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Manuscript title: Unsaturated hydraulic properties of vegetated soil under single and mixed planting conditions

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Abstract

Effects of plant roots on changes of soil hydraulic properties, including soil water retention curves (SWRC) and soil hydraulic conductivity functions (SHCF), are not well understood, especially when soil is unsaturated and vegetated with multiple plant species. This note aims to quantify the root effects on both SWRC and SHCF of silty sand using the instantaneous profile method. Four types of vegetated soil, namely bare, grass-only, tree-only and mixed tree-grass soils, were subjected to a controlled drying-wetting cycle in a plant room. Plant roots affect the air-entry value, saturated hydraulic conductivity and reduction rate of unsaturated hydraulic conductivity (with respect to suction) most significantly, but it does not affect the reduction rate of volumetric water content much. When planted with single species (grass or tree), the air-entry value of silty sand increased, while saturated hydraulic conductivity and reduction rate of unsaturated hydraulic conductivity with suction decreased. However, under the mixed planting conditions, opposite results are found.

Keywords: Partial saturation, hydraulic conductivity, vegetation, suction, seepage, water flow

Introduction

Vegetation is known to affect the hydrology and hence stability of earth infrastructure such as man-made slopes (Osman & Barakbah, 2011; Smethurst et al., 2015). Plant roots cause changes in soil matric suction (Simon & Collison, 2002; Veylon et al., 2015; Ng et al., 2016a; Ni et al., 2017) through evapotranspiration and soil hydraulic properties, including soil water retention curve (SWRC) and soil hydraulic conductivity function (SHCF). Some studies (Table 1) showed an increase in water retention capability when plant roots are present in the soil (Scanlan & Hinz, 2010; Rahardjo et al., 2014; Leung et al., 2015; Ng et al., 2016a, b; Jotisankasa & Siririrattanachat, 2017), probably because of the blockage of soil pore space by roots (Buczko et al., 2007). However, some studies reported an opposite result (Ng et al., 2016a; Jotisankasa and Sirirattanachat, 2017), arguably because of the formation of soil cracks due to, for instances, repeated soil shrinkage, swelling and root decay and growth (Vergani & Graf, 2015; Ng et al., 2016a; Ni et al., 2017; Leung et al., 2017).

There is a dearth of test data about the effects of plant roots on SHCF (Table 2). Jotisankasa and Sirirattanachat (2017) shows that root effects on hydraulic conductivity were prominent only when matric suction was less than 10 kPa, whereas the hydraulic conductivity measured by Song et al. (2017) found that roots affect unsaturated hydraulic conductivity for the entire suction range considered (< 100 kPa). Thus, the presence of plant roots does not necessarily always reduce or increase unsaturated hydraulic conductivity, depending both on the plant and soil types. Indeed, although Rahardjo et al. (2014) and Jotisankasa & Sirirattanachat (2017) tested the same grass type, the soil hydraulic properties of the vegetated soils measured were different possibly because of the different soil types considered in these two studies. Moreover, there is also a lack/no study that investigates the effects of multiple plant functional groups (i.e., mixed planting of herbaceous and woody species that typically exists in the field) on both SWRC and SHCF (Tables 1 and 2).

This study aims to investigate the unsaturated hydraulic properties of soil with four different vegetation covers (i.e., bare, grass-only, tree-only and mixed tree-grass planting). Replications of instrumented soil columns were subjected to controlled drying/wetting cycle, the results of which were used to determine the root effects on SWRC and SHCF via the instantaneous profile method. Any plant-induced changes in the two soil hydraulic properties were interpreted with plant root traits.

Materials and methods

Soil

Completely decomposed granite (CDG; silty sand, SM) was used for testing. At a dry density of 1777 kg/m^3 (the compaction level considered in this study), the saturated hydraulic conductivity, k_s, of the CDG was 1.4×10^{-6} m/s. Other index properties are summarised in Table 3.

