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1 **Plant-soil reinforcement response under different soil hydrological regimes**

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6
7 Abstract

8 The use of plants against shallow landslides and erosion has received considerable attention over time
9 as it is believed that vegetation provides mechanical and hydrological reinforcement to the soil.
10 However, neither the soil-root mechanical reinforcement under different hydrological regimes, nor the
11 hydrological effects of vegetation on soil reinforcement have been properly studied.

12 This paper explores how plants are able to provide mechanical and hydrological reinforcement to soil
13 under different soil hydrological regimes. To do this, we first defined a novel, simple and reproducible
14 laboratory protocol to investigate how changes in soil moisture affect the mechanical effects of
15 vegetation on soil reinforcement. We then explored how plants modify the relevant soil properties and
16 what implications this may have on soil reinforcement. We finally attempted to evaluate the suction
17 stress functions for both fallow and vegetated soil, as a proxy to quantify the hydrological plant-derived
18 soil reinforcement.

19 The results showed that plants significantly increased the soil organic matter and the angle of internal
20 friction, both with relevant hydro-mechanical implications. Vegetation presented a significant
21 mechanical soil reinforcement that was higher at the soil's hydrological transition regime, suggesting
22 the existence of optimum soil moisture content for an effective soil-root reinforcement response. The
23 hydrological regimes also imposed differences in terms of the hydrological reinforcement, which
24 differed between fallow and vegetated soil. However, the derived suction stress function for the fallow
25 soil in the experiments showed differences when compared to the theoretical predictions.

26 Our findings provide a good basis for future research to enhance our understanding of the nature of
27 plant-soil composites and shed light on the sustainable use of vegetation against shallow landslides.

28 Keywords: plant-soil, reinforcement, hydrological regimes, suction stress.

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43 1. INTRODUCTION

44

45 The use of plants against landslides and erosion has received considerable attention during the past
46 decades (e.g. Wu et al., 1979; Stokes et al., 2014). Plants effectively provide reinforcement to the soil
47 matrix (Waldron, 1977). In engineering, the soil-root reinforcement is normally attributed to the
48 transfer of mechanical energy from the roots to the soil (Ekanayake and Phillips, 1999) given the
49 differences between both root and soil materials (Greenway, 1987) converging into plant-soil
50 composites (e.g. Thorne, 1990).

51 The provision of plant-soil hydrological reinforcement, however, has received less consideration
52 (Stokes et al., 2014). In part, this is due to the difficulties of integrating the hydrological effects of
53 vegetation into the evaluation of soil strength. Moreover, the performance of the plant-soil
54 reinforcement response may also be influenced by the soil's hydrological conditions (e.g. moisture
55 content). A few studies have tried to address this gap (e.g. Pollen, 2007; Fan and Su, 2008; Mickovski
56 et al., 2009), but overall it has largely been neglected.

57 Soil moisture content is subject to seasonal variations (Rodriguez-Iturbe and Porporato, 2004). Given
58 the increased likelihood of landslide occurrence associated to certain seasons and hydrological
59 conditions (Lu and Godt, 2013), it is of the utmost importance to enhance our understanding on how
60 the plant-soil reinforcement response may change under these soil moisture variations.

61 Within a mass instability context, the soil strength (τ) is measured as the soil resistance to shear. This is
62 commonly quantified with the Coulomb's law, which represents the maximum possible state of soil
63 stress by means of a graphical line known as the 'failure envelope' (Head and Epps, 2011). A failure
64 envelope is defined through the cohesion and angle of internal friction of the soil (c' and ϕ' ,
65 respectively). It is believed that ϕ' does not change when roots are present in the soil (Waldron and
66 Dakesian, 1981; Gray and Ohashi, 1983; Ghestem et al., 2013) and, consequently, failure envelopes are
67 not normally portrayed for vegetated soils. The same methodology used to find a soil's failure
68 envelope, known as shear testing (Head and Epps, 2011), is also used to evaluate the additional shear
69 strength roots provide to soil (Waldron, 1977; Ekanayake and Phillips, 1999; Mickovski et al., 2009;
70 Ghestem et al., 2013).

71 Shear tests carried on vegetated soil are normally performed under saturated (e.g. Waldron and
72 Dakesian, 1981) or constant moisture levels (e.g. Mickovski et al., 2005; Mickovski et al., 2008;
73 Ghestem et al., 2013). As it has been observed that the moisture content may determine the mode by
74 which plant roots confer energy to the soil (i.e. influence the mode of root failure within the soil-root
75 continuum; Ennos, 1990), the moisture content should be taken into consideration. The few studies
76 attempting to explore the effects of the moisture content on soil-root reinforcement have taken care to
77 mimic natural conditions of root reinforcement (e.g. Pollen, 2007; Fan and Su, 2008), but have not
78 considered the range of different soil hydrological regimes possible (Vanapalli et al., 1996).

79 The soil hydrological regimes must be defined on the basis of the soil water characteristic curve
80 (SWCC; van Genuchten, 1980). They can be divided into Saturated Regime (i.e. all soil pores are full
81 of water), Transition Regime (i.e. air begins to enter in the soil-pore space) and Residual Regime (i.e.
82 just films of water are retained around the soil particles) (e.g. Lu and Likos, 2004). The hydrological

83 regimes are relevant because it is known that soil shear strength changes with the amount of water kept
84 within the soil-pore space (Vanapalli et al., 1996).

85 To include the soil shear strength effects from the mechanisms that take place within the soil-pore
86 space under variable hydrological regimes, Coulomb's law has been updated over the years (i.e.
87 *effective stress principle*: Terzaghi, 1943; Bishop, 1954; Fredlund and Morgensten, 1977). The effects
88 conferred by the soil-root mechanical reinforcement have also been included (e.g. Wu et al., 1979). In
89 an attempt to unify the different stresses that act within the soil-pore space (i.e. pore-water pressure,
90 pore-air pressure, physical-chemical forces at the particle contacts), Lu and Likos (2004) developed the
91 *unified effective stress principle*, which considers a unique stress variable, the suction stress (σ^s),
92 featured in the Coulomb's law (failure envelope) for variably saturated conditions as:

$$93 \tau = c' + (\sigma - u_a - \sigma^s) \tan \phi'$$

94 where u_a is the pore-air pressure, normally assumed to be at the atmospheric pressure and assigned a
95 value of 0 kPa; σ is the normal stress; c' and ϕ' are the soil effective cohesion and the angle of internal
96 friction, respectively, and τ is the shear stress (strength) of the soil.

