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Assessment of plant-induced suction and its effects on the shear strength of rooted soils

Anil Yildiz Dr Sc.
Postdoctoral Researcher, Institute for Geotechnical Engineering, ETH Zurich, Zurich, Switzerland; Guest Researcher, WSL Institute for Snow and Avalanche Research SLF, Davos Dorf, Switzerland; Guest Researcher, Swiss Federal Institute for Forest, Snow and Landscape Research WSL, Birmensdorf, Switzerland (corresponding author: anil.yildiz@igt.baug.ethz.ch) (Orcid:0000-0002-2257-7025)

Frank Graf Dr Sc. Nat.
Scientific Staff Member, WSL Institute for Snow and Avalanche Research SLF, Davos Dorf, Switzerland

Christian Rickli MSc
Scientific Staff Member, Swiss Federal Institute for Forest, Snow and Landscape Research WSL, Birmensdorf, Switzerland

Sarah M. Springman CBE, FREng, MA, MPhil, PhD, DSc (h.c.) mult., DPhil (h.c.), DEng (h.c.), FICE, FWES, MInstRE, SIA
Professor, Institute for Geotechnical Engineering, ETH Zurich, Zurich, Switzerland

Shallow landslides, either on bare or vegetated slopes, can be triggered after a rainfall event due to loss of suction. An extensive laboratory programme was performed in this study to assess the relationships between water content, plant-induced suction, root biomass and shear strength parameters. Root-permeated soils, planted with combinations of different species, were tested in an inclinable large-scale direct shear apparatus. The effects of mycorrhizal fungi were also investigated with inoculated specimens. The results suggested that the root biomass, as well as root/shoot ratio, was an indicator of plant-induced suction and shear strength of root-permeated soils tested under laboratory conditions. Longer plant growth duration and more species yielded higher mean values of matric suction and normalised shear stress. Mycorrhizal fungi were found to be beneficial in improving the plant functions related to water uptake.

Notation

dx_{max}	shear displacement at which peak shear stress occurs
e	void ratio
F_C	corrected shear force
G_S	specific gravity
N	total normal force
N_{app}	applied normal load
N_{max}	maximum normal load at peak shear stress
S_r	degree of saturation
T	total shear force
u_a	atmospheric pressure
w_{avg}	mean water content
w_s	mean water content at the surface
w_{sz}	mean water content at the shear zone
$(u_a - u_w)_{final}$	matric suction at the end of shearing
$(u_a - u_w)_{peak}$	matric suction at peak shear stress
γ	bulk unit weight
γ_w	unit weight of water
$\Delta(\tau_{max}/\sigma_n)$	contribution of vegetation to the shear strength
σ_n	net normal stress
τ_{max}	peak shear stress
τ_{max}/σ_n	normalised shear stress

1. Introduction

The Van Genuchten (1980) closed-form equation establishes a link between the water content and the matric suction – that is, matric suction decreases with increasing water content in partially saturated soils. Increase in saturation degree of a slope by water, in the form of rainfall, snowmelt or rising groundwater, can cause loss of suction, which is considered to be the primary triggering effect of landslides (Highland and Bobrowsky, 2008), since a decrease in suction causes a reduction in shear strength (Vanapalli *et al.*, 1996).

Vegetation serves two main functions in terms of improving the slope stability. Mechanical contributions are related generally to the roots crossing a potential failure surface (Wu *et al.*, 1979), while hydrological contributions are attributed to both below- and above-ground biomass (AGB). Interception due to AGB reduces the infiltration, indirectly induces matric suction and delays the saturation process during rainfall (Leung *et al.*, 2015a; Ng *et al.*, 2016a). Evapotranspiration also reduces the water content of soil by water uptake by way of roots, which results in suction (Biddle, 1983). Furthermore, vegetation is known to alter soil-water retention characteristics (Leung *et al.*, 2015b) and also the soil permeability (Vergani and Graf, 2016).

Plant-induced suction has been studied in the field on vegetated slopes by monitoring matric suctions (Oorthuis *et al.*, 2018; Smethurst *et al.*, 2017; Springman *et al.*, 2013), in the laboratory during drying (Leung *et al.*, 2015b) or through drying–wetting processes (Ng *et al.*, 2013), as well as by performing probabilistic analyses based on field monitoring (Hazra *et al.*, 2017). These studies did not relate the plant-induced suction to the shear strength, but focused on the temporal or spatial changes of matric suction depending on varying conditions, such as compaction (Ng *et al.*, 2014), lighting conditions (Leung *et al.*, 2015b) and planting density (Ng *et al.*, 2016b). Accordingly, reports with a focus on the impacts of plant-induced suction on the shear strength of root-permeated soil are rare in the literature.

Direct evaluation of shear strength and plant-induced suction has been of interest recently. Small-scale (Gonzalez-Ollauri and Mickovski, 2017), large-scale (Veylon *et al.*, 2015) and in situ (Fan and Su, 2008) direct shear tests, as well as triaxial compression tests (Zhang *et al.*, 2010), have been used to investigate the shear strength, while penetration resistance was studied recently with a portable penetrometer (Boldrin *et al.*, 2017).

Plant-induced suction and shear strength of partially saturated root-permeated soils have been investigated mostly by working with monocultures, either in the laboratory (Ng *et al.*, 2014; Yan and Zhang, 2015) or in the field (Rahardjo *et al.*, 2014). Competition between the individuals within the same species (Ng *et al.*, 2016b) or the effects of different species in different boxes (Boldrin *et al.*, 2018) have also been studied. Ni *et al.* (2017) presented one isolated case with field monitoring on plots with one tree and one grass species. However, competition among species does not appear to have been evaluated in the same box under controlled and instrumented laboratory conditions, which is novel in this study. Higher species diversity with different plant functions can be expected to increase the matric suction and shear strength for the same plant growth duration compared to a soil with lower species diversity.

In addition to the roots, the biological system below ground consists of different micro- and macro-organisms constituting the soil biota (e.g. bacteria, fungi, algae, earthworms, insects), which are known to alter soil structure (Amézketa, 1999). Among these, mycorrhizal fungi are crucial in enhancing the plant growth by increasing both the above- and below-ground biomass. They also change the soil structure by contributing to soil aggregate stability (Graf and Frei, 2013). Therefore, it can be suggested that symbiosis between the host plant and the mycorrhizal fungi can improve the plant functions regulating the hydrological regime of the soil.

A laboratory test programme consisting of large-scale direct shear tests under partially saturated conditions was conducted within this study. The specimens under investigation were prepared with different plant species either inoculated with mycorrhizal fungi or not. The plants considered represented grasses, legumes, herbs and trees abundantly found in sub-alpine grasslands and pastures, and commonly used for eco-engineering measures. The objectives of this study were to evaluate the effects of plant growth duration and mycorrhizal fungi on the hydrological characteristics, in terms of matric suction and gravimetric water content, and the shearing behaviour of root-permeated soils.

