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Transpiration reduction and root distribution functions for non-crop species *Schefflera heptaphylla*

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ABSTRACT:

Quantifying soil suction induced by plant transpiration is vital for engineers to analyse the performance of geotechnical infrastructure such as landfill covers. Transpiration reduction function (T_{rf}) and root distribution function (R_{df}) are the two plant properties that govern root-water uptake ability. These two functions have been quantified for various crop species, but they are sometimes used to study the behaviour non-crop species, even though they are known to be plant-specific. In this study, specific T_{rf} and R_{df} were measured for six replicates of *S. heptaphylla* that have a range of leaf area index (LAI) from 1.0 to 3.5 in silty sand. *S. heptaphylla* is a non-crop tree species that has been commonly used for ecological restoration in many subtropical regions. T_{rf} of each replicate was obtained by relating normalised transpiration rate with suction. After testing, the root system of each tree individual was imaged to determine normalised root area index (RAI) profile (i.e., R_{df}). Normalised transpiration rate for *S. heptaphylla* with higher LAI (3 and 3.5) has lower tolerance of water stress as their normalised transpiration rate reduced at much lower suctions, as compared to those with lower LAI (i.e., 1 – 2.5). It is found that only when suction is lower than 50 kPa, the measured T_{rf} of *S. heptaphylla* is similar to some of those presumed in the literature. The measurement of R_{df} shows that the maximum amount of roots for *S. heptaphylla* was at depths of 70-80% of the root depth, in contrast to crops species whose root distribution is typically uniform or linearly decreasing.

Keywords: transpiration reduction function, root distribution, suction, tree, leaf area index

1. Introduction

Understanding plant transpiration and its induced soil water potential (or soil suction) is important for agriculturists to design for irrigation scheduling of crops and also for engineers to analysis the performance of geotechnical infrastructure such as vegetated landfill covers and vegetated slopes. Various studies have been conducted to investigate the effects of vegetation on slope hydrology and slope stability (Simon and Collison, 2002; Rahardjo et al., 2014; Garg and Ng, 2015; Garg et al., 2015a; Garg et al., 2015b; Leung and Ng, 2013a, b; Leung et al., 2015a; Leung et al., 2015b). Plant transpiration depends on soil suction (Feddes et al., 1978) and also root characteristics such as root area index (RAI) (Garg and Ng, 2015a). Such soil-plant interaction is usually quantified by two plant-specific properties, namely transpiration reduction function (T_{rf}) (Feddes et al., 1978) and root distribution function ($R_{df;}$ Prasad, 1988). Both T_{rf} and R_{df} are also the key parameters for sink term (Feddes et al., 1978), which is usually coupled with Richards equation to model root water uptake and its induced suction in unsaturated soil.

T_{rf} is defined as the variation of the ratio of actual to potential transpiration rate of plant with soil suction (Feddes et al., 1978). The physical meaning of T_{rf} is the ability of plant to adjust its water uptake ability according to the amount of soil suction developed in the soil. Feddes et al. (1978) proposed a piece-wise linear T_{rf}, which is formulated by connecting *h1* (anaerobiosis point (denoted as *h2*), one empirical parameter (*h3*) and wilting point (*h4*). These values are usually presented in terms of suction, while *h1*, *h2*, *h3* and *h4* are deduced from soil water retention curve (SWRC). Anaerobiosis point refers to suction below which any water uptake by roots is negligible due to reduction in metabolic processes by deficiency of oxygen (Perata and Alpi, 1993). When soil suction is between *h2* and *h3*, the transpiration rate is considered to be maximum. Beyond *h3*, the value of transpiration rate reduces significantly. Wilting point (*h4*) refers to the suction value at which root-water uptake ceases. van Genuchten (1987) also proposed a semi-empirical nonlinear T_{rf}, which requires two empirical parameters, namely h_{50} (i.e., the suction head corresponding to 50% reduction in the normalised transpiration rate) and a constant, p. However, in both proposed T_{rf}, suction is indirectly deduced from SWRC through soil moisture measurement. This approach could be error-prone because water content is well-known to be not uniquely related to suction due to hysteretic nature of unsaturated soil (Ng and Leung, 2012). On the other hand, R_{df} is defined as the variation of total amount of roots (expressed as either root length density, RAI or root biomass) along depth. It describes the ability of root water uptake along root depth. The most commonly used R_{df} are linearly decreasing (Prasad, 1988) and uniform (Feddes et al., 1978), both of which were derived from crop species. Another plant characteristics i.e., Leaf area index (LAI; a dimensionless index defining the ratio of total one-sided green leaf area to projected area of an individual plant on soil surface in plan) is well known known to affect radiant energy, photosynthesis and transpiration rate (Legg et al., 1979; Asrar et al., 1984). This may further effect root growth (i.e., R_{df}) as well as T_{rf}, which is rarely investigated.