97 The suction stress (σ^s) is meant to have the form of a characteristic function of the soil (i.e. SSCC; Lu
98 and Likos, 2006) based on the SWCC fitting parameters – i.e. α : inverse of the air entry pressure and n :
99 pore-size distribution parameter (Lu et al., 2010; Song et al., 2012). In addition, σ^s is directly related to
100 the soil apparent cohesion (c'), which actually mobilises the suction stress to shear resistance under the
101 shear failure of soils (Lu and Godt, 2013). Thus, SSCC could be appraised by means of shear testing
102 under different moisture contents or matric suction levels (Lu and Likos, 2004, 2006) by extrapolating
103 the failure envelopes to intercept with the negative side of the abscissa axis (i.e. $\sigma^s = -c'/\tan \phi'$),
104 provided that changes in the degree of saturation, or matric suction ($u_a - u_w$), will lead to the upward shift
105 of the failure envelope (Vanapalli et al., 1996; Lu and Likos, 2006; Kim et al., 2013).

106 The direct dependency of σ^s on $u_a - u_w$ allows the former to be considered as a proxy to quantify the
107 plant-soil hydrological reinforcement. The matric suction increase derived from plant water uptake or
108 evapotranspiration processes is one of the most recognisable hydrological effects provided by the
109 vegetation on the soil (Rodriguez-Iturbe and Porporato, 2005). However, it cannot be employed alone
110 to quantify the plant-soil hydrological reinforcement as the mechanisms occurring within the
111 unsaturated soil-pore space are complex (Lu and Likos, 2004). Hence, the soil hydro-mechanical
112 properties (e.g. α and n) must be regarded in combination with $u_a - u_w$ for the quantification of σ^s (e.g.
113 Lu et al., 2010) and, thus, approaching the plant-soil hydrological reinforcement.

114 In addition, plants, as living organisms, modify the environment they live in and, in particular, plant
115 roots alter the surrounding soil (i.e. *rhizosphere*; e.g. Hinsinger et al., 2009) in many ways. These
116 changes are demonstrated not only as enhancements of the soil matrix structure and strength but also as
117 alterations of the mechanisms governing soil physicochemical processes, such as the retention and flow
118 of water in the soil (Carminati et al., 2010; Scholl et al., 2014). Hence, when plants are present in the
119 soil one should consider a new material (i.e. plant-soil composite) with specific hydro-mechanical
120 properties (Scanlan, 2009). However, testing the properties and behaviour of plant-soil composites, in
121 general, and soils under unsaturated conditions, in particular, is difficult – there is a need to develop
122 simpler and quicker protocols.

123 The aim of this paper is to explore how plants are able to provide mechanical and hydrological
124 reinforcement to the soil under different soil hydrological regimes. To do this, we first define a novel,
125 simple and reproducible laboratory protocol to investigate how changes in soil moisture modify the
126 mechanical response of vegetation upon soil reinforcement. We then look at how plants modify the soil
127 properties and what implications this may have for soil reinforcement. Finally we attempt to evaluate
128 the suction stress functions for both fallow and vegetated soil, as a proxy to quantify the plant-derived
129 soil hydrological reinforcement.

130

131 2. MATERIALS & METHODS

132

133 2.1. Soil type and testing program

134

135 A silty sand soil (Sand: 79.82%; Silt: 5.85%; Clay: 3.08%; BS 1377 Part 1:1990) was collected from
136 three sampling points at the crest of a landslide-prone slope in Catterline Bay, Northeast Scotland, UK,
137 from a depth of between 300 and 600 mm below ground level (b.g.l). The soil had intermediate to low
138 plasticity, (liquid limit, w_L , of 36.07 %; plastic limit, w_p , of 10.45 %; BS 1377 Part 2:1990) and a low
139 organic matter (OM) content (1.16 ± 0.01 %; OM baseline; Schulte and Hopkins, 1996).

140 The soil was oven-dried at 100°C for 48 hours after which it was pulverized with pestle and mortar and
141 sieved through a 2 mm sieve. Then, the sample was split into two replicate treatments – i.e. fallow and
142 vegetated, respectively.

143 The fallow replicates (4 in total) were progressively taken to saturation level by adding deionized water
144 while mixing the soil-water mixture thoroughly with a spatula. Water was added until no soil
145 aggregates were present and a shiny film was observed atop. Once saturated, the replicates were
146 covered with aluminium foil and refrigerated for 48 h at 4° C, after which they were removed from the
147 fridge and let to dry at 20°C up to the desired moisture regime prior to shear testing (Fig. 1a).

148 The vegetated replicates (4 in total) were placed in 650 ml plastic trays (46.2 mm deep) and sown with
149 7 g of alfalfa (*Medicago sativa* L.) seeds spread evenly over the soil surface. Each sample was gently
150 watered, covered with a plastic lid and left in darkness until the seeds germinated. Once they
151 germinated, the trays were placed under an incandescent bulb of 60 W and the alfalfa was left to grow
152 for 3 weeks without any fertiliser (Figs. 1b and 1c). Each sample was watered daily with 100 ml of tap
153 water. Once the vegetated replicates were ready for shear testing, they were taken to water-saturation
154 level and left to dry until they reached the desired moisture regime, as with the fallow samples.

155

156 Each replicate from both the fallow and vegetated treatments was tested in shear under three different
157 hydrological regimes (I: saturated regime, II: transition regime and III: residual regime; Vanapalli et
158 al., 1996). The hydrological regimes were identified on the basis of the soil water characteristic curve
159 (SWCC; Fig. 2) to mimic the natural environmental conditions. SWCC was evaluated onsite at the
160 three different sampling locations in Catterline Bay by collecting coupled measurements of the matric
161 suction ($u_a - u_w$; kPa) and the moisture content (w ; %) over time (Fredlund and Rahardjo, 1993). Then,
162 van Genuchten's SWCC function (van Genuchten, 1980) was iteratively fitted using R 3.2.1 (R Core

163 Team, 2015). Hence, each replicate was tested at $u_a-u_w = 0$ kPa (regime I), $u_a-u_w = 17$ kPa (regime II)
164 and $u_a-u_w = 78.5$ kPa (regime III). Two extra u_a-u_w levels were considered – i.e. 3 kPa and 13 kPa for
165 fallow and vegetated replicates, respectively, to enhance the number of repeats at the transition points
166 between the saturated and transition moisture regimes. The matric suction was monitored in all
167 samples by measuring the pore-water pressure with two UMS[®] T5 tensiometers (Figs. 1a-c) inserted at
168 ca. 20 mm b.g.l. and connected to a Campbell CR1000 data-logger until they achieved the desired
169 value for shear testing.

