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Effects of the roots of *Cynodon dactylon* and *Schefflera heptaphylla* on water infiltration rate and soil hydraulic conductivity

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1 **Effects of the roots of *Cynodon dactylon* and *Schefflera heptaphylla* on water infiltration**
2 **rate and soil hydraulic conductivity**

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1 **Abstract**

2 Water infiltration rate and hydraulic conductivity in vegetated soil are two vital hydrological
3 parameters for agriculturists to determine availability of soil moisture for assessing crop growths
4 and yields, and also for engineers to carry out stability calculations of vegetated slopes.
5 However, any effects of roots on these two parameters are not well-understood. This study aims
6 to quantify the effects of a grass species, *Cynodon dactylon*, and a tree species, *Schefflera*
7 *heptaphylla*, on infiltration rate and hydraulic conductivity in relation to their root characteristics
8 and suction responses. The two selected species are commonly used for ecological restoration
9 and rehabilitation in many parts of Asia and U.S. A series of in-situ double-ring infiltration tests
10 was conducted during a wet summer, while the responses of soil suction were monitored by
11 tensiometers. When compared to bare soil, the vegetated soil has lower infiltration rate and
12 hydraulic conductivity, due to the clogging of soil pore by plant roots. This results in at least
13 50% higher suction retained in the vegetated soil. It is revealed that the effects of root-water
14 uptake by the selected species on suction were insignificant due to the small evapotranspiration
15 (< 0.2 mm) when the tests were conducted under the wet climate. There appears to have no
16 significant difference (less than 10%) of infiltration rates, hydraulic conductivity and suction
17 retained between the grass-covered and the tree-covered soil. However, it is identified that the
18 grass and tree species having deeper root depth and greater root area retained higher suction.

19 **Keywords:** water infiltration rate, hydraulic conductivity, vegetation, soil suction

1 **Introduction**

2 In a hydrological cycle, water infiltration rate and hydraulic conductivity of vegetated soil are
3 two important parameters governing surface runoff, soil moisture/soil suction in vadose zone and
4 recharge of groundwater table. Quantifying the two hydrological parameters and the associated
5 suction response in soil are important for ecologists to figure maintenance of ecosystems such as
6 wetlands (Eldridge and Freudenberger, 2005; Colloff et al., 2010), and for engineers to analyze
7 suction distribution for stability calculations of vegetated soil slopes (Indraratna et al., 2006;
8 Genet et al., 2010). Water infiltration rate and hydraulic conductivity of vegetated soil are also
9 crucial for agriculturists to determine the availability of soil moisture for assessing crop yields
10 and to more accurately devise irrigation schedule (Wetzel and Chang, 1987; Zhang et al., 2004).
11 However, any effects of plant roots, due to clogging of soil pore (Gabr et al., 1995; Scanlan and
12 Hinz, 2010) or/and water uptake (Feddes et al., 1978; Ng et al., 2013) on the two important
13 hydrological parameters are not well-understood. Quantitative measurements of any of such
14 effects of plant roots on both infiltration rate and hydraulic conductivity of vegetated soil are rare.

15 Several past studies have been conducted to measure infiltration rates in soil vegetated
16 with different grass species, but the test results seem not to be conclusive. It was found that
17 infiltration rates in grass-covered soil can be higher (van Noordwijk et al., 1991; Mitchell et al.,
18 1995) or lower (Gish and Jury, 1983; Huat et al., 2006; Ng et al., 2014) than those in bare soil.
19 Infiltration rates in grass-covered soil were lower when roots were actively growing, but they
20 were higher when mature roots were decaying. However, it should not be overlooked that higher
21 infiltration rates found in natural soil were prone to be affected by preferential flow along surface
22 cracks due to excessive soil shrinkage in the field (Simon and Collison, 2002; Leung et al., 2011;
23 Ghestem et al., 2011; Leung and Ng, 2013), regardless the plant age.

1 In order to better interpret water infiltration rate, it may be useful to monitor also the
2 associated changes of soil suction upon infiltration. It is known that the amount and rate of water
3 infiltration in transient state primarily depends on soil hydraulic properties, including soil water
4 retention and hydraulic conductivity (Inoue et al., 2000; Vogel et al., 2000). Knowing the
5 responses of suction in association with infiltration is therefore important because suction is
6 well-recognized as one of the key stress-state variables (Coleman, 1962) governing the behavior
7 of unsaturated soil including the two hydraulic properties (Ng and Leung, 2012). However, most
8 infiltration tests conducted in vegetated soil lacked simultaneous monitoring of soil suction.
9 Without determining the associated responses of suction (and hence hydraulic gradient),
10 infiltration rate measured from a test could not be usefully utilized to further estimate hydraulic
11 conductivity through Darcy's law. Although some field studies included measurements of both
12 infiltration rates and responses of suction (Rahardjo et al., 2005; Huat et al., 2006), they were
13 conducted on natural vegetated soil slopes. This means that the suction recorded can be
14 potentially affected by three-dimensional water flow, from which is not easy to isolate the
15 vegetation effects for accurately interpreting infiltration rates.

16 Results from limited experiments have revealed that the growth of plant roots would have
17 occupied soil pore space and hence modified soil hydraulic conductivity (Gabr et al., 1995;
18 Buczko et al., 2007; Scanlan and Hinz, 2010). Such modification depends on root characteristics
19 (such as root depth and root diameter) present in the soil. The observed effects of pore clogging
20 by plant roots on soil hydraulic conductivity are species-specific and could not be generalized to
21 other species. In the literature, most findings of root-induced change of soil properties were
22 derived from crop species such as grain and maize. Their root characteristics, and hence the
23 impact on any change of soil hydraulic properties, may be different from the natural species that

1 are used for the purposes of ecological restoration and rehabilitation. However, rare field study is
2 available to quantify water infiltration rate, hydraulic conductivity, and the associated suction
3 responses in soil vegetated with this kind of natural species.

4 In order to improve our understanding on the effects of roots on water infiltration rates,
5 hydraulic conductivity and the associated suction distributions, a series of three repeated in-situ
6 double-ring infiltration tests (i.e., Inf1, Inf2 and Inf3) were carried out in vegetated soil in this
7 study during a wet summer. Two species, *Cynodon dactylon* (grass) and *Schefflera heptaphylla*
8 (tree), which are commonly found in many parts of Asia such as Hong Kong, Malaysia and U.S.
9 for ecological restoration purposes, were used for testing. In each test, constant-head ponding
10 was applied on ground surface, during which the water volume infiltrated and distributions of
11 suction were monitored by tensiometers. The suction measurements are used to determine
12 hydraulic gradient for estimating hydraulic conductivity of vegetated soil. By comparing the test
13 results obtained from bare and vegetated soil, any effects of plant roots on infiltration rates and
14 hydraulic conductivity are explored in relation to suction response and plant root characteristics.

15 **Materials and methods**

16 *Site description and soil properties*

17 This field study was carried out at a flat man-made test plot of 2 m x 2 m located at the site
18 called Eco-Park in Hong Kong. The test plot was made of compacted completely decomposed
19 granite (CDG), a soil type that is commonly found in Hong Kong. CDG material was compacted
20 to an in-situ dry density of 1.8 g/cm³, which is about 95% of the maximum dry density (i.e.,
21 relative compaction RC of 95%). The location of groundwater table (GWT) was determined by a
22 geophysical method, and it was identified at 4.5 m depth. To characterize the CDG, four soil
23 samples were collected at depths of 0.1, 0.2, 0.3, and 0.4 m for determining soil index properties.

1 The average gravel, sand, fine contents (i.e., silt and clay) of CDG were 9.5%, 83.1%, and 7.4%,
2 respectively. Based on the measured particle-size distribution and Atterberg limits, CDG is
3 classified as well-graded sand with silt (SW-SM; ASTM, 2011).

4 For measuring the hydraulic properties of unsaturated CDG including water retention
5 curves (WRCs) and hydraulic conductivity function ($k(\psi)$, where ψ is suction), soil column tests
6 were conducted in the laboratory based on the Instantaneous Profile Method (IPM) proposed by
7 Watson (1966). CDG sampled from the site was re-compacted to the identical in-situ dry density
8 (i.e., 1.8 g/cm^3) into a column with diameter of 140 mm and height of 600 mm. The soil column
9 was then subjected to a drying path by exposing it to natural evaporation, during which changes
10 of volumetric water content (VWC) and suction along the column were monitored by four pairs
11 of water content sensors and tensiometers, respectively. The drying test was stopped when
12 suction recorded by any tensiometer reached 80 kPa (i.e., limit of the working range of each
13 tensiometer). Then, ponding with a constant water head of 50 mm was applied on the soil surface
14 to undergo wetting process. Similarly, the associated changes of VWC and suction were
15 recorded. The drying and wetting WRCs were then obtained by relating the measured VWC with
16 the measured suction. More detailed testing procedures were reported by Ng and Leung (2012).

17 Figure 1(a) depicts the measured drying and wetting WRCs. Each curve was fitted with
18 the equation proposed by van Genuchten (1980) for interpretation. The fitting parameters are
19 given. It can be seen from the drying curve that the air-entry value was $\sim 1 - 2 \text{ kPa}$, beyond
20 which VWC dropped substantially. Hydraulic hysteresis is identified. For any given suction,
21 VWC on the wetting curve was about 15% – 20% lower than that on the drying curve. On the
22 other hand, the measured drying and wetting $k(\psi)$ s are depicted in Fig. 1(b). Similarly, the van
23 Genuchten (1980) equation was used to fit the experimental data. By setting the values of

1 saturated soil hydraulic conductivity, k_s , (one of the fitting parameters) to be 1.22×10^{-6} m/s for
2 the drying $k(\psi)$ and 5.15×10^{-7} m/s for the wetting one through statistical regression, a goodness-
3 of-fit of up to 0.983 could be achieved. Although these values of k_s were not measured directly,
4 the method of using the combination of the IPM and statistical regression has been considered to
5 give a reasonable estimation of k_s (Krisdani et al. 2009). These estimated values of k_s is found to
6 be close to the ranges of k_s of CDG from Hong Kong determined by Yin (2009) (from 2×10^{-6}
7 m/s to 1×10^{-8} m/s) and by Gan and Fredlund (2006) (from 1×10^{-7} m/s to 1×10^{-8} m/s for CDG
8 samples with particle-size distributions similar to this study). Some reported k_s values of
9 compacted well-graded sand with silt in the literature (Morris and Johnson 1967; Huang et al.,
10 1998; Rahardjo et al., 2004) are also found to be fairly close to the measurement made in this
11 study. Other measured index properties are summarized in Table 1.