2. Materials and methods

2.1 Study site and soil

Soil used in the experiments was obtained from a landslide location near Praettigau in the canton of Grison, Switzerland. The particle size distribution, after discarding particles greater than 20 mm, is illustrated in Figure 1(a), and was obtained from two samples from a main batch. The liquid limit (LL = 23·5%) and plastic limit (PL = 13·7%) were determined by applying the fall cone and thread-rolling methods, respectively (ASTM, 2010a). The plasticity index (PI) was 9·8%. The specific gravity (G_S) was determined by using a water pycnometer (ASTM, 2010b) as 2·69. Soil was classified as SC (clayey sand) according to the Unified Soil Classification System (USCS).

The soil-water retention curve (SWRC) of the fallow soil has been determined following the MIT technique (Toker *et al.*, 2004). A shear box was prepared in the same way as the planted specimens (see Section 2.4), and three samples were taken with a mould, 96 mm dia. and 120 mm high, to obtain the drying branch of the SWRC. Matric suction measurements of three specimens against the back-calculated water content values are plotted in Figure 1(b). The equation by Van Genuchten (1980) has been fitted to the mean values of the measurements using the R package 'minpack.lm', with fitting parameters given in Figure 1(b). Saturated hydraulic conductivity has been estimated as $8{\cdot}8 \times 10^{-9}$ cm/s using the equation of Mbonimpa *et al.* (2002) for plastic soils.

2.2 Testing programme

Treatments used in this study are shown in Table 1, while the information on the species used is given in Table 2. Four different treatments were chosen based on the plant species used, inoculation with mycorrhizal fungi and duration of growth. The biodiversity on a slope was mimicked by having two levels of plant diversity. 'Low plant diversity' (LP) consisted of *Poa pratensis* (L.), *Trifolium pratense* (L.) and *Alnus incana* (L.) Moench, while *Achillea millefolium* (L.), *Anthyllis vulneraria* (L.) and *Salix appendiculata* Vill., were used in addition to those in LP in 'high plant diversity' (HP).

The use of species of the genera *Salix* and *Alnus* in soil bioengineering applications has been reported under varying climatic conditions (Böll *et al.*, 2009; Lammeranner *et al.*, 2005; Rey and Burylo, 2014; Schaff *et al.*, 2002; Stangl, 2007). The other species are characteristic for subalpine grasslands and pastures (Jeangros and Thomet, 2004; Pohl *et al.*, 2009; Stampfli and Zeiter, 2004) and also applied in eco-engineering (Schiechtl and Stern, 1992). Some of the mechanical properties

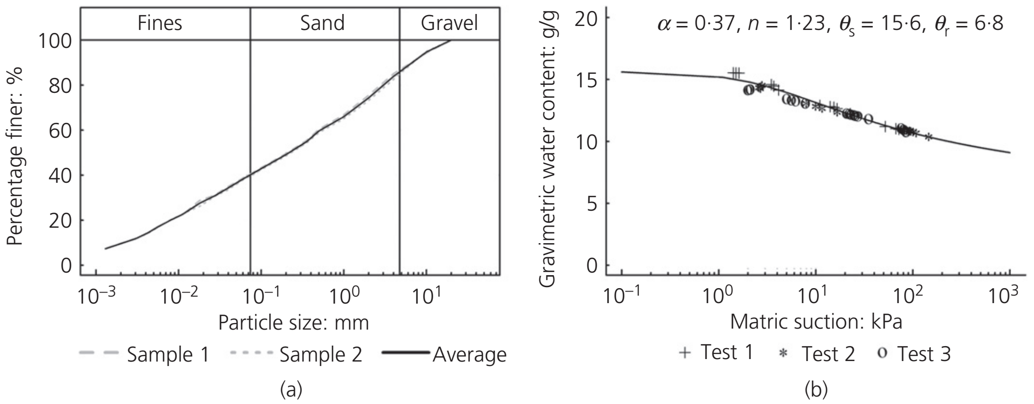


Figure 1. (a) Grain size distribution of Praettigau soil, classified as clayey sand based on USCS, obtained by a combination of wet sieving and hydrometer methods, performed on two samples from a main batch; (b) SWRC of the Praettigau soil and the fitting parameters for the equation of Van Genuchten (1980)

Table 1. Experimental programme and details of treatments

	Treatment 1	Treatment 2	Treatment 3	Treatment 4
Plant diversity	Low (LP)	Low (LP)	Low (LP)	High (HP)
Mycorrhizal fungi	No (LM)	No (LM)	Yes (HM)	No (LM)
Duration (months)	6	12	6	6
No. of tests × stress	2 × S1, 1 × S2, 2 × S3	2 × S1, 2 × S2	2 × S1, 2 × S2, 2 × S3	2 × S1, 2 × S2, 2 × S3
Specimen name	PLPLM6	PLPLM12	PLPHM6	PHPLM6

Table 2. Characteristics of the plant species and their use in the different treatments

Species	Plant type	Root type	Mycorrhiza type	Diversity level
P. pratensis (L.)	Grass	Non-woody	Arbuscular	Low/high
A. vulneraria (L.)	Legume	Non-woody	Arbuscular	High
T. pratense (L.)	Legume	Non-woody	Arbuscular	Low/high
A. millefolium (L.)	Herb	Non-woody	Arbuscular	High
A. incana (L.) Moench	Shrub/Tree	Woody	Arbuscular–ecto	Low/high
S. appendiculata Vill.	Shrub/Tree	Woody	Arbuscular–ecto	High

of the species used in this study can be found in Belfiore and Urciuoli (2004), Comino *et al*. (2010) and Gilardelli *et al*. (2017).

The effects of mycorrhizal fungi were investigated by adding an inoculated treatment into the testing programme. Two commercially available products ‘Forest’ and ‘Agri’ from INOQ were used together. This treatment was denoted as ‘High mycorrhizal fungi’ (HM), while non-inoculated treatments were denoted as ‘Low mycorrhizal fungi’ (LM). Plant growth duration was investigated by having 6 month and 12 month old treatments.

Treatments were named as follows: PHPLM6, PLPHM6, PLPLM12 and PLPLM6, where the first letter denotes the study site, the next four letters the plant and mycorrhizal fungi diversity and the last number is the growth duration. Furthermore, each specimen was also characterised based on the applied normal stress level (_S1, _S2 and _S3) and the number of repetitions (_1, _2 and _3). For example, the first specimen tested at the lowest applied normal load in PHPLM6 was denoted as PHPLM6_S1_1. In addition to the planted specimens, three unplanted specimens were tested under nearly saturated conditions for comparison.

