

Tree morphology dependent transpiration reduction function of *Schefflera arboricola* for landfill cover restoration

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Abstract: Changes in hydrological processes and water resources required to sustain vegetation for ecological restoration of landfill covers and post mining sites in arid environments pose challenges in the context of extended droughts. Knowledge of actual threshold and wilting suction values based on tree morphological feature or plant age is essential for understanding the variation of root water uptake with drought stress and numerically predict the pore water pressure profile in root zone. The objective of this study is to quantify the transpiration reduction function (TRF; in terms of stomatal conductance (SC) and xylem sap flow (SF)) of *Schefflera arboricola*, considering the effects of tree morphology. Continuous drought condition was applied on the plant quantified with leaf area index (LAI) values at 0.5, 2 and 3.5, wherein each LAI represent tree age. The soil matric suction (ψ) and volumetric water content were measured by embedded sensors in the root zone. Based on the TRF obtained from SC values, a unique threshold suction (ψ_{NTR}^t) ranging from 30 to 50 kPa was identified. Beyond this ψ_{NTR}^t , measured leaf abscisic acid concentration increased up to 35 ng/mL, indicating the start of water stress avoidance mechanism. It is evident that ψ_{NTR}^t is independent of tree morphological parameter- leaf area to root length ratio (LA/RL). On the contrary, a threshold suction (ψ_{SAP}^t), depending on LA/RL ratio, can be determined, indicating the start of xylem cavitation. This ψ_{SAP}^t values ranging from 80 to 500 kPa depending on the LA/RL value, imply that the plant could significantly resist xylem embolization at higher LA/RL. In contrast, the plant with low LA/RL values have less tolerance of drought stress and hence low survivability. The results from this research study can be vital for devising and predicting plant available water in water scarce arid environments by a flux-based approach which is dependent on the tree age.

Keywords: Vegetation; Suction; Transpiration; Partial saturation; Drought.

INTRODUCTION

The efficacy of using vegetation in for ecological restoration of a site and even geotechnical infrastructures has garnered attention in recent years (Addisie et al., 2020; Fatahi et al., 2010; Liu et al., 2014). Plant water uptake or transpiration influences soil suction and then induce slope stability in landfill covers, post mining sites, and earthen embankments (Ng et al. (2020a); Ni et al., 2018; Powrie and Smethurst, 2018; Rahardjo et al., 2014). Plant water uptake reduces the soil moisture content thereby inducing higher matric suction (ψ) around the root zone. This induced zone can range up to five times the plant root depth (Ni et al., 2018). In rooted soil, ψ induced by plant water uptake and evaporation is vital to maintain soil shear strength and reduce the soil permeability during and after rainfall events (Boldrin et al., 2018a; Zhu et al., 2018). Transpiration indicates water transfer from the soil to the plant root tips and then to the plant leaves due to the gradual difference in total hydraulic gradient within the plant (Boldrin et al., 2018b; Dainese and Tarantino, 2021). Transpiration and induced ψ share a 'love-hate' relationship. This is because at higher ψ , transpiration has been reported to reduce progressively (Feddes et al., 1976; Van Genuchten et al., 1987). There exists a threshold ψ where plants start to feel drought stress upon continued evapotranspiration and consequently plant water uptake is hindered (Ng et al., 2020a).

In recent times, plants are subjected to excessive drought stress due to climate change (Corona and Montaldo, 2020; Findlay et al., 2020; Leštianska et al., 2020). Past studies

(Balashov et al., 2021; Moore, et al., 2010; Pochodyła et al., 2022; Šimanský and Šrank, 2021) have employed drought mitigation approaches utilizing nutrients, biochar, and chemical surfactants. Root embolization or root death due to excessive drought stress can have drastic effects on the functioning of geo-environmental infrastructure such as landfill covers, and mining sites post closure of operations. This is particularly sensitive for current efforts undertaken under the umbrella of revegetation of these degraded topsoil layer. For instance, dead roots in landfill cover and vegetated slope can increase the saturated hydraulic conductivity of soil by one order (Ng et al., 2019; Ni et al., 2019). In conventional transpiration models, plant water uptake rate was considered to remain maximum at ψ lower than a threshold value and decreases linearly thereafter (Blight, 2003; Garg et al., 2015). This might not be a realistic condition in field wherein soil is saturated at low ψ (< 10 kPa) following an extreme rainfall event and lead to conditions of root anaerobiosis that hinders root water uptake (Andersen et al., 1984). To capture the plant-soil hydraulic interactions, previous theoretical models (Feddes et al., 1976; Wu et al., 1999) simulated drought induced change in water uptake rate by considering a general transpiration reduction function (TRF). TRF denotes the relationship between the normalized transpiration ratio (i.e., actual transpiration rate to potential maximum transpiration rate) and ψ .

Conventional water uptake models generally considered the root morphology and leaf canopy separately to simulate water uptake model (Feddes et al., 1976; Heppell et al., 2014; Klimešová et al., 2021; Li et al., 2001; Wu et al., 1999).

Moreover, these models assume that tree mortality occurs at 1500 kPa of soil matric suction, regardless of soil type and tree morphology (Garg et al., 2020). Recent studies (Hamblin and Tennant, 1987; Wang et al., 2017) have shown that plant or precisely root morphology can determine the moisture uptake from soil and consequently resist their ability to drought stress. Ng et al. (2020b) in a field study explored root length density (RLD) as a tree morphological parameter that affected the water uptake in shrubs.

Thus, irrigation schemes based on these models are either conservative (leading to plant death) or overcompensate resulting in excessive water loss (either by poor drainage or evaporation) (Kirkham, 2014). One of United Nations Sustainable Development Goals is to substantially increase plant water-use efficiency across all sectors including agriculture, urban green infrastructure, landfill covers and post-mining sites by 2030 (Connor, 2015; Hellegers and van Halsema, 2021; Wang et al., 2019). Knowledge of irrigation scheme based on actual threshold values and the wilting point is essential for efficient maintenance of vegetated green infrastructure, in line with concept of “precision irrigation”. This becomes more relevant in landfill cover layer, green roofs, and ecological restoration measures for quarry mining sites, wherein natural water table is not present (Jim, 2001; Savi et al., 2013).

The effects of tree morphology incorporating leaf canopy, xylem stem flow and root architecture on wilting ψ or threshold ψ was rarely investigated for transpiration models. In previous literature, tree morphology and inner permeability of plant through the xylem tissues have been indicated as the direct causes of plant aging effects on water uptake (Forrester et al., 2010; Lopez and Nobel, 1991). Recently, Ng et al. (2020a) have identified leaf area/root length (LA/RL) ratio as an indicator of structural burden on root, reflecting the water flux necessary to sustain plant transpiration. The work provides variable threshold suction values with different LA/RL ratios for *Schefflera heptaphylla*. However, these values provided are based on semi-empirical approach wherein soil hydrological data were back analysed. In their approach, no measurement of water flow within the plant was provided. It is ideal to measure water flow within the plant xylem and leaf at high drought stress to comprehensively understand the effects of tree morphology on threshold and wilting suction. A flux-based approach would be ideal to predict and calculate the plant available water content (de Melo et al., 2023; Turek et al., 2020), knowing the variations in flux associated with tree age.

The objective of this experimental study is to quantify the transpiration reduction function (TRF; in terms of stomatal conductance (SC) and xylem sap flow (SF)) of *Schefflera arboricola*, considering the effects of tree morphology. Nine individuals of *S. arboricola* with different leaf area indexes (LAIs) ranging from 0.3 to 3 were grown for three months in instrumented soil columns, compacted with completely decomposed granitic soil. Thereafter, continuous drought was applied on the plants from near saturated conditions to a point where plants eventually die. ψ and volumetric water content (θ) were measured by embedded sensors in the root zone. The SF and SC were measured at different ψ . The results were explained based on leaf morphology and detailed root morphology including root area indices, root length and root tips.

MATERIALS AND METHODS

Soil properties and sample preparation

Soil used in this study is completely decomposed granite (CDG). CDG was obtained from the Kadoorie Botanical Farm,

New Territories, Hong Kong. As per sieve and hydrometer analyses, the gravel, sand, silt, and clay percentage in CDG were found to be at 17%, 44%, 31% and 8%, respectively. Results from standard Proctor compaction tests show that the optimum moisture content and maximum dry density (MDD) were 11% and 1910 kg m⁻³, respectively. Based on the measured particle-size distribution, the soil is classified as silty sand according to Unified Soil Classification System. Other basic index properties of CDG are summarized in Table 1.

Table 1. Index properties of soil and biochar amended soil.

Standard compaction tests*	
Maximum dry density: kg m ⁻³	1910
Optimum moisture content: %	11
Particle-size distribution*	
Gravel content (> 2 mm): %	17
Sand content (≤ 2 mm): %	44
Silt content (≤ 65 μm): %	31
Clay content (≤ 2 μm): %	8
Coefficient of uniformity, C _u	13
Coefficient of curvature, C _c	2
Specific gravity	2.62
Saturated permeability	1.5 × 10 ⁻⁶
Agronomic properties	
pH	6.35±0.01
EC: ms cm ⁻¹	46.7±5.9

Figure 1 shows the schematic set-up of a vegetated soil column used in the current study. Ten columns were constructed with an inner diameter of 200 mm and height of 400 mm. Three test series with trees having different LAIs (i.e., 0.3, 2 and 3) were investigated in current study. The LAI values represent different stages of plant growth or plant foliage/root proliferation. In total, ten experiments were conducted, one for bare soil (control) and nine (including three replicates) for vegetated soils. Native medium tree species *S. arboricola* was used in this study based on their availability, drought tolerance and being ecologically suitable for the rehabilitation of man-made earthen slopes and landfills (GEO, 2011; Ng et al., 2020b). Soil was statically compacted in the column up to a depth of 375 mm at 80% of MDD to facilitate vegetation growth (Bordoloi et al., 2018). Individual trees conforming to the LAI mentioned previously were transplanted at the centre of each column with similar basal diameter (10 ± 2 mm) and root depth (125 ± 10 mm). Three miniature tip tensiometer (from Soil-moisture Equipment Corp.) were installed at depths of 50 mm, 150 mm, and 250 mm, to account for ψ distribution along the depth. To measure a wide range of ψ , a heat dissipation sensor (229-L from Campbell Scientific Inc. UK) was installed at a depth of 50 mm in each column. SM-300 probe (from DeltaT devices) was installed at a depth of 50 mm (accounting plant root depth) in each column to obtain the volumetric water content (θ). Soil specific calibration was done for both SM-300 and 229-L sensors. All columns were placed inside a temperature (25 ± 2 °C) and humidity (60 ± 3%) controlled room. Cool white-fluorescent lamps of 120 μmol m⁻² s⁻¹ intensity was uniformly provided to all columns throughout the testing period during the day for 12 hours. After transplantation, a small stem heat pulse velocity sap flow sensor was installed at same height (70 mm) in one replicate of each vegetated test series as shown in Fig. 1. The working principle and installation of the sap flow sensor is provided in a later section.

