
491 forest at higher elevations). Therefore, microclimate may be influencing root elongation but  
492 not soil properties. It is now well documented that soil temperature is a major driver of root  
493 growth in temperate forests (Mao et al., 2013, Germon et al., 2016, Mohamed et al., 2017,  
494 Wang et al., 2018). The slightly warmer soil in open gaps compared to closed forests may  
495 have accelerated  $c_r$  recovery in open gaps compared to closed forests. But if this was the case,

496 this phenomenon should be more obvious at 1700 m, where open gaps were significantly  
497 warmer than closed forest. It seems more likely that as coarse roots present in open gaps are  
498 distal to the tree, they will be thinner and have a greater potential for recovery after wounding  
499 (Stokes et al., 2009). Compared to proximal roots, distal roots also have greater quantities of  
500 non-structural carbohydrate (NSC, Wang et al., 2018). NSC is produced during  
501 photosynthesis and typically comprises mobile soluble sugars and large, non-mobile, granular  
502 starch, that can be mobilized for fast growth after wounding (Hoch et al., 2003). Therefore,  
503 distal roots have a better recovery rate than proximal roots.

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

517 required deeper in the soil, there will be little effect of surface roots on a slope's factor of  
518 safety.

#### 519 ***4.2 Recovery of mechanical reinforcement ( $c_r$ ): effect of root diameter***

520 Mean  $c_r$  recovery (over the whole soil profile), was dependent on root diameter, and roots in  
521 the 1 – 2 mm and 2 – 5 mm diameter classes were the main contributors to  $c_r$  after disturbance.  
522 We suggest that  $c_r$  recovery follows the “maximum efficiency” rule of root production, i.e.,  
523 more resources are required to construct thicker roots than fine roots (Kitajima et al., 2010;  
524 Valenzuela-Estrada et al., 2008). This rule also states that under suboptimal growth conditions,  
525 plants initially build ‘low-cost’ fine roots (0 – 2 mm) to create a transport pathway for  
526 resource provision, in order to then reach “maximum efficiency,” in terms of growth and  
527 functioning. We observed that the finest roots (0 – 1 mm diameter) were the first to be  
528 initiated after the disturbance, followed by those in the 1 – 2 m diameter class, and finally by  
529 those in the 2 – 5 mm diameter class (Figure 1). Similar results were also found in the grass  
530 species, *Zea mays*, during the winter (Barlow and Rathfelder, 1985), but data for woody  
531 species are rare. However, these very fine ‘low-cost’ roots also had a high turnover, and  
532 therefore were of an ephemeral nature. The function of these very fine roots would be to  
533 quickly explore soil and forage for resources in the short growing season, before being ‘shed’  
534 by the tree (Wang et al., 2018). Due to this high turnover, very fine roots therefore contribute  
535 little to  $c_r$  after disturbance. As these very fine ephemeral roots were rapidly initiated after  
536 disturbance, but contributed little to  $c_r$ , we estimated that at 1400 m and 1700 m, it took 1.3 –  
537 1.6 years before longer-lived and thicker roots were produced. However, at 2000 m,  $c_r$  never

538 returned to the original value during the 3.5 years of monitoring, underlining the fragility of  
539 these subalpine forests when exposed to disturbance.