170 Four drained direct shear test trials (i.e. shear stages) were carried out per replicate and hydrological
171 regime (total of 16 fallow and 16 vegetated). The shear tests were performed in a Matest Shearlab
172 shear-box (Fig. 1d; BS 1377-4, 1990) machine using a 23.27 mm depth by 48.95 mm diameter sample
173 and shearing at a rate of 0.5 mm min^{-1} under four normal stresses (i.e. shear stages: 26.04 kPa, 78.11
174 kPa, 104.15 kPa and 156.22 kPa; Head and Epps, 2011). The specimens to be sheared were carefully
175 sampled from their containers with a cylindrical knife of the same dimensions as the shear box (Fig.
176 1d), inserted into the shear box with no additional compaction and sheared at the middle plane (i.e. ca.
177 11.6 mm depth). For the case of the vegetated replicates, the vegetation was clipped to the ground level
178 with a precision knife before sampling and inserting into the shear-box. In between the shear stages,
179 the replicates of both fallow and vegetated soil were kept covered with aluminium foil in the fridge at
180 4°C from which a small sub-sample was collected to determine the gravimetric moisture content (Head,
181 1980).

182 After shear testing, each soil sample was oven-dried at 100°C for 24 hours to obtain the soil dry mass,
183 and then placed in a muffle at 500°C during 2 hours to determine the OM content by mass difference
184 respect to the dry sample mass (the LOI method; Schulte and Hopkins, 1996). The OM gain was then
185 calculated for the vegetated replicates as the OM mass percentage gain with respect to the OM baseline
186 (i.e. 1.16 ± 0.01 %). For comparison purposes, the root dry mass was determined in one of the vegetated
187 replicates (i.e. regime III: 78 kPa). To do so, the roots for each sub-replicate were separated by hand
188 from the soil with steel tweezers. Then, the root dry mass was determined by oven-drying the separated
189 material at 70°C for 24 hours. In addition, the dry bulk density was estimated as the ratio between the
190 sheared dry soil mass and the volume of the shear box.

191

192

193 2.2. Soil-root mechanical reinforcement

194

195 The soil-root mechanical reinforcement was assessed by comparing the stress-strain curves between the
196 fallow and vegetated replicates derived from the shear testing trials (e.g. Mickovski et al, 2008). The
197 stress-strain curves were evaluated at the three considered moisture regimes (see 2.1) and under three
198 different normal stresses (26 kPa, 78.11 kPa and 104.15/156.22 kPa). The fallow soil repeat at 0 kPa
199 could not be tested at 156.22 kPa of normal stress due to the effects of the normal confining pressure
200 on this specimen, as its plasticity exceeded the liquid limit (i.e. soil specimen behaved as a liquid;
201 Craig, 2004). Thus, the maximum normal stress compared between fallow and vegetated treatments for
202 the saturated regime was 104.15 kPa.

203 From each stress-strain curve a series of ‘mechanical properties’ were retrieved (Ghestem et al., 2013).
 204 Firstly, where a clear stress-strain curve peak was not obtained, a yield point (τ_{yield} ; kPa) was chosen for
 205 each curve as the first encountered inflexion point of the curve, which is meant to represent the
 206 transition between elastic and plastic behaviour. The tangential strain at which the yield point was fixed
 207 was considered to be the strain at the yield point ($\varepsilon_{\text{yield}}$; %). The area below the stress-strain curve up to
 208 the yield point was assumed to be the deformation energy (J; J m^{-3}). The difference between the
 209 vegetated and fallow deformation energies – i.e. $J_{\text{gain}} = J_{\text{vegetated}} - J_{\text{fallow}}$ (Ekanayake and Phillips, 1999),
 210 shear strength – i.e. $\Delta S_y = \tau_{\text{yield-vegetated}} - \tau_{\text{yield-fallow}}$ (Waldron et al., 1983) as well as the root reinforcement
 211 efficiency at the yield point – i.e. $\text{RE}_y = \Delta S_y / \tau_{\text{fallow}}$ (Fan and Su, 2008), were regarded as indicators of
 212 soil-root mechanical reinforcement. Additionally, the shear modulus (G; kPa) was calculated as the
 213 initial slope of each stress-strain curve.

214

215 2.3. Failure envelopes and suction stress function

216

217 A Coulomb’s failure envelope was obtained for each moisture regime and for the fallow and vegetated
 218 replicates, respectively (i.e. 4 envelopes per treatment). Each failure envelope was obtained by fitting a
 219 regression line in R 3.2.1 (R Core Team, 2015) to the point clouds formed between the maximum shear
 220 resistance and the normal stress (Head and Epps, 2011). From each failure envelope the soil cohesion
 221 (c' : intercept with shear stress axis) and angle of internal friction (ϕ' : inverse tangent of the failure
 222 envelope’s slope) were retrieved. Then, each failure envelope was extrapolated to intercept the normal
 223 stress axis. Each intercept point was considered to stand for the suction stress (σ^s ; kPa; Lu and Likos,
 224 2006; Kim et al., 2013; Lu and Godt, 2013), which was then plotted against the $u_a - u_w$ level obtained
 225 from the relevant tests. A new curve (the suction stress function; SSCC) was iteratively fitted in R 3.2.1
 226 for the fallow and vegetated sample points respectively, until the maximum goodness of fit (R^2) was
 227 achieved. To do so, values were given to α (inverse of the air entry pressure; kPa^{-1}) and n (pore-size
 228 distribution parameter) in the function for the determination of the suction stress (Lu et al., 2010; Eq.
 229 1):