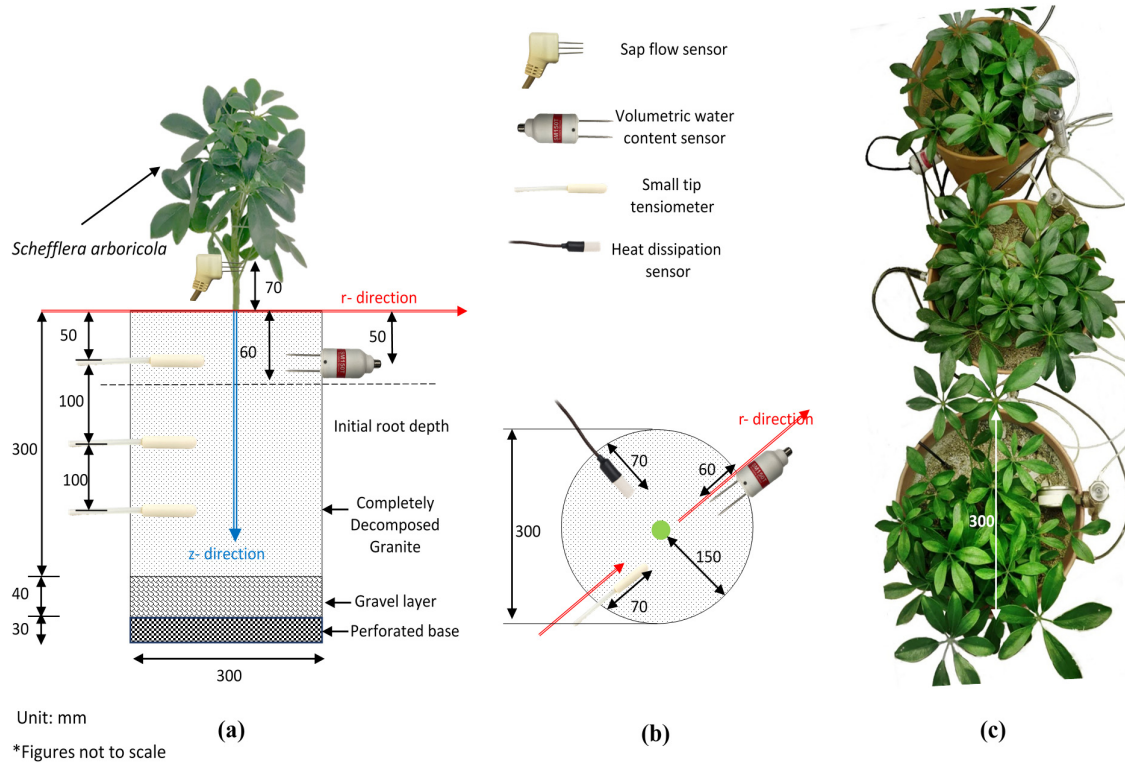


Fig. 1. Schematic diagram of (a) cross-sectional view and (b) plane view of the test set-up; (c) Top view of the experimental set-up.

Test procedure

After transplantation, all ten columns were irrigated every 48–72 hours to ensure that field capacity was maintained in the root zone up to 150 mm. The trees were grown for 80 days to ensure root establishment and any potential root growth. During the growth period, tree morphological parameters (Leaf area (LA), shoot length (SL)) were regularly measured. It is to be noted that the initial LAI at 0.3, 2 and 3 increased to final LAI at 0.5, 2.5 and 3.5 after the growth period. All three vegetated series are designated in this study with their final LAIs. The difference in LAI for all replicates were less than 5%. At the end of 90 days allotted for growth, ponding head was applied on the surface of the ten columns until percolation through the holes of the perforated base was observed. This ensured that water content of all soil columns was in a near saturated state. Ponding head was applied corresponding to 100-year rainfall return period (Lam and Leung, 1994). Thereafter, both bare and vegetated columns were exposed to the environment to quantify the effects of evapotranspiration induced suction on plant parameters (i.e., SC and sap flow). During this stage, SC, sap flow, ψ and θ were simultaneously measured between 11 AM to 12 PM every day. SC was measured by a leaf porometer (SC-1 from Meter Devices Inc., USA). CL-01 Chlorophyll Meter (Hansatech Instruments, UK) and WP4 was used periodically to measure the leaf water content and leaf water potential, respectively. The vegetation in each column ultimately wilted as no additional water was given. Permanent wilting was observed both visually or marked by the values of sap flow and leaf water content. After plant wilting, roots were carefully removed from the instrumented columns. Thereafter, RAI of the entire root system was determined using image analysis (Yildiz et al., 2020). Root biomasses were weighed after air-drying (at 25 °C) and oven-drying (at 60 °C) for 24 hours each, to calculate the bulk and dry weight,

respectively. After measurement of root biomass, the air-dried roots were carefully segregated into individual root strands. All dry roots were individually scanned and analysed using WinRhizo (version 2019) software (Meijer et al., 2018). The root diameter distribution analysis was conducted by root image scanning technique in WinRhizo. For a particular plant, the root length, root volume, root forks and root tips were calculated by adding up the values from individual root strands. In the case of root diameter, the value reported was averaged. The LA was calculated using image analysis technique; the details of which can be found in Ng et al. (2020a). The SL was measured manually using a flexible meter scale. Abscissic acid (ABA) was determined by Enzyme Linked Immunosorbent Assay (ELISA) (Wei et al., 2020). Leaf sample was collected from the pots, weighing around 270–330 mg per sample for measurement of ABA. These samples were grinded into fine powder by using liquid nitrogen. These powdered sample was added into 15 mL tube with 10 mL milli-Q water. Thereafter, the tube was put on a shaker at 4 °C overnight. The tubes were centrifuged at 14,000 r/min and then supernatants were collected for ABA analysis.

Instrumentation for water flow in leaf and stem

Water vapor flow in leaf can be designated by SC. It provides the magnitude of the rate of CO_2 entering, or water vapour exiting through the stomata. The working principle of SC-1 leaf porometer is based on relative conductance (Devises Meter, 2019). The measurement range of SC-1 is from 0 to 1000 $\text{mmol m}^{-2} \text{s}^{-1}$ with permissible error within 10%. The sample chamber aperture for measurement is about 6.35 mm. As SC varies diurnally, all readings were taken within 11 to 12 AM in the noon, wherein the SC is generally the highest (Gadi et al., 2019).

Heat-pulse sap flow sensors (Implexx, Edaphic Scientific Pvt. Ltd, Australia) were used to continuously monitor the tree trunk

sap velocity. In this method, the temperature response to a heat-pulse probe implanted into xylem layer of a tree trunk can be monitored by implanted thermistors at known distances above and below of a heating probe. The Implexx probe set consists of two thermistors (30 mm long) which is installed at 6 mm distance from the heater probe (30 mm long), respectively. Before installation of the sensors, the thermistors and probe were coated with a thermal grease. Three holes were first made using a drill guide (provided by the manufacturer) to ensure proper contact and alignment of the sap flow sensors. After installation of the sensor, the entire portion of the heat-pulse units was wrapped in cotton and reflective insulation foil. This insulating agent acted as a solar radiation shield and provided protection against sudden extreme variations in external temperature. The loggers were programmed to set off a heat pulse for 2 s every 30 min, returning two sap flux estimates each hour. Sap flux is defined as cubic centimetres of sap water flowing perpendicular to the direction of flow in unit time. Sap flow ($\text{cm}^3 \text{h}^{-1}$) can be calculated from Equations (1) and (2).

$$\text{SF} = \frac{\text{HPV} \times \rho C}{\rho_s C_s} \quad (1)$$

$$\text{HPV} = \frac{(x - x')}{2t} \quad (2)$$

where ρ is the density of sapwood, C is heat capacity of sapwood, ρ_s is the density of sap, C_s is the heat capacity of sap; HPV is heat pulse velocity; x and x' are respective downstream and upstream distances of the thermistors from the heater, and t is time taken to return through the starting temperature. The details of the working principle and formulation can be found in (Forrester et al., 2010).

RESULTS AND DISCUSSION

Correlations of shoot length, leaf, and root characteristics

Figure 2 shows the relationships among SL, LA and RL. The LA increases with SL and ultimately tapers down at higher

values of SL. The relationship is parabolic in nature ($R^2 = 0.90$) like that observed in Ng et al. (2020a) for *S. heptaphylla* ($R^2 = 0.75$). The RL exhibits a strong linear correlation ($R^2 = 0.98$) with the SL, unlike the parabolic relationship observed in Ng et al. (2020a) for *S. heptaphylla* ($R^2 = 0.97$). The change in relationship is expected as *S. arboricola* has higher and denser leaf foliage as compared to *S. heptaphylla*. Shoot length, leaf canopy and root architecture have been observed to be related to plant age (Yu et al., 2007). At higher SL (near 240 mm), the variation in LA is relatively more than that in lower SL (less than 170 mm). This can be attributed to higher leaf shedding for mature trees (Lowman, 1988). In the current study, there was very high leaf shedding at higher SL (i.e., more than 170 mm) comparable to those reported by Sawwan and Ghunem (1999). Leaf shedding was not observed for shorter trees in the current study similar to the findings by Ng et al. (2020b) for *S. heptaphylla*. Unlike LA, wherein rate of incremental growth decreases with SL; the RL increases substantially at higher SL. This behaviour can be probably attributed to the accelerated three-dimensional spread of the root front. This accelerated growth in the root front is due to the water requirement needed to substantiate the LA at a higher shoot length (Paz, 2003; Svecar, 1990).