2.3 Plant growth

Plant growth includes the following steps: germination, plant transfer and growth in the shear boxes. First, 100 mm dia. pots were filled for non-inoculated treatments with a 50–50 (by volume) peat–sand mixture of high water retention capacity. Inoculated treatments differ only in the germination phase. Commercial inoculum 'Forest' consists of arbuscular and ecto-mycorrhizal fungi with peat and expanded clay as the carrier material. 'Agri' consists of only arbuscular mycorrhizal fungi with vermiculite as the carrier material (INOQ GmbH, 2017a, 2017b). Equal volumes of two inocula were mixed with the peat–sand mixture in equal volumes in the germination pots.

Seeds were procured from the seed bank of the Swiss Federal Institute of Forest, Snow and Landscape Research WSL, placed randomly on the surface, and covered with a 1–2 mm thick peat–sand mixture. The pots were covered with petri dishes to prevent desiccation. The seedlings were left to germinate and grow in pots for 6–8 weeks. Four seedlings of each species were removed from the germination pots with care in order not to damage the roots, and then transferred to each of eight spots on the soil surface in the shear box (Yildiz *et al*., 2015). Each LP specimen consisted of 96 individual plants in total, which was doubled to 192 for HP specimens.

Planted shear boxes, as well as germination pots, were maintained in a climate-controlled chamber in a horizontal position for a total growth period of 6 months for PHPLM6, PLPHM6 and PLPLM6 and 12 months for PLPLM12. The temperature and humidity were maintained at 24°C and 70%, respectively, between the times of 5 a.m. and 8 p.m.; and 17°C and 55% for the remainder of the day. The germination pots were sprayed with 10 ml of water every day, while the boxes were watered with 1 litre of water, three times a week, in the first 2 months of growth. The watering frequency for the boxes was reduced to twice a week in the remaining growth period.

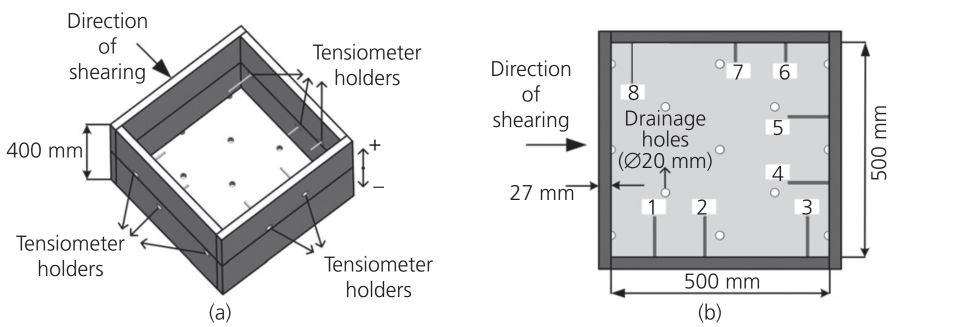
2.4 Sample preparation

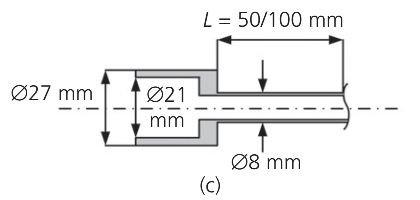
The samples were prepared in shear boxes built with 27 mm thick wood panels consisting of two halves, each having internal dimensions of $500 \times 500 \times 200$ mm. Figures 2(a) and 2(b) show the axonometric and top view of the shear boxes used in this study, respectively. The bottom part of the boxes contains 20 mm dia. holes to allow the water to drain, and was covered with a non-woven geotextile (Vivapol, 200 g/m^2) to prevent the loss of fine material. Stainless steel tensiometer holders were placed horizontally from the side of the box both above and below the shear zone on three sides of the box, excluding the side on which the shear force was applied. The cross-section of the tensiometer holders and the locations relative to the shear zone are given in Figures 2(c) and 2(d).

All samples were prepared with air-dried Praettigau soil. The boxes were filled with soil in three layers to 120, 220 and 300 mm from the bottom of the box. Yildiz *et al.* (2018) described the compaction method. Compacted specimens were then placed in a container filled with water and rinsed from the top as well. A homogeneous distribution of water with depth was assumed after the excess water was drained and the individual plants were transferred from the germination pots to the shear box.

2.5 Direct shear testing

Direct shear tests were performed with an inclinable large-scale direct shear apparatus (ILDSA), which was described in detail





Tensiometer holder	Distance to shear zone: mm
1, 4, 6	+20
2, 7	–50
3, 8	–25
5	+70

(d)

Figure 2. (a) Axonometric and (b) top-view of the shear box; (c) cross-section of the tensiometers holders and (d) distances of the centre-line tensiometers to the shear zone. Positive values are above the shear zone and negative values are below the shear zone. Tensiometer holders 1, 2, 3, 4, 5 and 8 extend 100 mm into the shear box, while 6 and 7 are 50 mm long

in Yildiz *et al.* (2018). Tests were performed with 1·50, 2·75 and 4·00 kN applied normal loads with a rate of shear displacement of 1 mm/min up to a shear displacement of 190 mm and at an inclination of 30° from the horizontal axis. Matric suctions were monitored throughout the test with tensiometers, UMS T5x, with a measuring range from 100 to −200 kPa and an accuracy of ±0·5 kPa (UMS GmbH, 2014). As soon as the test was finished, water content specimens were taken from the surface in a 3 × 3 grid, as well as from right above the shear zone, after removing the soil above the shear zone.

The AGB was cut prior to shearing as close as possible to the surface and separated according to the species. All the roots were dug out subsequent to sampling for water content, separated into those in the bottom and top boxes, and washed thoroughly to remove the soil particles. After that, the whole biomass was dried in an oven for 24 h at 105°C.

2.6 Data analysis

Data analyses were performed with the statistical software R 3.4.0 (R Core Team, 2017). Wilcoxon rank sum tests were applied to the parameters shown in Table 3 as post hoc tests at a significance level of $p < 0{\cdot}05$. Data from the sensors were recorded at 10 Hz and filtered to use every 50th data point, in order to reduce the noise and computation time.

Mean water content at the surface (w_s) and at the shear zone (w_{sz}) were calculated from nine samples of gravimetric water content from both surface (w_{s_1}, w_{s_2}, …, w_{s_9}) and shear zone (w_{sz_1}, w_{sz_2}, …, w_{sz_9})

1. $$w_s = \frac{1}{n}\sum_{i=1}^{n} w_{s\_i} (n = 9)$$

2. $$w_{sz} = \frac{1}{n}\sum_{i=1}^{n} w_{sz\_i} (n = 9)$$

Mean water content (w_{avg}) was taken as the average of w_s and w_{sz}. Bulk unit weight (γ) was calculated by dividing the weight of specimen by its volume. Void ratio (e) was obtained by using Equation 3.