Various numerical studies (Nyambayo and Potts, 2010; Fatahi et al., 2010; Garg et al., 2012) have been conducted to simulate transpiration-induced suction. In general, these studies assumed some empirical R_{df} and T_{rf} reported in the literature, even though the plant species studied in each of the numerical studies was/were not the same as those used to derive T_{rf} (Feddes et al., 1978; van Genuchten, 1987; Wesseling 1991; Utset et al., 2000) and R_{df} (López et al., 2001). The measurements of R_{df} and T_{rf} from the existing studies were mainly derived for crop species such as potato and wheat. However, the soil condition and plant properties of this kind of crop species can be significantly different from those of non-crop species, which is sometimes used for ecological restoration. In order to provide favourable conditions for better crop growths, the agricultural soil tested were often loosely compacted, and have rich organic contents and nutrient concentration (Williams, 1974; Vetterlein et al., 1993; Guber et al., 2008). Crop species also require specific irrigation scheduling and regular harvesting due to the concern on crop yield (Wetzel and Chang, 1987; Zhang et al., 2004). In contrast, non-crop species are normally vegetated in densely-compacted soil, which is commonly the case for geotechnical infrastructure due to stability considerations. They also do not require frequent irrigation due to their nature of drought tolerant. Such differences in water demand suggest that R_{df} and T_{rf} of crop species cannot be directly applied to capture the root water uptake behaviour and its induced soil suction by non-crop species.

The objectives of this study are to quantify T_{rf} and R_{df} that are specific for a non-crop species, *S. heptaphylla,* and to investigate any effects of LAI it might have on these two plant parameters. *S. heptaphylla* is a species commonly found in tropical and subtropical regions such as Hong Kong, Singapore, Malaysia and some parts of India and the mainland China (Hau and

Corlett, 2003; Li et al., 2005). It is known to possess high survival rate and is drought tolerant, which is suitable for the use of ecological restoration and rehabilitation (Hau and Corlett, 2003). This particular species has been one of the recommended native plant species of Hong Kong for landscape treatment and ecological restoration and rehabilitation due to their growth characteristics, ornamental and ecological values (GEO, 2011). Six individuals of *S. heptaphylla* with different LAIs ranging from 1.0 to 3.5 were vegetated in six separate, purpose-built test cylinder compacted with silty sand. Each vegetated test cylinder was then tested in an plant room, where the atmospheric conditions were well-controlled. The measured T_{rf} and R_{df} of *S. heptaphylla* are evaluated by comparing them with those assumed in the literature.

2. Material and methods

2.1 Experimental set up

In this study, six plastic test cylinders were designed for testing. Figure 1 shows an overview of a typical test cylinder vegetated with a tree individual. The test cylinder has a diameter of 70 mm and a height of 130 mm. At the bottom of each cylinder, there are five drainage holes with a diameter of 5 mm each for bottom drainage during testing. In order to measure the responses of soil suction, an array of three tensiometers were installed along the depth of each cylinder at 25, 50 and 75 mm. Each tensiometer has a ceramic tip that is fully saturated with de-aired water. When the ceramic tip is in contact with soil, pore-water pressure of the soil would establish equilibrium with the pressure of water column in the tensiometer due to total head difference between them. At equilibrium, the water tension induced in the tensiometer is equal to the negative pore-water pressure of the surrounding soil and it is recorded by a Bordon gauge. Because of the possibility of cavitation, each tensiometer can measure negative pore-water pressure (or suction) not more than 80 kPa only (Ng & Menzies, 2007). Due to this limitation, another type of suction sensor, namely heat dissipation matric water potential sensor (HDS; accuracy ± 5% (Fredlund et al., 2000), was installed at 50 mm depth for measuring suctions higher than 50 kPa. Calibration shows that the HDS can give reliable measurement when soil suction is higher than 50 kPa. A weighing balance of accuracy ± 1% was placed at the bottom of each cylinder for continuously monitoring the change of the cylinder weight. In each test cylinder, the bare soil surface around the tree individual was covered with a plastic sheet to minimise evaporation. As a result, any change of the cylinder weight was equal to the actual transpiration of the tree individual.