Plants

A tree (*Schefflera heptaphylla*; Ivy tree) and a grass (*Cynodon dactylon*; Bermuda grass) species were selected for testing. These species are ecologically suitable for slope rehabilitation and restoration in many parts of the Asia (GEO, 2011). Before transplantation, tree individuals with shoot length of 800 ± 35 mm (mean ± standard error of mean) and root depth of 140 ± 15 mm were provided by Tung Kee Garden Horticulture Ltd. in Hong Kong. Grass turf with shoot length of 50 ± 12 mm and root depth of 40 ± 14 mm were used for testing.

After transplantation, the plants were left grown for four months in a plant room (relative humidity 60 ± 5%, air temperature 25 ± 1 ^{o}C; radiant energy 120 (μmol/m^2/s) for facilitating plant growth (Ng et al., 2016a). During the growing period, all bare and planted columns were irrigated every three days so that the soil moisture content was close to the field capacity of the CDG (20%–22% by mass).

Test setup and instrumentation

Soil columns (400 mm height and 200 mm diameter; Fig. 1), were constructed for this study. The CDG was compacted to the column up to a depth of 350 mm at a dry density of 1777 kg/m^3. There were drainage holes made at the bottom of each column for free drainage. In total, nine planted columns were constructed, three for tree-only case, three for grass-only case and three for mixed tree-grass plantation. One bare column was prepared as control.

A vertical array of miniature-tip tensiometers (2100 F, Soil Moisture Equipment Cooperation) was installed in each column to measure negative pore water pressure or matric suction (Fig. 1). At the same instrument depths, an array of four calibrated soil moisture probes (SM 300, Delta-T Device Ltd) were installed to measure the soil volumetric water content (VWC).

Test procedures

After 4-month of growing, the surface of all planted and bare columns were ponded with water until basal percolation was observed and suction at all instrumented depths became zero. Then, all columns were left in the plant room for evapotranspiration for six days (referred to as drying test). Subsequently, the ten columns were ponded again, but with a controlled constant water head of 20 mm for two hours using a Mariotte's bottle (referred to as wetting test). During both drying and wetting tests, the bottom holes of each column remained open for free drainage. Responses of suction, VWC and any basal percolation were recorded continuously.

After testing, root traits including root volume and root depth were measured from each planted column, following the procedures described by Reubens (2010). Root volume ratio, R_v, was obtained by normalising the measured root volume by the soil volume of that depth range.

Interpretation methods

Soil water retention curve (SWRC) of each column was obtained by relating the measured suction and VWC at the same instrument depth. Volumetric water content of each SWRC was divided by the soil porosity to obtain degree of saturation, assuming that there is no soil volume change upon drying and wetting processes. Indeed, element tests performed by both Chiu & Ng (2012) and Leung & Ng (2016b) show that CDG compacted to a similarly high dry density to that of the present study has negligible volume change when suction is less than 100 kPa. Moreover, there was no observed collapse during the first wetting. Each SWRC was fitted by the equation proposed by van Genuchten (1980):

$$S_r = \left[1 + \left(\frac{s}{a}\right)^n\right]^{-m} \quad (1)$$

where S_r is the soil degree of saturation; s is matric suction; a is related to the air entry-value (AEV); n and m control the shape of an SWRC.

SHCF of each column was determined by the instantaneous profile method (Watson, 1966; Ng and Leung, 2012; Leung et al., 2016a). The measured SHCF was then compared with the equation proposed by van Genuchten (1980):

$$k_r = {S_r}^{0.5}[1-(1-{S_r}^{\frac{1}{m}})^m]^2 \quad (2)$$

where k_r is the relative soil hydraulic conductivity, which is the ratio between soil hydraulic conductivity k and saturated hydraulic conductivity k_s.

k_s of each vegetated case was determined by back-analysing the suction data obtained during the wetting phase of each test using the numerical model developed by Shao et al. (2017). The k_s value is summarised in Table 3. Statistical analysis was performed using Microsoft Excel. Significant differences were assessed with one way-ANOVA, followed by post hoc Fisher’s least significant difference test. Results were considered statistically significant when p-value ≤ 0.05. Different letters (i.e., a, b, c and d) were used to indicate statistical significance of differences among groups when p-value is ≤ 0.05. This means that when any two groups (e.g., suction in bare and grass-only soil) have the same letter, they have no statistical difference. On the contrary, when they have different letters, the groups are significantly different statistically.