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

#### 544 ***4.3 Which type of reinforcement contributes more to slope stability?***

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

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

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

#### 576 ***4.4 How does disturbance and recovery of roots affect slope stability?***

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

584

585 The rapid recovery of root production and growth is important for reducing the window of  
586 landslide susceptibility after a disturbance. We showed that this recovery was fastest in open  
587 gaps growing at the lowest elevation (1400 m). In closed forests, there were more roots  
588 initially, as well as the presence of coarse root systems, binding and nailing soil in place.  
589 However,  $c_r$  recovery was poor, particularly deeper in the soil. To reinforce a slope, it is  
590 important that the contribution from  $c_r$  is high deeper in the soil where the potential shear  
591 zone is likely to be located (Stokes et al., 2009). As a result, after soil disturbance, slopes  
592 under closed forests at 1400 m and 1700 m had a lower FoS than in open gaps, except during  
593 the summer, when  $c_h$  was high, but this is the time of year when precipitation-induced  
594 landslides are minimal in this region. Our results show therefore that very dense closed forests  
595 have higher resistance, but lower resilience than open gaps, when subjected to disturbances  
596 that can cause root mortality. The presence of very dense, closed forest around small gaps  
597 (<625 m<sup>2</sup>), also hastens root recovery in gaps, especially at lower elevations where  
598 temperatures are warmer. Therefore, high elevation forests, with small, sparsely distributed

599 trees, have a lower resilience to soil disturbance, increasing the window of susceptibility to  
600 landslides and natural hazards.

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



## 620 **5 Conclusions**

621 We show that after a soil disturbance event, distinct differences occurred in the recovery of  
622 root initiation and growth in open gaps and closed forests at different elevations. Mean  
623 mechanical reinforcement (over the whole soil profile) never fully recovered to the value  
624 before the disturbance. However, in open gaps, mechanical reinforcement at depths of 0.8 –  
625 1.0 m recovered after 12 months at elevations of 1400 m and 24 months at 1700 m. In closed  
626 forests, recovery took 48 months at the same depth. In forests at 2000 m, root initiation and  
627 growth were minimal after the disturbance and only recovered by 25% of the initial value,  
628 even after 41 months. Therefore, these high elevation forests are particularly vulnerable to  
629 disturbance. Although mechanical reinforcement under closed forests was higher than that in  
630 gaps before disturbance, the recovery after disturbance was slow, compromising slope  
631 stability for at least 4 years. Such distinct effects of elevation and forest patchiness should be  
632 considered by managers working in landslide prone areas. Regarding the type of cohesion, we  
633 demonstrate that hydrological reinforcement due to transpiration and drying of soils was high  
634 during the summer, particularly in the closed forests. However, during the winter months,  
635 when soil was saturated and transpiration was minimal, hydrological reinforcement was  
636 negligible. The mechanical effects of roots on soil cohesion was much more stable throughout  
637 the year, and increased over the years following disturbance. Therefore, hydrological  
638 reinforcement contributed little to long-term slope stability, and mechanical reinforcement  
639 from roots was a much more reliable contributor to slope stability.

640

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839 **TABLES**

840 Table 1 Physical and chemical soil properties at different altitudes at the study site (from Stokes et al.,  
841 2020).

Altitude (m)	Soil depth (cm)	Clay- silt-sand (%)	Organic carbon content (%)	Bulk density (g cm <sup>-3</sup> )	Mean saturated hydraulic conductivity (cm h <sup>-1</sup> )	FAO soil type
2000	0-30	29-44-27	5.1	1.5	12.73	Histic Hyperskeletal Cambisol (Turbic)
	30-50	13-40-47	1.9	1.3		
1700	0-20	36-41-23	15.1	1.4	19.04	Histic Orthoskeletal 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		

842 In the dataset from Stokes et al., (2020), soil samples were taken from a nearby transect along  
843 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;  
844 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-  
845 54 cm at 2000 m. We used the soil properties measured at 1600 m to represent those at 1700  
846 m in this study.

847

848 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  
 849 recovery process of root initiation quantity ( $I_{ij}$ , m<sup>-2</sup>), root mortality quantity ( $M_{ij}$ , m<sup>-2</sup>), cumulative net root intersection production ( $C_{ij}$ , m<sup>-2</sup>) and mechanical  
 850 reinforcement ( $c_r$ , kPa). Asterisks indicate significant correlations (where, \*\*\*,  $p < 0.001$ ). Numbers in bold indicate the highest contributions (%).  
 851

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

852

853

854

855 Table 3. Ratio between mechanical reinforcement ( $c_r$ ) before and after the soil disturbance event. The table was filled with different background  
856 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,  
857 12], ]12, 24], ]24, 36], ]36, 48]and ]48, 53] represent the five periods of recovery since disturbance.