2.2 Soil properties and preparation of test box

Completely decomposed granite (CDG), which is commonly found in Hong Kong, was tested in this study. The gravel, sand, silt and clay contents of CDG are 19% 42%, 27%, and 12%, respectively. CDG is classified as clayey sand with gravel (SC) according to the Unified Soil Classification System (USCS). In each test cylinder, silty sand with a depth of 100 mm was compacted at a targeted dry density of 1580 kg m^{-3} ± 2% (i.e., equivalent to 95% of the maximum dry density) at water content (by mass) of 12% using the under-compaction method (Ladd, 1977). It has been shown in the field study conducted by Garg et al. (2015b) that *S. heptaphylla* is able to survive and develop its root system when it was grown in an compacted embankment with a compaction degree of 95%. It should be noted that it is common to construct a man-made slope at a relatively high degree of compaction of 95% due to the consideration of slope stability in particular and in civil engineering applications in general (TDOT, 1981; Gray and Sotir, 1996; GCO, 2000; CEDD, 2006; Ng et al., 2014). The field capacity, which is defined as the amount of water content held in soil after excess water has drained away and the rate of water movement is negligible (Veihmeyer and Hendrickson, 1931), for the CDG at the targeted dry density, is 16%. This corresponds to soil suction of 25 kPa. In this study, fertilizer is not added in soil to prevent any development of osmotic suction. Other index properties of soil are summarized in Ng et al. (2013; 2014).

2.3 Test procedures

2.3.1 Measurement method of transpiration reduction functions

In total, six *S. heptaphylla* individuals with similar shoot length of 400±50 mm were selected for testing. They were transplanted in the centre of six separate test cylinders. Before transplanting to each test cylinder, all six tree individuals were grown in a nursery under the same soil dry density and the same environmental condition. LAI of each tree individual was determined by dividing the total surface area of leaf with the corresponding canopy area (assuming diameter equal to the distance between two ends of canopy). Total surface area of leaves was determined by image analysis using an open source java program, Image J (Rasband, 2011; a public domain Java image processing program that can calculate area and pixel value statistics of user-defined selections, i.e., root area in this study). A high resolution photograph was taken with leaf on a planar surface and it was converted into binary image using Image J. Total pixels of binary image were then determined and converted to total surface area. More detailed procedures are described in Garg et al. (2015a). The measured LAI of the six tree individuals are found to be 1.0, 1.5, 2.1, 2.5, 3.0 and 3.5. The resulting differences of LAI among the six individuals are attributed to genetic variation (Richards, 2000).

The measurement of T_{rf} for each of the six tree individuals consists of two phases. The first phase aims to measure T_{rf} using tensiometers for suctions lower than 50 kPa. When soil suction is above 50 kPa, the second phase was to measure the T_{rf} using HDSs. The rational of choosing 50 kPa is based on the consideration of the measurement limits of tensiometers and HDSs. The former is not able to measure any suction approaching 80 kPa, while the latter works well for suctions higher than 20 kPa. Choosing an intermediate value (i.e., 50 kPa) between these two limiting suctions therefore allow for some overlapping between the two phases of measurement.