Results and discussion

Plant root traits

R_v of grass roots distributed almost linearly along depth, peaked at the soil surface (Fig. 2). On the other hand, trees have parabolic distribution of R_v, with the maximum R_v located approximately at the mid-depth of their root zone. The peak R_v of trees was almost 70% larger than that of grass in both single- and mixed planting conditions. In the top 85 mm, R_v of trees is statistically significantly higher than that of grasses (p-value < 0.01). Whether the trees and grasses were planted individually or together (i.e., mixed plantation) has minimal change on the R_v (Fig. 2).

When grown in relatively coarse soil (e.g., silty sand tested in this study), plant roots tend to grow laterally for exploring greater soil volume for resources such as water and nutrients (Hamer et al., 2016). On the contrary, due to the relatively poor aeration and low hydraulic conductivity in fine-grained soil, root growth would be more restricted and localised (Travlos & Karamanos, 2006).

Soil water retention curves

Figure 3(a) shows the measured and fitted drying SWRCs of the bare, grass-only and tree-only soils. SWRCs of grass-only and tree-only soils are similar to each other (Table 4), and the amount of VWC retained for a given suction in these vegetated cases is statistically higher than that of the bare soil (p-value < 0.001). Although the parameter n which describes the desorption rate of SWRC is similar between the bare and vegetation soils, the parameter a (which controls AEV) of both vegetated soils is noticeably lower than that of the bare case. This is consistent with the models proposed by Scanlan & Hinz (2010) and Ng et al. (2016b), who hypothesizes that root occupancy in the pore space of coarse-grained soil would reduce the soil pore diameter, causing an increase in matric suction according to the capillary law. Indeed, the root diameter range, for both grass and tree, is 0.15 – 2 mm. Recalling the capillary law and for a given surface tension, this diameter range affects soil pore space that corresponds to a low range of matric suction no more than 2 kPa. However, for fine grained soil with clay content > 12%, there are many factors possibly affecting the soil hydraulic properties, such as the release of organic matter as root exudates in the rhizosphere (Helliwell et al., 2014), soil aggregation due to plant-bacteria interaction in soil (Horn and Smucker, 2005) or/and formation of micro-cracks/fissures associated with continual drying-wetting process due to root-water uptake (Daly et al., 2015).

The SWRCs of tree-only soils reported by Ng et al. (2016a) are superimposed in Fig. 3(b). They tested the same tree species and soil type as the present study and obtained the SWRC from soil that was planted with multiple trees with different spacing (60 and 180 mm; namely test S60 and S180). When the tree spacing was wide, the SWRC was similar to that of single tree-only soil in the present study (Table 4). This is because the tree spacing is wide enough that the growth and water uptake action from each tree individual were not affected by the neighbouring trees (Ng et al., 2016a). For closer tree spacing, the water retention capability reduced as compared to the bare soil. The SWRC of this close tree spacing case is similar with the one obtained under mixed planting condition in this study. In both occasions, root decay is observed due to the competition of interspecies (tree-grass) and intra-species (tree-tree). This has created soil macro-pores (Ghestem et al., 2011), causing not only an increase in saturated hydraulic conductivity but also a reduction of water holding capacity.

Unsaturated soil hydraulic conductivity

Figure 4(a) compares the relative drying SHCFs, k_r, (i.e., normalized by k_s of the respective case). Each SHCF is obtained at 50 mm depth within root zone, so any root effects can be investigated. Both Fig. 4(a) and Table 5 show that the reduction rate of k_r with respect to an increase in suction (parameterized by the parameter *n*), decreased in grass- and tree-only cases, but increased in the mixed-species cases (p-value < 0.001). This means that the presence of plant roots, depending on the plant types and planting method (i.e., single versus mixed), does not only affect the AEV, but also plays a prominent role to affect the ease of water flow in unsaturated soil (see both the fitting parameters *a* and *n* in Table 5; p-value < 0.001).