230

$$231 \quad \sigma^s = - \frac{(u_a - u_w)}{(1 + (\alpha(u_a - u_w))^n)^{\frac{n-1}{n}}} \quad \text{Eq. 1}$$

232

233

234 2.4. Statistical analysis

235

236 The distribution density was plotted for all studied independent variables (i.e. c' , ϕ' , OM, ρ_b , σ^s , τ_{yield} , J,
 237 G, $\varepsilon_{\text{yield}}$) to check for normality. Kruskal-Wallis tests were carried out to infer statistical differences
 238 between the non-normally distributed variables and the two treatments (i.e. fallow and vegetated) while
 239 ANOVA tests were implemented for the normally distributed variables at 95% and 99% confidence
 240 levels. The same tests were used to find statistical differences between each independent variable and
 241 the tested hydrological regimes and normal stress levels, respectively. Where statistically significant
 242 differences were encountered, the differences within the groups were evaluated by means of Wilcoxon

243 tests and t-tests for the non-normal and normally distributed variables, respectively. The same
 244 procedures were followed for the soil-root reinforcement indicators (i.e. J_{gain} , ΔS_y and RE_y). In
 245 addition, the correlation between these indicators and the OM was assessed by means of Pearson's
 246 correlation tests. The latter tests were also implemented to evaluate the potential relationships between
 247 all of the considered variables.

248 The statistical differences between the obtained failure envelopes were assessed by comparing the
 249 envelopes' slope (s) and their respective standard errors (SE) through the estimation of a t-statistic
 250 ($t = s1 - s2 / \sqrt{SE1^2 + SE2^2}$; Paternoster, 1998) evaluated at the 95% and 99% confidence levels.
 251 Effects derived from the treatment (i.e. fallow or vegetated), hydrological regime, organic matter and
 252 dry bulk density (ρ_b) on the failure envelopes' parameters (c' : effective cohesion and ϕ' : angle of
 253 internal friction) and the suction stress were evaluated by means of Pearson's correlation tests.
 254 All statistical analyses were carried using the statistical software R 3.2.1 (R Core Team, 2015).

255

256 3. RESULTS

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260

261 Table 1. Soil-root mechanical reinforcement properties for the three tested hydrological regimes (i.e. I:
 262 $u_a - u_w = 0$ kPa II: $u_a - u_w = 17$ kPa III: $u_a - u_w = 78$ kPa) and the different normal stresses (σ_N , kPa); τ_{yield} :
 263 shear strength at yield point (kPa), $\varepsilon_{\text{yield}}$: strain at yield point (%), J_{yield} : deformation energy at yield
 264 point (J m^{-3}), J_{gain} : deformation energy gain for vegetated respect to fallow soil (J m^{-3}), G: shear
 265 modulus (kPa), ΔS_y : shear strength increase for vegetated respect to fallow soil (kPa), RE_y : root
 266 efficiency at yield point.

Treatment	$u_a - u_w$ (kPa)	σ_N (kPa)	τ_{yield} (kPa)	$\varepsilon_{\text{yield}}$ (%)	J_{yield} (J m^{-3})	J_{gain} (J m^{-3})	G (kPa)	ΔS_y (kPa)	RE_y
Vegetated	0	26.03	14.87	3.00	33.11	13.96	20.21	6.90	0.87
Vegetated		78.11	34.01	6.00	119.95	76.88	20.37	5.32	0.18
Vegetated		104.15	50.48	8.00	255.69	207.28	14.86	17.54	0.53
Fallow		26.03	7.97	8.00	19.14	-	10.89	-	-
Fallow		78.11	28.69	3.00	43.07	-	54.59	-	-
Fallow		104.15	32.94	2.50	48.41	-	67.20	-	-
Vegetated	17	26.03	39.85	2.50	60.62	39.32	83.84	19.23	0.93
Vegetated		78.11	53.67	2.50	112.89	82.55	105.41	34.01	1.73
Vegetated		156.22	66.42	6.00	293.79	136.28	60.11	35.60	1.15
Fallow		26.03	20.72	7.00	21.30	-	21.30	-	-
Fallow		78.11	19.66	6.00	30.35	-	31.81	-	-
Fallow		156.22	30.82	3.00	157.52	-	27.97	-	-
Vegetated	78.5	26.03	41.44	6.00	147.36	46.34	58.15	5.84	0.16
Vegetated		78.11	43.57	2.50	90.93	-43.06	68.41	-14.15	-0.24
Vegetated		156.22	60.58	3.00	124.07	-88.25	92.30	-16.47	-0.21
Fallow		26.03	35.60	4.00	101.02	-	66.42	-	-
Fallow		78.11	57.92	3.00	133.99	-	101.02	-	-
Fallow		156.22	77.05	4.00	212.32	-	91.21	-	-

267

268

269 3.1. Soil-root reinforcement

270

271 A clear increase of the soil shear strength was observed in most of the trials (Fig. 3) when the soil was
272 vegetated. The yield strength (τ_{yield} ; Table 1) was generally higher for the vegetated treatments and
273 increased with the normal stress. There were statistical differences in τ_{yield} with regard to the applied
274 normal stress ($F=4.49$ $df=3$ $p<0.05$), where the maximum applied normal stress (i.e. $\sigma =156.22$ kPa) led
275 to significantly higher τ_{yield} ($t=-3.40$ $df=8$ $p<0.01$). However, no statistically significant differences
276 were detected in terms of τ_{yield} between the treatments as τ_{yield} tended to be relatively similar between
277 vegetated and fallow soil under the residual regime (Fig. 3g-i). Additionally, τ_{yield} did not show
278 significant differences between the different hydrological regimes, although the trend differed between
279 vegetated and fallow treatments (Fig. 4).

280 In terms of the energy of deformation (J; Table 1), it showed significant differences between fallow and
281 vegetated treatments ($\chi^2=4.32$ $df=1$ $p<0.05$), where the vegetated soil generally presented higher J.
282 Also, J differed significantly among the tested normal stresses ($\chi^2=10.086$ $df=3$ $p<0.05$; highly
283 significant for $\sigma = 156.22$ kPa; $p<0.001$) but did not between the degree of saturation.