858

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 <sup>#</sup>	-	0.09	0.23	0.27	0.29 <sup>#</sup>	-
	20-40	0.21	0.51	0.56	0.58 <sup>#</sup>	-	0.43	0.44	0.47	0.49 <sup>#</sup>	-
	40-50	0	0.01	0.01	0.01 <sup>#</sup>	-	0.00	0	0	0 <sup>#</sup>	-
	<b>Average</b>	<b>0.07</b>	<b>0.20</b>	<b>0.22</b>	<b>0.23<sup>#</sup></b>	-	<b>0.06</b>	<b>0.16</b>	<b>0.17</b>	<b>0.19<sup>#</sup></b>	-
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 <sup>##</sup>	0.35	1.10	1.48	1.48	1.48	-	-	-	-	-
	<b>Average</b>	<b>0.09</b>	<b>0.33</b>	<b>0.39</b>	<b>0.44</b>	<b>0.46</b>	<b>0.08</b>	<b>0.14</b>	<b>0.18</b>	<b>0.25</b>	<b>0.29</b>
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
	<b>Average</b>	<b>0.71</b>	<b>0.82</b>	<b>0.88</b>	<b>0.90</b>	<b>0.91</b>	<b>0.05</b>	<b>0.11</b>	<b>0.15</b>	<b>0.22</b>	<b>0.26</b>

859

860 <sup>#</sup> 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  
861 months.

862 <sup>##</sup> No roots were observed at 0.8 – 1.0 m in the closed forest at 1700 m, so there were no corresponding data (-).

863

864 Table 4 Effects of patch (open gaps and closed forest) at different altitudes (1400, 1700 and 2000 m)  
 865 on mechanical reinforcement ( $c_r$ ) before and after the disturbance.  $R_{1400}$ ,  $R_{1700}$  and  $R_{2000}$  indicate the  
 866 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

867

868

869 **FIGURE CAPTIONS**

870 Figure 1 Root initiation quantity and mortality quantity in open gaps and closed forests from  
871 different root diameter classes at (a,b) 2000 m, (c,d) 1700 m, (e,f) 1400 m. Root diameter  
872 classes are indicated in subscript in the legend and represented by: (a,c,e) squares ( $R_{0-1}$  for  
873 roots ]0,1] mm), (b,d,f) triangles ( $R_{1-2}$  for roots ]1,2] mm) and circles ( $R_{2-5}$  for roots of ]2,5]  
874 mm). When root initiation quantity and mortality quantity were significantly correlated ( $p <$   
875 0.01), regression lines were plotted (see Table S1 for equations) for data from open gaps  
876 (dashed lines, filled symbols) and closed forests (solid lines, empty symbols).