After preparing each cylinder as shown in Fig. 1, a small ponding head of six mm for a duration of six minutes was applied on the soil surface, while all the bottom drainage holes were opened to allow free drainage. This procedure was stopped when zero suction was recorded by all the tensiometers. It has been shown by Leung et al. (2015a) that the soil investigated in this study has remarkable hydraulic hysteresis. This means that at a ny given suction, water content along the wetting curve is always lower than that along the drying curve. Although zero suction was recorded after the ponding, water content of soil did not refer to the saturated value necessarily. Thereafter, the bare soil surface of each cylinder was covered with a laminated plastic sheet and the six tree individuals were allowed to transpire in an atmospheric-controlled plant room. The radiation, air temperature and air relative humidity in the room were maintained constant at 7.1±1 $MJ/m^2/d$, 22.3±1^oC and 53±7 %, respectively. During transpiration, any changes in soil suction and the cylinder weight were measured every two hours. This process was stopped when soil suction in each cylinder reached 350 kPa, which is the maximum calibrated range of the HDS. This phase of testing took around four days. The relatively short testing duration means that effects on any change in the biomass of tree individual can be neglected (Allmen et al., 2012). After testing, daily volume of water (mm^3) transpired by each tree individual (i.e., actual transpiration rate) was determined by dividing the measured weight change by the density of water. Finally, T_{rf} was obtained by normalising the measured actual transpiration rate by the maximum value (i.e., referred to as potential transpiration rate) for each tree individual. The measurement method of T_{rf}, although applicable to the laboratory condition, may be difficult to be applied in the field condition. This is because the change of soil moisture content due to plant transpiration is not easy to be determined in the field, unless a test setup similar to lysimeter is used for water balance calculation. Moreover, the measurements of T_{rf} were made at one specific environmental condition in the laboratory. More research is needed to investigate how atmospheric parameters such as relative humidity and radiation might affect T_{rf}.

2.3.2 Measurement of root distribution function

In order to determine R_{df}, RAI distribution was measured using an image analysis of root system of six tree individuals. After testing the T_{rf}, each tree individual was removed from the test cylinder. This was followed by the separation of root system from the soil by careful washing. The root system was then clamped and pictures were taken using a high-resolution digital camera from six different angles including from the top and the bottom. These pictures were superimposed to generate a three-dimensional (3-D) picture of root system. By using Image J, 3-D picture of root system was converted to binary image, which was then discretized into grids in both directions. Area in each grid containing roots was calculated in each grid. The total surface area of roots in all grids at a given depth was normalized by the planar cross sectional area of soil to determine RAI at any depth. Planar cross sectional area is defined as the circular area (in mm^2) with a diameter representing the largest lateral spread of roots in that grid. Detailed procedures for measuring RAI of a plant are discussed in Garg et al. (2015a). Finally, RAI at each depth was normalized by the peak value of RAI measured within the entire root zone. The variation of normalized RAI with depth represents R_{df}.

3. Results and discussion

3.1 Measured transpiration reduction function (T_{rf}) for *S. heptaphylla*

3.1.1 Effects of LAI on T_{rf}

Figure 2 shows the T_{rf} of the six tree individuals with different LAI. It can be seen that for soil suction lower than 50 kPa, the measured values of normalized transpiration rate of the six tree individuals were rather similar and appear to be independent of LAI. However, beyond this particular suction, some differences are observed. The normalized transpiration rate of *S. heptaphylla* with lower LAI (i.e., 1.0, 1.5, 2.0 and 2.5) showed significant reduction from the peak value (i.e., 1.0) at soil suction of around 65 – 90 kPa (i.e., *h3*). On the contrary, for the tree individuals having higher LAI of 3.0 and 3.5, the reduction of the normalized transpiration rate occurred at lower suctions of 52 – 55 kPa. The range of *h3* (i.e., 52 – 90 kPa) for *S. heptaphylla* is found to be lower than the typical value reported in the literature (i.e., 100 kPa; Feddes et al., 1978). The measurements imply that the tree individuals having a higher LAI have lower tolerance of water stress, as lower suction is needed to reduce the ability of the tree root-water uptake. Such LAI dependency of T_{rf} observed in this study is somewhat not identified in the past. However, as soil suction increased further beyond 215 kPa, there seems to have no discernible difference among the T_{rf} of the six tree individuals.