3. $$e = \frac{G_s\gamma_w(1 + w_{avg}) - \gamma}{\gamma}$$

where G_s is the specific gravity of soil solids and γ_w is the unit weight of water. Degree of saturation (S_r) was calculated using Equation 4 with w_{sz}, as the measurements of matric suction were taken around the shear surface.

4. $$S_r = \frac{w_{sz} G_s}{e}$$

A combined frictional correction, based on Yildiz *et al.* (2018), and as explained in Supplementary Material 1, was applied to the measured shear force (F). Since the tests were performed at an inclined angle of 30° to the horizontal axis, the component of the weight of soil (W_{soil_top}) perpendicular to the shear zone was added to the applied normal force (N_{app}). The component of W_{soil_top} parallel to the shear zone was added to the corrected shear force (F_c). The total normal force (N) and shear force (T) were calculated, as described in Equations 5 and 6, respectively.

5. $$N = N_{app} + W_{soil\_top}\cos 30°$$

6. $$T = F_c + W_{soil\_top}\sin 30°$$

The maximum value of T between 0 to 80 mm of shear displacement was chosen as the maximum shear force (T_{max}). Total normal force and corresponding shear displacement

Table 3. Means ± standard deviation values of dry weight of AGB and roots, and root/shoot ratios for treatments

	PHPLM6	PLPHM6	PLPLM12	PLPLM6
Dry weight of roots: g				
Roots in top box	3·68 ± 1·60[a]	4·25 ± 0·93[a]	5·08 ± 3·01[a]	3·10 ± 0·99[a]
Roots in bottom box	0·63 ± 0·63[a]	0·60 ± 0·32[a]	0·45 ± 0·21[a]	0·62 ± 0·15[a]
Total	4·32 ± 2·17	4·85 ± 1·05	5·53 ± 3·18	3·72 ± 0·88
Roots in top/roots in bottom ratio	10·2 ± 6·66[a]	8·69 ± 4·36[ab]	11·8 ± 5·06[abc]	5·58 ± 3·34[ab]
Dry weight of AGB: g				
Woody AGB	0·67 ± 0·56[a]	3·00 ± 1·79[b]	2·78 ± 3·82[abc]	0·80 ± 0·62[ac]
Non-woody AGB	24·2 ± 8·54[a]	18·5 ± 2·25[ab]	27·2 ± 7·53[ac]	20·4 ± 5·25[abc]
Total	24·9 ± 8·74	21·5 ± 1·78	30·0 ± 7·14	21·2 ± 5·71
Non-woody/woody AGB ratio	52·2 ± 24·75[a]	10·8 ± 11·90[b]	27·3 ± 21·57[abc]	32·7 ± 15·52[ac]
Root/shoot ratio	0·17 ± 0·07[a]	0·23 ± 0·06[a]	0·18 ± 0·07[a]	0·18 ± 0·02[a]

Superscript letters indicate significance at $p < 0{\cdot}05$

at the point where T_{max} occurs were denoted as N_{max} and dx_{max}. An area correction was applied to both T_{max} and N_{max} to obtain maximum shear stress (τ_{max}) and net normal stress (σ_n), which are calculated as shown in Equations 7 and 8.

7. $$\tau_{max} = \frac{T_{max}}{[500 \times (500 - dx_{max})]}$$

8. $$\sigma_n = \frac{N_{max}}{[500 \times (500 - dx_{max})]} - u_a$$

where u_a is the atmospheric pressure.

A normalised shear stress (τ_{max}/σ_n) was calculated for each experiment as a ratio of τ_{max} and σ_n to provide a valid comparison across the stress levels (Casini *et al.*, 2011). Data from the unplanted experiments were analysed in the same way and the contribution of the vegetation to the shear strength, $\Delta(\tau_{max}/\sigma_n)$, was calculated as the difference of τ_{max}/σ_n from a planted and an unplanted specimen.

Data from tensiometers were recorded every 2 s with a separate data logger. Tensiometer readings were commenced prior to shearing, and the matric suction data were matched afterwards with data from the ILDSA by taking the initialisation of the shearing as the datum point. Subsequently, data at 100 s intervals were used for calculations. The average matric suction value in the last 30 min of shearing was denoted as $(u_a - u_w)_{final}$, and correlated with water content and saturation as the water content specimens were taken subsequent to testing. The matric suction value at the point when T_{max} occurred was denoted as $(u_a - u_w)_{peak}$, and taken for correlations with shear strength parameters.

3. Results

Data from all experiments are given in Yildiz (2017).

3.1 Biotic parameters

Means and standard deviations of biotic parameters are given in Table 3. Mean dry weights of total and non-woody AGB were highest in PLPLM12, while that of woody AGB was observed in PLPHM6. PLPLM12 contained the highest amount of mean root biomass, while PLPLM6 had the lowest. Mean root/shoot ratio was highest in PLPHM6, which had the lowest non-woody/woody AGB ratio and the highest root biomass among 6 month old treatments. Figures 3(a), (3(b) and 3(c) show the positive correlations of the dry weight of AGB ($R^2 = 0{\cdot}42$, $p < 0{\cdot}01$), dry weights of roots in the top box ($R^2 = 0{\cdot}97$, $p < 0{\cdot}001$) and in the bottom box ($R^2 = 0{\cdot}31$, $p < 0{\cdot}01$), respectively, with the dry weight of all roots.

3.2 Abiotic parameters

Table 4 summarises the hydrological and mechanical characteristics of the root-permeated soils at the end of the corresponding growth period of each treatment, as well as the fallow specimens, and the general trends of all experiments are depicted in Figures 4 and 5. The highest and lowest values of both $(u_a - u_w)_{final}$ and $(u_a - u_w)_{peak}$ were observed for PLPLM12 and PLPLM6, respectively. Consequently, PLPLM12 had the lowest mean values of w_{sz}, w_s, w_{avg}, while PLPLM6 had the highest mean values of the same parameters. PLPHM6 had the highest mean $(u_a - u_w)_{final}$ and $(u_a - u_w)_{peak}$ among the 6 month old treatments. The fallow specimens had higher water content values than all the treatments.