The RAI distribution along the depth is presented in Fig. 3 to compare the RAI of all three-test series. The RAI does not change to a greater extent below the initial transplanted root depth (i.e., 50–60 mm). However, it is evident that root zone area increased in case of trees with higher LAI below 50 mm (i.e., LAI = 2 and 3.5). This trend contrasts with that observed for *S. heptaphylla* by Ng et al. (2016), wherein at higher LAI (1.3), the RAI decreases as compared to tree with lower LAI (0.9 and 1.18). For a detailed interpretation of the root architecture for the three different vegetated series, the results from the root scanning analysis are presented in Table 2. In comparison to LAI = 0.5 test series, the total root length increases by 191% and 673% for LAI = 2.5 and LAI = 3.5 test series, respectively. This means that even though the RAI for LAI = 2.5 and LAI = 3.5 are not very different in magnitude, the root length density would be much higher for LAI = 3.5. Moreover, at LAI = 3.5, the average root diameter is lowest (0.61 mm), indicating that the roots enter finer

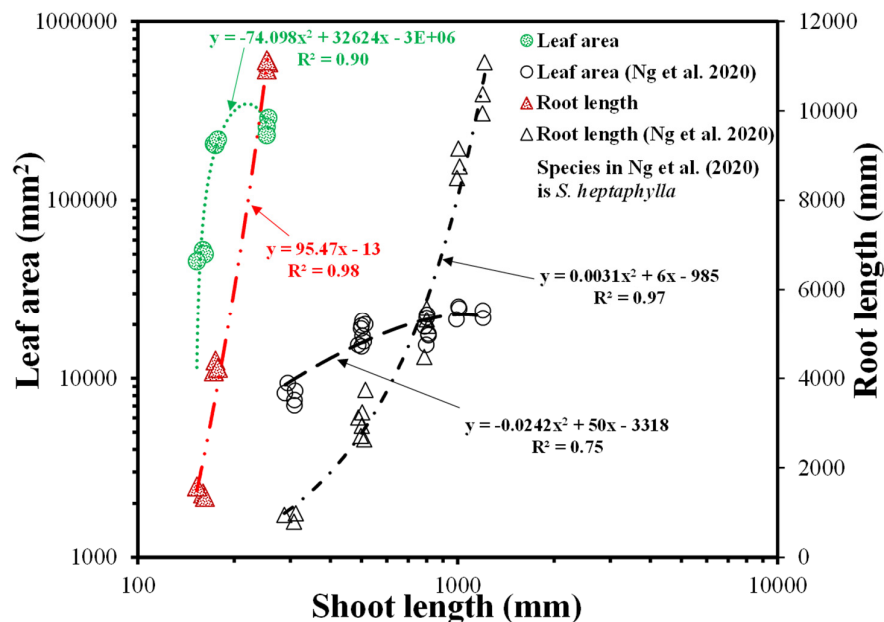


Fig. 2. Correlations between shoot length, leaf, and root characteristics in terms of leaf area and root length.

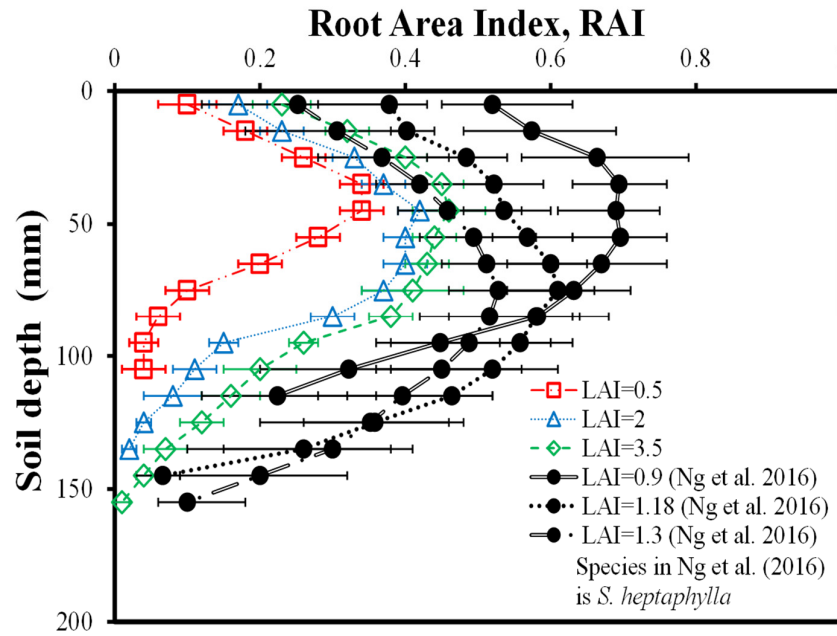


Fig. 3. Distributions of root area index along the soil depth.

Table 2. Summary of root architecture characterisation using root scanner.

Parameter	Unit	LAI = 0.5	LAI = 2	LAI = 3.5
Total root length, RL	[mm]	1428	4161	11086
Average root diameter	[mm]	0.77	0.78	0.61
Root volume	[mm ³]	673	1996	3273
Number of root tips	[-]	573	2856	4392
Number of root forks	[-]	1543	3453	9854
LA/RL	[-]	0.37	1.69	4.27

pores to satiate the water requirement of the canopy. Finer roots contribute to higher water uptake ability as compared to coarser roots (Gwenzi et al., 2011). This change in root morphology for the satiation of leaf canopy is also reflected from the highest amount of root tips measured at LAI = 3.5. The measured LA/RL values for *S. arboricola* increased with higher LAI or SL. This trend contrasts with that reported by Ng et al. (2020a) for *S. heptaphylla*. Thus, it can be concluded that for *S. arboricola*, taller trees have higher LA/RL ratios.

Induced soil suction distribution and water retention ability of soil

The vertical distributions of induced ψ along the soil depth for bare and vegetated soils after drying for 5 days can be compared in Fig. 4. All bare and vegetated columns were initially subjected to ponding conditions as stated in earlier section. The ψ readings in all tensiometer was observed to be at zero after the ponding exercise. Thus, it can be assumed that soil was at near saturated state (Leung et al., 2015). The magnitude of ψ in bare soil was always greater than those observed for the vegetated soils. This is in stark contrast to the ones observed for *S. heptaphylla* with the same initial conditions and days allowed for drying (Ng et al., 2016). In their study, ψ induced by bare soil was lower (by at least 9 kPa at 50 mm depth) than vegetated soils with variable LAIs (0.9, 1.18, 1.30). ψ increase is due to both evaporation as well as transpiration (in case of vegetated soil). Evaporation rate is dependent on the incident radiant energy on the soil whereas

transpiration rate is dependent on the leaf area. As the leaf canopy was very dense for *S. arboricola* (refer Fig. 1c), it is quite evident that the canopy would intercept radiant energy thereby decreasing the evaporation rate as compared with bare soil. Leung et al. (2015) reported that *S. heptaphylla* with LAI of 1.6, 2.3 and 3.9 intercepted light (measured from quantum sensors) by 45%, 72% and 83%, respectively. If the canopy is too dense, the induced ψ can be lower than bare soil. *S. arboricola*, having a denser leaf foliage than *S. heptaphylla* will likely intercept even more percentage radiant energy, thus lowering the evaporation rate. Only considering the vegetated soils, the role of LAI on transpiration induced ψ is evident as seen in Fig. 4. Higher LAI induced a greater magnitude of ψ as also observed for *S. heptaphylla* (Albalasmeh, 2013). Within the average root depth, the amount of ψ induced at a depth of 50 mm was always higher than that at 100 mm. As surface evaporation rate would be minimal, it is evident that a major reason for larger ψ at lower depths was due to higher values of RAI at that depth (Fig. 3). This is likely as higher RAI will induce higher root water uptake (Garg et al., 2015). The results of ψ distribution along depth imply that vegetated soil does not necessarily induce higher ψ as compared to bare soil after a high rainfall event.

The measured drying soil water retention curves (SWRCs) of bare soil and vegetated soil at different LAIs are presented in Fig. 5a–c. The van Genuchten equation was used to fit the measured data for SWRC. All fitting parameters are tabulated in Table 3. After the application of ponding, the drying SWRCs were obtained by relating the measured datapoints (θ , ψ ; datapoints

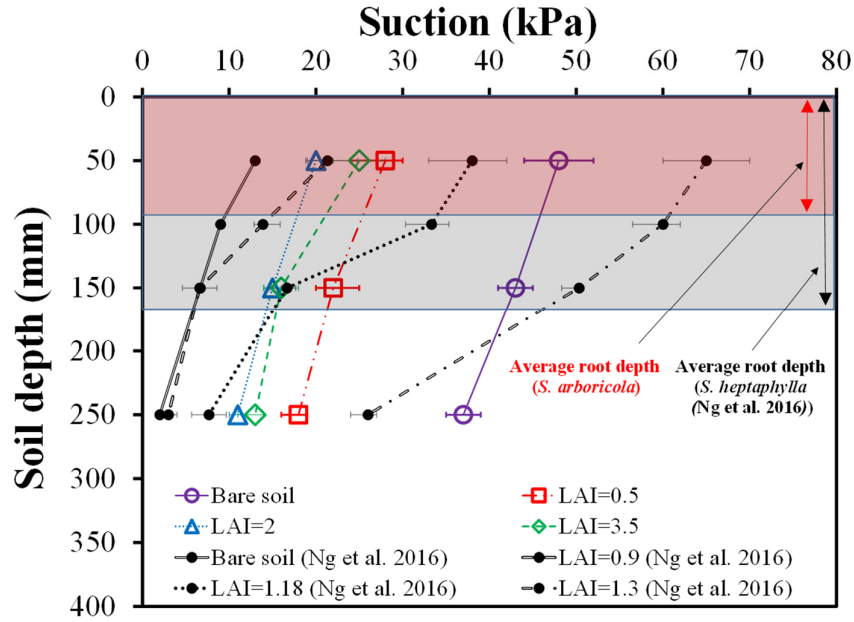


Fig. 4. Measured suction along the soil depth for bare and vegetated soils.