3.1.2 Comparisons with measured or assumed T_{rf} in literature

In Fig. 2, the measured T_{rf} of potato (Utset et al. 2000) and the T_{rf} proposed by Feddes et al. (1978) and van Genutchen (1987) were shown for comparison. It should be noted that the T_{rf} proposed by Feddes et al. (1978) was obtained by connecting *h1* (0 kPa), *h2* (5 kPa), *h3* (100 kPa) and *h4* (1500 kPa). On the other hand, the T_{rf} proposed by van Genutchen (1987) was determined by fitting h_{50} from the experiments conducted in this study. The values of h_{50} were identified to be 140 kPa for the tree individual with LAI of 3.5 and about 210 kPa for the other two tree individuals with LAI of 1.0 and 2.5, respectively. The parameter *p* is set to be 1.0 as no salt ion is present in the CDG. It is revealed that when suction is between 0 and 5 kPa, normalized transpiration rate of *S. heptaphylla* is much higher than that proposed by Feddes et al. (1978) but similar to that proposed by van Genuchten (1987). When the soil suction is between 5 kPa and 50 kPa, the normalized transpiration rate of *S. heptaphylla* is generally similar to those proposed two empirical functions. The values of *h3* of *S. heptaphylla* (i.e., 52- 90 kPa) are found to be higher than that observed in various crop species, including potato (i.e., 30 kPa; Utset et al. 2000), sugar beet (i.e., 32kPa； Wesseling, 1991) and wheat (i.e., 50 kPa; Wesseling, 1991). The normalized transpiration rate of *S. heptaphylla* at suction of around 350 kPa is 40% lower than that proposed by Feddes et al. (1978), but it is around 10 times higher than that suggested by van Genuchten (1987) for various crop species.

When compared to the T_{rf} of potato (Utset et al. 2000), the normalized transpiration rate for *S. heptaphylla* is found to be much higher for the entire suction range. Moreover, it can be seen that the range of suction, at which the maximum normalized transpiration rate (i.e., 1.0) is attained, is much wider for the *S. heptaphylla* (0 – 90 kPa), as compared to the potato (20 – 28 kPa). The normalized transpiration rate of *S. heptaphylla* reached 0.6 at suction of around 78 kPa. This is around three times than that for the potato (i.e., 0.2). Such observed discrepancy highlights that T_{rf} is species-specific and T_{rf} derived from a crop species should not be used to describe the root-water uptake ability of a non-crop species.

3.2 Measured root distribution function (R_{df}) for *S. heptaphylla*

Figure 3 shows the comparison of R_{df} of the six tree individuals that have different values of LAI. The R_{df} proposed by Feddes et al. (1978) and Prasad (1998) are also shown for comparison. Normalized depth is used in this figure by dividing the depth of RAI measurement by the root depth of each tree individual. It can be seen that for LAI equal to 1.0, there is an evident increase in normalized RAI from 0.25 to about 1.0 at normalised depths of 0.7 to 0.8. On the contrary, a substantial decrease in normalized RAI is observed below this particular depth range. A similar trend of R_{df} distribution is identified for the other five tree individuals, though the magnitude is different due to genetic variation. It may be seen from the figure that normalized RAI in shallower depths (i.e., within 80 mm) is generally proportional to LAI. Such correlation, however, may be apparent because LAI is a variable that is a function of the growth period of plants. Previous studies (Causton and Venus, 1981; Liedgens, 1998; Liedgens and Richner, 2001) have revealed that most significant correlations between LAI and root density of maize were found during maturity stage of plant and at depth corresponding to the maximum rooting density. The observed nonlinear distribution of R_{df} of *S.hetpaphylla* appears not to be able to be captured by neither the uniform distribution proposed by Feddes et al. (1978) nor the linearly decreasing distribution proposed by Prasad (1998).

4. Summary and Conclusions

This study quantifies specific T_{rf} and R_{df} for a non-crop species, *S. heptaphylla*, vegetated in compacted silty sand. T_{rf} was determined by relating soil suction with transpiration rate of the species obtained by continuous monitoring of the loss of water volume being transpired. R_{df} was determined by measuring RAI through a series of image analyses on the root system. Six tree individuals were tested to explore any effects of plant variability in LAI on both plant properties.