12 *Characteristics of selected grass and tree species*

13 In this study, a grass species (*Cynodon dactylon*; known as Bermuda grass) and a tree species
14 (*Schefflera heptaphylla*; known as Ivy tree) were selected for investigation. These species were
15 chosen because of (i) their commonness in the South-East Asia including Hong Kong and India
16 as well as parts of the US at sub-tropical regions (Hau and Corlett, 2003; Frodin et al., 2010);
17 and also (ii) their ability of drought tolerant that may be suitably used for ecological restoration
18 and rehabilitation at warm climates of the world (Carrow et al., 1996; Hau and Corlett, 2003; Hu
19 et al., 2010). Before testing, sods of *Cynodon dactylon* were germinated and grown in 120 mm-
20 thick CDG at a nursery one year in advance. Note that the CDG used was identical to soil type
21 tested in this field study and was re-compacted at the same in-situ dry density. Figure 2(a) shows
22 the overview of the typical grasses (after one year of germination) tested in series Inf1. It can be
23 seen that the shoot length of grass ranged from 87 to 105 mm. On the other hand, the grass roots

1 are fibrous and they have lengths ranging from 86 to 131 mm (i.e., root depth). Similar
2 characteristics of shoot and roots were identified for grasses vegetated in series Inf2 and Inf3.
3 Table 2 summarizes the range, mean and standard deviation of the lengths of grass shoot and
4 roots in all three test series.

5 Each tree individual tested in this study was also grown in CDG in the nursery for a year.
6 Similarly, the CDG used as the growing medium was identical to that tested in the field. Figure
7 2(b) depicts the overview of a typical tree individual (after one year of growing) tested in series
8 Inf1. The shoot system of the typical individual consisted of a main stem having a length of 978
9 mm. It is determined that Leaf Area Index (LAI), which is a dimensionless index defining the
10 ratio of total one-sided green leaf area to projected area of an individual plant on soil surface in
11 plan, of the tree individual was 0.8. A closer view of the roots shows that the root length was 280
12 mm. A tap root with a diameter of 6 mm was identified. There were clusters of root hair with
13 diameters ranging from 1 – 2 mm, which were mainly responsible for root-water uptake. The
14 observed shoot and roots systems were similarly found for tree individuals tested in series Inf2
15 and Inf3. Measured ranges, mean and standard deviation of tree properties in all three test series
16 are summarized in Table 2.

17 *Test setup and instrumentation*

18 Figure 3 shows the schematic setup of a typical double-ring infiltration test and the arrangement
19 of instruments for the test plot vegetated with the selected tree species. The setup consisted of an
20 inner ring (0.3 m in diameter), an outer ring (0.6 m diameter), and a calibrated Mariotte's bottle
21 for maintaining water head inside the inner ring. The inner and outer rings were inserted into the
22 ground by 0.75 and 0.15 m depths, respectively. Any gaps between the two rings and the ground
23 were sealed using cement paste to ensure no water leakage during testing. The reason of having a

1 deeper inserted depth of the outer ring is to help reducing any water flow beneath the inner ring
2 towards the lateral direction, and this hence promotes nearly exclusively one-dimensional (1D)
3 vertical water flow. It should be noted that the 1D flow condition in a double-ring infiltration test
4 is an idealization of natural condition of infiltration, where water flow is generally three-
5 dimensional (3D). The idealised 1D flow is useful to isolate the effects of vegetation on
6 infiltration rate and suction distributions from any effects due to 3D flow. The test setup was
7 similar to that described by the ASTM Standard D3385 (ASTM, 2009). The only difference was
8 that grass and tree were transplanted inside both inner and outer rings.

9 In order to monitor the responses of negative pore-water pressure (PWP) or suction
10 during an infiltration test, an array of three jet fill tensiometers (JFTs) were installed at 0.1, 0.3
11 and 0.5 m depths. The aim of choosing these installation depths was to quantify the magnitude of
12 plant-induced suction both within (0.1 m) and below (0.3 and 0.5 m) root zones. This would also
13 help identifying any vertical influence zone of suction due to the effects of plant upon ponding.
14 Before installation, the ceramic tip of each JFT was fully saturated with de-aired water, while the
15 plastic tube of each JFT was completely filled with de-aired water in the laboratory. Inside the
16 inner ring, two holes having a diameter (30 mm) slightly larger than that (22 mm) of the ceramic
17 were drilled to the two installation depths. After installation, gaps between JFT and installation
18 hole were backfilled with in-situ soil around the ceramic and then with cement paste for the rest.
19 This aimed to minimize any preferential water flow. It is well-known that air bubbles would
20 accumulate in a JFT due to air diffusion through the ceramic disk. During testing, any observed
21 air bubbles were removed by pressing a jet fill button so that air bubbles can be displaced by
22 water from reservoir stored at the top of the JFT.

23 *Test methods and procedures*

1 In order to investigate any effects of both in-situ soil heterogeneity (i.e., spatial variability) and
2 plant variability on infiltration characteristics, a series of three repeated double-ring infiltration
3 tests (Inf1, Inf2 and Inf3) were conducted. Within the 2 m x 2 m test plot, three double-ring
4 infiltrometers were installed at separate locations with approximately 0.75 m spacing between
5 each other. In each repeated series, infiltration test on bare soil (Inf1-B, Inf2-B and Inf3-B) was
6 carried out first, followed by tests on the same location covered with the selected grass species
7 (Inf1-G, Inf2-G and Inf3-G) and then the tree species (Inf1-T, Inf2-T and Inf3-T). The advantage
8 of testing in such sequence is to eliminate the effects of soil heterogeneity when comparing
9 results between the three surface covers within each individual series. The three repeated tests
10 for each soil surface condition were carried out simultaneously. However, there were difficulties
11 in producing a test plot with a uniform distribution of soil dry density in the field. This is because
12 a much bigger compaction machine was needed to construct the relatively big size of the test plot
13 at the site (compared to the much better controlled of compaction of a smaller sample size in the
14 laboratory). Before testing on the bare soil for series Inf-1 (i.e., Inf1-B), the initial suction at 0.1,
15 0.3 and 0.5 m depths were 6, 9.5 and 13.5 kPa, respectively. An infiltration test following the test
16 procedures described in the ASTM Standard D3385 (ASTM, 2009) was then performed. Inside
17 both the inner and outer rings, the same constant water head of 0.1 m (the average value
18 suggested by the Standard) was applied using the Mariotte's bottle (Fig. 3). Upon ponding, any
19 changes of (i) water level in the bottle and (ii) suction at all three depths were recorded. The test
20 was run for two hours so as to ensure that the volume of water infiltrated and suction at both
21 depths reached steady state. As a result, infiltration rate (I) at any time interval, dt , during
22 ponding can be determined as follows:

$$23 \quad I(t) = \frac{1}{A} \frac{dV}{dt} \quad (1)$$

1 where dV is change of volume of water infiltrated within a given dt ; and A is ponded surface area
2 inside the inner ring. The test was conducted during a wet, cloudy summer, when the average
3 solar radiation, air temperature and relative humidity (RH) in air were 8.8 MJ/m²/day, 16.1 °C,
4 and 87%, respectively. According to Penman equation, the rate of potential evaporation (PE) is
5 estimated to be 0.1 mm/hr.

6 After testing on bare soil, infiltration test was then carried out on the same location but
7 vegetated with the selected grass species for test Inf1-G. After growing the grasses one year in
8 advance in the nursery, grass sods including the 120 mm-thick bulk soil (i.e., roots remain intact
9 and alive) were transplanted to the entire test plot of 2 m x 2 m. Since the CDG used for
10 germinating grass sods in the nursery was identical to that tested in the field, transplanting these
11 pre-grown grass sods to form grass-covered soil in the field was considered equivalent to nature
12 germination of grass seeds over the test plot in-situ. After transplanting, the technique adopted by
13 Wang et al. (2007) was used to ensure favourable growth conditions for the grass sods. The
14 grass-covered soil was irrigated every two days over two months so as to maintain the level of
15 average suction similar to the field capacity of the CDG (i.e., 23 – 28 kPa) The duration of two
16 months of frequent irrigation schedule has been shown to be sufficient for plant roots to establish
17 with in-situ soil after transplantation (Shock et al. 2000; Wang et al. 2007). To allow for direct
18 comparisons of test results between bare and grass-covered soil, it is important to have similar
19 initial suction before the start of test Inf1-G. This is because soil having different initial
20 conditions is known to affect both water retention capability and hydraulic conductivity (Ng and
21 Leung, 2012), hence affecting the subsequent infiltration process and the associated suction
22 responses. Therefore, the grass-covered soil was exposed for natural variation until the initial
23 suction at 0.1, 0.3 and 0.5 m depths (7, 8 and 14 kPa, respectively) were close to those recorded

1 in bare soil. This took five days. The identical test procedures described above were then adopted.
2 The test was undertaken under similar climatic condition (solar radiation of 9.3 MJ/m²/day, air
3 temperature of 17.1 °C, and RH of 81%), which resulted in the rate of potential
4 evapotranspiration (PET) of 0.2 mm/hr according to Penman-Monteith equation.