284 The hydrological regimes led to significant differences in terms of the root reinforcement efficiency
285 (ER_y ; $F=12.41$ $df=2$ $p<0.01$, Table 1), which was significantly higher (ER_y ; $t=-5.04$ $df=3$ $p<0.05$) for
286 the transition moisture regime (II: 17 kPa). Moreover, the shear strength increase (ΔS_y ; Table 1) also
287 presented statistically significant differences with the moisture regimes ($\chi^2=6.49$ $df=2$ $p<0.05$).
288 Although no statistical differences were detected, a similar pattern was seen for the energy gain (J_{gain} ;
289 Table 1) between the considered treatments, normal stresses or moisture regimes.

290 The strain at the yield point (ϵ_{yield} ; Table 1) did not show significant differences for the investigated
291 cases and it was found to occur within 2.5% and 8% strain in all cases. On the other hand, the moisture
292 regimes did lead to significant differences in terms of the shear modulus (G; $\chi^2=14.71$ $df=4$ $p<0.01$),
293 which was significantly higher for the residual regime ($Z=2$ $p<0.01$). In addition, statistically
294 significant differences in G were detected between the fallow and vegetated treatments for the
295 transition regime ($t=4.17$ $df=2.22$ $p<0.05$; Table 1).

296 It is worth noting that J_{gain} , ΔS_y and ER_y became negative under the residual moisture regime (III: 78.5
297 kPa) for the intermediate and highest normal stress tested (Fig. 3; Table 1), implying a low root
298 reinforcement under this hydrological regime. Furthermore, these three variables (J_{gain} , ΔS_y and ER_y)
299 did not correlate well with the OM ($R_{J_{\text{gain}}}=0.34$; $R_{\Delta S_y}=0.36$; $R_{ER_y}=0.46$).

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310 3.2 Organic matter gain

311

312 All vegetated replicates presented a significant OM gain (0.84% to 1.44%; Table 2) with respect to the
 313 baseline (i.e. 1.16 ± 0.01 %). The vegetated treatments exhibited a significantly ($F=34.15$ $p<0.01$) higher
 314 OM content when compared to fallow samples. However, no statistical differences were encountered
 315 between the two determination methods for the vegetated treatments.

316

317 3.3 Failure envelopes

318

319 Failure envelopes were fitted with a high goodness of fit (R^2 ; Table 2) for all shear testing trials (Fig.
 320 5). The fitted envelopes did not statistically differ among each other for neither type of treatment
 321 ($t_{\text{fallow}} < 2.015$ $df=5$; $t_{\text{vegetated}} < 1.89$ $df=7$), nor between the treatments ($t < 1.943$ $df=6$).

322 However, the angle of internal friction (ϕ' ; Table 2; Fig. 5) was shown to be significantly higher
 323 ($\chi^2=5.33$ $df=1$ $p<0.05$) in the vegetated replicates ($\phi'=20.09^\circ$ - 25.31°) when compared to the fallow
 324 samples ($\phi'=17.86^\circ$ - 19.84°) in all cases. These differences led, on average, to the following linear
 325 relationship: $\phi'_{\text{vegetated}}=1.2\phi'_{\text{fallow}}$. Additionally, ϕ' was highly positively correlated with the organic
 326 matter ($R=0.69$) and with the bulk density ($R=0.86$).

327 On the other hand, the soil cohesion (c' : failure envelope's intercept; Table 2; Fig. 5) ranged from 2.20
 328 kPa (regime I) to 55.47 kPa (regime III) for the fallow soil and from 10.40 kPa (regime I) to 51.46 kPa
 329 (regime III) for the vegetated soil. It was highly positively correlated with the moisture regime
 330 ($R=0.97$) and the bulk density ($R=0.53$).

331

332 Table 2. Shear strength parameters (c' : apparent cohesion, ϕ' : angle of internal friction), suction stress
 333 (σ^s), organic matter content (OM) and gain (OM_{gain}) for the different tested replicates, for which matric
 334 suction (u_a-u_w), gravimetric moisture content (w) and bulk density (ρ_b) at testing is indicated. Values
 335 indicate mean \pm standard deviation.

Treatment	u_a-u_w (kPa)	w (%)	ρ_b (g cm ⁻³)	c' (kPa)	ϕ' (°)	R^2	σ^s (kPa)	OM (%)	OM gain (%)
Fallow	0.00 ± 0.11	38.58 ± 1.15	1.61 ± 0.16	2.20	19.21	0.90	-6.32	1.16 ± 0.23	-
Fallow	3.08 ± 0.74	29.56 ± 2.57	1.60 ± 0.18	5.40	19.84	0.99	-14.97	1.44 ± 0.17	-
Fallow	16.91 ± 0.41	25.46 ± 2.01	1.59 ± 0.13	14.1 6	17.86	0.97	-43.94	1.39 ± 0.02	-
Fallow	78.60 ± 9.71	12.43 ± 0.29	1.53 ± 0.15	55.4 7	19.61	0.96	-155.65	1.04 ± 0.05	-
Vegetated	0.67 ± 0.09	39.78 ± 3.75	1.39 ± 0.13	10.4 0	23.88	0.98	-23.49	2.00 ± 0.19	0.84 ± 0.19
Vegetated	12.96 ± 0.67	24.89 ± 4.00	1.44 ± 0.13	12.4 7	25.08	0.98	-26.65	2.59 ± 0.29	1.44 ± 0.29
Vegetated	16.94 ± 0.80	23.87 ± 3.09	1.53 ± 0.13	25.9 1	20.09	0.96	-70.84	2.44 ± 0.24	1.28 $\pm 0.$ 24
Vegetated	78.46 ± 0.76	11.32 ± 1.98	1.17 ± 0.07	51.4 6	25.31	0.74	-108.81	2.05 ± 0.44	0.89 ± 0.44

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339

340 3.4 Suction stress

341

342 The suction stress (σ^s ; Table 2; Fig. 5) showed an increasing trend with the matric suction for the
343 fallow and vegetated treatments. Both treatments presented a different σ^s curve fit using Eq. 1. The
344 fitting parameters, α and n , were $\alpha=0.05 \text{ kPa}^{-1}$ and $n=0.6$, for the fallow, and $\alpha=0.001 \text{ kPa}^{-1}$ and $n=2$,
345 for the vegetated soil. The goodness of fit (R^2) was 0.99 and 0.73 for the fallow and vegetated soil,
346 respectively. Nonetheless, no statistical differences were observed between the two treatments and
347 none of the considered soil variables (OM and ρ_b) had a significant effect on σ^s besides the matric
348 suction ($R=-0.94$) and the soil cohesion ($R=-0.98$).