The test results show that the tree individuals having higher values of LAI (i.e., 3 and 3.5 in this study) has lower tolerance of water stress because their normalised transpiration rate reduced at much lower suctions, as compared to the tree individuals with lower LAI (i.e., 1 – 2.5). It is found that only for suction range between 5 kPa and 50 kPa, the measured T_{rf} of *S. heptaphylla* is similar to those proposed by Feddes et al. (1978) and van Genutchen (1987). Beyond this particular suction, T_{rf} proposed by Feddes et al. (1978) and van Genuchten (1987) give a normalised transpiration rate higher and lower by 100% and 45%, respectively. The normalized transpiration rate for *S. heptaphylla* is around three times than that of potato reported by Utset et al. (2000),

The measurements of R_{df} of *S. heptaphylla* show that the distribution of normalised RAI is nonlinear, which is not able to be captured by some existing simplified distributions commonly assumed in the literature. The depth of maximum RAI of *S. heptaphylla* is at the depths of 0.7 to 0.8 times of its root depth.

Both T_{rf} and R_{df} are the important plant properties that reflect the ability of water uptake of a specific plant species in soil. It should be noted that the conclusion drawn from this note is based on one specific species *S. heptaphylla* at a specific plant age and environmental condition, and hence should not be generalized. Quantifying these two properties are necessary for more correctly assessing the distributions of soil suction and hence the stability of geotechnical infrastructure such as vegetated slopes, green roofs and landfill covers. T_{rf} and R_{df} are also the two key input parameters of macroscopic sink term that is used to take into account the effects of plant transpiration and root-water uptake in various geotechnical infrastructures.

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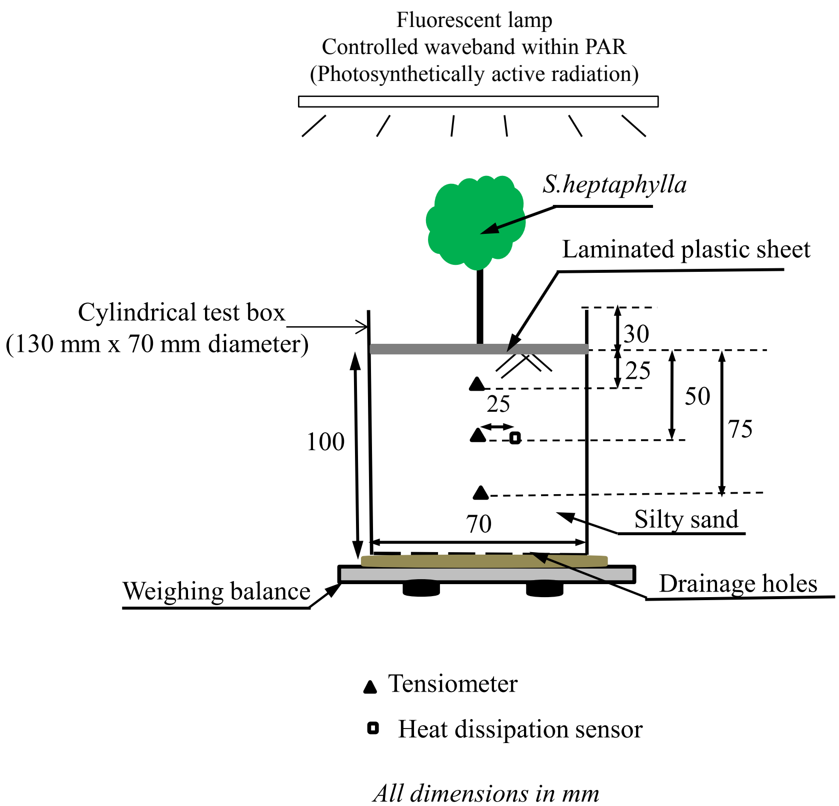

Fig. 1. Schematic diagram of test set up and instrumentation for measuring T_{rf}