5 When test Inf1-G was completed, the top 0.15 m of the soil was excavated for removing
6 all grass roots and it was backfilled with in-situ soil to restore the original ground level. Tree
7 individuals together with their soil/root balls (i.e., the entire root systems remain intact and alive)
8 were then transplanted from pots at the nursery to the site for infiltration tests (Inf1-T). The
9 individuals were distributed uniformly (i.e., same tree spacing) over the entire test plot. Similar
10 to the grass-covered soil, all tree individuals transplanted were also irrigated regularly every two
11 days over two months, based on the technique adopted by Wang et al. (2007). Note that the
12 applied experimental scheme for the tree-covered soil was consistent with some typical and
13 standardized procedures adopted for ecological restoration and rehabilitation of some
14 infrastructure such as slopes, road embankments and landfill cover systems (Hau and Corlett
15 2003; Urhin et al. 2009). The tree-covered soil was then subjected to natural variation, until
16 initial suction recorded at 0.1, 0.3 and 0.5 m depths (8, 9 and 15 kPa, respectively) were close to
17 those observed in bare and grass-covered soil. This process took three days. Infiltration test was
18 then conducted on the tree-covered soil according to the identical test procedures described
19 above. The climatic condition during the testing of tree-covered soil was similar to that of grass-
20 covered soil, undergoing a PET rate of about 0.2 mm/hr.

21 For the repeated series Inf2 and Inf3, the above test procedures were repeated identically,
22 but they were conducted on two separate locations of the site. In order to achieve similar initial
23 suction for the two series Inf2 and In3 before testing, the same method described above for series

1 Inf1 was adopted. Table 3 compares the initial suctions measured at 0.1, 0.3 and 0.5 m depths
2 between the three test series Inf1, Inf2 and Inf3. In each series, the maximum difference of initial
3 suction between bare and vegetated soil is found to be less than 3 kPa.

4 *Measurements of distribution of root area index of tree roots*

5 After testing on tree-covered soil in tests Inf1-T, Inf2-T and Inf3-T, all tree individuals were
6 removed carefully for determining root characteristics (in terms of Root Area Index, RAI) in the
7 laboratory. RAI is an index normalising total root surface area for a given depth range within
8 root zone by plan cross-section area of soil. After removal of each tree individual from the site,
9 soil attached to the root system was washed out carefully. The entire branch of plant roots was
10 clamped and high-resolution images were taken around 360°, which were then superimposed to
11 generate a three-dimensional (3D) picture of a root system. Through image analysis, each full
12 pixel image of 3D root system was discretized into grids, and area in each grid containing roots
13 for a given depth was then determined to obtain RAI.

14 Figure 4 compares the RAI profiles of three typical tree individuals sampled from the
15 three test series. For the individual tested in Inf1-T, RAI increased almost linearly from 0.35 to
16 0.80 with an increase in depth in the top 150 mm. This means that there was an increasing
17 number of root hair in deeper depths. Below 150 mm depth, the measured RAI decreased
18 substantially to about 0.18 at the root depth of 300 mm. Similar shapes of RAI profiles were
19 found for the other two individuals, but the RAI of the individuals in tests Inf2-T and Inf3-T
20 were higher and lower than that in Inf1-T at all depths, respectively. The peak RAIs are found at
21 a depth range between 140 – 160 mm for all three individuals consistently. The observed lower
22 RAI in shallow depths may be because the near-surface soil condition is not as favorable as that
23 in deeper depths for root development (López et al., 2001). The near-surface soil is generally

1 drier and warmer (Blight, 1997), which could suppress the root metabolism and its growth
2 (López et al., 2001). On the other hand, the reduction of RAI below 160 mm depth may be
3 because of the increasing significance of overburden pressure in deeper depths, where
4 mechanical resistance for root penetration and growth prevails (Bengough and Mullins, 1990).
5 The measured range, mean and standard deviation of the peak RAI of the ten tree individuals in
6 each test series are summarized in Table 2.

7 **Results and discussions**

8 *Observed infiltration characteristics for different surface covers*

9 Figure 5 compares measured cumulative water infiltration with time between bare, grass-covered,
10 and tree-covered soil during the two hours of ponding from series Inf1. In bare soil, water
11 volume infiltrated is found to increase at a decreasing rate. After ponding for two hours, the
12 amount of water volume infiltrated appears to increase linearly with time, indicating that steady-
13 state condition was reached. Similar trend of variation is observed for both grass-covered and
14 tree-covered soil, and it is found that the volume of water infiltrated in these two types of
15 vegetated soil was similar. Although the initial suction between bare, grass-covered, and tree-
16 covered soil were comparable (Table 3), the volume of water infiltrated in both vegetated soil
17 was less than that in the bare soil by up to 50% at steady state. This indicates that the presence of
18 plant roots has a significant effect in reducing the volume of water infiltration.

19 In order to determine infiltration rate, each measured variation of cumulative water
20 volume infiltrated with time is best-fitted by ordinary least-square method and each best-fitted
21 curve is then differentiated with respect to time (Eq 1). As shown in Fig. 5, the infiltration rate
22 in bare soil decreased exponentially at a decreasing rate, as expected. At steady state, the
23 infiltration rate approached the laboratory k_s of CDG. For grass-covered soil, the infiltration rate

1 was always lower than that in bare one. The difference was the largest (45%) at the beginning of
2 the test, but it then decreased as ponding progressed with time. When comparing the infiltration
3 rates between grass-covered and tree-covered soil, they appear to have no discernible difference
4 throughout the ponding event.

5 *Effects of natural variability of plants on water infiltration rates*

6 Figure 6 compares the measured upper and lower bounds of infiltration rates between bare and
7 vegetated soil tested in the three repeated series Inf1, Inf2 and Inf3. It can be seen that the
8 infiltration rates measured in bare soil in tests Inf1-B, Inf2-B and Inf3-B exhibited some
9 variations. The maximum difference between the lower bound (from test Inf1-B) and upper
10 bound (from test Inf3-B) of infiltration rates was relatively large during the first 20 min of test,
11 but it reduced gradually as ponding progressed with time. Given that the soil density and the
12 initial suction were similar between the repeated tests, the observed variation is likely attributed
13 to the in-situ soil heterogeneity (i.e., spatial variability) at the three locations tested at the site.

14 For grass-covered soil, it can be seen that both upper bound (from test Inf3-G) and lower
15 bound (from test Inf1-G) of infiltration rates were lower than those in bare soil. The observed
16 variations of infiltration rate in grass-covered soil are attributed to not only in-situ soil
17 heterogeneity but also natural variability of grass root characteristics. It can be seen that the
18 upper and lower bounds of infiltration rates correspond to the test for grass having the shortest
19 (Inf3-G; 75 mm) and the longest (Inf1-G; 131 mm) root depths, respectively (Table 2). As the
20 root depth of grass increased by 75%, the infiltration rate decreased by up to 100% during the
21 first 20 min of ponding. This seems to suggest that grass with longer roots would have occupied
22 more soil space, and hence blocked more channels for water flow during infiltration.

1 For tree-covered soil, the infiltration rates are also found to be lower than that in bare soil
2 consistently. The difference could be as small as 5% (compare the upper bound for tree-covered
3 soil and the lower bound for bare soil). Although similar infiltration rate between grass-covered
4 and tree-covered soil is identified in one particular test series Inf1 (Fig. 5), it is revealed in Fig. 6
5 that the in-situ soil heterogeneity and natural variability of trees could result in higher infiltration
6 rate in tree-covered soil (see upper bound from test Inf3-T) than in grass-covered soil (see upper
7 bound from test Inf3-G), by not more than 10% though. The observed similar infiltration rates
8 between the two different types of vegetated soil may be somewhat unexpected because the grass
9 and tree species have rather distinctive root system (see Fig. 2).

10 In order to explain this, some grass sods and soil/root balls of tree individuals were taken
11 for measuring soil void ratio, following the steps typically adopted in plant science literature
12 (Liang et al., 1989). It is revealed that the void ratio of soil contained the grass roots (i.e., top 0.1
13 m) and the tree roots (i.e., top 0.3 m) is quite similar (i.e., 0.53 – 0.62). This is equivalent to RC
14 of 87% – 91%, which is less than the in-situ target of 95%. This is most likely because a
15 substantial volume of soil pore/void was occupied by roots during its growth and penetration.
16 The similar void ratio between two types of vegetated soil indicates that the effects of root
17 occupancy, and hence any associated change of hydraulic properties including hydraulic
18 conductivity (Gabr et al., 1995; Buczko et al., 2007; Scanlan and Hinz, 2010), are likely to be
19 similar. This may explain the close responses of infiltration rate between the grass-covered and
20 tree-covered soil consistently observed in all three repeated series (see Figs 5 and 6).
21 Nevertheless, it should be noted that the measured responses of the two types of vegetated soil
22 were based on the specific design of the experimental scheme adopted in this study. The

1 measured results only reflect the effects of two specific plant species tested at a certain age and
2 at a given atmospheric condition.