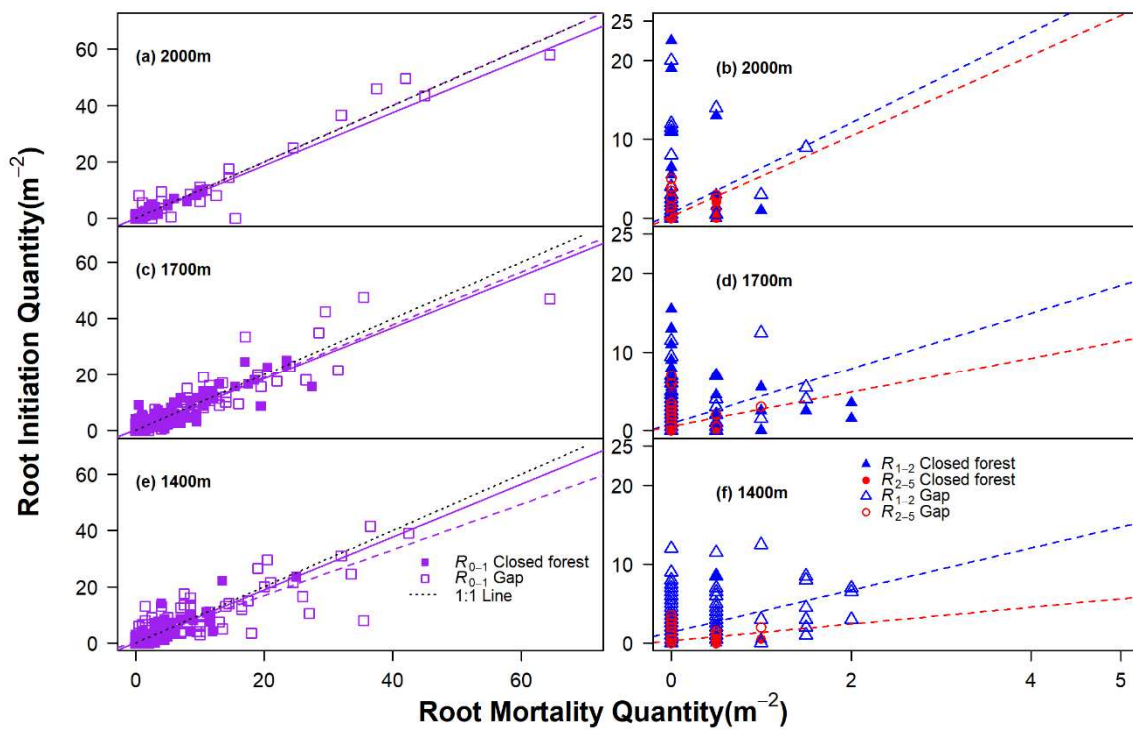
877 Figure 2 Mechanical reinforcement ( $c_r$ ) due to roots of different diameter classes before and  
878 after disturbance in (a, c, e) open gaps and (b, d, f) closed forests, at different altitudes (1400,  
879 1700 and 2000 m) from 2009 to 2014. Triangles indicate hydrological reinforcement  
880 monitored from July 2012 to November 2013. The horizontal line corresponds to the initial  $c_r$   
881 prior to the disturbance; the arrow indicates the time when the disturbance occurred. The grey  
882 background indicates the time when the soil surface was covered by snow.