In Fig. 4(b), the best-fitted SHCFs of the four cases are compared with the predicted ones based on the best-fitted SWRC and k_s using the van Genuchten (1980) equation. Not surprisingly, the best-fitted and predicted k_r for the bare soil has only a small difference. However, evidently, for tree- and grass-only cases, the predicted reduction rate of k_r is greater than the best-fitted one. On the contrary, for mixed tree-grass soil, the predicted reduction rate of k_r is less than the best-fitted case. Comparison of the results in Tables 4 and 5 reveals that for a given vegetated condition, the fitted parameters for SWRC are not always the same as those for SHCF. This implies that the presence of plant roots changed the soil pore size and its distribution, which are the fundamental properties that govern soil water retention and hydraulic conductivity (Scholl et al., 2014; Ng et al., 2016b). Indeed, most existing predictive equations of SHCF, including that suggested by van Genuchten (1980; Eqs (1) and (2)), do not take into account the root effects on the changes of soil pore size distribution and hence soil hydraulic properties. Based on the comparison in Figs 4(a) and (b), it may be important to link both the parameters *a* and *n* in the van Genuchten (1980) equation, or equivalent parameter that describes the reduction rate of k_r in other prediction equations, with root trait(s).

Concluding remarks

This study used the instantaneous profile method to quantify the effects of plant roots on unsaturated hydraulic properties of vegetated soil, under single- and mixed-species planting conditions. Water retention ability of both the tree-only and grass-only soils was greater than

that of the bare soil. Although there was no discernible difference in terms of the rate of water desorption, the air-entry value of silty sand increased substantially due to the presence of roots. However, under mixed-species planting where root decay was found, vegetated soil showed evident reduction of the air-entry value. Compared with the bare soil, soils planted with single species reduced saturated hydraulic conductivity, whereas soils with mixed-species planting showed an increase due to preferential flow through soil macro-pores associated with root decay. Prediction of soil hydraulic conductivity function based on known soil water retention curve using existing equation works well for bare soil, but there are discrepancies with measurements for all vegetated soil cases, either single- or mixed-species planted. The rate of reduction of hydraulic conductivity is substantially overestimated for the tree- and grass-only cases, while underestimated for mixed planting case.

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NOTATION

k	Soil hydraulic conductivity
k_r	Relative soil hydraulic conductivity
k_s	Saturated hydraulic conductivity
R_v	Root volume ratio
s	Matric suction
S_r	Degree of saturation of soil
a	Fitting parameter in van Genuchten (1980)’s equation
m	Fitting parameter in van Genuchten (1980)’s equation
n	Fitting parameter in van Genuchten (1980)’s equation

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Table 1. Summary of existing studies on the effects of plant on SWRC

Plant species	**Soil type**	**Dry density (Mg/m^3)**	**Observed plant effects**	**Reference**
Orange Jasmine (*Murraya paniculata*); Vetiver grass (*Chrysopgon zizanioides*)	Poorly graded sand (SP)	1.31	Water retention capacity increased in both vegetated soils	Rahardjo et al. (2014)
Ivy tree *(Schefflera heptaphylla)*	Silty sand (SM)	1.49	Vegetated soil has higher air-entry value but similar desorption rate, compared with bare soil	Leung et al. (2015)
Ivy tree *(Schefflera heptaphylla)*	Silty sand (SM),	1.78	Water retention capacity increased at intermediate (e.g., 120 mm) and wide plant spacing (e.g., 180 mm) but it reduced at close plant spacing (e.g., 60 mm).	Ng et al. (2016a)
Vetiver grass (*Chrysopgon zizanioides*)	Low plasticity Silt (ML)	1.31	Air-entry value increased with root biomass but then decreased at certain threshold root biomass	Jotisankasa and Sirirattanachat (2017)

Table 2. Summary of existing studies on the effects of plant on unsaturated SHCF

Plant species	**Soil type**	**Dry density (Mg/m^3)**	**Observed plant effects**	**Reference**
Vetiver grass (*Chrysopgon zizanioides*)	Low plasticity Silt (ML)	1.31	Root induced changes in SHCF mainly within low matric suction range less than 10 kPa	Jotisankasa and Sirirattanachat (2017)
Bermuda grass (*Cynadon dactylon*); Vetiver grass (*Chrysopgon zizanioides*)	Lean clay (CL)	1.38	Unsaturated hydraulic conductivity of soil vegetated with either Bermuda or Vetiver grass is higher than that of bare soil at any given suction	Song et al. (2017)