3 *Effects of vegetation on soil hydraulic conductivity*

4 At steady state after two hours of ponding, it was identified from the PWP measurements (as
5 shown later) that suctions at 0.1 m depth in all bare, grass-covered and tree-covered soil were
6 zero. With the applied ponding head of 0.1 m (i.e., equivalent to 1 kPa) at the soil surface, it can
7 be estimated that a hydraulic gradient between the 0.1 m thick of soil in all three cases was 10.
8 By Darcy's law, the value of field k_s in each test can hence be determined using the hydraulic
9 gradient and measured steady-state infiltration rates. Note that since the suction measurements
10 made at 0.1 m depth was within the root zones of the two types of vegetated soil, the values of
11 field k_s determined for these two cases would thus reflect any effects of plant roots on the ability
12 of soil to transmit water under saturated conditions. Figure 7 compares the field k_s of bare, grass-
13 covered, and tree-covered soil for each repeated test series. Due to the in-situ soil heterogeneity,
14 the field k_s of bare soil varied from 9.8×10^{-7} to 15.8×10^{-7} m/s. However, the average value of
15 field k_s (i.e., 12.6×10^{-7}) is consistent with the laboratory value (i.e., 12.2×10^{-7} m/s) determined
16 by soil column tests (refer to Fig. 1(b)).

17 As compared to bare soil, it can be seen that the values of field k_s in grass-covered and
18 tree-covered soil are significantly lower. The same trend is observed in all three repeated tests
19 consistently. Because of soil heterogeneity and natural variability of plants, the values of field k_s
20 in both vegetated soil could be lower than that in the bare soil by as high as 6 times. The average
21 estimated value of field k_s of bare, grass-covered and tree-covered soil is 12.6×10^{-7} , 6.1×10^{-7} ,
22 and 6.6×10^{-7} m/s, respectively. This further suggests that the presence of vegetation could lower
23 the soil hydraulic conductivity. One possible mechanism is the blockage of water flow channels

1 in soil pore space by roots (Gabr et al., 1995; Buczko et al., 2007; Scanlan and Hinz, 2010). On
2 the other hand, any changes of soil structure, and hence soil pore size, due to root exudation
3 (Grayston, 1997; Traoré et al., 2000) might also contributed to the observed change of field k_s .

4 *Effects of vegetation on measured suction responses*

5 Figure 8 compares the measured variations of suction at 0.1, 0.3 and 0.5 m depths with time
6 between bare, grass-covered and tree-covered soil during ponding in series Inf1. In bare soil, the
7 suction recorded at all depths decreased substantially during the first 60 min of ponding, and they
8 reached steady state after two hours of ponding. All suction at 0.1 m disappeared. When
9 compared to the measurement made at 0.5 m depth, the decrease in suction at 0.3 m depth was
10 greater because hydraulic gradient in shallower depths was relatively higher upon surface
11 ponding. Similarly, no suction was retained at 0.1 m depth in both the grass-covered and tree-
12 covered soil. The decreasing rate of suction at 0.3 m depth between these two vegetated soil was
13 similar, but the suction retained in tree-covered soil was always slightly higher by 1 kPa. This
14 difference is, however, apparent as it is within the measurement accuracy of JFT (± 1 kPa). The
15 observed similar suction responses between the two types of vegetated soil, in this particular
16 series Inf1, were in line with the measurements of comparable infiltration rates shown in Fig. 4.

17 When compared to bare soil, it is revealed that the measured decreasing rates of suction
18 at 0.3 m depth in the two types of vegetated soil were more moderate during the first 60 min of
19 ponding (Fig. 8). This indicates that the hydraulic conductivity should have been reduced when
20 plant roots were present to occupy soil pore space, consistent to the trend of hydraulic
21 conductivity discussed in Fig. 7. Except time zero, suction in both grass-covered and tree-
22 covered soil are found to be always higher than that in bare soil. This is mainly because there
23 was less volume of water infiltrated in both types of vegetated soil, as compared to bare soil (Fig.

1 5). Another reason may be attributed to the change of soil water retention ability when roots
2 occupy soil pore space and modify soil pore size and its distribution (Scanlan and Hinz, 2010).
3 Although root-water uptake might induce additional suction, it is minimal because the PET rate
4 during the monitoring periods was small (< 0.2 mm/hr) under the wet summer climate, as
5 compared to the observed water infiltration rate of $5 - 145$ mm/hr (i.e., equivalent to $1 \times 10^{-6} -$
6 40×10^{-6} m/s in Fig. 6).

7 At deeper depth of 0.5 m, similar suction response was recorded between the two types of
8 vegetated soil (Fig. 8). Contrasting to the immediate decrease of suction in bare soil at the same
9 depth, some delayed responses of at least 30 min are found in both vegetated soil. This further
10 suggests the possible reduction of soil hydraulic conductivity due to the presence of plant roots.
11 After ponding for two hours, there were limited decreases of suction (less than 2 kPa) in both
12 vegetated soil. At steady state, suctions in grass-covered and tree-covered soil were at least 50%
13 higher than that in bare soil.

14 *Distributions of pore-water pressure profiles for different surface covers*

15 To further investigate the effects of the grass and the tree species on PWP distribution, the PWP
16 profiles measured in bare, grass-covered and tree-covered soil in series Inf1 are compared in Fig.
17 9. Before ponding, the initial distributions of PWPs in all three types of soil were close to each
18 other. When compared to the hydrostatic line that represents the GWT at 4.5 m depth, it can be
19 seen that the initial PWP profiles of all three types of soil were substantially higher, suggesting
20 net downward water flow. When the ponding head of 0.1 m was maintained during each test,
21 PWP of 1 kPa was fixed at the ground surface and it is thus added in the figure to supplement
22 each PWP profile. After ponding the bare soil for two hours, similar PWP increases of 10 kPa

1 were found at all three depths. This suggests that the depth of influence of suction (i.e., negative
2 PWP) after ponding was deeper than 0.5 m.

3 For the grass-covered and tree-covered soil, the PWP profiles after ponding were close to
4 each other. It can be seen that suction retained at all depths in both vegetated soil were higher
5 than those in bare soil. Higher suction retained in vegetated soil was also observed by Ng et al.
6 (2014), who compared suction distributions in flat silty sand with and without vegetated with
7 grass species *Cynodon dactylon* (the same species as this study) upon one hour of rainfall in
8 laboratory. As shown in the figure, the measured PWPs at 0.5 m depth in both the grass-covered
9 and tree-covered soil changed very slightly. This suggests that the depths of influence of suction
10 in both vegetated soil were below the root zones between 0.3 and 0.5 m depths. This was
11 shallower than that identified in bare soil as there was less water infiltrated in the two vegetated
12 soil. For the laboratory tests reported by Ng et al. (2014), a much shallower depth of influence
13 (within root depth) was found in the vegetated soil after subjecting to a one-hour rainfall with
14 intensity of 100 mm/hr. Although both this field study and the laboratory study tested CDG
15 compacted at the same RC of 95%, the soil type for the latter case was much finer (fine content
16 of 39%), and thus has a k_s value (1.10×10^{-9} m/s) one order of magnitude lower than that in the
17 former case (5.15×10^{-7} m/s for wetting $k(\psi)$ shown in Fig. 1(b)). Moreover, the duration of the
18 laboratory rainfall test (one hour) was one hour less than that of the field ponding test (two
19 hours). They are likely the two major reasons for the laboratory case to have relatively smaller
20 volume of water infiltrated, and hence shallower influence zone of suction than the field case.

21 *Effects of natural variability of plants on suction retained after ponding*

22 Figure 10(a) compares the final suction retained at 0.3 m depth between bare and vegetated soil
23 in the three repeated test series. After subjecting to two hours of ponding, the suction retained in

1 bare soil was 0 – 1 kPa. On the contrary, it is consistent in all three repeated tests that both grass-
2 covered and tree-covered soil retained suction of at least 2 kPa higher than bare soil, due to the
3 clogging of soil pore space and hence blockage of water flow by plant roots. For grass-covered
4 soil, it can be seen that the amount of suction drop was the least in test Inf1-G, but it was the
5 largest in test Inf3-G. This is because tests Inf1-G and Inf3-G showed the lowest and highest
6 infiltration rates, respectively (Fig. 6). For tree-covered soil, the measured suction drop in test
7 Inf3-T was the greatest (Fig. 10(a)) again because the infiltration rate was the highest between
8 the three repeated tests (Fig. 6). Interestingly, in series Inf2, the final suction retained in tree-
9 covered soil (6 kPa) was remarkably high, even though this particular test did not result in the
10 lowest infiltration rate (Fig. 6). As listed in Table 2, the tree individuals investigated in test Inf2-
11 T have the highest RAI (as compared to those in tests Inf1-T and Inf3-T), which is likely to have
12 modified soil pore-size distribution and soil water retention ability more significantly.

13 Comparisons of suction measured at the deeper depth 0.5 m between bare and vegetated
14 soil are shown in Fig. 10(b). Unlike series Inf1, suction recorded in both vegetated soil in series
15 Inf2 and Inf3 showed much more substantial reductions during infiltration. This means that due
16 to plant variability, the depths of suction influence zone could be deeper than 0.5 m. Similar to
17 the measurements made at 0.3 m depth, the amounts of suction drop at 0.5 m depth in both bare
18 and vegetated soil were the largest in series Inf3 due to the relatively high infiltration rates. After
19 ponding, the final suction retained at 0.5 m depth in both vegetated soil are higher than those in
20 bare soil by 50% – 150%. When comparing the two types of vegetated soil, the final suction
21 retained in grass-covered soil was generally close to that in tree-covered one.

22

23

1 **Summary and conclusions**

2 This study investigates and compares the effects of *Cynodon dactylon* (grass) and *Schefflera*
3 *heptaphylla* (tree) on infiltration rates, hydraulic conductivity, and suction distributions during a
4 wet summer. Three repeated double-ring infiltration tests were conducted at a vegetated sandy
5 soil, where tensiometers were installed to measure the responses of suction. This allowed
6 hydraulic gradient to be determined for the estimation of hydraulic conductivity for each
7 vegetated soil. Measured infiltration rates and hydraulic conductivity of each vegetated soil were
8 interpreted with suction measurements together with plant root properties, in terms of RAI.