349

350 3.5. Correlation tests

351

352 The correlation tests (Fig. 6) showed a highly significant correlation between the yield stress (τ_{yield}) and
353 the suction stress ($R=-0.81$), the matric suction ($R=0.71$) and the soil cohesion ($R=0.82$). However,
354 τ_{yield} appeared to correlate, to a greater or lesser extent with most of the studied variables (Fig. 6). It is
355 also worth mentioning the high positive correlation between the organic matter content and the energy
356 of deformation ($R=0.53$), and, the wide influence of the bulk density (i.e. compaction) over most of the
357 assessed variables.

358

359

360 4. DISCUSSION

361

362 4.1. Soil mechanical strength under fallow and vegetated conditions

363

364 A significant mechanical soil reinforcement response was observed when the soil was vegetated (Figs.
365 3 and 5; Tables 1 and 2). The same response was noted in previous studies (e.g. Waldron et al., 1983;
366 Ekanayake and Phillips, 1999; Mickovski et al., 2008; Ghestem et al., 2013). The transfer of energy
367 from the root to the soil (Ekanayake and Phillips, 1999) as roots fail under shear conditions (i.e. break
368 or pull-out; Waldron, 1977) may explain the observed soil-root reinforcement effect.

369 However, the soil-root reinforced shear strength could also be explained by emergent soil structural and
370 mechanical properties induced by the vegetation. For instance, the presence of roots affected the angle
371 of internal friction when compared to the fallow soil (i.e. $\phi'_{\text{vegetated}}=1.2\phi'_{\text{fallow}}$; Table 2; Fig. 5a). This
372 response contradicts the traditional belief that the presence of roots in the soil does not change ϕ'
373 (Waldron and Dakesian, 1981; Gray and Ohashi, 1983; Ghestem et al., 2013). Roots do cause soil
374 structural changes (Whalley et al., 2005) and, thus, changes in strength. In addition, roots, as a foreign
375 material to the mineral soil, are likely to act as an additional friction agent to the intrinsic soil inter-
376 particle friction, ultimately conferring more soil shear resistance (i.e. steeper envelopes; Fig. 5a). This
377 claim is also supported by the fact that ϕ' was highly correlated with OM (see 3.2; Fig. 6), which
378 experienced a consistent increase after only three weeks of vegetation growth (Table 2). The effect of

379 the OM gain was also seen in the relatively strong observed correlation between OM and the
380 deformation energy (J; Fig. 6), which tended to be consistently higher for the vegetated repeats (i.e.
381 roots give ductility to the soil; Table 1). Counter intuitively to our other results, the OM seemed to
382 present a high negative correlation with the strain at the yield point (ϵ_y ; Fig. 6). This outcome is
383 concurrent with previous studies (e.g. Mickovski et al. 2009; Mickovski et al. 2011) and supports the
384 idea that the rooted soil strength is not fully mobilized until larger shear displacements. However, this
385 effect should be treated with caution as the location of the yield point was not obvious in most cases; a
386 known issue (Ghestem et al. 2013).

387 The observed soil-root mechanical reinforcement, in terms of τ_{yield} and J, was higher compared to
388 published values (e.g. Ekanayake and Phillips, 1999; Ghestem et al., 2013), and there are several
389 reasons that could be contributing to this difference. Firstly, higher normal loads were applied than in
390 previous work. This could have led to consolidation effects on the tested specimens (Head and Epps,
391 2011) and, consequently, to an increase of the specimen's bulk density upon testing. Low or null
392 normal loads are commonly used in soil-root reinforcement studies (e.g. Waldron et al., 1983;
393 Ekanayake and Phillips, 1999; Pollen, 2007; Fan and Su, 2008; Mickovski et al., 2009; Ghestem et al.,
394 2013) to mimic the effects derived from the plant surcharge, as these loads are normally assumed to be
395 negligible (Norris et al., 2008). However, as the normal applied loads increase together with the
396 specimen's bulk density, the soil shear strength also increases (Head and Epps, 2011), as it can be seen
397 in the failure envelopes (Fig. 5a). Secondly, a high planting density (Loades et al., 2010), more than ten
398 times higher than the one recommended for agricultural plantations (e.g. Mateo, 2005), and a smaller-
399 scale shear box (see 2.1) were used, which could have prevented the roots from sliding from the soil,
400 increasing resistance to shear even if the roots were broken (Ghestem et al., 2013). This issue may
401 explain why the shear strength continued to rise in the tested samples (Fig. 3). This has been found in
402 other systems (Waldron et al. 1983) and numerically predicted (Mickovski et al. 2011). Alternatively,
403 the necessary shear displacement for complete failure to occur may not be reached due to root
404 stretching effects (De Baets et al., 2008) or due to apparatus limitations (i.e. maximum shear
405 displacement limited to 20 mm; Mickovski et al. 2009). Nonetheless, the presence of many roots that
406 have not broken and are yet to mobilise their full tensile strength (Docker and Hubble, 2008) seems to
407 be a more plausible reason for the former issue. As a result, most of the vegetated treatments' stress-
408 strain curves (Fig. 3) presented smooth profiles without a clear peak (e.g. Waldron et al., 1983;
409 Ekanayake and Phillips, 1999; Su and Fan, 2010; Ghestem et al., 2013; Bordoloi et al., 2015).
410 However, further compaction was not applied to the soil specimens before shear testing, a step directly
411 related to the specimen's bulk density (Table 2), and could be why shear peaks were absent in the
412 fallow treatments (Head and Epps, 2011). In this regard, the lower observed bulk density for the
413 vegetated repeat tested under the residual hydrological regime (Table 2) might explain the lower soil-
414 root reinforcement effect for this trial (Figs. 3f-h; Table 1).