PHPLM6 had the highest mean τ_{max}, while the same values but different standard deviations were observed for the PLPHM6 and PLPLM12. PLPLM6 yielded the lowest mean τ_{max} value. However, PLPLM12 had higher mean value of τ_{max}/σ_n than the other treatments, while the PLPLM6 had the

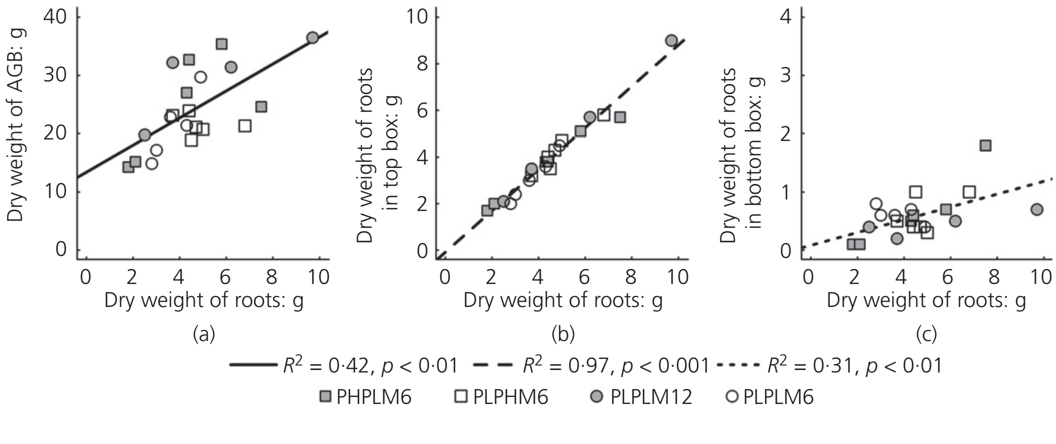


Figure 3. Relationships of (a) dry weight of AGB with roots and (b) roots in the top and (c) bottom halves of the shear box with the dry weight of all roots

Table 4. Means ± standard deviation values of hydrological and mechanical properties of treatments and fallow soil

	Fallow	PHPLM6	PLPHM6	PLPLM12	PLPLM6
Matric suction: kPa					
$(u_a - u_w)_{final}$	−0·15 ± 2·98	25·9 ± 18·2	32·3 ± 22·3	35·7 ± 41·9	17·4 ± 9·48
$(u_a - u_w)_{peak}$	−0·53 ± 3·45	26·0 ± 19·4	27·6 ± 7·66	36·7 ± 40·7	20·5 ± 5·47
Water content: %					
w_s	11·5 ± 1·65	10·5 ± 1·06	10·5 ± 0·82	9·69 ± 1·83	11·1 ± 0·91
w_{sz}	12·6 ± 0·96	10·9 ± 0·96	11·3 ± 1·34	10·3 ± 2·03	11·5 ± 0·88
w_{avg}	12·0 ± 1·22	10·7 ± 0·97	10·9 ± 1·03	9·99 ± 1·92	11·3 ± 0·84
γ: kN/m^3	20·42 ± 0·64	19·93 ± 0·28	19·99 ± 0·48	20·07 ± 0·81	19·97 ± 0·42
e	0·45 ± 0·03	0·47 ± 0·02	0·47 ± 0·03	0·45 ± 0·03	0·47 ± 0·02
S_r: %	75·8 ± 9·96	62·8 ± 5·85	65·6 ± 8·98	62·9 ± 15·9	65·8 ± 7·52
τ_{max}: kPa	5·97 ± 1·00	19·6 ± 7·50	17·9 ± 6·38	17·9 ± 8·40	15·1 ± 6·51
τ_{max}/σ_n	0·45 ± 0·14	1·61 ± 1·13	1·39 ± 0·57	1·86 ± 1·40	1·10 ± 0·27
$\Delta(\tau_{max}/\sigma_n)$	—	1·16 ± 1·08	0·94 ± 0·54	1·33 ± 1·37	0·65 ± 0·25

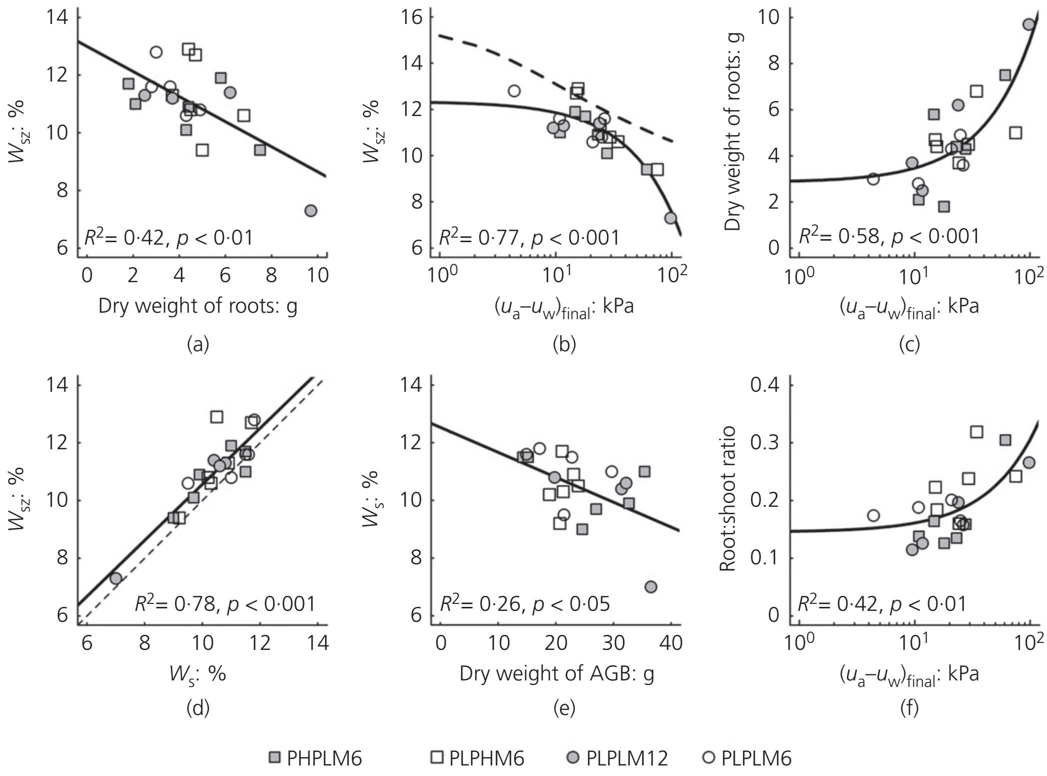


Figure 4. Relationships of water content at the shear zone, w_{sz}, with: (a) dry weight of roots; (b) matric suction at the end of shearing, $(u_a - u_w)_{final}$; (c) dry weight of roots and $(u_a - u_w)_{final}$; water content at the surface of the specimen, w_s with: (d) w_{sz} and (e) dry weight of AGB; and (f) root/shoot ratio and $(u_a - u_w)_{final}$. Solid lines show the linear regressions based on all specimens. Dashed curve in (b) shows the SWRC of the fallow soil, whereas in (d) it shows the 1–1 line

lowest mean value of τ_{max}/σ_n. The fallow specimens yielded τ_{max}/σ_n values of 0·58, 0·47 and 0·30 at applied normal loads of 1·5, 2·75 and 4 kN, respectively. All the planted specimens had higher τ_{max}/σ_n values than the fallow specimens. $\Delta(\tau_{max}/\sigma_n)$, was highest in PLPLM12 and lowest in PLPLM6 treatments. The maximum mean value of $\Delta(\tau_{max}/\sigma_n)$ was observed in the PHPLM6 treatment among the 6 month old treatments.