9 Based on the interpretation of the test results, the infiltration rates and hydraulic
10 conductivity in soil covered with the two selected species were revealed to be always lower than
11 those in bare soil, when soil heterogeneity (i.e., spatial variability) and natural variability of plants
12 are taken into account. It is found that although the difference of infiltration rates between the
13 vegetated and bare soil could be as large as 100% at the beginning of tests, such difference was
14 minimal when steady state was reached. When comparing the two types of vegetated soil, the
15 infiltration rate was not always similar. The tree-covered soil could have higher infiltration rates
16 by 10% due to natural variability of tree root properties. At steady-state, it is determined that the
17 average values of hydraulic conductivity of the grass-covered and the tree-covered soil are $6.1 \times$
18 10^{-7} , and 6.6×10^{-7} m/s, respectively, which are about two times lower than that in bare soil (12.6
19 $\times 10^{-7}$ m/s). This is likely to be attributed to the clogging of soil pore when plant roots are
20 presence in the soil.

21 Due to the lower infiltration rates and hydraulic conductivity in the two types of
22 vegetated soil, the measured amounts of suction drop were always less than those in bare soil.
23 While some delayed suction drops of up to 30 mins (since ponding commenced) were identified

1 in the vegetated soil, immediate response (within 10 mins) is observed in bare soil. After
2 ponding, the final suction retained below the root zone (at 0.5 m depth) in the vegetated soil are
3 50% – 150% higher than that in bare soil. Because of the similar infiltration rates and hydraulic
4 conductivity between the tree-covered and the grass-covered soil, the amount of suction retained
5 in the two types of vegetated soil is found to be indiscernible. Moreover, it is identified that for
6 the tree-covered soil, the final suction retained is higher when the soil was vegetated with the
7 trees having deeper root depth and high RAI (i.e., root surface area).

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Table 3. A summary of initial suctions in each series before infiltration tests

Figure

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Table 1. A summary of measured index properties of completely decomposed granite (CDG) sampled at 0.1, 0.2, 0.3 and 0.4 m depths

Index property	Measured value/range
<i>In situ</i> dry density (g/cm ³)	1.78 – 1.82
<i>In situ</i> water content by mass (%)	11 – 17 %
<i>Compaction characteristic</i>	
Maximum dry density (kg/m ³)	1870
Optimum moisture content (by mass, %)	13
<i>Particle-size distribution</i>	
Gravel content (> 2 mm, %)	9.0 – 10.0
Sand content (≤ 2 mm, %)	79.6 – 85.0
Silt and clay contents (≤ 63 μm, %)	5.0 – 10.4
Specific gravity	2.60 – 2.63
<i>Atterberg limits</i>	
Plastic limit (%)	22 – 30
Liquid limit (%)	42 – 46
Plasticity index (%)	16 – 20
Volumetric field capacity (%)	20
Air-entry value (kPa)	~1 – 2
Unified soil classification system (USCS)	Well-graded sand with silt (SW-SM)

Table 2. A summary of measured characteristics of grass and tree tested in the three series Inf1, Inf2 and Inf3

Plant characteristics	Inf1	Inf2	Inf3
<i>Cynodon dactylon</i> (Grass)	Inf1-G	Inf2-G	Inf3-G
Shoot length (mm)	87 – 105 Mean: 96 S.D.*: ±5	89 – 108 Mean: 100 S.D.: ±6	86 – 106 Mean: 94 S.D.: ±7
Root depth (mm)	86 – 131 Mean: 112 S.D.: ±10	79 – 113 Mean: 92 S.D.: ±10	75 – 108 Mean: 85 S.D.: ±8
<i>Schefflera heptaphylla</i> (Tree)	Inf1-T	Inf2-T	Inf3-T
Shoot height (mm)	950 – 1000 Mean:978 S.D.: ±13	900 – 1100 Mean:1013 S.D.: ±55	800 – 1050 Mean:955 S.D.: ±68
Plant canopy diameter (mm)	110 – 200 Mean:153 S.D.: ±18	100 – 220 Mean:145 S.D.: ±34	90 – 180 Mean:127 S.D.: ±30
Leaf area index (LAI)	0.8 – 1.3 Mean:1.1 S.D.: ±0.16	1.0 – 2.1 Mean:1.8 S.D.: ±0.3	0.6 – 1.7 Mean:1.2 S.D.: ±0.3
Root depth (mm)	262 – 305 Mean:280 S.D.: ±22	254 – 320 Mean:291 S.D.: ±20	211 – 260 Mean:232 S.D.: ±12
Peak root Area Index (RAI) (refer to Fig. 4)	0.64 – 0.94 Mean:0.80 S.D.: ±0.11	0.72 – 1.28 Mean:0.97 S.D.: ±0.15	0.59 – 0.75 Mean:0.68 S.D.: ±0.05

*S.D. stands for standard deviation

Table 3. A summary of initial suctions in each series before infiltration tests

Test series	Measured initial suction (kPa)								
	Bare (B)			Grass (G)			Tree (T)		
Depth (m)	0.1	0.3	0.5	0.1	0.3	0.5	0.1	0.3	0.5
Inf1	6	9.5	13.5	7	8	14	8	9	15
Inf2	5	11	16	9	10	17	8	11	17
Inf3	8	12	17	10	11.5	18	11	12	17.5

