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Plant-soil reinforcement response under different soil hydrological regimes

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Abstract

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

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

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

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

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

1. INTRODUCTION

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

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

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

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

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

The soil hydrological regimes must be defined on the basis of the soil water characteristic curve (SWCC; van Genuchten, 1980). They can be divided into Saturated Regime (i.e. all soil pores are full of water), Transition Regime (i.e. air begins to enter in the soil-pore space) and Residual Regime (i.e. just films of water are retained around the soil particles) (e.g. Lu and Likos, 2004). The hydrological regimes are relevant because it is known that soil shear strength changes with the amount of water kept within the soil-pore space (Vanapalli et al., 1996).

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

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

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

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

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

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

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

2. MATERIALS & METHODS

2.1. Soil type and testing program

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

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

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

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

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

Team, 2015). Hence, each replicate was tested at u_a-u_w = 0 kPa (regime I), u_a-u_w = 17 kPa (regime II) 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 fallow and vegetated replicates, respectively, to enhance the number of repeats at the transition points between the saturated and transition moisture regimes. The matric suction was monitored in all samples by measuring the pore-water pressure with two UMS® T5 tensiometers (Figs. 1a-c) inserted at ca. 20 mm b.g.l. and connected to a Campbell CR1000 data-logger until they achieved the desired value for shear testing.

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

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

2.2. Soil-root mechanical reinforcement

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

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

2.3. Failure envelopes and suction stress function

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

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

2.4. Statistical analysis

The distribution density was plotted for all studied independent variables (i.e. c', ϕ', OM, ρ_b, σ^s, τ_{yield}, J, G, ε_{yield}) to check for normality. Kruskal-Wallis tests were carried out to infer statistical differences between the non-normally distributed variables and the two treatments (i.e. fallow and vegetated) while ANOVA tests were implemented for the normally distributed variables at 95% and 99% confidence levels. The same tests were used to find statistical differences between each independent variable and the tested hydrological regimes and normal stress levels, respectively. Where statistically significant differences were encountered, the differences within the groups were evaluated by means of Wilcoxon tests and t-tests for the non-normal and normally distributed variables, respectively. The same procedures were followed for the soil-root reinforcement indicators (i.e. J_{gain}, ΔS_y and RE_y). In addition, the correlation between these indicators and the OM was assessed by means of Pearson's correlation tests. The latter tests were also implemented to evaluate the potential relationships between all of the considered variables.

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

All statistical analyses were carried using the statistical software R 3.2.1 (R Core Team, 2015).

3. RESULTS

Table 1. Soil-root mechanical reinforcement properties for the three tested hydrological regimes (i.e. I: 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}: shear strength at yield point (kPa), ε_{yield}: strain at yield point (%), J_{yield}: deformation energy at yield point (J m^{-3}), J_{gain}: deformation energy gain for vegetated respect to fallow soil (J m^{-3}), G: shear modulus (kPa), ΔS_y: shear strength increase for vegetated respect to fallow soil (kPa), RE_y: root efficiency at yield point.

Treatment	u_a-u_w (kPa)	σ_N (kPa)	τ_{yield} (kPa)	ε_{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	-	-

3.1. Soil-root reinforcement

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

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

The hydrological regimes led to significant differences in terms of the root reinforcement efficiency (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 the transition moisture regime (II: 17 kPa). Moreover, the shear strength increase (ΔS_y; Table 1) also presented statistically significant differences with the moisture regimes (χ^2=6.49 df=2 $p<0.05$). Although no statistical differences were detected, a similar pattern was seen for the energy gain (J_{gain}; Table 1) between the considered treatments, normal stresses or moisture regimes.

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

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

3.2 Organic matter gain

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

3.3 Failure envelopes

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

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

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

Table 2. Shear strength parameters (c': apparent cohesion, ϕ': angle of internal friction), suction stress (σ^s), organic matter content (OM) and gain (OM_{gain}) for the different tested replicates, for which matric suction (u_a-u_w), gravimetric moisture content (*w*) and bulk density (ρ_b) at testing is indicated. Values indicate mean ± 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	14.16	17.86	0.97	-43.94	1.39 ±0.02	-
Fallow	78.60 ±9.71	12.43 ±0.29	1.53 ±0.15	55.47	19.61	0.96	-155.65	1.04 ±0.05	-
Vegetated	0.67 ±0.09	39.78 ±3.75	1.39 ±0.13	10.40	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	12.47	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	25.91	20.09	0.96	-70.84	2.44 ±0.24	1.28±0.24
Vegetated	78.46 ±0.76	11.32 ±1.98	1.17 ±0.07	51.46	25.31	0.74	-108.81	2.05 ±0.44	0.89 ±0.44