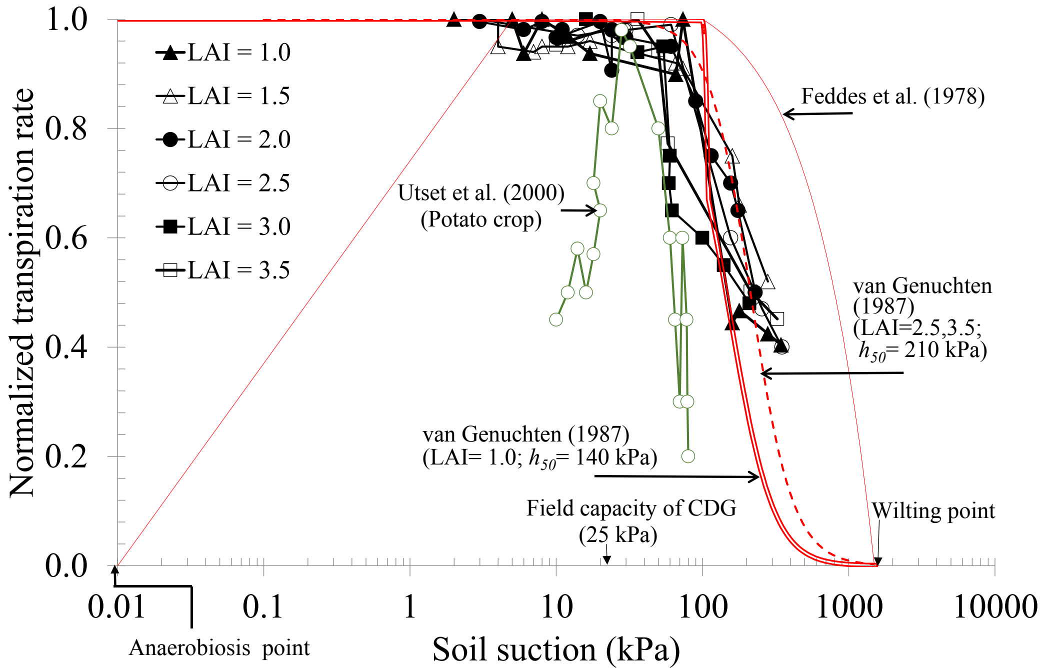

Fig. 2. Measured T_{rf} for *Schefflera heptaphylla* at different values of LAI

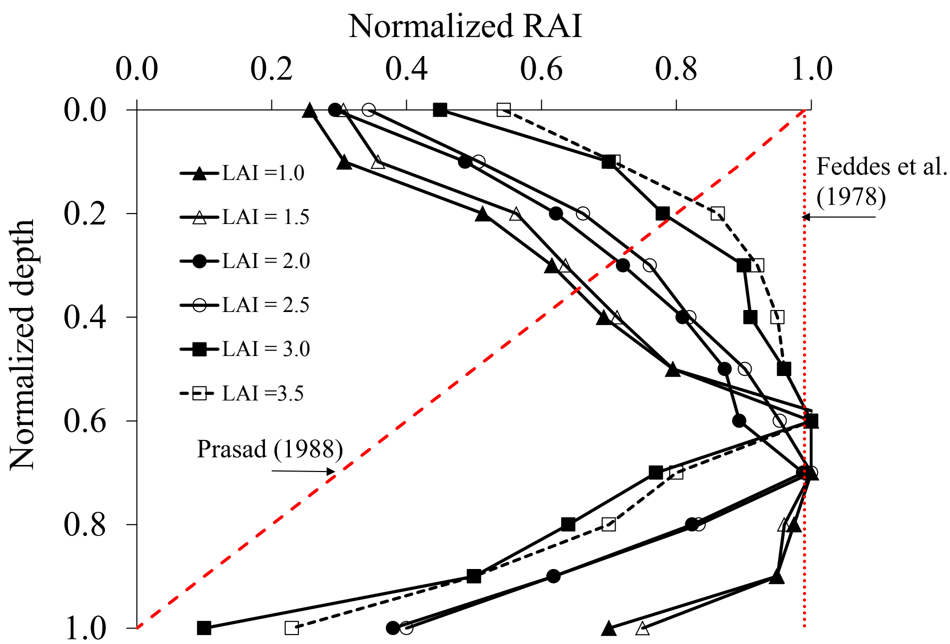

Fig. 3. Measured R_{df} of *Schefflera heptaphylla* at different values of LAI