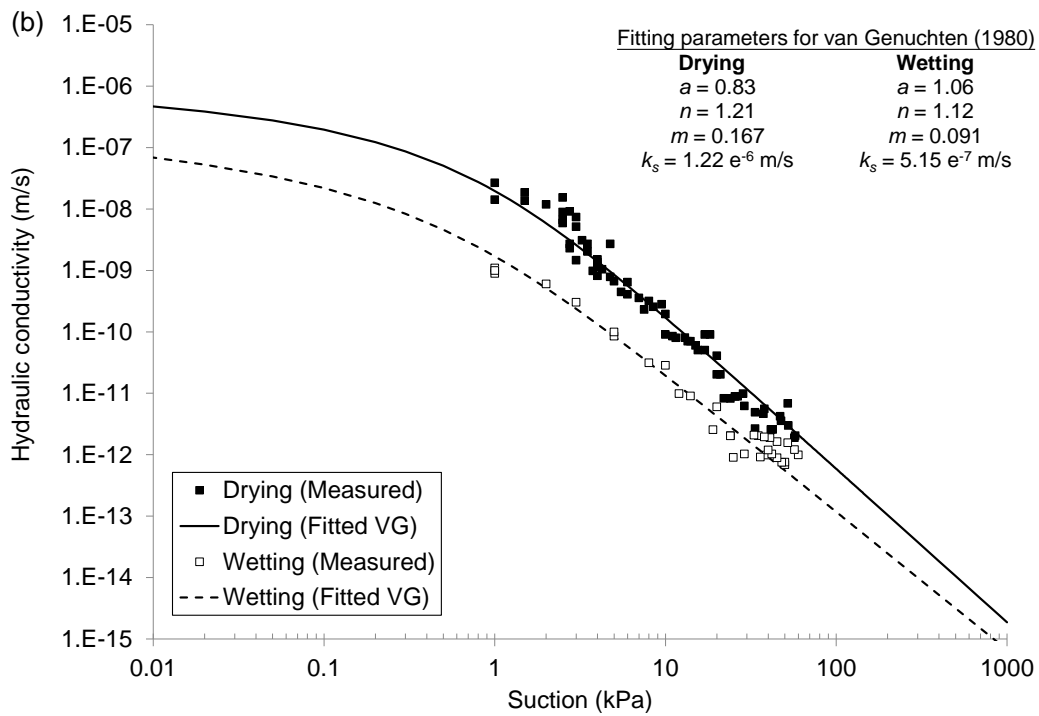
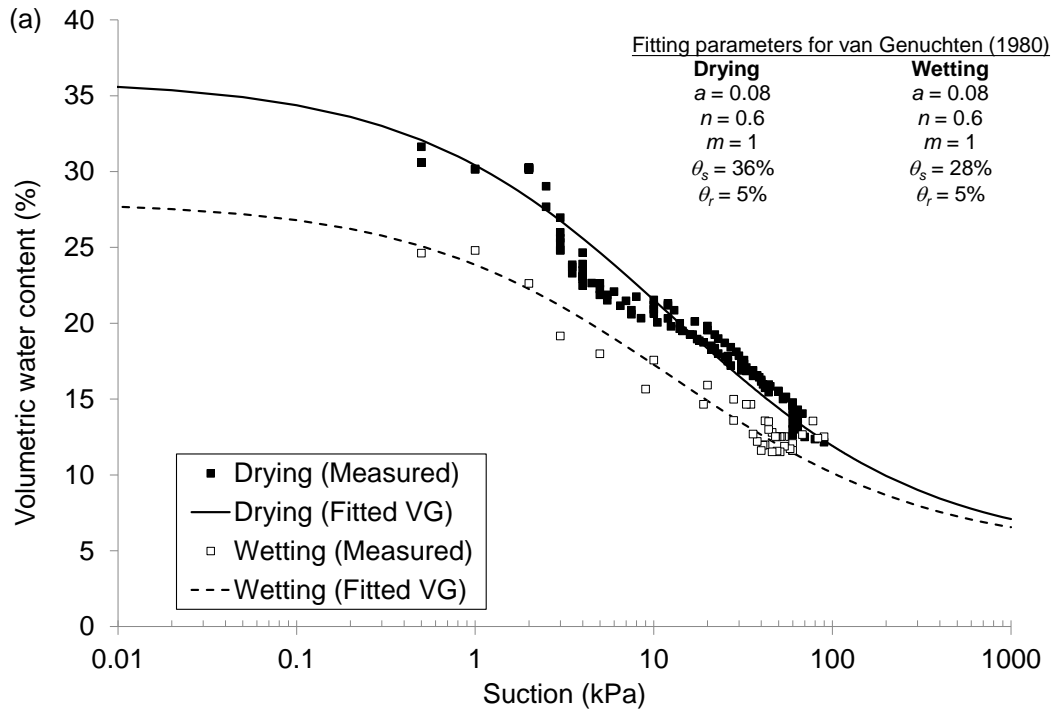
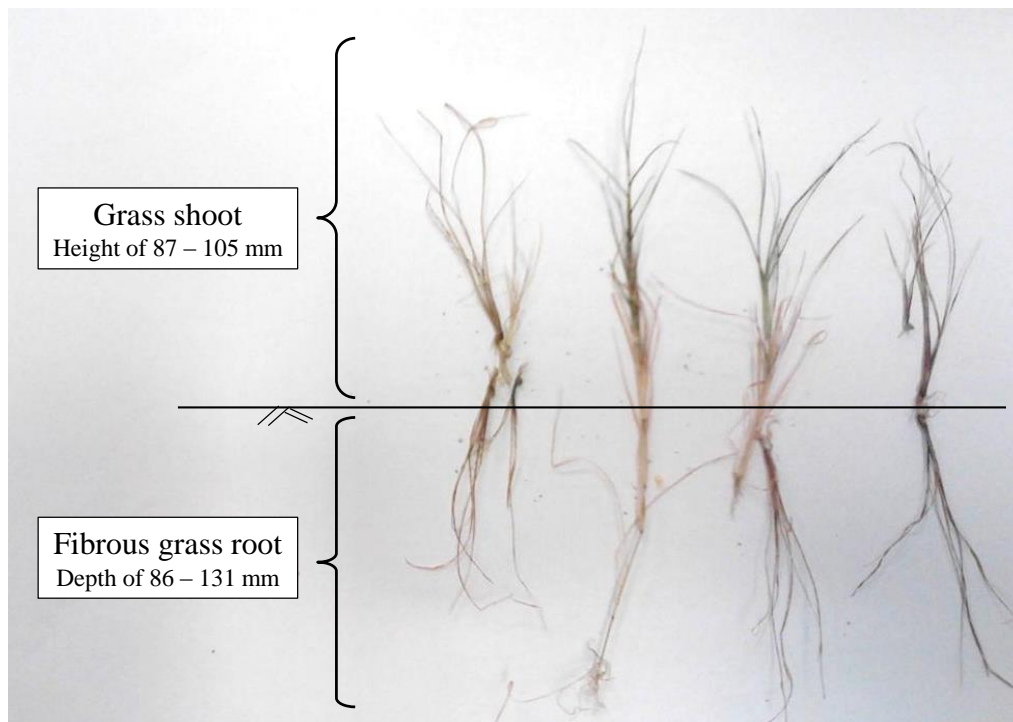
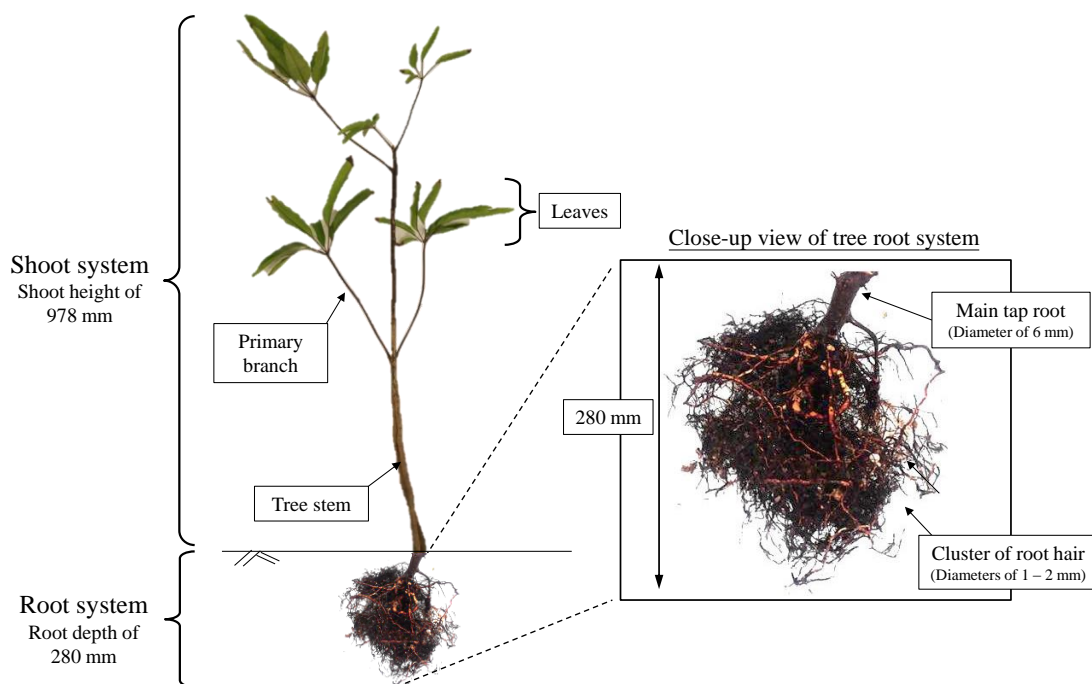


Fig. 1 Measured drying and wetting branches of (a) water retention curves (WRCs) and (ii) hydraulic conductivity function of CDG re-compacted to an in-situ dry density identical to the field condition

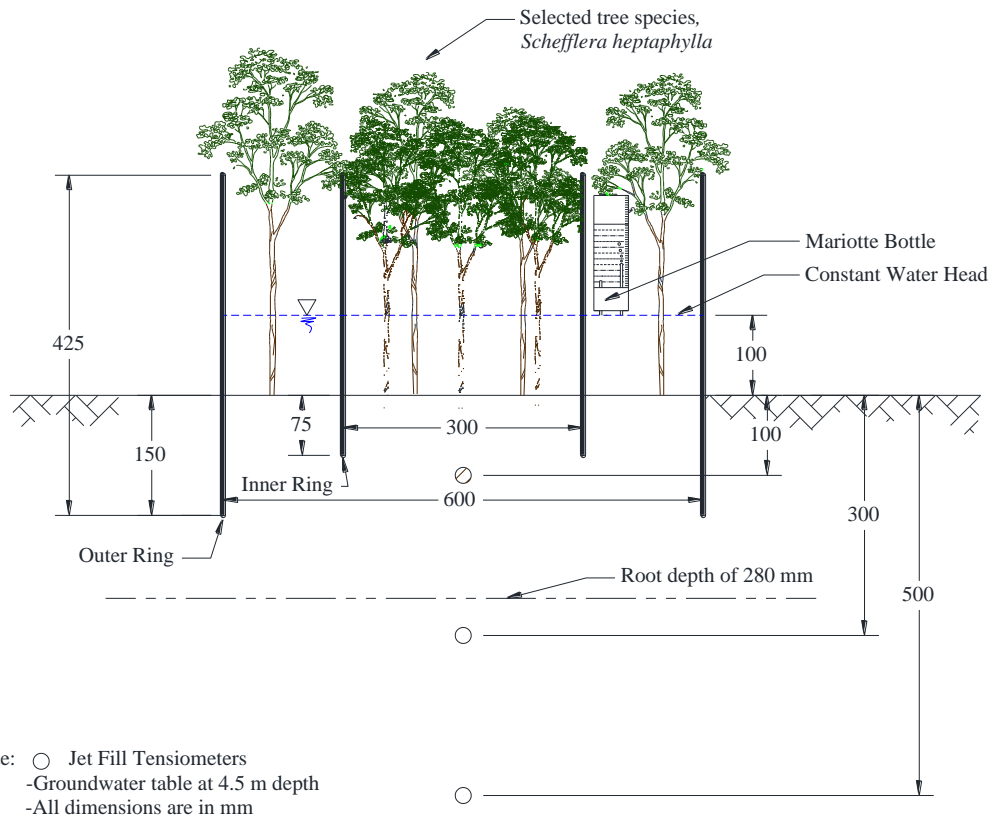


(a)



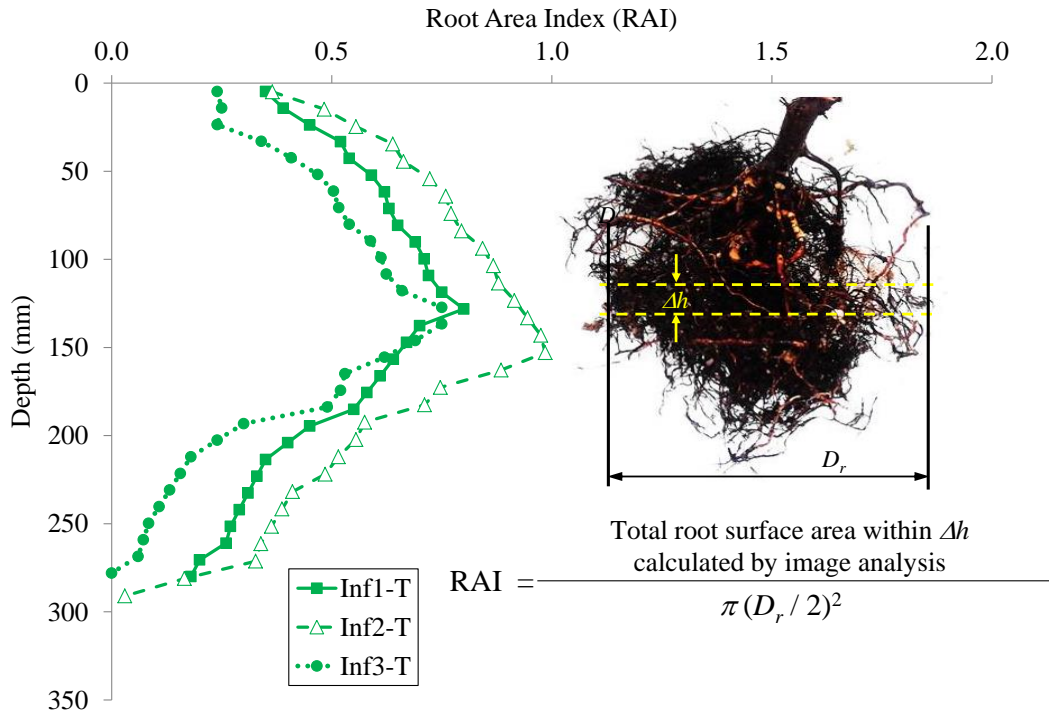
(b)