Table 3. Index properties of completely decomposed granite (CDG)

Index properties	**Value**
Standard compaction tests	
Maximum dry density: kg/m^3	1870
Optimum moisture content: %	12
Particle-size distribution	
Gravel content (>2mm): %	19
Sand content (≤2mm): %	42
Silt content (≤63μm): %	27
Clay content (≤2μm): %	12
Specific gravity	2.60
Atterberg limit	
Plastic limit: %	26
Liquid limit: %	44
Plasticity index: %	18
[1]Permeability k_s	
Bare (m/s)	1.4×10^{-6}
Grass-only soil (m/s)	$(4.2\pm0.8)\times10^{-7}$
Tree-only soil (m/s)	$(3.3\pm0.6)\times10^{-7}$
Mixed tree-grass soil (m/s)	$(9.6\pm1.1)\times10^{-6}$
[2]Unified Soil Classification System (USCS)	Silty sand (SM)

[1] According to falling-head hydraulic conductivity test outlined in ASTM (2010b)

[2] According to Unified Soil Classification System (USCS; ASTM 2010a)

Table 4. Statistical testing of the fitting parameters of SWRC using van Genuchten (1980) equation for the four treatments examined in this study and data from Ng et al. (2016a)

Test	**a**	**n**	**m**
B (this study)	8±1.0c	1.14±0.01a	0.12±0.01a
G (this study)	5±1.0b	1.13±0.02a	0.12±0.02a
T (this study)	3.5±0.5ab	1.13±0.01a	0.12±0.01a
M (this study)	13.0±1.4d	1.15±0.03a	0.13±0.02a
S60 (Ng et al., 2016)	12.1±1.5d	1.16±0.03a	0.15±0.02a
S180 (Ng et al., 2016)	1.8±0.4a	1.17±0.02a	0.14±0.01a
p-value	<0.001	0.384	0.462

Table 5. Statistical testing of the fitting parameters of SHCF using van Genuchten (1980) equation

Test	**a**	**n**	**m**
B (this study)	8±1.0c	1.13±0.01c	0.12±0.02b
G (this study)	5±1.0ab	1.03±0.01ab	0.03±0.01a
T (this study)	3.5±0.5a	1.01±0.01a	0.01±0.002a
M (this study)	13±1.4d	1.27±0.03d	0.2±0.02c
p-value	<0.001	<0.001	<0.001

Figure captions:

Figure 1. Schematic diagram and overview of the planted soil columns. All unit is expressed in mm

Figure 2. Distributions of root volume ratio in different soil treatments

Figure 3. Measured and fitted SWRCs of (a) bare, grass-only and tree-only soil and (b) mixed tree-grass soil together with the data from Ng et al. (2016a) for tree-only soil

Figure 4. (a) Measured and best-fitted SHCF and (b) comparisons of fitted and predicted SHCF of the four treatments