3.4 Suction stress

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

3.5. Correlation tests

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

4. DISCUSSION

4.1. Soil mechanical strength under fallow and vegetated conditions

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

However, the soil-root reinforced shear strength could also be explained by emergent soil structural and mechanical properties induced by the vegetation. For instance, the presence of roots affected the angle of internal friction when compared to the fallow soil (i.e. $\phi'_{vegetated}=1.2\phi'_{fallow}$; Table 2; Fig. 5a). This response contradicts the traditional belief that the presence of roots in the soil does not change ϕ' (Waldron and Dakesian, 1981; Gray and Ohashi, 1983; Ghestem et al., 2013). Roots do cause soil structural changes (Whalley et al., 2005) and, thus, changes in strength. In addition, roots, as a foreign material to the mineral soil, are likely to act as an additional friction agent to the intrinsic soil inter-particle friction, ultimately conferring more soil shear resistance (i.e. steeper envelopes; Fig. 5a). This claim is also supported by the fact that ϕ' was highly correlated with OM (see 3.2; Fig. 6), which experienced a consistent increase after only three weeks of vegetation growth (Table 2). The effect of the OM gain was also seen in the relatively strong observed correlation between OM and the deformation energy (J; Fig. 6), which tended to be consistently higher for the vegetated repeats (i.e. roots give ductility to the soil; Table 1). Counter intuitively to our other results, the OM seemed to present a high negative correlation with the strain at the yield point (ε_y; Fig. 6). This outcome is concurrent with previous studies (e.g. Mickovski et al. 2009; Mickovski et al. 2011) and supports the idea that the rooted soil strength is not fully mobilized until larger shear displacements. However, this effect should be treated with caution as the location of the yield point was not obvious in most cases; a known issue (Ghestem et al. 2013).

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

4.2. Soil-root reinforcement under different hydrological regimes

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

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

There are two main reasons that, independently or in combination, could be contributing to the observed results.

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

Secondly, root tensile strength may change under distinct root moisture contents, which, in turn, will vary depending on the surrounding soil´s moisture. The root tissues' mechanical behaviour will likely change depending on the tissue's cells hydration (e.g. Böhm, 1979; Stokes et al., 2008). As we have observed during root tensile strength tests (Tardio and Mickovski, 2016), roots tend to be stiffer and present a lower tensile strength when dry. Conversely, when roots are very wet, they tend to slip out from the tensile testing machine. Thus, optimum root moisture contents for the mobilisation of the maximum root tensile strength could exist and explain the observed results (Table 1; Figure 3). The former may also explain the observed bias at 13 kPa of u_a-u_w for the vegetated replicates tested (Fig. 5a), where the root moisture may have not been at its optimum despite the soil's transition regime conditions. The hypothesis of optimum root moistures is also supported by the G differences between the two treatments (Table 1). Roots should present a maximum elasticity (i.e. tensile strain) under optimum root moisture content (e.g. Ekevand and Axelsson, 2012). As a result, the soil-root composite should be more elastic too and, consequently, the vegetated repeats showed significantly higher G than the fallow repeats within the transition regime in all cases (Table 1).

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

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

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

4.3. Suction stress functions: hydrological reinforcement

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

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

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

Finally, it is worth noting that the closed-form equation of SSCC (Lu and Likos, 2004) was derived for soil only and not for plant-soil composite material, which is probably the largest source of variation in the observed data from the theoretical prediction. Only considering the data we observed for the three hydrological regimes (i.e. 0 kPa, 17 kPa and 78 kPa), a different function was analytically fitted for the vegetated soil taking into account the curve's graphical shape (Fig. 5c: full red line). The alternative function was implemented with the same hydro-mechanical parameters derived from the SWCC: $\sigma^s{}_{vegetation} = -n/\alpha(1-\exp(\alpha(ua-uw)) + c_R$. We recommend the use of this function for estimating the plant-derived soil hydrological reinforcement as opposed to the function derived from the experimental protocol (Fig. 5c; dashed green line) because it considers the hydro-mechanical parameters derived from the SWCC, it is consistent with the different soil hydrological regimes – it tends to become constant within the residual regime – and, it predicts a solid plant hydrological reinforcement compared to the fallow soil, as it is believed to occur in nature (Wilkinson et al., 2002). Nonetheless, further work is needed to establish reliable experimental protocols able to find expressions for predicting the soil hydrological reinforcement provided by vegetation, to shed light on the myriad changes that vegetation produce upon the soil's hydro-mechanical properties and to enhance our understanding on the behaviour of plant-soil composites.

5. CONCLUSIONS

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

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

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

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