Figure 4 illustrates the relationships of w_{sz}, $(u_a - u_w)_{final}$, w_s, S_r and the dry weight of roots. w_{sz} was negatively correlated with the dry weight of roots ($R^2 = 0{\cdot}42$, $p < 0{\cdot}01$) and $(u_a - u_w)_{final}$ ($R^2 = 0{\cdot}77$, $p < 0{\cdot}001$). An increase in $(u_a - u_w)_{final}$ was observed with an increase in the dry weight of roots ($R^2 = 0{\cdot}58$, $p < 0{\cdot}001$). A positive correlation is depicted in Figure 4(d) between w_{sz} and w_s ($R^2 = 0{\cdot}78$, $p < 0{\cdot}001$). Dry weight of AGB was negatively correlated

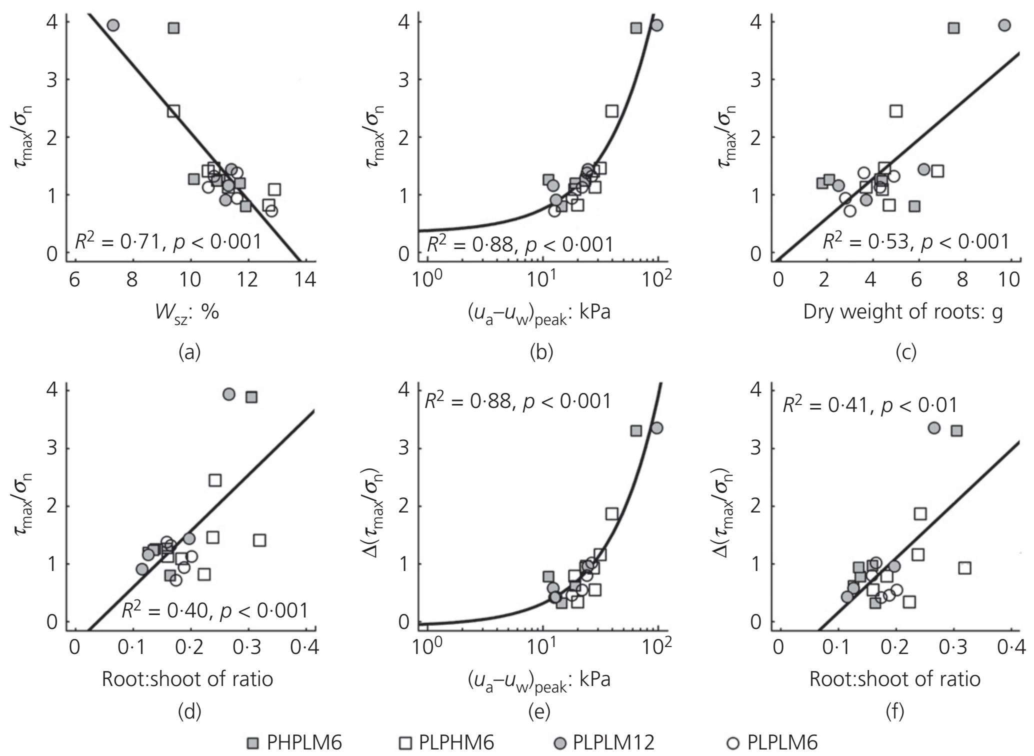


Figure 5. Relationships of normalised shear stress, τ_{max}/σ_n, with: (a) water content at the shear zone, w_{sz}; (b) matric suction at peak shear stress, $(u_a - u_w)_{peak}$; (c) dry weight of roots; and (d) root/shoot ratio. Relationships of contribution of vegetation to the shear strength, $\Delta(\tau_{max}/\sigma_n)$, with: (e) matric suction at peak shear stress, $(u_a - u_w)_{peak}$; and (f) root/shoot ratio

with w_s ($R^2 = 0{\cdot}26$, $p < 0{\cdot}05$). Finally, the root/shoot ratio was shown to be positively correlated with $(u_a - u_w)_{final}$ ($R^2 = 0{\cdot}42$, $p < 0{\cdot}01$).

The relationships of w_{sz}, $(u_a - u_w)_{peak}$, the dry weight of roots and root/shoot ratio with τ_{max}/σ_n are illustrated in Figure 5. Figure 5(a) shows that lower values of τ_{max}/σ_n were observed with increasing w_{sz} ($R^2 = 0{\cdot}71$, $p < 0{\cdot}001$), and with S_r ($R^2 = 0{\cdot}55$, $p < 0{\cdot}001$). τ_{max}/σ_n was positively correlated with $(u_a - u_w)_{peak}$ ($R^2 = 0{\cdot}88$, $p < 0{\cdot}001$), the dry weight of roots ($R^2 = 0{\cdot}53$, $p < 0{\cdot}001$) and root/shoot ratio ($R^2 = 0{\cdot}40$, $p < 0{\cdot}01$). Figures 5(e) and 5(f) show that $\Delta(\tau_{max}/\sigma_n)$ was positively correlated both with $(u_a - u_w)_{peak}$ ($R^2 = 0{\cdot}88$, $p < 0{\cdot}001$) and the root/shoot ratio ($R^2 = 0{\cdot}41$, $p < 0{\cdot}01$).

4. Discussion

4.1 Hydrological characteristics of root-permeated soils

Removal of water in the soil around the roots causes a decrease in water content (Aston and Lawlor, 1979), and water uptake is often assumed to be proportional to root biomass (Kulmatiski *et al.*, 2017). However, this assumption ignores the point that uptake rates may differ within a root system (Hodge, 2004). Figure 4(a) confirms that higher root biomass implies lower water content – that is, root biomass can still be an indicator of water uptake under the same growing conditions with varying species diversity. The negative correlation between w_{sz} and $(u_a - u_w)_{final}$, as shown in Figure 4(b), is consistent with other findings in the literature (Leung *et al.*, 2015b; Ng *et al.*, 2016a).