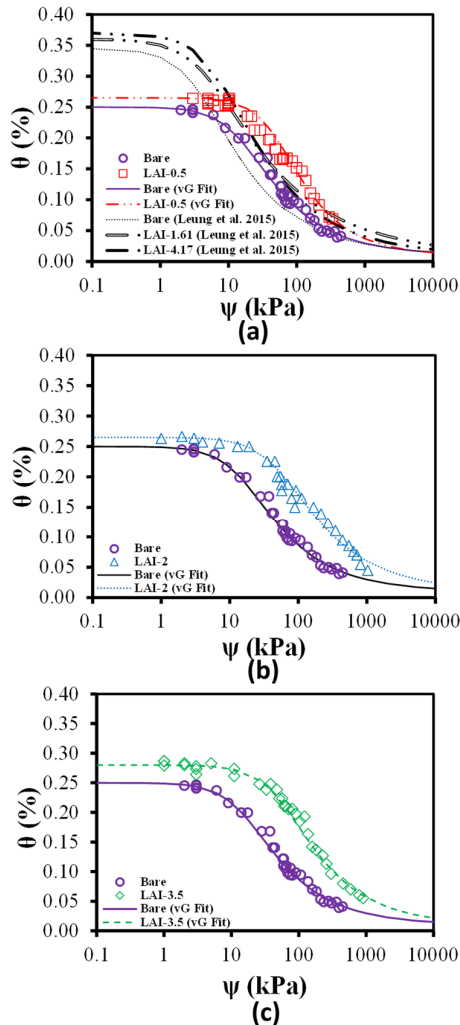


Fig. 5. Measured and fitted drying soil water retention characteristics of bare and vegetated soils.

were from all the three replicates) at 50 mm soil depth. The SWRC of vegetated soil was different from that of bare soil, and the difference can be attributed to the difference in LAI and roots. The presence of roots increases the air-entry value (AEV) from 15 kPa for bare soil to more than 50 kPa for vegetated soil (regardless of LAI). Similar percentage increase (250–270%) in AEV for rooted soil has been reported for *S. heptaphylla* (Albalasmeh, 2013). The desorption rate denoted by ‘n’ parameter, seemed to be dependent on the root morphology. Highest n (at 1.75) was observed for tree with LAI = 0.5. On the other hand, n for other vegetated soils (with LAI higher than 2.5) were equal or lower than that of bare soil (n = 1.6). Nevertheless, ψ induced by root was higher than bare soil for a certain θ . Root occupancy in soil pore space would reduce the diameter of the soil pore throat, which in turn increases the magnitude of ψ . In addition, the soil pore throats near the roots (rhizosphere) may also be reduced due to secretion of mucilage and other root exudates (van Genuchten, 1980; Zhu et al., 2019). Based on the measured SWRCs, it can be implied that rooted soil can substantially alter the drying SWRCs, although the rate of desaturation would be dependent on the root morphology.

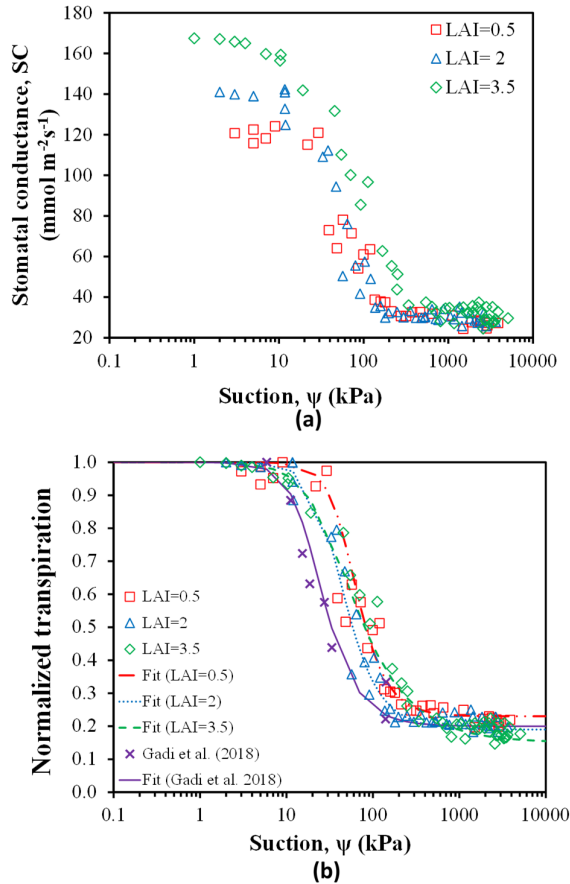
Water uptake through leaf and stem xylem

Figure 6a compares the SC response of the three vegetated series at different values of ψ upon continued drying. Datapoints for measurement of ψ were taken at 50 mm depth from all the three replicates. Maximum SC is maintained at low ψ for all soil treatments. Thereafter, SC values decreased gradually as ψ increased until it reaches a specific residual suction value. After reaching this residual suction value, the SC values remain constant with variations less than 5%. The gradual decrease in SC at higher ψ can be explained based on the phenomena of partial stomata closure. Stomatal opening act as pressure regulators against stresses due to higher concentration of abscisic acid, vapour pressure deficient or CO_2 flux required for photosynthesis (Comstock, 2002). Upon exposure to minimal abiotic water stress, the roots gradually release abscisic acid, which initiates a chemical signalling cascade to decrease the stomatal opening (Munemasa et al., 2015). Liu et al. (2003) found that an increase of 5% in leaf

Table 3. Summary of fitting coefficients for SWRC and transpiration reduction function.

SWRC							
Parameter	θ_s	θ_r	A	n	m	AEV	
Unit	[%]	[%]	[kPa ⁻¹]	[-]	[-]	[kPa]	
Bare	25.0	1	0.07	1.6	0.37	15.4	
LAI = 0.5	26.5	1	0.02	1.75	0.43	50.0	
LAI = 2.5	26.5	1	0.02	1.55	0.35	52.6	
LAI = 3.5	28	1	0.02	1.6	0.37	54.0	
TRF (Stomatal water flow)							
Parameter	NTR_{min}	α_{sc}	n_{sc}	m_{sc}	R^2	ψ_{NTR}^t	
Unit	[-]	[kPa ⁻¹]	[-]	[-]	[%]	[kPa]	
LAI = 0.5	0.23	0.02	2.9	0.65	95	52	
LAI = 2	0.19	0.03	2.6	0.61	96	35	
LAI = 3.5	0.20	0.04	1.7	0.41	87	30	
Gadi et al. (2018) *	0.20	0.05	2.6	0.61	90	20	
TRF (maximum daily sap flow)							
Parameter	a_1	a_2	b_1	b_2	ψ_{SAP}^M	ψ_{SAP}^t	R^2
Unit	[-]	[-]	[-]	[-]	[kPa]	[kPa]	[%]
LAI = 0.5	0.31	0.43	0.30	2.63	9	79	0.92
LAI = 2	0.18	0.60	0.15	4.69	66	500	0.82
LAI = 3.5	0.37	0.81	-0.72	5.95	120	495	0.91

* θ_s is volumetric water content at saturation, θ_r is residual volumetric water content, α is fitting parameter primarily dependent on the air entry value, n = fitting parameter depending on the rate of desaturation of water from the soil, $m = 1 - (1/n)$. In Gadi et al. (2019), species is *Axonopus compressus* and soil is silty sand (ML) as per USCS classification.

**Fig. 6.** (a) Relationship of stomatal conductance with soil suction and (b) Transpiration reduction function considering stomatal water flow.

abscisic acid concentration results in a decrease of stomatal conductance in *Glycine max* by 60%. They found that after a certain maximum value of abscisic acid is reached in leaf xylem, SC becomes constant thereafter. Similar, response in terms of SC with respect to an increase in ψ was also observed in the current study. The maximum SC increased with higher LAI for *S. arboricola*. This is expected as higher water transport is required for a larger LA to minimize any potential cavitation and facilitate photosynthesis process in the leaves (Patanè, 2011).

In Figure 6b, the SC values are normalized by dividing it with the maximum SC for each series and then plotted against the corresponding ψ , to obtain the TRF in terms of SC. This normalisation is generally done to compare the test series and incorporate any allied effects of wind, radiant energy that may alter the SC values of species in field conditions (Rice, 1975). It is to be noted that the experiments were conducted in constant light intensity and effects of wind were negligible. Based on the measured data obtained in the current study, an S-shaped relation of the normalised transpiration rate (NTR) with ψ was fitted by the proposed Eq. (3).

$$NTR = NTR_{min} + \frac{(1 - NTR_{min})}{[1 + (\alpha_{sc}(\psi))^{n_{sc}}]^{m_{sc}}} \quad (3)$$

where NTR_{min} is the minimum value of NTR ; m_{sc} is a fitting parameter wherein it is equal to $(1 - \frac{1}{n_{sc}})$; n_{sc} and $\alpha_{sc}(\psi)$ are also fitting coefficients, respectively. n_{sc} is related to the slope of curve and $\alpha_{sc}(\psi)$ is related to a threshold suction value (ψ_{NTR}^t) where NTR starts to decrease. The fitted curve is termed as the normalized transpiration conductance (NTC) curve and the fitting parameters for each series are given in Table 3. The NTC curve could also model ($R^2 = 0.90$) the variation of SC with ψ reported by Gadi et al. (2019) on grass species (*Axonopus compressus*) grown in silty sand. It can be observed from the

fitted data that vegetation with higher LAI had a lower ψ_{NTR}^t values. This suggested that plants with higher LAI would be subjected to lowering down of SC due to drought stress at an earlier rate. This behaviour can be attributed to the parameters related to tree morphology such as higher root density, LA/RL values and root tips (Table 2). Water demand is greater where root density and LA/RL ratio is higher (Ng et al., 2019) which causes a decrease in water availability. At ψ lower than ψ_{NTR}^t , plants could transpire with a water-stress-free condition. Beyond ψ_{NTR}^t , it can be speculated that negative water pressure might develop inside the roots triggering gradual xylem cavitation or embolization of roots (Pockman and Sperry, 2000). However, based on sap flow data (discussed in later sections), major xylem cavitation happened at higher drought stresses than ψ_{NTR}^t . Based on results by Liu et al. (2003), it is feasible to state that lowering down of SC is in fact due to secretion of abscisic acid (ABA) within the xylem. Of course, cavitation ultimately occurs and is marked by a gradual decrease in sap flow (discussed later in detail). This would also contribute to residual SC values. Table 4 provides the measured ABA concentration in the leaf. It is observed that the leaf ABA concentration were only traceable beyond the ψ_{NTR}^t as drought progressed. However, after 100 kPa of soil suction, there is no marked variation in the ABA concentration. The results give insight on the effects of tree morphology in resisting initial drought stress due to induced chemical signals.