415

416 4.2. Soil-root reinforcement under different hydrological regimes

417

418 Most of our results are consistent with the idea that there is an optimum soil moisture level for most
419 effective soil-root reinforcement (Figs. 3d, 3e and 4a). This implies that the vegetation's mechanical
420 performance is strongly affected by the soil hydrological conditions. These conditions are expected to
421 vary seasonally (e.g. higher soil moisture saturation levels in winter). Hence, the vegetation's
422 mechanical response is expected to experience seasonal variations too.

423 The root systems seemed to have been able to mobilize their whole strength only at 17 kPa of matric
424 suction (i.e. transition regime; Fig. 3-II), for which a clear failure peak was observed in two cases
425 (Figs. 3d and 3e). Consequently, the vegetated soil presented maximum shear strength at the transition
426 moisture regime (Fig. 4a) after which it decreased or remained relatively constant. A similar pattern
427 was observed in the root reinforcement efficiency (RE_y ; Table 1). RE_y achieved values beyond unity
428 (i.e. shear strength increased by more than 100 % respect to the fallow soil) at 17 kPa of matric suction.
429 There are two main reasons that, independently or in combination, could be contributing to the
430 observed results.

431 Firstly, the soil-root bonds may change with the soil moisture (Ennos, 1990). As a result, the
432 mechanisms of root failure (e.g. breakage or pull-out; Waldron, 1977) can vary (Pollen, 2007) along
433 with the amount of energy conferred to the soil by the root system (Waldron, 1977). The maximum
434 energy is thought to be provided when the roots break (Waldron, 1977; Stokes et al., 2008). Yet, when
435 the soil is extremely saturated, roots will be more likely to pull-out (Ennos, 1990) as a consequence of
436 the soil's physical consistency loss (i.e. soil behaves as a liquid once the liquid limit is exceeded; Craig,
437 2004) and derived soil-root bonds loss (Ennos, 1990). However, as the soil dries out, there is an
438 increase of the soil shear strength (Vanapalli et al., 1996) derived from the pore water pressure
439 dissipation (Lu and Godt, 2013), along with a soil stiffness increase (Cosentini and Foti, 2014). These
440 effects were observed under both fallow and vegetated treatments on the upward shift of the failure
441 envelopes (Fig. 5a) and on the increasing trend of G with the matric suction (Table 1), respectively.
442 The high soil strength under the residual regime may therefore obscure soil-root reinforcement effects
443 (Figs. 3g-h, 4a; Table 1) and explain the lower root efficiency (Table 1) under high u_a-u_w . Nonetheless,
444 as it has been mentioned above, vegetated soil tended to maintain the soil shear strength constant
445 beyond the optimum (Fig. 4a). This issue may be produced by a buffering effect of the soil stiffness
446 when roots are embedded in the soil (i.e. soil becomes more elastic and ductile); also supported by the
447 trend seen in the fallow soil (Fig. 4b), where a non-linear strength increase with the matric suction was
448 observed. The latter is consistent with the observations gathered in Vanapalli et al. (1996).

449 Secondly, root tensile strength may change under distinct root moisture contents, which, in turn, will
450 vary depending on the surrounding soil's moisture. The root tissues' mechanical behaviour will likely
451 change depending on the tissue's cells hydration (e.g. Böhm, 1979; Stokes et al., 2008). As we have
452 observed during root tensile strength tests (Tardio and Mickovski, 2016), roots tend to be stiffer and
453 present a lower tensile strength when dry. Conversely, when roots are very wet, they tend to slip out
454 from the tensile testing machine. Thus, optimum root moisture contents for the mobilisation of the
455 maximum root tensile strength could exist and explain the observed results (Table 1; Figure 3). The
456 former may also explain the observed bias at 13 kPa of u_a-u_w for the vegetated replicates tested (Fig.
457 5a), where the root moisture may have not been at its optimum despite the soil's transition regime

458 conditions. The hypothesis of optimum root moistures is also supported by the G differences between
459 the two treatments (Table 1). Roots should present a maximum elasticity (i.e. tensile strain) under
460 optimum root moisture content (e.g. Ekevad and Axelsson, 2012). As a result, the soil-root composite
461 should be more elastic too and, consequently, the vegetated repeats showed significantly higher G than
462 the fallow repeats within the transition regime in all cases (Table 1).

463 The idea of an optimum soil moisture level for most effective soil-root reinforcement is to some extent
464 also supported when comparing our findings with results from previous studies. For example, root
465 mechanical reinforcement observations were higher than those reported for saturated moisture
466 conditions by Waldron et al. (1983) with respect to the saturation and transition moisture regimes but
467 lower, in terms of RE_y , for the residual regime (Table 1). However, root efficiency outcomes (RE_y ;
468 Table 1) were in disagreement with the findings from Fan and Su (2008), who claimed that RE_y
469 increased with the soil moisture content, with values between 0.9 and 1.3 under saturated conditions.
470 RE_y findings also differed from the observations provided in Pollen (2007), where it is indicated that
471 the reinforcement is likely to be at a minimum when the soil is saturated. Based on the consistent
472 reduction in soil strength under the saturated regime (Figs. 3 and 5a), there is some consistency with
473 Fan and Su (2008) in that the reinforcement effect provided by vegetation roots is more significant
474 under saturated conditions. Nonetheless, the former studies (Pollen, 2007; Fan and Su, 2008) did not
475 consider soil hydrological regimes in light of the SWCC, only testing two discrete soil moisture
476 contents (i.e. ca.10 % and 20 %) without providing further soil physical information or adjusting the
477 selected moisture contents to real-life hydrological regimes.

478 The observed bias between the two vegetated repeats tested within the transition regime (i.e. 13 kPa vs.
479 17 kPa) warrants further research along the same lines presented herein in order to shed light on which
480 factors (e.g. soil moisture, root moisture, emerging soil-root composite properties, root features, etc.)
481 led to the optimum soil-root reinforcement and to the observed bias. Additionally, it would be ideal to
482 consider other soil hydrological processes. For example, SWCCs are subject to soil hysteresis, which
483 cause soil hydro-mechanical differences between the drying and wetting paths (e.g. Lu and Likos,
484 2004). The hydrological regimes will therefore change under wetting conditions - when landslides are
485 more likely to occur - and, accordingly, the soil-root reinforcement performance.