Matric suctions measured in this study are due to evapotranspiration: evaporation from the soil surface and transpiration through stomata. Furthermore, AGB acts as a shield over the soil surface and intercepts a considerable amount of rainfall, resulting in reduced infiltration (Dunkerley, 2000). However, direct evaporation is lower when vegetation cover is higher, due to the reduction of direct radiation (Ng *et al.*, 2016a; Yan and Zhang, 2015). As the dry weight of AGB is negatively correlated with w_s in this study, it can be argued that the interception due to AGB was more prominent than blocking the direct radiation with the corresponding decrease in soil evaporation. The effects of evaporation from the soil surface are also reflected in the differences between w_s and w_{sz}, the latter was higher, as shown in Figure 4(d).

The relationships of different plant traits with matric suction in partially saturated root-permeated soils have been studied, such as root length density (Boldrin *et al.*, 2017) and root area index (Ng *et al.*, 2016a; Ni *et al.*, 2017), all of which showed positive correlations with matric suction. Root biomass was the main root trait investigated in this study, and $(u_a - u_w)_{final}$ was positively correlated with the dry weight of roots. This is consistent with the aforementioned upward trends of matric suction with plant traits in the literature. Additionally, Ni *et al.* (2017) found a positive correlation with root area index and root biomass for mixed grass and tree species, and suggested that root biomass can be correlated with matric suction. The correlations of w_{sz} and $(u_a - u_w)_{final}$ with the root biomass found in this study also support the use of biomass as an indicator of hydrological characteristics of root-permeated soils. Furthermore, an increase in root/shoot ratio resulted in an increase in matric suction, suggesting that the hydrological functions of AGB and roots can be combined into root/shoot ratio.

Although root biomass may not be sufficient to represent all the root traits, it was still directly linked with evapotranspiration for crops (Kang *et al.*, 2002) – that is, higher biomass resulted in higher evapotranspiration values. Approximately 90% of the dry weight of a plant originates from the product of photosynthesis (Poorter *et al.*, 1990), and a higher photosynthesis rate was shown to yield a higher stomatal conductance (Tognetti *et al.*, 2004). Photosynthesis can be the underlying reason of the biomass–evapotranspiration relationship.

When the measured matric suctions and calculated water contents in Figure 4(b) are compared with the SWRC in Figure 1(b), the root-permeated specimens had lower water content than the fallow soil at the same matric suction. Root-permeated soils with lower water retention capacity than the unplanted specimens were documented with specimens at a low degree of compaction (Ng *et al.*, 2014) and with specimens at low planting density along the drying path, from tests carried out by Ng *et al.* (2016b). This reduction in the water retention capacity was attributed to the development of macropores during plant growth or root decay. Root decay was not an issue in these tests. Alterations in the pore structure of the soil can explain the variation in the water retention capacity of the rooted and fallow soil tested in this study.

4.2 Shearing behaviour of root-permeated soils

A striking feature seen in the shear force–displacement graphs, as depicted in the Supplementary Material (Figure S1), of the experiments in this study was that specimens with higher matric suctions showed a distinct peak shear force at low shear displacements, followed by a sharp decrease in shear force with increasing displacement. Specimens with lower values of suction did not show a clear peak and the maximum shear force occurred at larger displacements. This response was also reflected with the negative correlations of $(u_a - u_w)_{peak}$ with dx_{max} ($R^2 = 0{\cdot}60$, $p < 0{\cdot}001$).

Rahardjo *et al.* (2003) showed that the peak shear stress of residual soils was mobilised at smaller displacements when the matric suction was high due to the greater soil stiffness. Five out of 22 root-permeated specimens tested by Veylon *et al.* (2015) showed clear peaks in the shear stress against displacement plots. These specimens, all planted with *Ricinus communis*, had the lowest degree of saturation, implying higher matric suction, compared to the other treatments in the same study. Similarly, specimens with a low degree of saturation exhibited a peak shear stress at small shear displacements. The positive correlation between S_r and dx_{max} ($R^2 = 0{\cdot}52$, $p < 0{\cdot}001$) also supports this observation.

Decrease in τ_{max}/σ_n was observed with increasing w_s, w_{sz} and w_{avg}, similar to data from Fan and Su (2008) from in situ direct shear tests and Zhang *et al.* (2010) from triaxial tests. They related the reduction in shear strength to the loss of cohesion between the soil particles. Matric suctions were not measured in either of these two studies. Nevertheless, Figure 4(b) confirms that matric suction decreases substantially with increasing water content. The decrease in the shear strength can be attributed to the loss of suction with increasing water content.

Figures 5(c) and 5(d) suggest that normalised shear stress can be explained with root biomass and root/shoot ratio, respectively, although there are differences in plant growth duration and number of species. Relationships of angle of internal friction with organic matter, based on small-scale direct shear tests (Gonzalez-Ollauri and Mickovski, 2017), root reinforcement with root area ratio, based on large-scale direct shear tests (Veylon *et al.*, 2015) and penetration resistance with root/shoot ratio (Boldrin *et al.*, 2017) were reported.

The contribution of vegetation to the shear strength, $\Delta(\tau_{max}/\sigma_n)$, consists of the contribution of roots passing through the shear plane, plant-induced suction and alterations in soil structure due to mycorrhizal fungi on the shear strength. The fallow specimens were prepared under nearly saturated conditions, and no separation between hydric and mechanical contribution was made. Since both root biomass and matric suction were correlated with the normalised shear stress and maximum shear stress, similar trends were also found for $\Delta(\tau_{max}/\sigma_n)$, as shown in Figures 5(e) and 5(f).

4.3 Effects of treatments

Temporal effects, biodiversity and inoculation with mycorrhizal fungi were studied with different treatments. First of all, a principal component analysis (PCA) has been performed to understand which factors are crucial to the determination of the shear strength of root-permeated soil in unsaturated conditions, and the bi-plot is given in Figure 6. PCA showed that the first two principal components explain 71·2% of the variance in the data. The relatively small angles between $(u_a - u_w)_{peak}$, $(u_a - u_w)_{final}$, τ_{max}/σ_n and $\Delta(\tau_{max}/\sigma_n)$ show how