The diurnal variation of sap flow after transplantation for three trees with different LAI are presented in Fig. 7. It is observed that the sap flow changes its flow rate during different stages of the day. Even though the light intensity provided to the trees was constant during the day, trees inherently regulate their water uptake during the day as per the amount of light intensity from the sun (Rice, 1975). Considering readings from a single day, the sap flow reaches a maximum daily value around noon and thereafter decreases to a minimum value at night. Similar diurnal variation patterns were observed for species such as *Populus alba*, *Styrax ferrugineus*, *Roupala montana* and *Ouratea hexasperma* (Bucci et al., 2004; Xu et al., 2011). The maximum daily value increased with the LAI of the tree. At the end of 13 days since transplantation, the maximum daily sap flow of tree corresponding to LAI = 3.5 was higher by 250% and 142% than that of trees with LAI = 0.5 and LAI = 2.5, respectively. This increase in sap flow is expected as higher flow in the stem xylem will be required to accommodate the water vapor flow exiting from the leaves. Figure 8 presents the change in maximum daily value of sap flow with the corresponding ψ upon continued drought after ponding exercise. Regardless of LAI, the maximum daily sap flow values initially exhibit a smaller value at lower ψ . The maximum daily sap flow values were small at very low ψ , possibly due to ponding conditions that results in “root anaerobiosis”. Oxygen deprivation due to saturated conditions and subsequent accumulation of toxic secondary metabolites within

Table 4. Measured abscisic acid (ABA) concentration at different suction.

Suction	0 kPa	5 $\pm$ 2kPa	30 $\pm$ 3kPa	50 $\pm$ 5kPa	100 $\pm$ 5kPa	250 $\pm$ 5kPa
LAI=0.5	ND	ND	ND	26.35	27.25	27.35
LAI=2	ND	ND	0	30.25	32.12	33.52
LAI=3.5	ND	ND	12.98	35.65	35.02	34.50

*Unit for ABA concentration given in ng/mL, ND is not detected

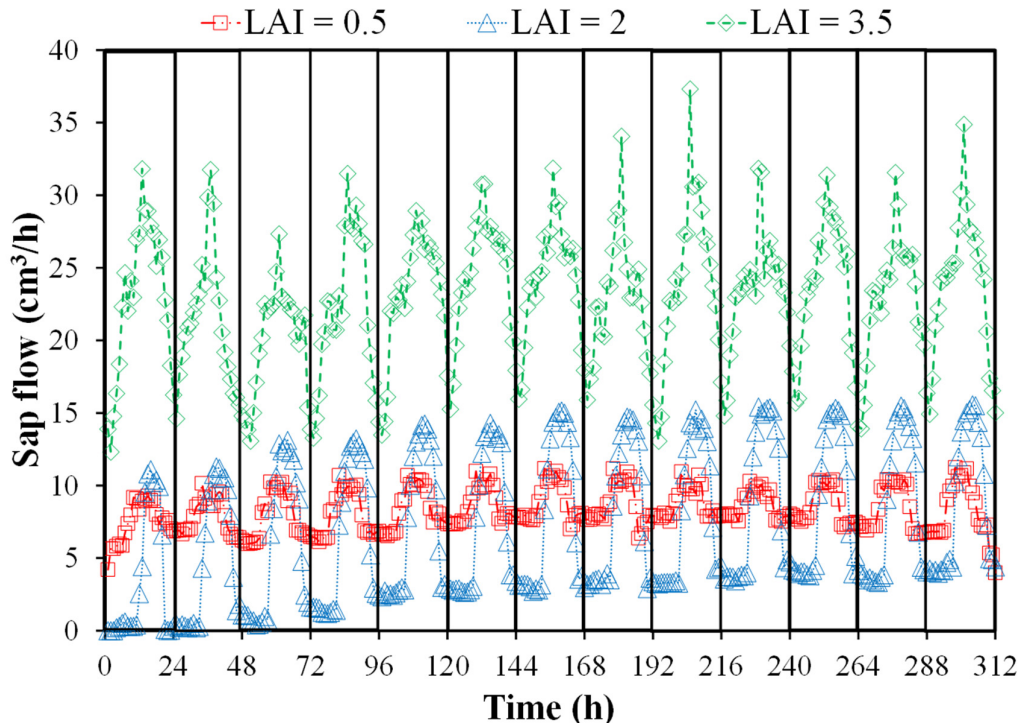


Fig. 7. Diurnal variation of sap flow after transplantation.

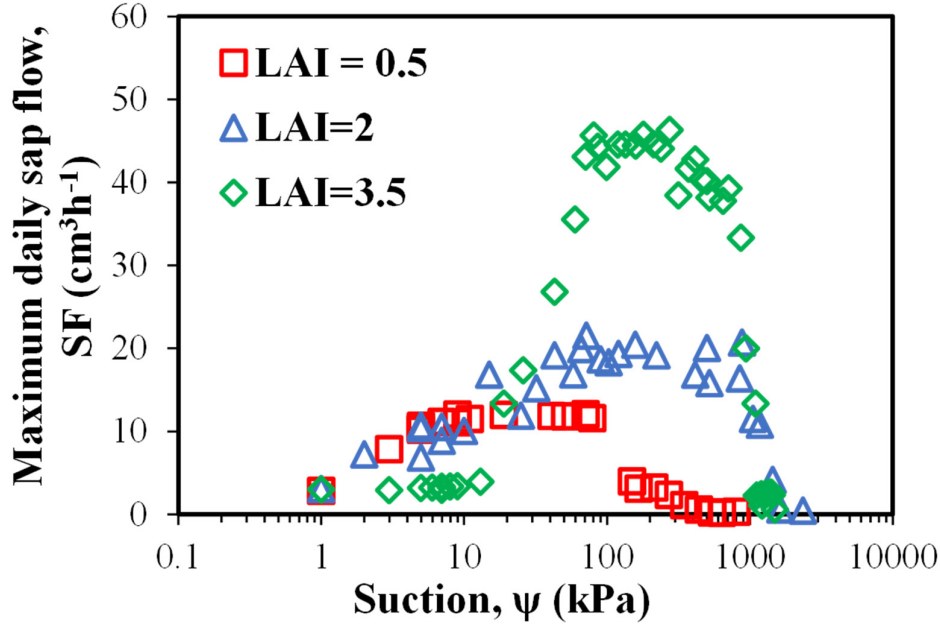


Fig. 8. Relationship of maximum daily sap flow with soil suction.

the roots result in root anaerobiosis (Pang and Shabala, 2010). During this condition, decreased root hydraulic conductance is due to an inhibition of plasma- membrane aquaporins that hinder O_2 transport to the roots (Arru and Fornaciari, 2010). As moisture evaporates gradually, the effects of anaerobiosis on root water uptake decreases as soil O_2 content increases. The maximum daily sap flow values gradually increase and ultimately reaches a maximum value at (ψ_{SAP}^M) and maintains it through a certain range of ψ upon continued drying. This range is corresponding to maximum potential hydraulic transport of sap fluid, representing highest potential tree water uptake. The magnitude of this maximum daily sap flow was proportional to the LAI of the trees. Tree corresponding to LAI = 3.5 exhibited this potential sap flow higher by 220% and 125% than that of trees with LAI = 0.5 and LAI = 2.5, respectively. A threshold suction value (ψ_{SAP}^t) is reached upon continued drought at which the maximum daily sap flow rate gradually decreases indicating gradual cavitation. Ultimately, the maximum daily sap flow reaches a zero-value marking permanent wilting point. After reaching this stage, the sap flow values become negative indicating that water potential in soil is lower than that within the plant xylem. This was further confirmed by individually measuring the leaf water potential at that stage using a dew-point potentiometer (Dong et al., 2012). Based on the measured leaf water potential, the head at the leaf water was seen to be higher than that of the root zone, indicating water flow from top to bottom. To compare the water stress function with sap flow for all trees, the normalised maximum daily sap flow (NDMSF) is plotted against corresponding ψ in Fig. 9. NDMSF is basically the maximum daily sap flow divided by potential maximum daily sap flow recorded after ponding and subsequent drought stage. NDMSF is same as one proposed by Feddes et al. (1978). The measured data of the normalized sap flow data with ψ can be modelled by Equation (4) and is designated as the sap flow reduction function.

$$NDMSF = \begin{cases} a_1 \ln(\psi) + b_1 & \text{up to } \psi_{SAP}^M \\ 1 & \text{from } \psi_{SAP}^M \text{ to } \psi_{SAP}^t \\ -a_2 \ln(\psi) + b_2 & \text{after } \psi_{SAP}^t \end{cases} \quad (4)$$

where a_1 and a_2 are fitting coefficients related to the gradient of increase and decrease of NDMSF, respectively. b_1 and b_2 are empirical fitting coefficients. The fitting parameters for Equation (4) is added in Table 3 and it can be seen that R^2 values were higher than 82% for all cases.