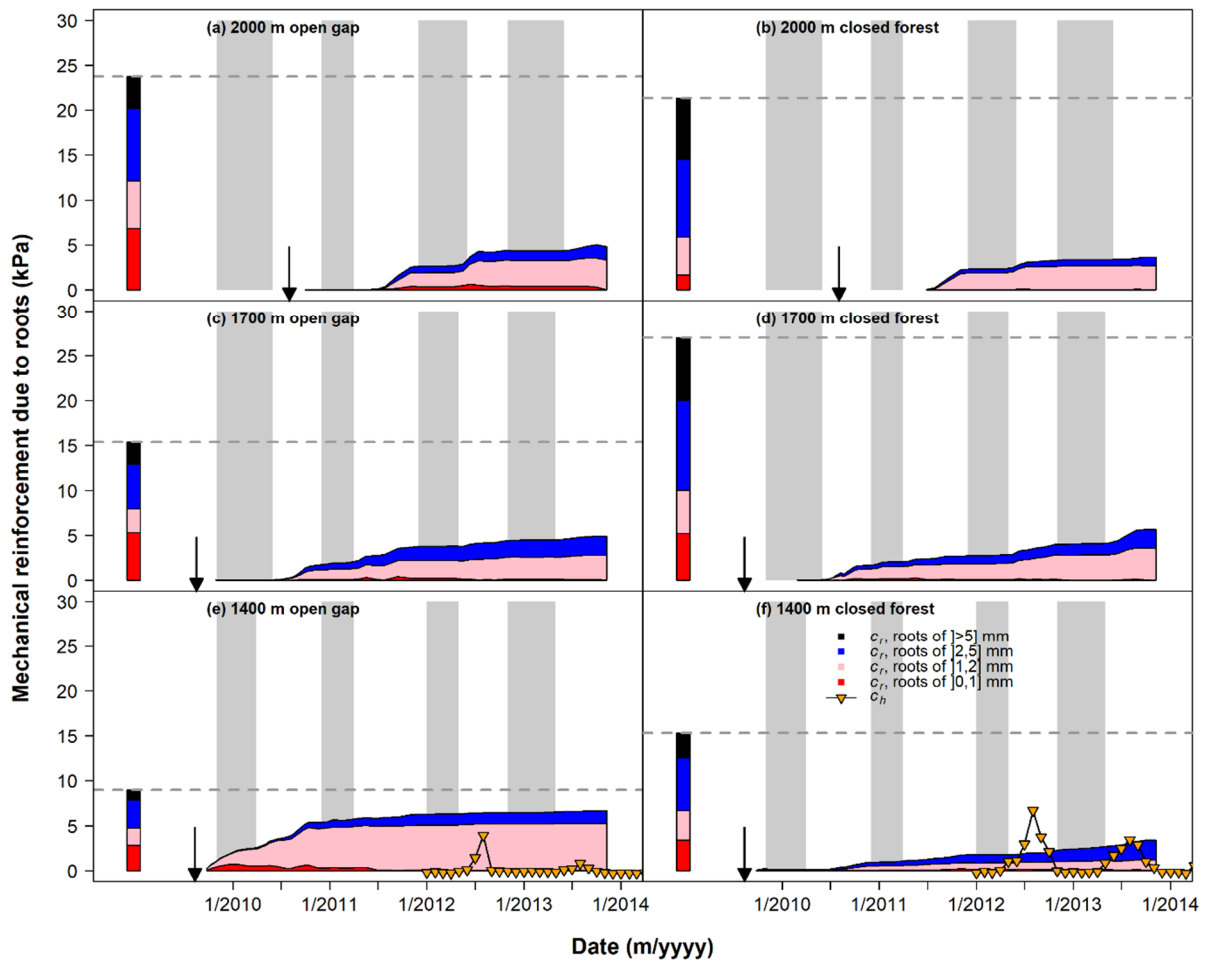
883 Figure 3 Mechanical reinforcement ( $c_r$ ) due to roots of different diameter classes before and  
884 after the disturbance in: (a, c, e, g, i) open gaps and (b, d, f, h, j) closed forests at different soil  
885 depths (every 0.20 m) at an altitude of 1400 m. Triangles indicate hydrological reinforcement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

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

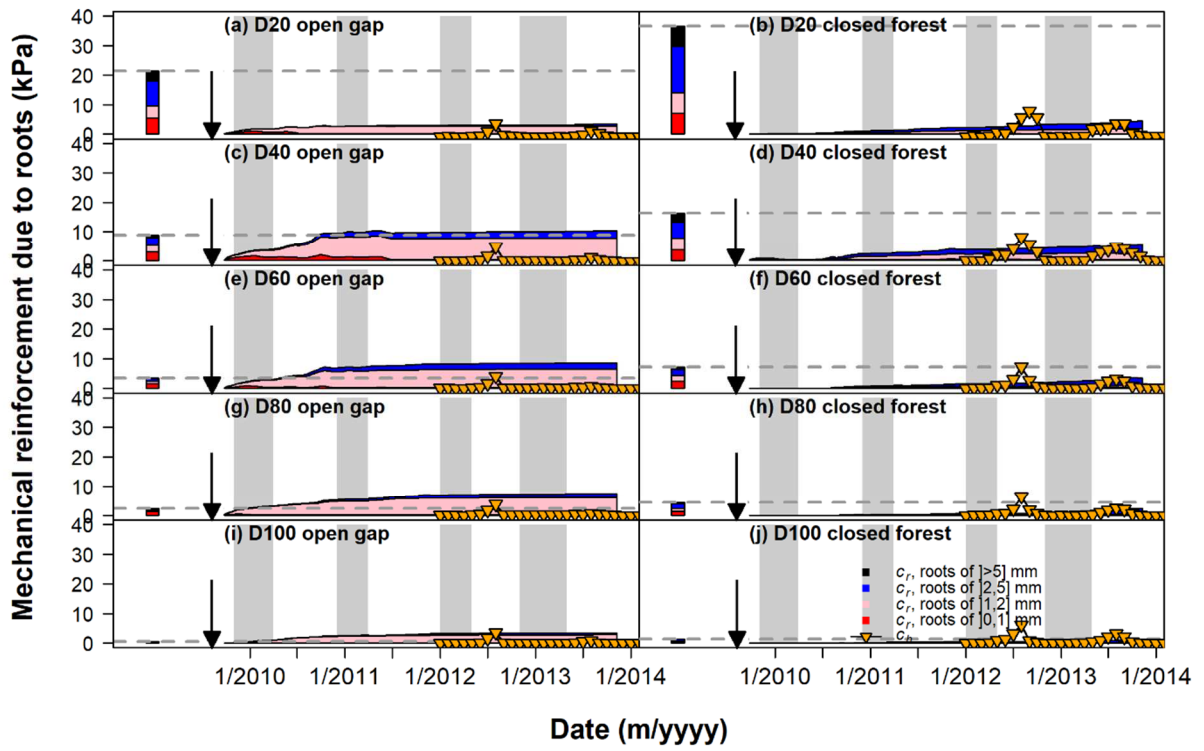
892 calculation after the disturbance. There were no significant differences between altitudes and  
893 between patch types (open gaps versus closed forests). Data are means  $\pm$  standard error.