Figure 1_Lab picture

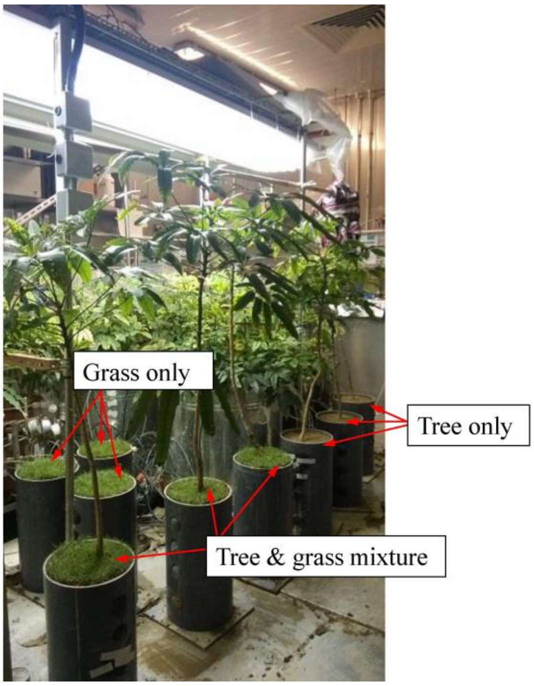


Figure 1_Schematic

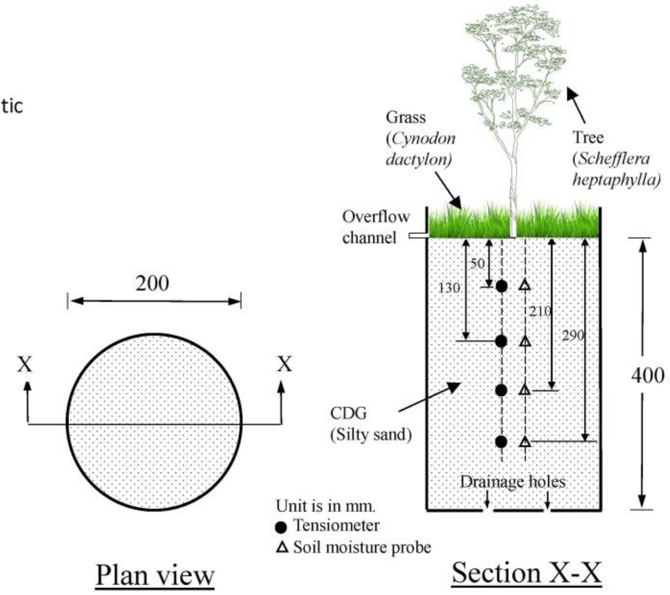


Figure 2

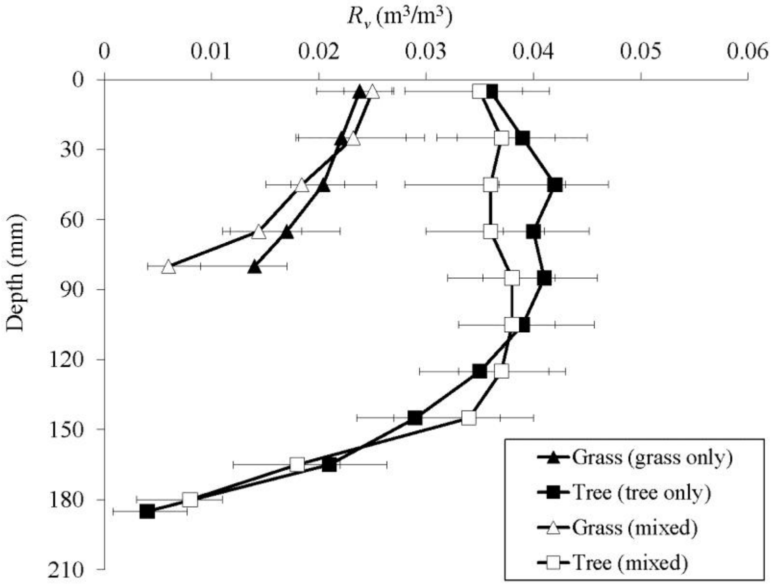

R_v (m³/m³)
0
0.01
0.02
0.03
0.04
0.05
0.06
Depth (mm)
0
30
60
90
120
150
180
210
Grass (grass only)
Tree (tree only)
Grass (mixed)
Tree (mixed)