ψ_{NTR}^t , is associated with release of abscissic acid (Liu et al., 2003) whereas ψ_{SAP}^t is directly related to cavitation in the xylem (Steppe et al., 2015). Comparing ψ_{SAP}^t and ψ_{NTR}^t (Fig. 6b and Fig. 9), it is observed that water transport in the tree stem is affected at high suction range as compared to the leaves. Yang et al. (2013) have also reported threshold suction value for *Allocasuarina verticillata* tree in field conditions at 300 kPa based on sap flow measurements. They do not report measurements at lower ψ due to instrumental limitations as well as the experiment being a field monitoring exercise in arid regions of Australia. It is interesting to note that threshold suction is much lower for trees with low LA/RL ratio (LAI = 0.5) than those with higher LA/RL ratio (LAI = 2.5 and 3.5). This is in contrast to observations reported by Ng et al. (2020b) for *S. heptaphylla*, wherein LA/RL ratio is inversely proportional to magnitude of threshold ψ . The explanation of this contrasting trend could be discussed based on number of root tips (Table 2). Number of root tips for trees with LAI = 2.5 and 3.5 were much higher than those of LAI = 0.5. Pore water can be availed easily even when the soil water content decreases overall if the root tips ingrained in the soil pores are high in number. Thus, trees with LAI = 2.5 and 3.5 would be able to uptake water easily as compared to tree with LAI = 0.5. Moreover, judging the RAI of tree for LAI = 0.5 with the other two series in Fig. 3, it is evident that tree with LAI = 0.5 could draw water only till a depth of 60 mm. On the contrary, the rooting depth for the other two series goes beyond 100 mm depth. However, for trees with higher LAI, once threshold suction is reached, the transpiration drops down at a very steep rate as compared to those with low LAI. Thus, it can be concluded that a higher RAI and root depth ensures that trees will feel drought at higher ψ as compared to trees with lower RAI. Moreover, the results imply that trees with higher RAI will wilt quickly once threshold conditions are reached, particularly due to the high water demand of the dense root system.

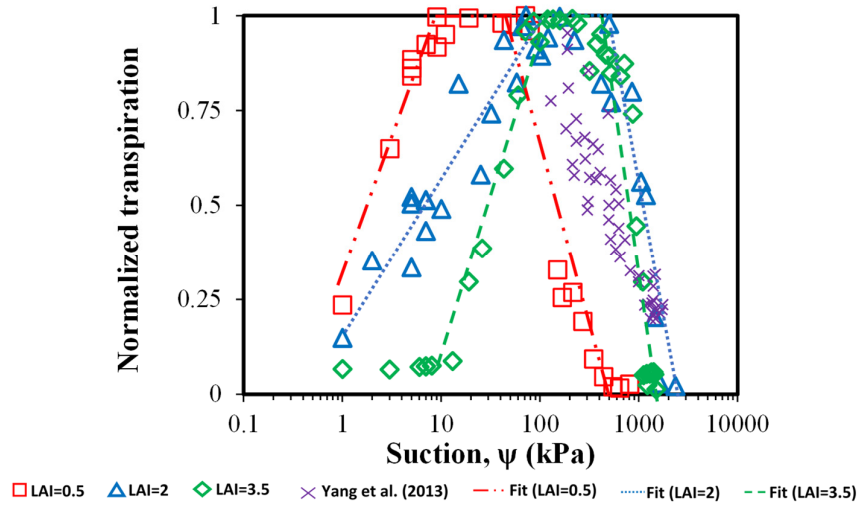


Fig. 9. Transpiration reduction function considering maximum daily sap flow.

Effects of tree morphology on threshold and wilting suction

The relationship of threshold ψ associated with different LA/RL ratio is shown in Fig. 10a. LA/RL ratio was recently identified by Ng et al. (2020a) as a morphological tree parameter to compare threshold values of water stress. A negative linear relationship between ψ_{NTR}^t and LA/RL ratio is observed with R^2 value at 0.90. It is to be noted that ψ_{NTR}^t for trees with similar LA/RL (including replicates) values varied within 5%. The results with respect to threshold ψ by the measured SC approach agree with the findings by Ng et al. (2020a). They estimated threshold ψ using a semi empirical water uptake intensity (WUI) model. Ng et al. (2020a) hypothesized that smaller threshold ψ values for *S. heptaphylla* having higher LA/RL ratio can be due to larger water head loss, causing higher water pressure difference between tree roots and soil. They suggested that the higher head loss may trigger negative water pressure causing cavitation within the roots at ψ range from 65 to 80 kPa. However, in the present study cavitation is unlikely to occur for *S. arboricola* at such low ψ range (30–50 kPa as per sap flow values). No evidence of excessive cavitation is observed in that ψ range based on the measured sap flow values. Literature suggests that roots secrete abscisic acid in the xylem tissue as an initial reactionary measure against early stages of drought stresses (Bacon et al., 1998; Davies and Zhang, 1991). This initial reactionary measure is known as chemical signalling (Davies et al., 1994). Liu et al. (2003) stated that it is only when drought stresses become more severe, hydraulic signals due to cavitation results in lower water uptake. Comparing the difference of ψ_{NTR}^t and ψ_{SAP}^t (refer Fig. 10a), it is prudent to imply that plant water uptake is not uniform throughout the tree upon drought conditions. These non-uniformities of water flow rate in stem and leaves upon drought conditions was not considered in plant water uptake models (Feddes et al., 1978; Ng et al., 2020a). Relationship between ψ_{SAP}^t and LA/RL ratio was logarithmic in nature with a good R^2 value of 0.95. At low LA/RL ratios, threshold ψ was reached at lower drought stress (79 kPa). At higher LA/RL ratios, ψ_{SAP}^t ranged between 400 to 500 kPa. At these LA/RL ratios, the shoot length was relatively high (170–240 mm) (refer Fig. 2). The increase of threshold suction with plant height has also been reported for *S. heptaphylla* (Ng et al., 2020a). They state that longer distance of water transport from root to stem and finally to leaves, necessitates higher head loss in xylem, thus having a higher threshold ψ . This

hypothesis is corroborated in the current study based on limited measured ψ_{SAP}^t values, wherein at higher tree height the range of threshold suction narrows down. This maybe a possible reason to explain why trees have a limiting height for a specific species (Koch et al., 2004).

Figure 10b shows the limiting suction at different LA/RL ratio. The term “limiting suction” implies to the ψ at which the water uptake reaches its minimum value or stops (possibly wilting). Based on the semi empirical model by Ng et al. (2020a), they found that limiting suction is constant at around 130 kPa regardless of tree morphology and they term it to be wilting suction. In the current study, the limiting ψ as per the measured SC values was found to be same at a higher suction about 256 kPa. Thus, it may seem that limiting ψ will not be affected by change in root morphology as per the measured data using SC values. More likely, this limiting ψ is that value at which plant response against drought resistance through chemical signalling. Thereafter, plant reaches wilting point due to allied effects of cavitation (i.e., hydraulic signalling). The relationship obtained between limiting ψ as per the measured sap flow values and LA/RL ratio is logarithmic in nature with R^2 value of 0.83. This suggests that limiting suction is dependent on the root morphology. As plants with low RAI (have lower root tips, refer Table 2 and Fig. 3) cannot readily access the soil water, it is very likely that it will wilt first as compared to plants with high RAI and uniform spread. This limiting ψ due to sap flow can be described as the actual wilting point because after this water flow happens downward, i.e., total head in soil will be higher than the xylem head. The wilting point for *Axonopus compressus* was recently measured by Garg et al. (2020), wherein they also stated that a uniform and well distributed RAI reaches permanent wilting later as compared to those with lower RAI. As per the classic definition given by Briggs and Shantz (1912), “the permanent wilting point is the moisture content of the soil at which the leaves of the plant undergo a permanent reduction in their moisture content as a result of a deficiency in the soil-moisture supply”. The leaf water content (measured by the chlorophyll meter) near limiting ψ (by measured sap flow approach) reduced by almost 80% as compared to those at threshold ψ . This further adds evidence to the fact that the trees have wilted permanently at this limiting ψ . The findings from this result imply that during early plant establishment, young trees are more susceptible to wilt if proper irrigation is not provided for their survival.

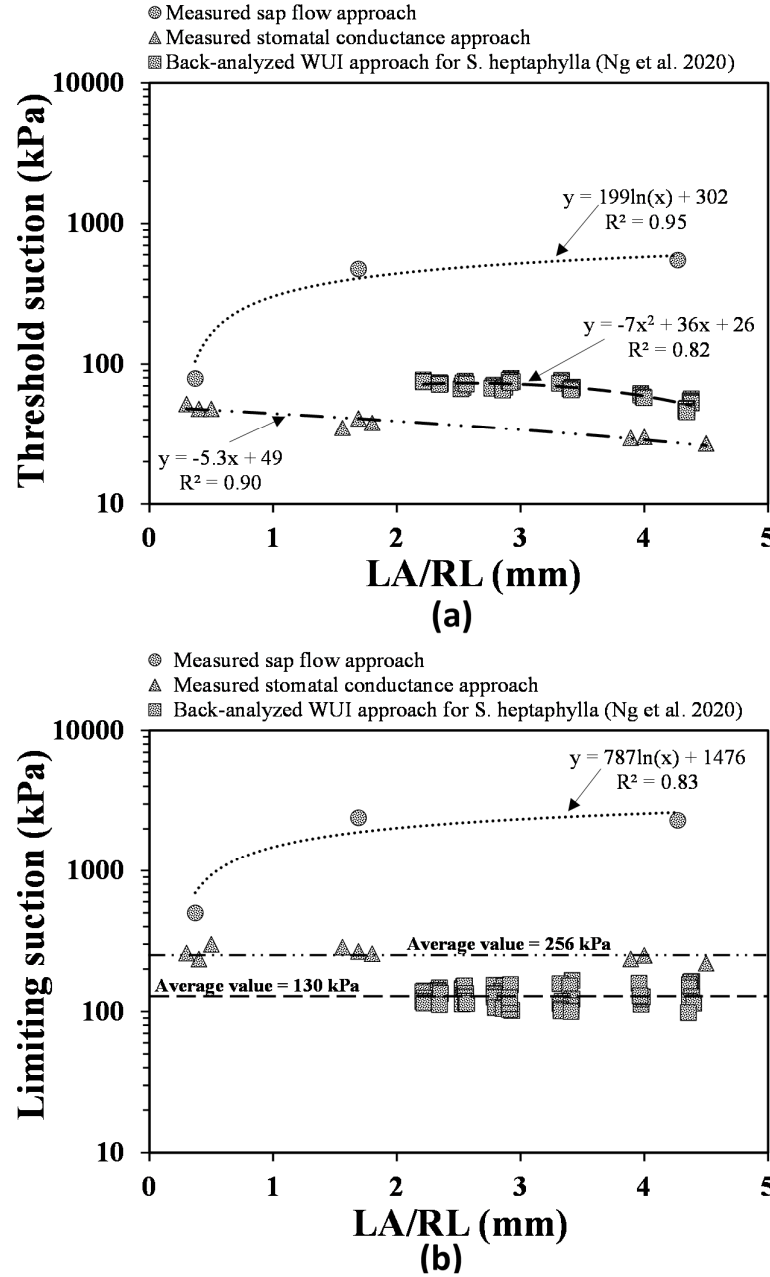


Fig. 10. Effect of LA/RL on the (a) threshold and (b) limiting suction.