Fig. 2 Overview of typical shoot and root systems of the selected (a) grass species, *Cynodon dactylon*, and (b) tree species, *Schefflera heptaphylla* tested in series Inf1



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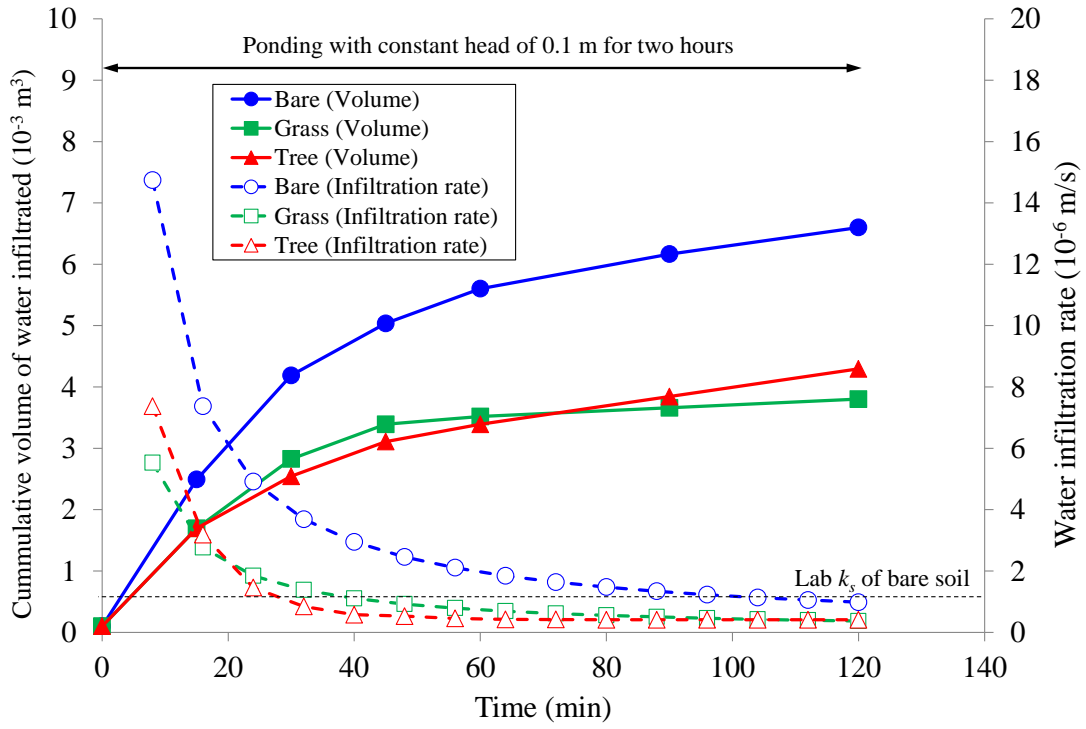
2 **Fig. 3** A schematic diagram showing a typical test setup and instrumentation for tree-covered
 3 soil in test series Inf1 (Inf1-T)



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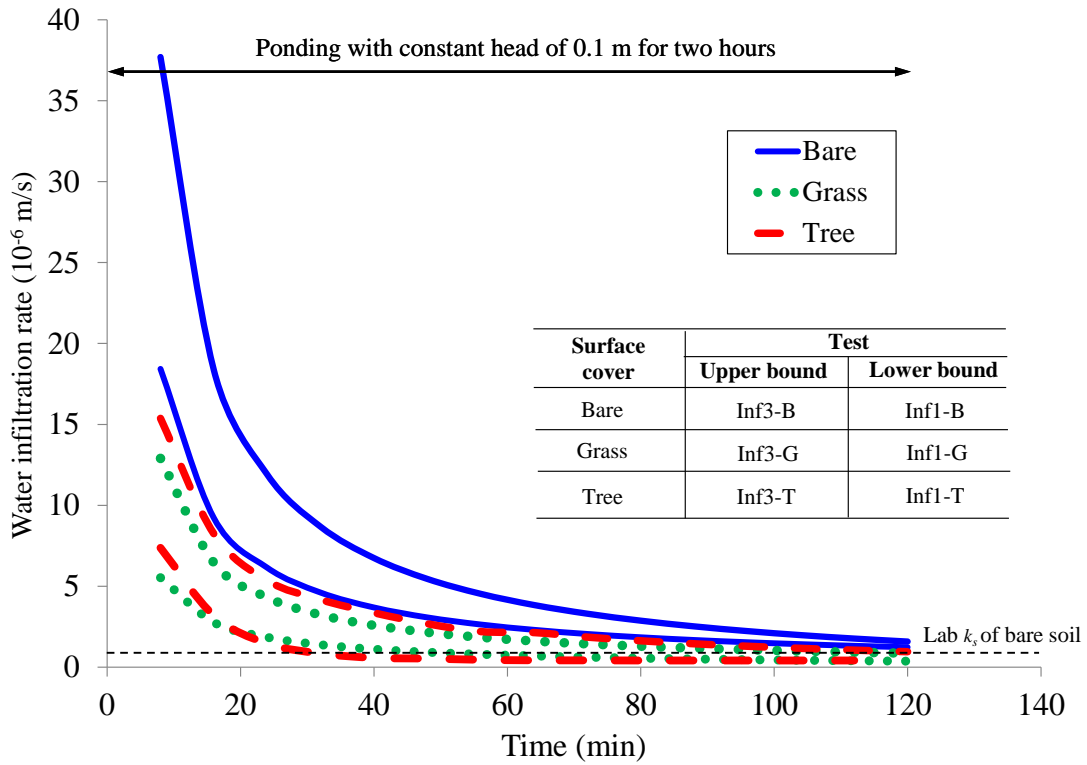
2 **Fig. 4** Comparisons of measured distributions of Root Area Index (RAI) along depth of three
 3 typical tree individuals tested in the three series Inf1, Inf2 and Inf3

4



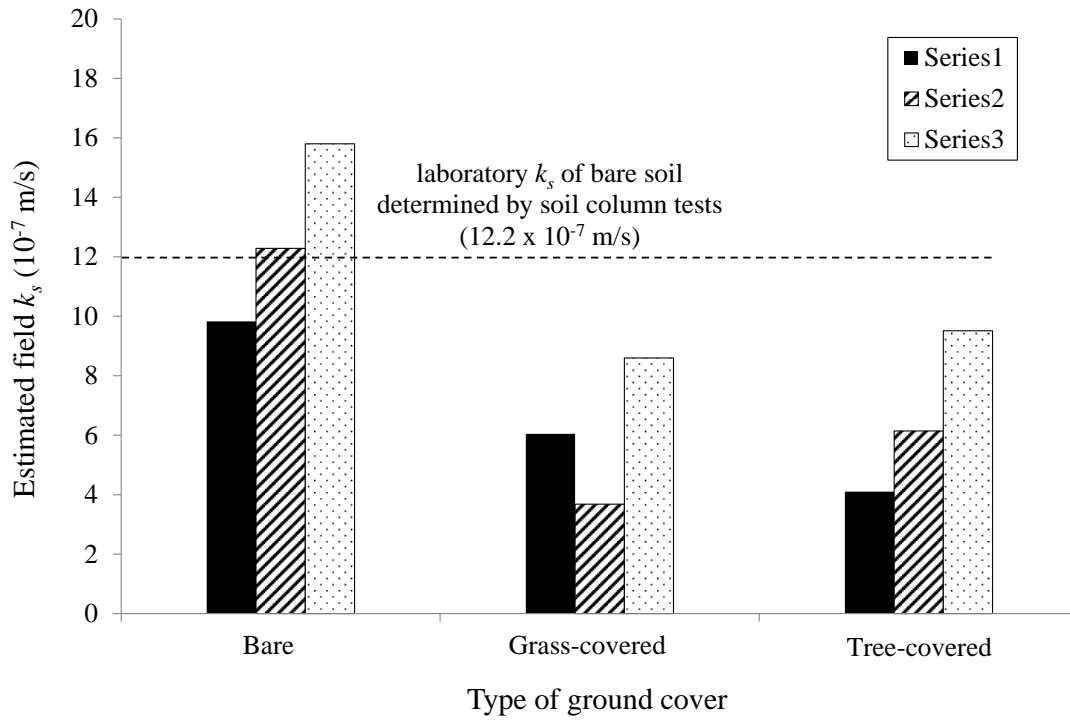
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Fig. 5 Measured variations of cumulative volume of water infiltrated and infiltration rate with time for bare, grass-covered and tree-covered soil in series Inf1