Figure 3a

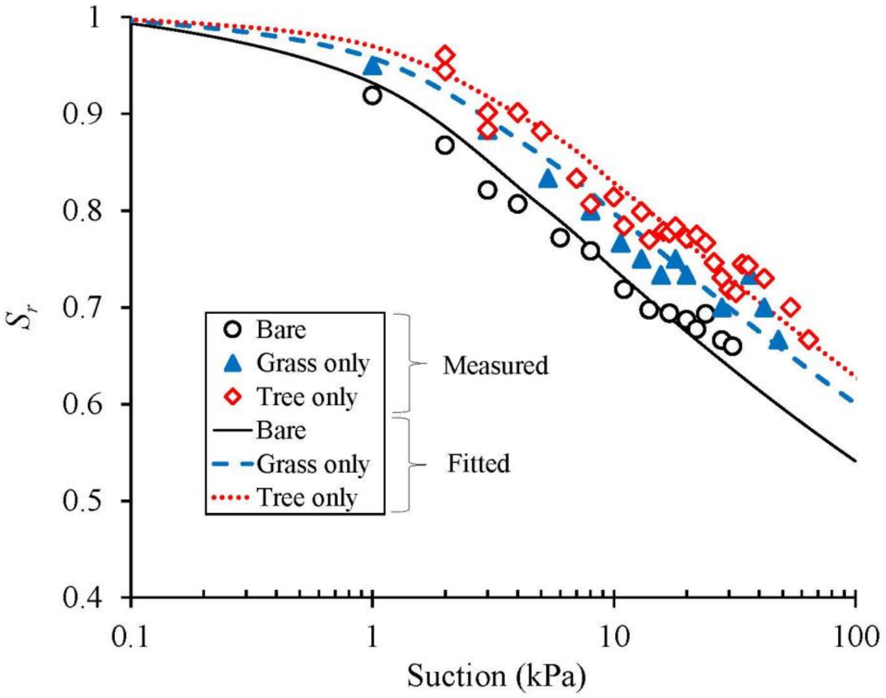

1
0.9
0.8
0.7
0.6
0.5
0.4
S_r
0.1
1
10
100
Suction (kPa)
Bare
Grass only
Tree only
Measured
Bare
Grass only
Tree only
Fitted

Figure 3b

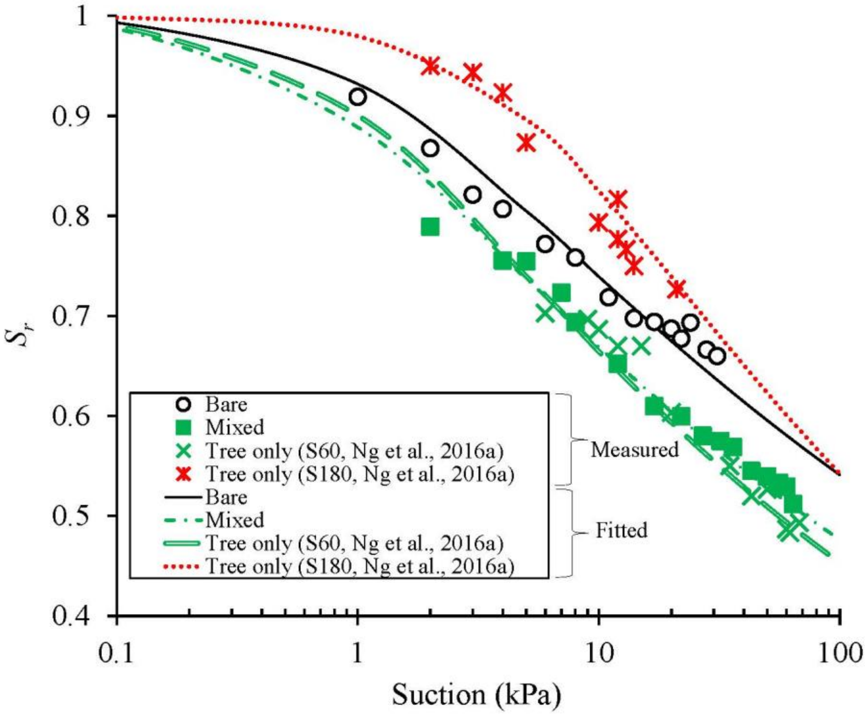

1
0.9
0.8
0.7
0.6
0.5
0.4
S_r
0.1
1
10
100
Suction (kPa)
Bare
Mixed
Tree only (S60, Ng et al., 2016a)
Tree only (S180, Ng et al., 2016a)
Bare
Mixed
Tree only (S60, Ng et al., 2016a)
Tree only (S180, Ng et al., 2016a)
Measured
Fitted