SUMMARY AND CONCLUSIONS

The consequent variation in water uptake ratio (i.e., actual plant water uptake to potential water uptake) in the stem and leaves at different soil suction value were quantified and empirically modelled. The key conclusions that can be drawn from the current study are discussed below.

1. Plant water uptake efficiency decreases beyond ψ_{NTR}^t values ranging from 30 to 52 kPa. It was observed that any further increase in drought stress beyond ψ_{NTR}^t resulted in an increase in the measured abscisic acid concentration in the leaf xylem. This acted as an initial chemical response by the plant to decrease the stomatal opening. Before reaching ψ_{NTR}^t , the SC is higher for trees with greater LAI to facilitate water for optimum

photosynthesis in the leaves. At this stage, no abscisic acid was traced in the leaf xylem.

2. The maximum daily value of xylem sap flow increased with the LAI. This was attributed to higher flow in the stem xylem necessitated to accommodate the water vapor flow exiting from the leaves. From the sap flow reduction function, it was observed that the normalized maximum daily sap flow rate initially exhibits a smaller value at lower ψ , possibly due to “root anaerobiosis”. Thereafter, the normalized flow reaches a maximum value at a certain ψ , indicating highest stem water uptake. Upon continued drought conditions, the normalized daily sap flow rate decreased after a threshold suction (ψ_{SAP}^t), which ranged between 80 to 500 kPa. An empirical equation was used to model the change in normalized maximum daily sap flow values with ψ .

3. ψ_{NTR}^t was independent of LA/RL ratio, meaning that initial chemical signalling mechanism by *S. arboricola* against drought stress is independent of tree morphology. However, a unique relationship between ψ_{SAP}^t and LA/RL ratio was observed and can be attributed to the relative growth of root tips and root area index. It was observed that ψ_{SAP}^t is much lower for trees with low LA/RL ratio than those with higher LA/RL ratio. The results from this study reveal that drop in transpiration in *S. arboricola* due to xylem cavitation upon extreme drought is dependent on their tree morphology.

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Limitations and future scope: The current study is conducted in a laboratory greenhouse setup with controlled atmospheric conditions, which is not feasible in real field conditions. The inferences drawn from the current study need to be extended or validated for field conditions. Moreover, the equations presented are specific to the species studied. The study should be extended for other species type.

Data availability statement. The authors confirm that the data supporting the findings of this study are available within the article.

REFERENCES

- Addisie, M.B., Ayele, G.K., Hailu, N., Langendoen, E.J., Tilahun, S.A., Schmitter, P., Parlange, J.-Y., Steenhuis, T.S., 2020. Connecting hillslope and runoff generation processes in the Ethiopian highlands: the Ene-Chilala watershed. *J. Hydrol. Hydromech.*, 68, 313–327.
- Albalasmeh, A.A., 2013. Biophysical controls on rhizosphere dynamics. Doctoral Dissertation. UC aMerced.
- Andersen, P.C., Lombard, P.B., Westwood, M.N., 1984. Effect of root anaerobiosis on the water relations of several *Pyrus* species. *Physiol Plantarum*, 62, 2, 245–252.
- Arru, L., Fornaciari, S., 2010. Root oxygen deprivation and leaf biochemistry in trees. In: Mancuso, S., Shabala, S. (Eds.): *Waterlogging Signalling and Tolerance in Plants*. Springer, Berlin, Heidelberg, pp. 181–195.
- Bacon, M.A., Wilkinson, S., Davies, W.J., 1998. pH-regulated leaf cell expansion in droughted plants is abscisic acid dependent. *Plant Physiol*, 118, 4, 1507–1515.
- Balashov, E., Buchkina, N., Šimanský, V., Horák, J., 2021. Effects of slow and fast pyrolysis biochar on NO emissions and water availability of two soils with high water-filled pore space. *J. Hydrol. Hydromech.*, 69, 4, 467–474.
- Blight, G.E., 2003. The vadose zone soil-water balance and transpiration rates of vegetation. *Géotechnique*, 53, 1, 55–64.
- Boldrin, D., Leung, A.K., Bengough, A.G., 2018a. Effects of root dehydration on biomechanical properties of woody roots of *Ulex europaeus*. *Plant Soil*, 431, 1, 347–369.
- Boldrin, D., Leung, A.K., Bengough, A.G., 2018b. Hydrologic reinforcement induced by contrasting woody species during summer and winter. *Plant Soil*, 427, 1–2, 369–390.
- Bordoloi, S., Gadi, V.K., Hussain, R., Sahoo, L., Garg, A., Sreedeeep, S., Mei, G., Poulsen, T.G., 2018. Influence of *Eichhornia crassipes* fibre on water retention and cracking of vegetated soils. *Géotech. Lett.*, 8, 2, 130–137.
- Briggs, L.J. Shantz, H.L., 1912. The wilting coefficient and its indirect determination. *Botanical Gazette*, 53, 1, 20–37.
- Bucci, S.J., Scholz, F.G., Goldstein, G., Meinzer, F.C., Hinojosa, J.A., Hoffmann, W.A., Franco, A.C., 2004. Processes preventing nocturnal equilibration between leaf and soil water potential in tropical savanna woody species. *Tree Physiol*, 24, 10, 1119–1127.
- Comstock, J.P., 2002. Hydraulic and chemical signalling in the control of stomatal conductance and transpiration. *J Exp Bot*, 53, 367, 195–200.
- Connor, R., 2015. The United Nations world water development report 2015: water for a sustainable world (Vol. 1). UNESCO Publishing.
- Corona, R., Montaldo, N., 2020. On the transpiration of wild olives under water-limited conditions in a heterogeneous ecosystem with shallow soil over fractured rock. *J. Hydrol. Hydromech.*, 68, 338–350.
- Dainese, R., Tarantino, A., 2021. Measurement of plant xylem water pressure using the high-capacity tensiometer and implications for the modelling of soil–atmosphere interaction. *Géotechnique*, 71, 5, 441–454.
- Davies, W.J., Zhang, J., 1991. Root signals and the regulation of growth and development of plants in drying soil. *Annu. Rev. Plant Biol.*, 42, 1, 55–76.
- Davies, W.J., Tardieu, F., Trejo, C.L., 1994. How do chemical signals work in plants that grow in drying soil? *Plant Physiol*, 104, 2, 309.
- Devices Meter, 2019. Leaf porometer – operator’s manual. 9th Ed. Pullman, USA. <https://www.metergroup.com/environment/products/sc-1-leaf-porometer/>
- de Melo, M.L.A., Inforsato, L., Pinheiro, E.A.R., van Lier, Q.D.J., 2023. Plant available water predicted by a flux-based approach. *Geoderma*, 429, 116253.
- Dong, X., Ling, N., Wang, M., Shen, Q., Guo, S., 2012. Fusaric acid is a crucial factor in the disturbance of leaf water imbalance in *Fusarium*-infected banana plants. *Plant Physiol. Bioch.*, 60, 171–179.
- Fatahi, B., Khabbaz, H., Indraratna, B., 2010. Bioengineering ground improvement considering root water uptake model. *Ecol. Eng.*, 36, 2, 222–229.
- Feddes, R.A., Kowalik, P., Kolinska-Malinka, K., Zaradny, H., 1976. Simulation of field water uptake by plants using a soil water dependent root extraction function. *J. Hydrol.*, 31, 1–2, 13–26.
- Feddes, R.A., Kowalik, P.J., Zaradny, H., 1978. *Simulation of Field Water Use and Crop Yield*. Wiley, 188 p.
- Findlay, A., 2020. Six centuries of drought. *Nat. Clim. Change*, 10, 9, 802–802.
- Forrester, D.I., Collopy, J.J., Morris, J.D., 2010. Transpiration along an age series of *Eucalyptus globulus* plantations in southeastern Australia. *Forest Ecol. Manag.*, 259, 9, 1754–1760.
- Gadi, V.K., Hussain, R., Bordoloi, S., Hossain, S., Singh, S.R., Garg, A., Sekharan, S., Karangat, R., Lingaraj, S., 2019. Relating stomatal conductance and surface area with evapotranspiration induced suction in a heterogeneous grass cover. *Journal of Hydrology*, 568, 867–876.
- Garg, A., Bordoloi, S., Ganesan, S.P., Sekharan, S., Sahoo, L., 2020. A relook into plant wilting: observational evidence based on unsaturated soil–plant–photosynthesis interaction. *Scientific Reports*, 10, 1, 1–15.
- Garg, A., Leung, A.K., Ng, C.W.W., 2015. Transpiration reduction and root distribution functions for a non-crop species *Schefflera heptaphylla*. *Catena*, 135, 78–82.
- GEO, 2011. Technical guidelines on landscape treatment for slopes. Geotechnical Engineering Office (GEO), Civil Engineering and Development Department, The Government of