486 The root tissue composition of the young Alfalfa seedlings (i.e. cellulose to lignin ratio; Zhang et al.,
487 2014), which has been proved to affect the root tensile strength (Genet et al., 2005), was not considered
488 and neither was the root length or the age of the plants – all of which may lead to soil-root
489 reinforcement differences (Loades et al., 2010). For instance, it is normally accepted that roots transfer
490 different energy into the soil depending on the root length (e.g. Ennos, 1990). Additionally, young and
491 adult plants tend to present root tissue compositional variations (i.e. cellulose to lignin ratio; Genet et
492 al., 2006), leading to different root reinforcement effects (Zhang et al., 2014).

493

494

495 4.3. Suction stress functions: hydrological reinforcement

496

497 Fallow and vegetated soil showed distinct suction stress characteristic curves (SSCC; Fig. 5c). These
498 derived from changes in the soil hydro-mechanical parameters required to fit Eq. 1 (Lu et al., 2010) to
499 the obtained data points (Fig. 5c). Changes in the physical properties of vegetated soil when compared
500 to fallow soil were observed as expected (Table 2). As a result, differences were found in terms of the
501 hydro-mechanical parameters (Scanlan, 2009; Carminati et al., 2010). The obtained values for α and n
502 after fitting Eq. 1 (Fig. 5c) would imply that the hydro-mechanical behaviour of the vegetated soil in
503 this study shifted towards the expected behaviour of a 'clay material' (Lu et al., 2010). This shift can be
504 seen in the observed higher moisture retention capacity of the vegetated soil within the saturated
505 regime and in the potential to buffer the suction levels within the residual regime (Table 2; also see
506 Whalley et al., 2005).

507 Regarding the SSCC for vegetated soil (Fig. 5c), a suction stress baseline (i.e. -23.49 kPa; Table 2; Fig.
508 5c) within the saturated regime was detected. This baseline indicates a possible relationship between
509 the apparent root cohesion (c_R ; Wu et al., 1979) and the suction stress, which was also seen in the
510 correlation between σ^s and τ_{yield} (Fig. 6). Furthermore, it is likely that suction stress regimes exist (Fig.
511 5c; dark green triangles) reflecting differences between the soil hydrological regimes (Fig. 2). σ^s
512 increased with the matric suction within the saturated regime and was relatively constant within the
513 transition regime before slowly increasing within the residual regime. In this respect and, considering
514 the role of σ^s within the *unified effective stress principle* (Lu and Likos, 2004), the soil strength would
515 experience a consistent increase derived from the soil matric suction rise. Consequently, and given the
516 acknowledged increase of the matric suction induced by plant-water uptake or evapotranspiration (e.g.
517 Rodriguez-Iturbe and Porporato, 2004), σ^s has good features to be used as a proxy to quantify the
518 hydrological effect of vegetation on the soil shear strength (i.e. plant hydrological reinforcement) and,
519 hence, the vegetated soil resistance against shallow landslides (e.g. Gonzalez-Ollauri and Mickovski,
520 2014, 2015).

521 However, the fallow soil SSCC (Fig. 5c; bold curve) differed from the theoretical prediction (Fig. 5c;
522 dashed light grey curve; Lu et al., 2010; Song et al., 2012); the hydro-mechanical parameter, n , differed
523 from that of the SWCC (Figs. 2 and 5c; see 3.4). For the soil being studied, considering both the
524 SWCC parameters and theory, the SSCC should have reached a maximum at AEV (i.e. air entry
525 pressure) preceded by a 1:1 relationship between σ^s and $u_a - u_w$ (Fig. 5c; dashed light grey curve). It did
526 not here, but the processes that take place in the soil-pore space under unsaturated conditions (Lu and
527 Likos, 2004) are highly complex and extremely difficult to fully replicate in a laboratory. Thus,
528 development of simplified methods to evaluate the SSCC in fallow soil should be continued.

529 Finally, it is worth noting that the closed-form equation of SSCC (Lu and Likos, 2004) was derived for
530 soil only and not for plant-soil composite material, which is probably the largest source of variation in
531 the observed data from the theoretical prediction. Only considering the data we observed for the three
532 hydrological regimes (i.e. 0 kPa, 17 kPa and 78 kPa), a different function was analytically fitted for the
533 vegetated soil taking into account the curve's graphical shape (Fig. 5c: full red line). The alternative
534 function was implemented with the same hydro-mechanical parameters derived from the SWCC:
535 $\sigma^s_{\text{vegetation}} = -n/\alpha(1 - \exp(\alpha(u_a - u_w))) + c_R$. We recommend the use of this function for
536 estimating the plant-derived soil hydrological reinforcement as opposed to the function derived from

537 the experimental protocol (Fig. 5c; dashed green line) because it considers the hydro-mechanical
538 parameters derived from the SWCC, it is consistent with the different soil hydrological regimes – it
539 tends to become constant within the residual regime – and, it predicts a solid plant hydrological
540 reinforcement compared to the fallow soil, as it is believed to occur in nature (Wilkinson et al., 2002).
541 Nonetheless, further work is needed to establish reliable experimental protocols able to find
542 expressions for predicting the soil hydrological reinforcement provided by vegetation, to shed light on
543 the myriad changes that vegetation produce upon the soil's hydro-mechanical properties and to enhance
544 our understanding on the behaviour of plant-soil composites.

545

546 5. CONCLUSIONS

547

548 In light of our observations and findings it can be concluded that:

549

- 550 • The presence of vegetation in the soil can change the soil composition with relevant hydro-
551 mechanical implications.
- 552 • Vegetation is able to mechanically reinforce the soil but the magnitude of this reinforcement
553 will depend on the soil's hydrological regimes – most effective reinforcement will be expected
554 within the transition regime.
- 555 • The presence of roots in the soil can induce an increase in the angle of internal friction of up
556 to 20% when compared to fallow soil.
- 557 • Vegetated soil has a suction stress function that is distinctly different from the one of fallow
558 soil. This function is governed by the soil's hydrological regime, it can be used as a proxy to
559 quantify the plant-derived hydrological reinforcement of the soil, and it stresses the intimate
560 relationship between plant-derived mechanical and hydrological soil reinforcement.

561

562 Our results provide a good basis for future research along the same lines to enhance our understanding
563 upon the nature of plant-soil composites and shed light on the sustainable use of vegetation against
564 shallow landslides.

565

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570

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