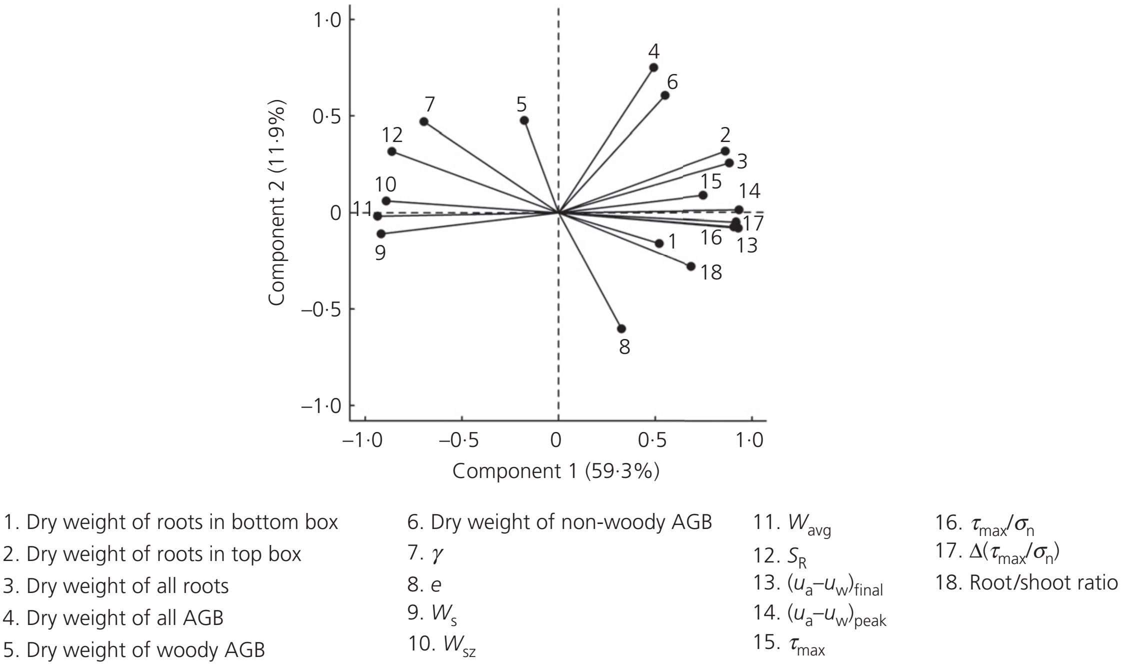


Figure 6. Principal component analysis on the vegetation, hydrological and shear strength parameters

closely these parameters (13, 14, 16 and 17 in Figure 6) are linked – that is, the shear strengths of the root-permeated soils tested in this study were controlled primarily by the plant-induced suction. Furthermore, water content of the soil (9, 10, 11 and 17 in Figure 6) is inversely related to matric suction and shear strength, as the angles between these parameters are close to 180°, underlining the water uptake functions of the plants. Parameters affecting the shear strength of the root-permeated soils were related to the root biomass and the root/shoot ratio.

Extending the plant growth duration, increasing the number of species and inoculation with mycorrhizal fungi resulted in higher mean values of root biomass and AGB, compared to the basic treatment, PLPLM6. Symbiosis between the host plant and mycorrhizal fungi is known to enhance the root growth (Graf *et al.*, 2015). Beglinger (2011) showed that inoculated specimens produced more roots than the basic treatment for the same time frame, although there were no significant differences in AGB. The average dry weights of roots were highest in PLPHM6 among the 6 month old treatments, similar to the findings of Beglinger (2011), while the AGB was not the highest. However, PLPHM6 had more woody AGB compared to the other treatments.

The contribution of mycorrhizal fungi can also be seen in the root/shoot ratios. Non-inoculated treatments yielded an average root/shoot ratio of 0·18, while the average value for the inoculated treatment, PLPHM6, was 0·23. The differences between the root/shoot ratios for the inoculated and non-inoculated treatments show the former produced more roots for the same amount of AGB. Boldrin *et al.* (2017) found that root/shoot biomass ratio explained best the matric suction and the penetration resistance for different woody species. Matric suction at peak shear stress, matric suction at the end of shearing and maximum shear stress were significantly and positively correlated with the root/shoot biomass in this study as well.

Genera *Salix* and *Alnus* are known to form symbiosis with both arbuscular and ecto-mycorrhizal fungi (Roy *et al.*, 2007; van der Heijden and Kuyper, 2003), while genera *Poa* and *Trifolium* achieve this only with arbuscular mycorrhizal fungi (Betekhtina *et al.*, 2016; Eriksson, 2001; Giovannetti *et al.*, 1988). The commercial products of INOQ used in this study contain arbuscular and ecto-mycorrhizal fungi. Individuals from genera *Salix* and *Alnus* probably profited particularly from the ecto-mycorrhizal fungal partners to produce the highest amount of woody AGB, compared to the non-woody plant species (grass, herb and legume), that are purely arbuscular mycorrhizal.

Symbiosis between the plants and the fungi did not directly increase the shear strength; however, it clearly affected the root/shoot ratio, which in turn affected the matric suction and shear strength. The limited contribution of the mycorrhizal fungi can be attributed to the rather short plant growth duration, as they were shown to be effective in terms of aggregate stability and root length density over a longer period compared to non-inoculated cases (Bast *et al.*, 2016).

Temporal effects on matric suction, water content and shear stress were mirrored by the PLPLM12 treatment in this study. Matric suction in root-permeated soil due to evapotranspiration was shown to increase, while the water content decreased with time and planting density, as illustrated by Ng *et al.* (2016b). The PLPLM12 treatment had a longer duration of plant growth than the other treatments, which yielded higher mean root biomass, lower water content values and higher matric suction values.

Although the highest mean maximum shear stress was obtained from the PHPLM6 treatment, the experiments for the PLPLM12 treatment were conducted only at the first two applied normal load levels. Thus, comparison of τ_{max}/σ_n among the treatments show that the highest mean τ_{max}/σ_n and $\Delta(\tau_{max}/\sigma_n)$ were observed for PLPLM12 specimens. The differences among the treatments resulted from the varying vegetation and hydrological regimes, and the effects of relative density were neglected as the void ratios of specimens did not differ significantly.

Finally, engineers can benefit from the findings in this research by reviewing the implications for slope stability in practice from the companion paper, in which a statistical analysis of variations in key parameters has been reported (Yildiz *et al.*, 2019).

5. Conclusions

Inter-relationships of water content, matric suction, normalised shear stress and root biomass, as well as the comparison of different treatments suggest the following.

- Both the AGB and below-ground biomass play an important role in regulating the water content and matric suction of the root-permeated soil through different mechanisms.
- Root biomass, as well as the root/shoot ratio, was an indicator of both matric suction and shear strength under laboratory conditions.
- Longer plant growth duration, higher number of species and the inoculation with mycorrhizal fungi increased the mean root biomass, and in turn, mean matric suction and shear strength of root-permeated soil.
- Inoculation with mycorrhizal fungi enhanced the different plant functions related to water extraction from the soil due to better growth performance of their hosts compared to non-mycorrhized plants, even for a limited plant growth duration.
- Further work related to this study and the corresponding investigated influencing factors should separately analyse their effects on hydrological and mechanical reinforcement.

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