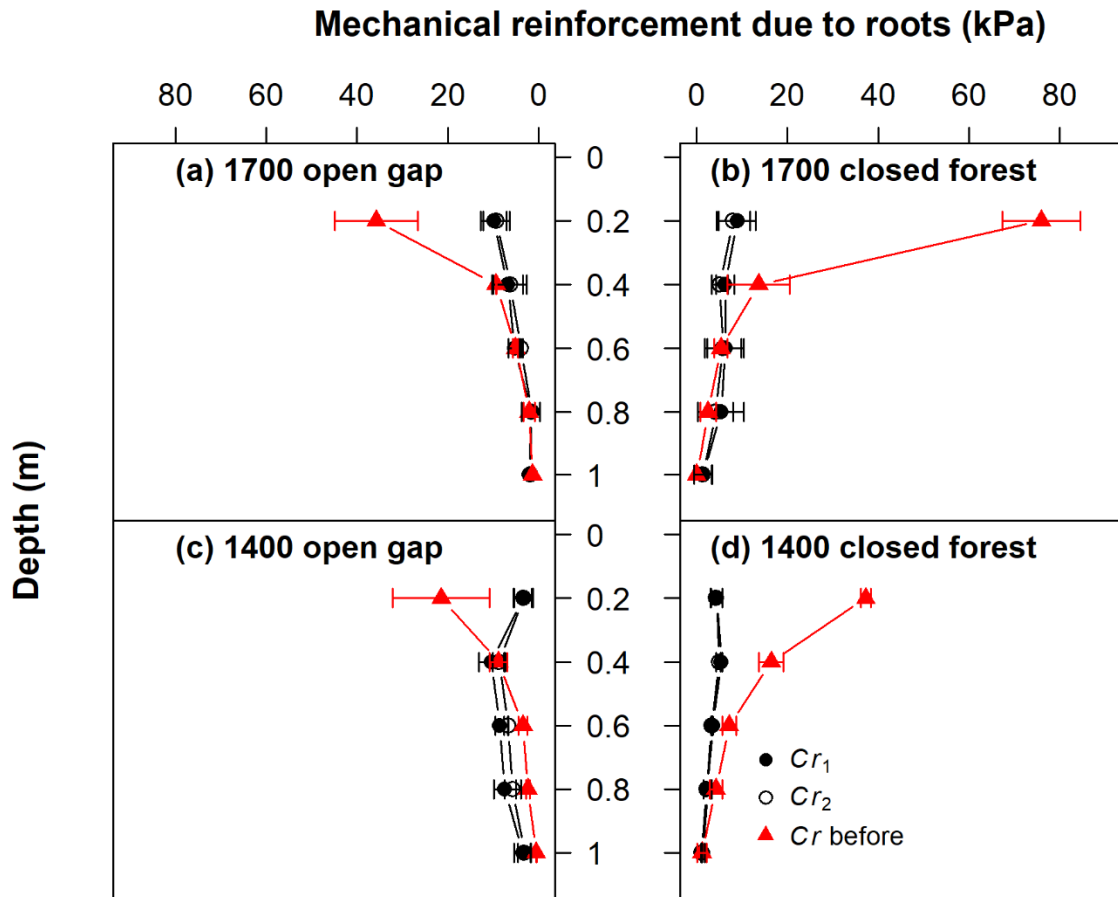
894 Figure 5 Global factor of safety (FoS) of slopes in open gaps and closed forests at 1400 m  
895 during the monitoring period (2009 – 2014). Each component of FoS is shown where soil load,  
896 water load and biomass correspond to  $W_z$  in Eq. (9); soil cohesion corresponds to  $\frac{c'_z}{W_z \sin \beta}$  in Eq.  
897 (9), which was obtained from root free direct soil shear tests and is given as 3.0 kPa; mechanical  
898 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;  
899 hydrostatic-uplifting corresponds to  $U_z$  in Eq. (9), which gives a negative value to FoS when  
900 soil is saturated. The arrow indicates the time when the soil moisture was included. FoS > 1.3  
901 indicates that the slope is stable;  $1 < \text{FoS} < 1.3$  the slope is safe but should be monitored and  
902 FoS < 1 is an unstable slope. The grey background indicates the time when the soil surface  
903 was covered by snow.