- the Hong Kong Special Administrative Region, Kowloon, Hong Kong.
- Gwenzi, W., Veneklaas, E.J., Holmes, K.W., Bleby, T.M., Phillips, I.R., Hinz, C. 2011. Spatial analysis of fine root distribution on a recently constructed ecosystem in a water-limited environment. *Plant Soil*, 344, 1–2, 255–272.
- Hamblin, A.P., Tennant, D., 1987. Root length density and water uptake in cereals and grain legumes: how well are they correlated. *Australian Journal of Agricultural Research*, 38, 3, 513–527.
- Hellegers, P., van Halsema, G., 2021. SDG indicator 6.4. 1 “change in water use efficiency over time”: Methodological flaws and suggestions for improvement. *Sci. Tot. Environ.*, 801, 149431.
- Heppell, J., Payvandi, S., Zygalakis, K.C., Smethurst, J., Fliege, J., Roose, T., 2014. Validation of a spatial–temporal soil water movement and plant water uptake model. *Geotechnique*, 64, 7, 526–539.
- Jim, C.Y., 2001. Ecological and landscape rehabilitation of a quarry site in Hong Kong. *Restor. Ecol.*, 9, 1, 85–94.
- Kirkham, M.B., 2014. *Principles of Soil and Plant Water Relations*. 2nd Ed. Academic Press, 598 p.
- Klimešová, J., Středová, H., Klimek-Kopyra, A., Středa, T., 2021. Transpiration and water use efficiency of maize in different soil moisture conditions. *Acta Horticulturae et Regiotecturae*, 24, 2, 105–109.
- Koch, G.W., Sillett, S.C., Jennings, G.M., Davis, S.D., 2004. The limits to tree height. *Nature*, 428, 6985, 851–854.
- Lam, C.C., Leung, Y.K., 1994. Extreme rainfall statistics and design rainstorm profiles at selected locations in Hong Kong. Royal Observatory.
- Leung, A.K., Garg, A., Ng, C.W.W., 2015. Effects of plant roots on soil-water retention and induced suction in vegetated soil. *Eng. Geol.*, 193, 183–197.
- Leštianska, A., Fleischer, P. Jr., Fleischer, P., Merganičová, K., Střelcová, K., 2020. Interspecific variation in growth and tree water status of conifers under water-limited conditions. *J. Hydrol. Hydromech.*, 68, 368–381.
- Li, K.Y., De Jong, R., Boisvert, J.B., 2001. An exponential root-water-uptake model with water stress compensation. *J. Hydrol.*, 252, 1–4, 189–204.
- Liu, F., Jensen, C.R., Andersen, M.N., 2003. Hydraulic and chemical signals in the control of leaf expansion and stomatal conductance in soybean exposed to drought stress. *Funct. Plant Biol.*, 30, 1, 65–73.
- Liu, Y.J., Wang, T.W., Cai, C.F., Li, Z.X., Cheng, D.B., 2014. Effects of vegetation on runoff generation, sediment yield and soil shear strength on road-side slopes under a simulation rainfall test in the Three Gorges Reservoir Area, China. *Sci. Tot. Environ.*, 485, 93–102.
- Lopez, F.B., Nobel, P.S., 1991. Root hydraulic conductivity of two cactus species in relation to root age, temperature, and soil water status. *J. Exp. Bot.*, 42, 2, 143–149.
- Lowman, M.D., 1988. Litterfall and leaf decay in three Australian rainforest formations. *J. Ecol.*, 451–465.
- Meijer, G.J., Bengough, G., Knappett, J., Loades, K., Nicoll, B., 2018. In situ root identification through blade penetrometer testing – part 2: field testing. *Geotechnique*, 68, 4, 320–331.
- Moore, D., Kostka, S., Boerth, T., Franklin, M., Ritsema, C., Dekker, L., Oostindie, K., Stoof, C., Wesseling, J., 2010. The effect of soil surfactants on soil hydrological behavior, the plant growth environment, irrigation efficiency and water conservation. *J. Hydrol. Hydromech.*, 58, 3, 142–148.
- Munemasa, S., Hauser, F., Park, J., Waadt, R., Brandt, B., Schroeder, J.I., 2015. Mechanisms of abscisic acid-mediated control of stomatal aperture. *Curr. Opin. Plant Biol.*, 28, 154–162.
- Ng, C.W.W., Ni, J.J., Leung, A.K., Zhou, C., Wang, Z.J., 2016. Effects of planting density on tree growth and induced soil suction. *Geotechnique*, 66, 9, 711–724.
- Ng, C.W.W., Wang, Z.J., Leung, A.K., Ni, J.J., 2019. A study on effects of leaf and root characteristics on plant root water uptake. *Geotechnique*, 69, 2, 151–157.
- Ng, C.W.W., Wang, Z.J., Ni, J.J., 2020a. Effects of plant morphology on root-soil hydraulic interactions of *Schefflera heptaphylla*. *Can. Geotech. J.*, 58, 5. DOI: 10.1139/cgj-2019-0647
- Ng, C.W.W., Ni, J.J., Leung, A.K., 2020b. Effects of plant growth and spacing on soil hydrological changes: a field study. *Geotechnique*, 70, 10, 867–881.
- Ni, J.J., Leung, A.K., Ng, C.W.W., Shao, W., 2018. Modelling hydro-mechanical reinforcements of plants to slope stability. *Comput. Geotech.*, 95, 99–109.
- Ni, J.J., Leung, A.K., Ng, C.W.W., 2019. Modelling effects of root growth and decay on soil water retention and permeability. *Can. Geotech. J.*, 56, 7, 1049–1055.
- Pang, J., Shabala, S., 2010. Membrane transporters and water-logging tolerance. In: Mancuso, S., Shabala, S. (Eds.): *Water-logging Signalling and Tolerance in Plants*. Springer, Berlin, Heidelberg, pp. 197–219.
- Patanè, C., 2011. Leaf area index, leaf transpiration and stomatal conductance as affected by soil water deficit and VPD in processing tomato in semi-arid Mediterranean climate. *J. Agron. Crop Sci.*, 197, 3, 165–176.
- Paz, H., 2003. Root/shoot allocation and root architecture in seedlings: variation among forest sites, microhabitats, and ecological groups. *Biotropica*, 35, 3, 318–332.
- Pochodyła, E., Jaszczak, A., Illes, J., Kristianova, K. and Joklova, V., 2022. Analysis of green infrastructure and nature-based solutions in Warsaw–selected aspects for planning urban space. *Acta Horticulturae et Regiotecturae*, 25, 1, 44–50.
- Pockman, W.T., Sperry, J.S., 2000. Vulnerability to xylem cavitation and the distribution of Sonoran Desert vegetation. *Am. J. Bot.*, 87, 9, 1287–1299.
- Powrie, W., Smethurst, J., 2018. Climate and vegetation impacts on infrastructure cuttings and embankments. In: *Proc. International Congress on Environmental Geotechnics*, pp. 128–144.
- Rahardjo, H., Satyanaga, A., Leong, E.C., Santoso, V.A., Ng, Y.S., 2014. Performance of an instrumented slope covered with shrubs and deep-rooted grass. *Soils Found.*, 54, 3, 417–425.
- Rice, R.C., 1975. Diurnal and seasonal soil water uptake and flux within a Bermudagrass root zone. *Soil Sci. Soc. Am. J.*, 39, 3, 394–398.
- Savi, T., Andri, S., Nardini, A., 2013. Impact of different green roof layering on plant water status and drought survival. *Ecol. Eng.*, 57, 188–196.
- Sawwan, J.S., Ghunem, R.S., 1999. Light acclimatization of *Schefflera arboricola*. *Adv. Hort. Sci.*, 13, 151–155.
- Šimanský, V., Šrank, D., 2021. Relationships between soil organic matter and crop yield after biochar substrates application and their combination with mineral fertilizers on sandy soil. *Acta Horticulturae et Regiotecturae*, 24, 1, 14–20.
- Steppe, K., Vandegheuchte, M.W., Tognetti, R., Mencuccini, M., 2015. Sap flow as a key trait in the understanding of plant hydraulic functioning. *Tree Physiol.*, 35, 4, 341–345.
- Svejar, T., 1990. Root length leaf area, and biomass of crested wheatgrass and cheatgrass seedlings. *Rangeland Ecology &*

- Management/Journal of Range Management Archives, 43, 5, 446–448.
- Turek, M.E., van Lier, Q.D.J., Armindo, R.A., 2020. Estimation and mapping of field capacity in Brazilian soils. *Geoderma*, 376, 114557.
- van Genuchten, M.T., 1980. A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. *Soil Sci. Soc. Am. J.*, 44, 5, 892–898.
- Van Genuchten, M.T., 1987. A Numerical Model for Water and Solute Movement in and Below the Root Zone. United States Department of Agriculture Agricultural Research Service U.S. Salinity Laboratory.
- Wang, G.L., Liu, F., Xue, S., 2017. Nitrogen addition enhanced water uptake by affecting fine root morphology and coarse root anatomy of Chinese pine seedlings. *Plant and Soil*, 418, 177–189.
- Wang, F., Yu, C., Xiong, L., Chang, Y., 2019. How can agricultural water use efficiency be promoted in China? A spatial-temporal analysis. *Resources, Conservation and Recycling*, 145, 411–418.
- Wei, Z., Fang, L., Li, X., Liu, J., Liu, F., 2020. Effects of elevated atmospheric CO₂ on leaf gas exchange response to progressive drought in barley and tomato plants with different endogenous ABA levels. *Plant Soil*, 447, 1, 431–46.
- Wu, J., Zhang, R., Gui, S., 1999. Modeling soil water movement with water uptake by roots. *Plant Soil*, 215, 1, 7–17.
- Xu, X., Tong, L., Li, F., Kang, S., Qu, Y., 2011. Sap flow of irrigated *Populus alba* var. pyramidalis and its relationship with environmental factors and leaf area index in an arid region of Northwest China. *J. For. Res.*, 16, 2, 144–152.
- Yang, Y., Guan, H., Hutson, J.L., Wang, H., Ewenz, C., Shang, S., Simmons, C.T., 2013. Examination and parameterization of the root water uptake model from stem water potential and sap flow measurements. *Hydrological Processes*, 27, 20, 2857–2863.
- Yildiz, A., Graf, F., Springman, S.M., 2020. On the dilatancy of root-permeated soils under partially saturated conditions. *Géotech. Lett.*, 10, 2, 227–230.
- Yu, G.R., Zhuang, J., Nakayama, K., Jin, Y., 2007. Root water uptake and profile soil water as affected by vertical root distribution. *Plant Ecol.*, 189, 1, 15–30.
- Zhu, H., Zhang, L.M., Garg, A., 2018. Investigating plant transpiration-induced soil suction affected by root morphology and root depth. *Comput. Geotech.*, 103, 26–31.
- Zhu, H., Indupriya, M., Gadi, V.K., Sreedeeep, S., Mei, G.X., Garg, A., 2019. Assessment of the coupled effects of vegetation leaf and root characteristics on soil suction: an integrated numerical modeling and probabilistic approach. *Acta Geotech.*, 15, 1331–1339.

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