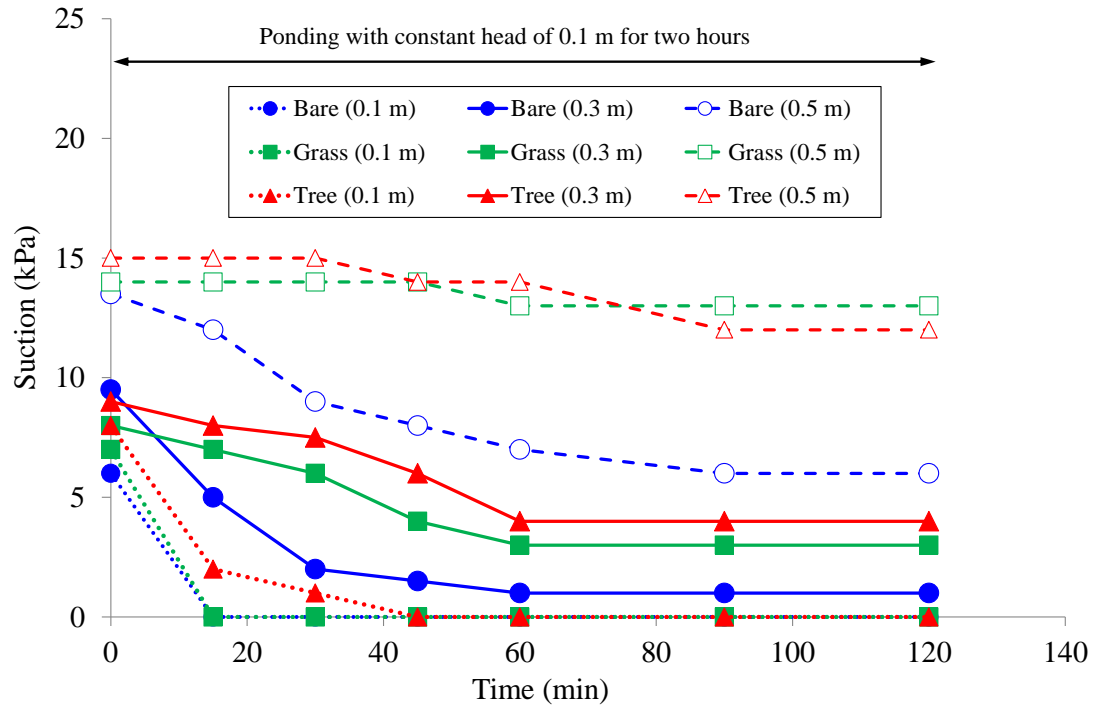
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Fig. 6 Comparisons of upper and lower bounds of infiltration rates for each type of soil tested in the three repeated series Inf1, Inf2 and Inf3



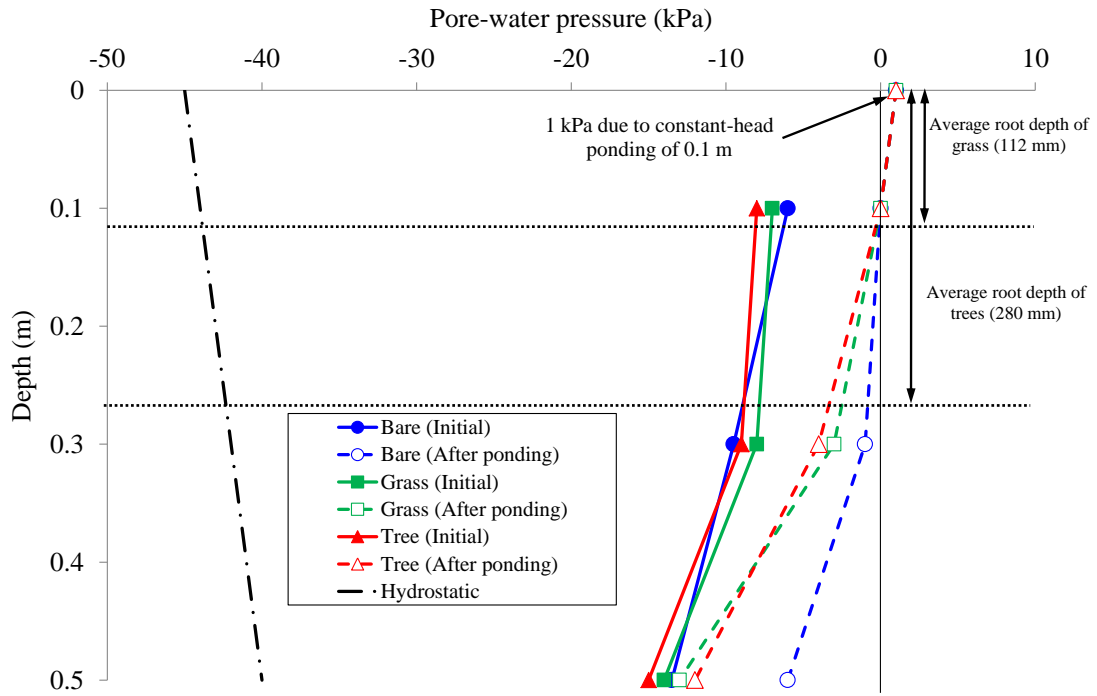
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Fig. 7 Estimated field saturated hydraulic conductivity, k_s , of bare and vegetated soil



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Fig. 8 Comparisons of suction responses at 0.1, 0.3 and 0.5 m depths between bare, grass-covered and tree-covered soil during ponding in series Inf1



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3 **Fig. 9** Measured distributions of pore-water pressure along depth before and after ponding in
 4 bare, grass-covered and tree-covered soil tested in series Inf1

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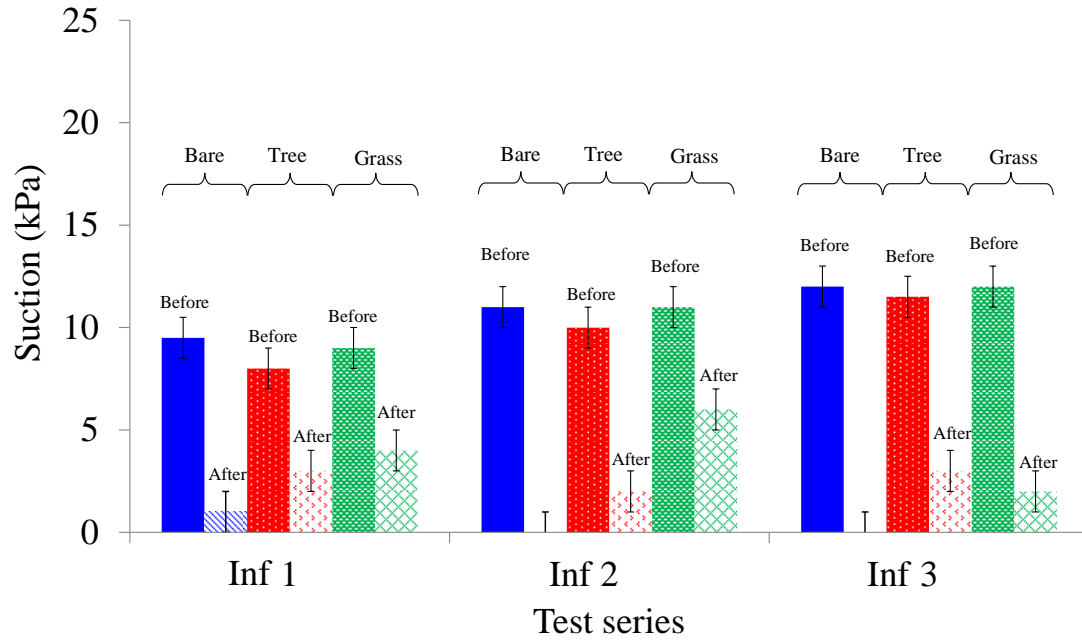
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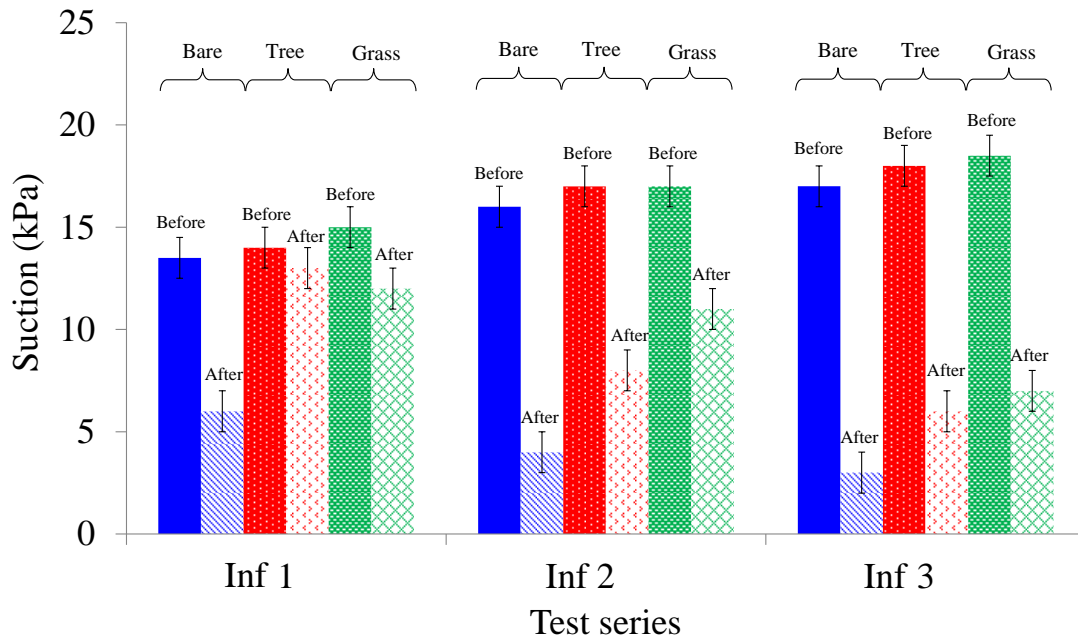
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(a)



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(b)

6 **Fig. 10** Comparison of final suction retained at (a) 0.3 m and (b) 0.5 m depths after two-hour of
7 ponding between each type of soil in the three repeated tests