Figure 4a

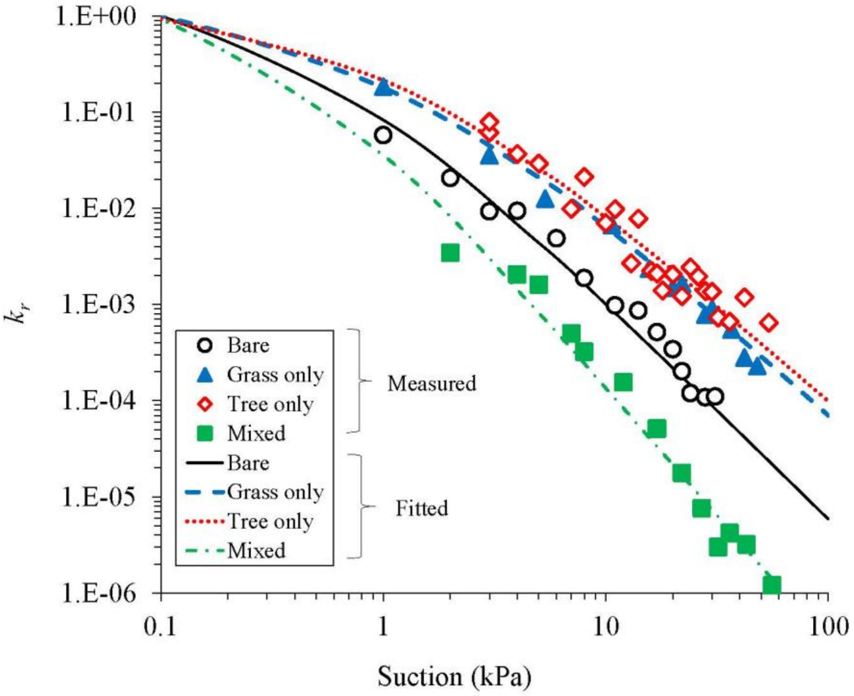
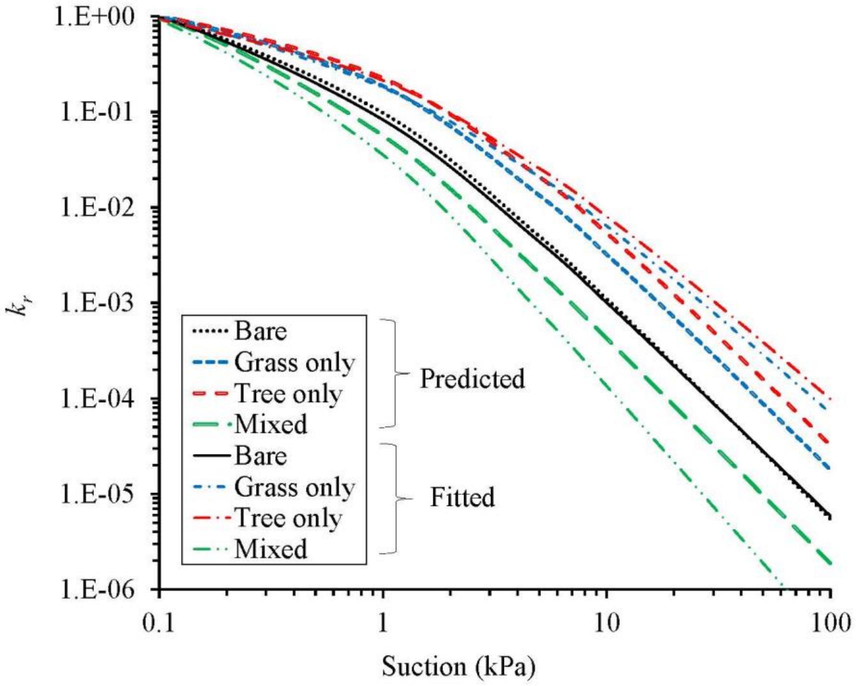

1.E+00
1.E-01
1.E-02
1.E-03
1.E-04
1.E-05
1.E-06
k_r
0.1
1
10
100
Suction (kPa)
Bare
Grass only
Tree only
Mixed
Measured
Bare
Grass only
Tree only
Mixed
Fitted

Figure 4b


1.E+00
1.E-01
1.E-02
1.E-03
1.E-04
1.E-05
1.E-06
k_r
0.1
1
10
100
Suction (kPa)
Bare
Grass only
Tree only
Mixed
Predicted
Bare
Grass only
Tree only
Mixed
Fitted