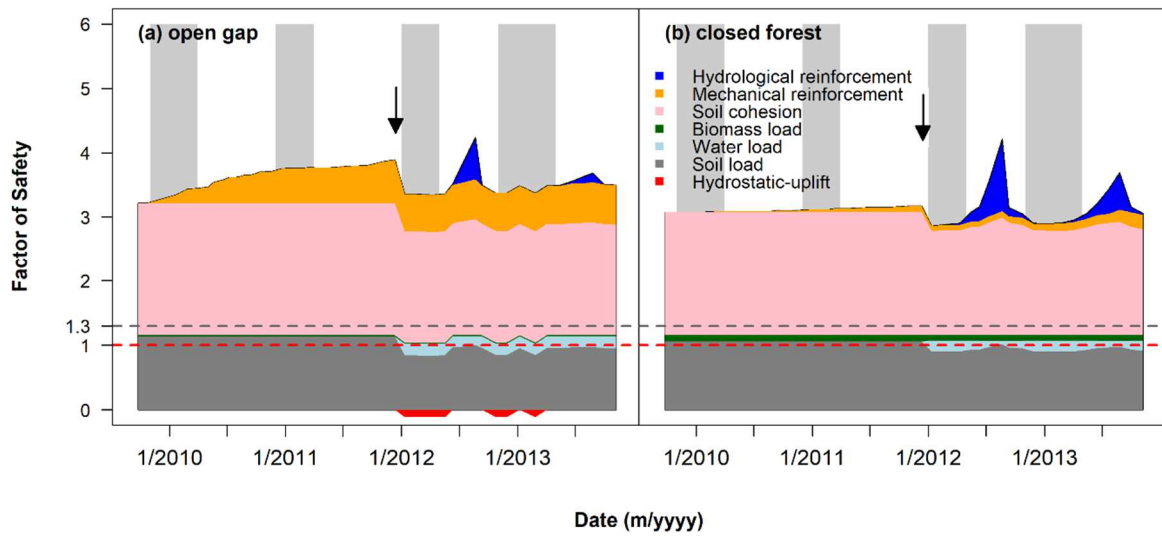








912 Figure 5



913